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Driver-pedestrian interaction under legal and illegal pedestrian crossings

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Abstract

Pedestrian crossing outside of a zebra crossing (jaywalking) is one of those pedestrian behaviors that may highly affect safety and operations. Unlike permissible crossings at zebra crossings, jaywalking events are not often anticipated by drivers, which may result in less driver reaction time and different vehicle operation dynamics.
The objective of the research was to study driver's behavior as well as to model the interaction with a pedestrian, who was crossing at and outside (jaywalker) of designated zebra crossings. Data were collected through an instrumented vehicle study.
Sixteen participants took part in the survey. Each participant's vehicle was instrumented with a video camera and a global positioning system (GPS) device. Each participant drove his vehicle along two streets of the center of Rome, during which numerous events of crossings at and outside the zebra crossing were detected. The acquired data allowed obtaining the driver's speed profiles in approach to the pedestrian crossing.
The analysis was based on variables that were obtained from the speed profiles of drivers. The driver's behavior under legal and illegal crossings was analyzed in terms of driver yielding rates and yielding types, relationship between speed and distance of the vehicle from the conflict point at the decision point, and for different times left for the vehicle to get to the conflict point at the moment the pedestrian reaches the curb as well as pedestrian origin (form the right or left).
Significant differences were detected in driver's behavior during the interaction with the pedestrian crossing at and outside of the zebra crossing. 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.
The obtained results provide the basis for modeling interactions between pedestrians crossing at and outside of crosswalks and approaching drivers in a micro-simulation environment.

Keywords: Pedestrian; Driver's behavior; Road safety; Human factors

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1. Introduction

The number of road traffic deaths on the world's roads remains unacceptably high, with 1.35 million people dying each year. More than half of global road traffic deaths are amongst pedestrians, cyclists and motorcyclists who are still too often neglected in road traffic system design in many countries. Number of pedestrians' deaths are particularly relevant. In 2018, World Health Organization stated that 23% of total deaths by road user type are referring to pedestrians. In Europe, according to the data provided by the European Road Safety Observatory (2015), in 2015 about 5,435 pedestrians were victims of road accidents, which correspond to 21% of all fatal accidents. Finally, referring to the last Italian's accident data of ACI-ISTAT (2018), in 2017, 7,336 accidents were caused by drivers who did not yield to pedestrians, while 7,204 accidents were due by an irregular behavior of the pedestrian.

The aim of this study is to better understand the driver's behavior when a pedestrian crosses at and outside the zebra crossing in order to provide the basis for modelling these interactions in micro-simulation environments for traffic operational analyses.

2. Driver – Pedestrian Interaction

The driver-pedestrian interaction occurs when a driver, while traveling along a road, perceives a pedestrian who wants to cross. This interaction can happen both in legal pedestrian crossing, i.e. where there is the zebra crossing, and in illegal pedestrian crossing, i.e. outside the zebra crossing (jaywalking).

The interaction between driver and pedestrian is a rather complex dynamic to analyze. During this interaction the pedestrian waits for the best time gap to proceed with the crossing, on the other, the driver must understand if he/she has enough time to pass the critical point before the pedestrian, or should yield letting the pedestrian passes first (Bella et al., 2019). In this process the behavior of the driver and the pedestrian are strictly dependent. In fact, the driver modulates his behavior based on the pedestrian's intentions and can decide whether to pass first (not yielding to pedestrian) or not. Similarly, the pedestrian starts crossing only when he/she confides that the driver will yield to him/her. Therefore, both the subjects involved make choices and consequently act based on a series of dynamic and temporal variables. Varhelyi (1998) observed the driver's behaviour, approaching at zebra crossings, influenced by the arrival time of pedestrian at the curb and the arrival time of the vehicle at the crossing. Specifically, he defined the parameter TTZ (Time To Zebra) as the remaining time for the vehicle to reach the pedestrian crossing, i.e. the potential point of collision between vehicle and pedestrian, at the moment in which the pedestrian is located at the edge of the curb. Varhelyi used a flowchart to create a theoretical framework for studying driver-pedestrian interaction, based on the "Threat Avoidance Model", a model of threat prevention developed by Fuller (1984), which is based on the concept of defensive driving. According to Fuller, the driver can alternatively have a "discriminative stimulus" for a potential threat (i.e. pedestrian presence) or a "non-discriminatory stimulus". When the driver approaches a pedestrian crossing and a discriminative stimulus arise (i.e. there is a pedestrian), the driver can act different responses: a) the driver slows down and yields to the pedestrian (anticipatory avoidance response); b) the driver does not slow down (non – avoidance response) to communicate to the pedestrian that he/she wants to pass first. In the b) case, two possible conditions could occur: (i) the driver passes first or (ii) the pedestrian assumes a "competitive behavior", and therefore, the driver is forced to a delayed avoidance response (braking) or a collision occurs. The pedestrian's point of view as been widely discussed in the past, analyzing both legal and illegal crossings. According to the literature, legal crossings were analyzed by studying the pedestrian's behavior (Deb et al., 2017, Zhuang et al., 2018), the pedestrian's crossing speed (Iryo-Asano and Alhajyaseen, 2017, Zhuang and Wu, 2018) and the time gap acceptance of the pedestrians for passing or not (Petzoldt, 2014, Lobjois and Cavallo, 2007, Lobjois et al., 2013). Zheng et al. (2015) analyzed the illegal crossings, by both examining the pedestrian's behavior in terms of acceptance of time gap and speed adopted, and the corresponding reactions of the driver, in terms of yielding to pedestrian. Zhuang and Wu (2011, 2012) also analyzed pedestrian's behavior in illegal crossings, investigating the waiting time at the curb and the speed in crossing the road. Differences in pedestrian's behavior between legal and illegal crossings were studied by Mitman et al. (2008), who stated that pedestrians crossing outside the zebra crossing are more likely to look on both sides before crossing, to increase their speed and to wait for wider time acceptance gaps. Most of the past studies to investigate the driver-pedestrian conflict were conducted using fixed driving simulators (Bella et al., 2019, Bella and Silvestri, 2016, Petzoldt, 2014, Lobjois and Cavallo, 2007, Lobjois, 2013), fixed cameras along the road (Zhuang et al., 2018, Iryo-Asano and Alhajyaseen, 2017, Zhuang and Wu, 2011, 2012, Mitman et al., 2008) or questionnaires submitted to users (Deb et al., 2017). Only Zheng et al.

(2015) analyzed the interaction between drivers and pedestrians in illegal crossings using an instrumented vehicle. However, no studies have focused on the comparative analysis of the driver's behavior during interaction with a pedestrian who crosses at and outside the zebra crossing.

The present work aims to analyze, through an instrumented vehicle, the driver's behavior under different (legal and illegal) pedestrian crossings.

3. Field study

An instrumented vehicle was used in the study to understand drivers' attitudes and their behaviors during interaction with pedestrians, which perform legal and illegal crossings. The research team recruited subjects who drove along a predetermined route. The route had a total length of 3.5 km and consisted of two streets: Via Tagliamento and Via Po, in the center of the municipality of Rome. On the path there were 4 signalized intersections and 11 non-signalized intersections. The interested roads had the same cross-section: a single carriageway with a travel lane for direction with a width of 5.0 m, two parking lanes 2.0 m wide and two sidewalks of 1.5 m (Fig. 1). On both roads there was a parking lane up to the zebra crossings. For all the different zebra crossings, the pedestrian visibility conditions were similar; this allowed avoiding the influence on driver behavior due to the different levels of visibility.

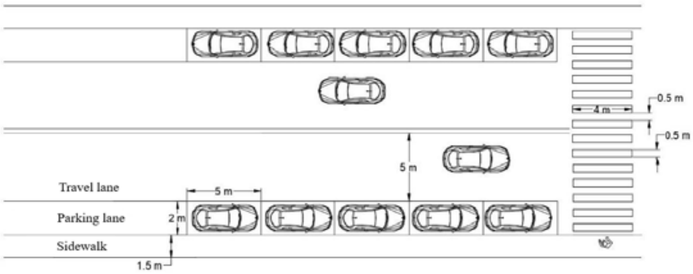

Fig. 1. Features of the cross-section of the two surveyed roads.

To perform this experimentation, a sample of 16 participants was involved. The age ranged from 23 to 45 years with an average of 31 years. All participants had at least 4 years of driving experience. They were recruited on a voluntary basis among students, faculty, staff of the University and other volunteers from outside of the University. Each participant used his own vehicle to avoid the potential conditioning in the experimentation, due to low confidence of the driver with not his own vehicle. The study was conducted in peak-off hours, to avoid conditioning due to vehicular traffic, and under dry weather conditions. The road pavement was therefore in dry conditions and it guaranteed maximum friction between tire and road pavement. To make the participants familiar with the path, they performed before each experiment a test run, in which the data were not recorded.

Drivers' vehicles involved in the survey were instrumented with a global positioning system (GPS) device and a GoPro Hero3 camera installed on the dashboard and oriented in the direction of the road, in order to record road environment and all the events that occurred during driving, such as pedestrian crossings. The driver had to face several pedestrian crossings (legal and illegal) and the video camera – synchronized with the GPS – recorded the videos from which, in the data processing phase, useful data were obtained for the analyses. GoPro's videos and GPS data were subsequently elaborated to quantify the parameters that allow analysing the driver's behavior in the interaction with the pedestrian under legal and illegal pedestrian crossings.

4. Methodology in data acquisition

The camera installed in the vehicles allowed obtaining video frames from which to extract driver-pedestrian longitudinal distances. In particular, the calculation of the driver-pedestrian longitudinal distances was carried out following the methodology defined by Psarianos et al. (2001). This allows calculating the longitudinal distances by playing on the perspective effect of stills. The correct determination of the vanishing point is of fundamental importance in the method used to estimate the longitudinal spacing. To automate the process and to obtain a more correct result, the MATLAB software was used and the Canny algorithm (1986) and subsequently DBSCAN algorithm (Ester et al., 1996) were implemented. Such algorithms allow obtaining the vanishing point starting from the image frame. The GPS device allowed obtaining vehicles position in time, and therefore vehicle speeds approaching the crossing point. The achievement of longitudinal distances and the related speed values that were obtained from GPS allowed the plotting of the vehicle speed profiles approaching legal and illegal crossings. Once the speed profiles approaching the conflict point (i.e. the crossing point) were plotted, the variables of interest were obtained.

5. Data Processing

For the analysis of the drivers' behavior towards the different pedestrian crossings, an amount of 76 driver-pedestrian interactions were recorded and the corresponding drivers speed profiles were plotted. The parameters of interest for the study were extracted from the speed profiles of the participants, for which three conditions in yielding to pedestrian occurred:

- the driver does not slow down, Not Yielding to pedestrian (NY);
- Yielding to pedestrian with a soft slowdown (Soft Yielding - SY), i.e. the driver slows down to a speed higher than 10 km/h to allow the pedestrian to pass;
- Yielding to pedestrian with a high slowdown (Hard Yielding - HY), i.e. the driver slows down to a speed lower than 10 km/h to allow the pedestrian to pass.

The descriptive variables of the driver's behavior, deduced from the speed profiles, in case of soft yielding or hard yielding, are shown in Figure 2 and explained in the following bullet list:

- L_i (m): distance between vehicle and conflict point when pedestrian has just reached the curb;
- V_i (km/h): vehicle's speed when pedestrian reaches the curb;
- L_m (m): distance between vehicle and conflict point when the driver starts a deceleration maneuver to yield to the pedestrian. This value is obtained observing the decrease in the speed profile;
- V_m (km/h): vehicle's speed when the deceleration maneuver begins;
- V_{min} (km/h): the minimum speed registered at the end of the deceleration phase;
- L_{min} (m): distance from the conflict point where V_{min} is located;
- d_{av} (m/s^2): the average deceleration to pass from V_m to V_{min}, evaluated with $d_{av}= (V_m^2-V_{min}^2)/[2*(L_m-L_{min})]$.

The driver decision point was also identified, defined as the location where the driver starts to react to the presence of pedestrians. For yielding cases, the decision point was identified at the point where the deceleration maneuver began, while for not yielding cases, it was assumed to coincide with the point at which the vehicle is located at the moment when pedestrian has reached the curb. Finally, the following inferred parameters were obtained: TTZ (Time To Zebra) and TTC (Time To Collision) calculated as Li/Vi (s), i.e. the time left for the vehicle to get to the crossing point at the moment the pedestrian reaches the curb. The difference between TTZ and TTC is that the first variable refers to a legal crossing while the second to an illegal one.

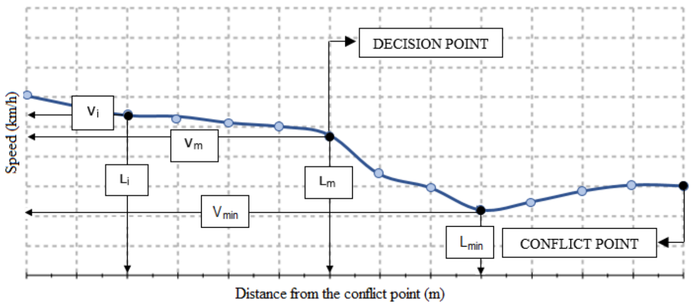

Fig. 2. Identification of the variables of interest from the driver's speed profile.

6. Results and Discussion

Among 76 driver-pedestrian interactions, 47 events were legal crossings (62%) and 29 events were recorded as illegal crossings (38%).

6.1. Driver yield rates and deceleration rates

Analysing the legal crossing, of the 47 driver-pedestrian interactions, 37 (79%) were events in which the driver yields to the pedestrian (Y), while only 10 interactions (21%) were events of not yielding (NY) to the pedestrian (Fig. 3.a). The percentage of drivers who yielded to the pedestrian with a soft slowdown (SY) (54% of Y) was greater than that recorded for yielding to pedestrian with a high slowdown (HY), (46% of Y) (Fig 3.b).
Regarding the illegal crossing, of the 29 driver-pedestrian interactions, 16 events were yielding to pedestrian (55%), while 13 were not yielding to pedestrian (45%) (Fig. 3.c). Also in this case, the percentage of drivers who yielded to the pedestrian with a soft slowdown (SY) (63% of Y) was higher than that recorded for yielding to pedestrian with a high slowdown (HY) (37% of Y) (Fig 3.d). As expected the drivers do not yield to pedestrian mostly when the pedestrian crosses outside of the zebra crossing (NY equal to 45%), compared to the legal crossing (NY equal to 21%). It should be noted that the rate of yielding to jaywalkers (55%) and that to permissible crossings (79%) are in line with those obtained by Zheng et al. (Zheng et al., 2015) (51% and 73%, respectively).

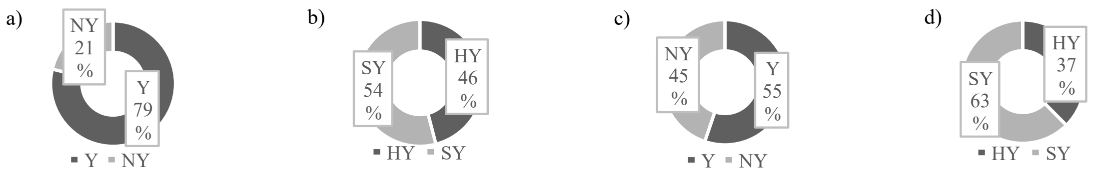

Fig. 3. Subdivision of legal events Y and NY (a); HY and SY (b); and illegal events Y and NY (c); HY and SY (d).

The average deceleration rates calculated in the HY and SY type conditions return a different driver's behavior for the legal and illegal crossings. At illegal crossings, the average deceleration rate was 1.5 m/s^2 in the HY condition and 1.0 m/s^2 in the SY condition. These values were respectively significantly higher than those for the legal crossings in which d_{av} was equal to 1.2 m/s^2 for the HY condition (p value=0.060) and 0.7 m/s^2 for the SY condition (p value=0.046). These values (both for legal and illegal crossings) were higher than those obtained by Zheng et al. (Zheng et al., 2015) which carried out their study on routes of the campus in University of Florida and also found non-significant differences in average HY deceleration rates (about 1 m/s^2) between permissible and illegal crossings.

6.2. Driver distance-speed relationship from the conflict point

Figure 4 shows the values of speed and distance from the conflict point that were recorded at the decision point for all the interactions (SY, HY and NY) for legal (fig. 4a) and illegal (fig. 4b) events.

The graphs highlight the possibility of classifying the decision of yielding to pedestrian based on the distance-speed relationship at the decision point. In both legal (Fig 4.a) and illegal (Fig 4.b) crossings, drivers are more likely to perform a high slowdown (HY) if their speed is low and are close to the crossing. Drivers with a higher speed decide to perform a soft slowdown (SY), if they are more distant from crossing, otherwise they cannot stop and decide not to yield (NY) when the decision distance is lower. It should be noted that for the illegal case, fixing the distance, the drivers do not yield to pedestrians (NY) even for lower speeds compared to the legal case.

Moreover, it should be pointed out that the average distance recorded at the decision point of all the manoeuvres (SY, HY and NY) was calculated at around 28 meters for legal events and 24 meters for illegal events. Consistently with past studies (Zheng et al., 2015), this highlights that drivers have less reaction time in interaction with a jaywalker (i.e. pedestrian who crosses outside the zebra crossing).

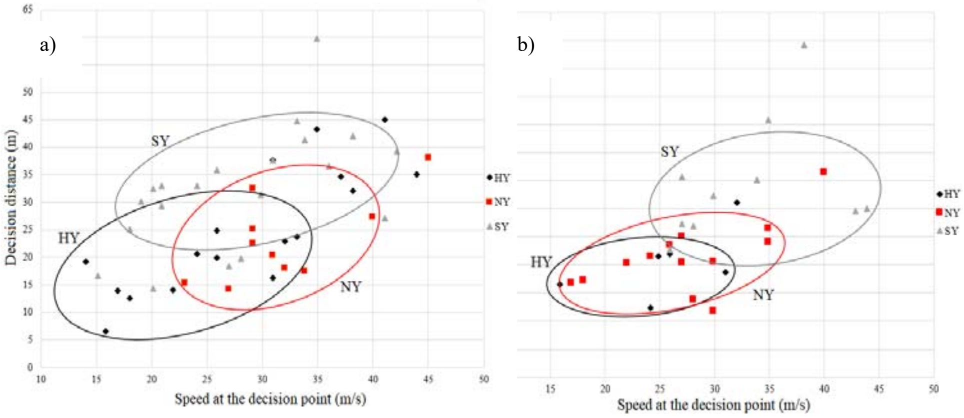

Fig. 4. Distance-speed relationship in the decision point for legal (a) and illegal (b) events.

6.3. Classes of TTZ and TTC

Drivers' behavior was also studied based on the different times of Time To Zebra (TTZ) in the case of legal crossing and Time To Collision (TTC) in the case of illegal crossing (see Tab. 1). Different times of such parameters return different conditions of driver-pedestrian interaction in terms of time left for the vehicle to get to the crossing point at the moment the pedestrian reaches the curb. Four classes were identified for these times:

- Class 1: TTZ (TTC for illegal crossing) ≤ 2.5 s;
- Class 2: 2.5 s < TTZ (TTC for illegal crossing) ≤ 3.5 s;
- Class 3: 3.5 s < TTZ (TTC for illegal crossing) ≤ 4.5 s;
- Class 4: TTZ (TTC for illegal crossing) > 4.5 s.

Tab. 1 shows the partition in Y, NY and in different conditions of yielding (SY and HY) for legal and illegal crossings according to the classes of TTZ and TTC respectively.

Table 1 - Subdivision of Y, NY, SY and HY events for legal and illegal crossings based on classes of TTZ and TTC respectively.

Classes		Legal					Illegal				
		Event	%Y	%NY	%SY	%HY	Event	%Y	%NY	%SY	%HY
1	TTZ (or TTC) < 2.5 s	10	40.0	60.0	25.0	75.0	3	0.0	100.0	0.0	0.0
2	2.5 < TTZ (or TTC) < 3.5 s	12	75.0	25.0	22.2	77.8	10	40.0	60.0	25.0	75.0
3	3.5 < TTZ (or TTC) < 4.5 s	8	87.5	12.5	42.9	57.1	9	55.6	44.4	60.0	40.0
4	TTZ (or TTC) > 4.5 s	17	100.0	0.0	82.4	17.6	7	100.0	0.0	85.7	14.3

In the case of legal crossing, drivers with TTZ lower than 2.5 s (class 1) tend predominantly not to yield (NY) to pedestrian (60%), while in classes 2, 3 and 4 with TTZ greater than 2.5 s, the rate of NY decreases as TTZ increases (25%, 12.5% and 0 %, respectively). In the case of yielding (Y), the driver performs a HY maneuver if TTZ is less than 4.5 s (% HY increasing with decreasing TTZ). Only when the driver has TTZ greater than 4.5 s, he/she yields with a SY maneuver. In the case of illegal crossing, none of the drivers yield when they have a TTC less than 2.5 s (class 1), and most of the drivers with a TTC between 2.5 and 3.5 s decide not to yield (NY) to pedestrians (60%). Also in the illegal case, the rate of NY decreases as TTZ increases. In the case of yielding (Y), the driver performs a HY maneuver if TTZ is more than 2.5 s but less than 3.5 s (% HY increasing with decreasing TTZ). The driver yields mainly in HY mode (75% on the total Y), having a shorter time to react and not expecting the presence of the pedestrian out of the zebra crossing. Only when driver has a TTC greater than 3.5 s, he/she yields with a SY maneuver.

Therefore, based on the TTZ (legal crossings) and the TTC (illegal crossings), it emerges that for values of such parameters less than 4.5 s the drivers yield for the legal case in a much higher percentage than the illegal case.

6.4. Pedestrian origin: right or left

An analysis of the origin of the pedestrian was conducted, whether from the right or the left of the driver (Tab. 2).

Table 2 – Pedestrian crossing origin from right or left.

	Legal				Illegal			
	Event	NY %	SY%	HY%	Event	NY %	SY%	HY%
Right	25	32.0	36.0	32.0	15	53.0	27.0	20.0
Left	22	9.0	50.0	41.0	14	36.0	43.0	21.0

One of the risk factors in driver-pedestrian interaction is the visibility of the pedestrian to be detected by the driver. The presence of parking lane decreases the visibility of the pedestrian crossing from the right. In fact, from Table 2 it is clear that the driver does not yield to pedestrian coming from the right and that the most critical conditions are for illegal crossings. In particular, 53% and 32% of interactions with pedestrians from the right result in NY events, for illegal and legal crossings respectively. In the case of a pedestrian from the left, on the other hand, the percentage of NY events is 36% for illegal crossings and only 9% for legal crossings, once again highlighting a greater criticality for illegal crossings. The motivation lies in the fact that the pedestrian coming from the left is more easily visible from the driver than the pedestrian coming from the right. The NY rates, both for pedestrian coming from left or right, are greater for the illegal crossing than for the legal one. This shows the driver's lower tendency to yield in the illegal case, because he/she is aware of the irregular behavior of the pedestrian who is considered a threat by the driver, according to the "Threat Avoidance Model" by Fuller (1984). Analyzing yielding cases, both for legal and illegal crossing, both for pedestrian from left and right, the SY maneuver is the most frequently adopted. Therefore, if the driver decides to yield to the pedestrian, he/she prefers to adopt a maneuver that does not require the need for slows down to speed lower than 10 km/h to allow the pedestrian to pass.

7. Conclusions

A methodology for data recording was defined to study the driver's behavior in the driver-pedestrian interaction at and outside the pedestrian crossings (legal and illegal crossings respectively). Field tests were carried out by a sample of drivers. Each driver drove own vehicle, which was instrumented with a GoPro Hero3 video camera and a GPS device, on two streets of Rome, Via Tagliamento and Via Po. Numerous events of crossings at and outside the zebra crossing were detected. The driver’s behavior under the two types of interaction with the pedestrian (legal and illegal crossings) was analyzed in terms of driver yielding rates and yielding types, relationship between speed and distance of the vehicle at the decision point, and for different classes of TTZ and TTC as well as pedestrian origin (form the right or left). The results showed that the driver has a greater tendency to yield to pedestrian if the latter is on the legal crossing (the yield rate was about equal to 80%), while he/she decide not to yield facing a jaywalker in almost half of the interactions. Even the average deceleration rates were higher in the case of illegal crossing, signaling greater ease for drivers in facing the pedestrian at the legal crossing.

Concerning the speed and distance of the vehicle at the decision point, it emerged that they affect the type of maneuver adopted by the driver, for both types of interaction (legal and illegal). In particular, the higher speed and the smaller distance from the conflict point leads to no yielding maneuver (NY). However, some relevant differences were detected for legal and illegal crossings. For the illegal case, the drivers do not yield to pedestrians even for lower speeds compared to the legal case, and they take the decision to yield or not to pedestrian for a lower average distance than that recorded for the legal crossing. This highlights that drivers have less reaction time in interaction with the jaywalker. Also the analysis of the driver’s behavior for different classes of time left for the vehicle to get to the crossing point at the moment the pedestrian reaches the curb (i.e. TTZ and TTC for the legal and illegal crossings respectively) highlighted relevant differences between the two types of crossing. For such time values less than 4.5 s, the percentage of cases in which the driver not yielded (NY) was always higher in the case of illegal crossings than that detected in the case of legal crossings.

The origin of the pedestrian also affected the driver's decision. Both for legal and illegal crossings, the percentage of NY is greater, in the case of a pedestrian crossing from the right. This result seems to be due to a lower visibility of the pedestrian, which is hidden from the driver's view by vehicles parked in the parking lane. However, the comparison of NY rates for legal and illegal crossings shows that, both for pedestrian coming from left or right, NY rates for the illegal crossings are greater than for legal crossings. This highlights the driver's lower tendency to yield in the illegal case, being aware of the irregular behavior of the pedestrian that, according the "Threat Avoidance Model" by Fuller (1984), is considered a threat by the driver.

The results of the present study highlight the need of a reduction of pedestrian exposure on the road by planning pedestrian paths in order to avoid crossings outside of a zebra crossing. Moreover, measures of the "Traffic calming" aimed at speed reduction and at adoption of road configurations that guarantee appropriate pedestrian visibility are incisive in increasing safety in driver-pedestrian interaction. Moreover, such outcomes, allowing a better understanding of the driver’s behavior, provide the basis for modeling interactions between pedestrians crossing at and outside of crosswalks and approaching drivers in a micro-simulation environment.

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References

ACI-ISTAT: Rapporto ACI - ISTAT sugli incidenti stradali, 2017. (in italian)

Bella, F., Borrelli, V., Silvestri, M., Nobili, F., 2019. Effects on Driver’s Behavior of Illegal Pedestrian Crossings. Advances in Human Aspects of Transportation 786, 802-812.

Bella, F., Silvestri, M., 2016. Driver's braking behavior approaching pedestrian crossings: A parametric duration model of the speed reduction times. Journal of Advanced Transportation, Volume 50, Issue 4, 630-646

Canny, J., 1986. A computational approach to edge detection. Journal of IEEE Transactions on Pattern Analysis and Machine Intelligence 8.6, 679–698.

Deb, S., Strawderman, L., DuBien, J., Smith, B., Carruth, D.W., Garrison, T.M., 2017. Evaluating pedestrian behavior at crosswalks: validation of a pedestrian behavior questionnaire for the U.S. population. Journal of Accident Analysis and Prevention 106, 191–201.

Ester, M., Kriegel, H.P., Sander, J., Xiaowei, X., 1996. A Density-Based Algorithm for Discovering Clusters in Large Spatial Databases with Noise, 2nd International Conference on Knowledge Discovery and Data Mining. Portland, Oregon, 226-231.

European Road Safety Observatory (source: CARE): Traffic Safety Basic Facts, 2015.

Fuller, R., 1984. A conceptualization of driver behaviour as threat avoidance. Journal of Ergonomics 27, 1139–1155.

Iryo-Asano, M., Alhajyaseen, W.K.M., 2017. Modeling pedestrian crossing speed profiles considering speed change behavior for the safety assessment of signalized intersections. Journal of Accident Analysis and Prevention 108, 332–342.

Lobjois, R., Benguigui, N., Cavallo, V., 2013. The effects of age and traffic density on street crossing behavior. Journal of Accident Analysis and Prevention 53, 166–175.

Lobjois, R., Cavallo, V., 2007. Age-related differences in street-crossing decisions: the effects of vehicle speed and time constraints on gap selection in an estimation task. Journal of Accident Analysis and Prevention 39, 934–943.

Mitman, M.F., Ragland, D.R., Zegeer, C.V., 2008. The Marked Crosswalk Dilemma: Uncovering Some Missing Links in a 35Year Debate. Journal of Transportation Research Record 2073, 86-93.

Petzoldt, T., 2014. On the relationship between pedestrian gap acceptance and time to arrival estimates. Journal of Accident Analysis and Prevention 72, 127–133.

Psarianos, B., Paradisis, D., Nakos, B., Karras, G., 2001. A Cost-Effective road surveying method for the assessment of road alignments, IV International Symposium Turkish-German Joint Geodetic Days. Berlin, Germany.

Varhelyi, A., 1998. Drivers’ speed behaviour at a zebra crossing: a case study. Journal of Accident Analysis and Prevention 30, 731–743.

World Health Organization: Global status report on road safety, 2018.

Zheng, Y., Chase, T., Elefteriadou, L., Schroeder, B., Sisiopiku, V.P., 2015. Modeling vehicle– pedestrian interactions outside of crosswalks. Jounrla of Simulation Modelling Practice and Theory 59, 89–101.

Zhuang, X., Wu, C., 2011. Pedestrians’ crossing behaviors and safety at unmarked roadway in China. Journal of Accident Analysis and Prevention 43, 1927–1936.

Zhuang, X., Wu, C., 2012. The safety margin and perceived safety of pedestrians at unmarked roadway. Journal of Transportation Research Part F 15, 119–131.

Zhuang, X., Wu, C., 2018. Display of required crossing speed improves pedestrian judgment of crossing possibility at clearance phase. Journal of Accident Analysis and Prevention 112, 15–20.

Zhuang, X., Wu, C., Ma, S., 2018. Cross or wait? Pedestrian decision making during clearance phase at signalized intersections. Journal of Accident Analysis and Prevention 111, 115–124.