Crossing Behaviour of the Elderly: Road Safety Assessment through Simulations

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Abstract. The assessment of the safety of road crossing facilities in urban scenarios can be supported by means of advanced computer-based simulations. Integrated models considering the vehicular and pedestrian traffic, and their interactions, still lack empirical evidences about the heterogeneous features of pedestrians, with particular reference to age-driven crossing behaviour. Elderly pedestrians are indeed one the most vulnerable road users, due to the progressive decline of cognitive and motor ability linked to ageing. In this paper we introduce the results of an observation at a non-signalised intersection aimed at characterising the crossing behaviour of the elderly. In particular, we compare the results about the crossing speeds and accepted safety gap among two sample of adult and elderly pedestrians while crossing. Then, the paper proposes an innovative approach for modelling pedestrians and vehicles interactions in the area of a zebra crossing, either signalized or not, considering the impact of age.

Keywords: Ageing, Pedestrian, Crossing, Modelling, Simulation

1 Introduction and Related Works

The Global Status Report on Road Safety by the WHO [23] showed that road accidents represent the 8th leading cause of death in the world population: 1.2 million people are killed on roads every year. Despite recent efforts, the measures currently in place to reduce road traffic deaths and injuries are mainly aimed at protecting car occupants. However, results showed that almost 50% of those dying on the world's roads are vulnerable road users (e.g., pedestrians, motorcyclists, cyclists). In particular, the percentage of pedestrians fatalities corresponds to 26% of the overall traffic victims in EU (16% in Italy, 14% in France, 14% in USA). This figure is even higher in low and middle-income countries, due to the rapidly increased number of registered vehicles.

To effectively contrast the social cost of traffic accidents it is necessary to integrate theoretical knowledge, analytical data and experience about pedestrian-vehicle interactions in urban scenarios, within an evidenced-based approach. From a methodological perspective, the complexity of such field of study requires a cross-disciplinary knowledge (e.g., traffic engineering, traffic psychology, safety science, computer science) and different techniques for data collection (e.g., on field observations, experiments in virtual reality environments, computer-based simulations). The achieved empirical results can support the development of advanced traffic management strategies and design solutions, to enhance the safety of transportation infrastructures and to prevent the occurrence of road fatalities.

In this framework, several empirical contributions [19, 18, 16] investigated the impact of the *physical environment* on pedestrian crossing behaviour (e.g., road width, traffic volumes, type of intersection, cross-walk location). Other researches studied how the *demographical* characteristics of pedestrians can impact their crossing behaviour, taking into account also the specific needs of vulnerable pedestrians such as the elderlies. Aged pedestrians are indeed more likely to die or be seriously injured in road traffic collisions than adult people due to their body fragility [1]. Moreover, the crossing behaviour of the elderly is negatively affected by decline in a range of motor functions and cognitive skills linked to ageing, as follows:

– *locomotion limitations* [15, 21], such as:
  - reduced range of motion;
  - loss of muscle strength and coordination;
  - changes in posture;
  - decreased walking speed.

– *perceptual-cognitive decline* [20, 13, 5], such as:
  - limited perception of light and colours;
  - inability to tune out background noise;
  - diminished attention and reaction time;
  - spatial disorientation;
  - slower and uncertain decision-making;
  - scarce assertiveness in communicating their intention to cross.

The necessity to guarantee the safety of aged pedestrians at road crossing infrastrictures has been highlighted by the World Health Organisation [22]: the concept of *Age-friendly Cities* describes indeed a framework for the development of cities which encourages the active ageing of the citizens by enhancing their mobility. This consists of guidelines and policies for assessing and increasing the accessibility and safety of urban facilities for the elderly. The mobility of aged people represents indeed a key factor for supporting them in maintaining an active and productive status, their social and civic participation and access to community and health services, in spite of the progressive social isolation linked to ageing [17].

In this context, the use of advanced computer-based simulation gives the possibility to test the safety of crossing intersections by testing alternative layouts and traffic management solutions. Whereas separately simulation approaches about vehicular traffic or pedestrian dynamics have produced a significant impact (see [14] for a review of different approaches), efforts characterized by an integrated micro-simulation model considering the simultaneous presence of vehicles and pedestrians are not as frequent or advanced. With the notable exception of [12], most efforts in this direction are relatively recent, such as [9], and they just analyse simple scenarios not even validated

Fig. 1. (a) A video frame of the analysed measurement area.

against real data. The most significant and recent work in this direction is represented by [24] which adapt the social force model to this kind of scenario; while this work considers real world data, the crossing behaviour of pedestrians is not thoroughly analysed.

The current work is aimed at producing an empirically validated model for the simulation of pedestrian-vehicles interactions at non-signalized crossings, considering the crossing behaviors of elderlies. The research effort is, thus, driven by the necessity to develop advanced and sustainable transportation strategies to contrast the social costs of pedestrians' injury and death due to car accidents [23].

Within this framework, this paper presents the results of an observation performed at a non-signalised intersection in Milan, focusing on data regarding elderly pedestrian while crossing (see Section 2). Then, it presents an example of integrated model for the simulation of pedestrian and vehicular traffic flows, allowing the specific evaluation of the level of efficiency and safety of the considered scenario (see Section 3). The paper ends with a discussion on results.

2 Observation Results

The video-recorded observation has been performed on May 2015 in a particular area of the city of Milan (the intersection between Via Padova, Via Cambini and Via Cavezzali). The scenario (see Fig. 1) has been selected by means of a preliminary analysis which was aimed at crossing the geo-referred information related to the socio-demographic characteristics of the inhabitants of Milan and the localization of road traffic accidents. Results showed that the chosen residential area is characterized by a significant presence of elderly inhabitants and an high number of accidents involving pedestrians in the past years[1]. See [10] for a detailed description of the observation methodology.

2.1 Level of Service and Drivers' Compliance

The bidirectional flows of vehicles and pedestrians passing through the observed zebra crossing have been counted minute by minute to estimate the traffic volumes (1379 ve-

[1] See `http://aim.milano.it/en/pubblicazioni-en/archivio-pubblicazioni-en`

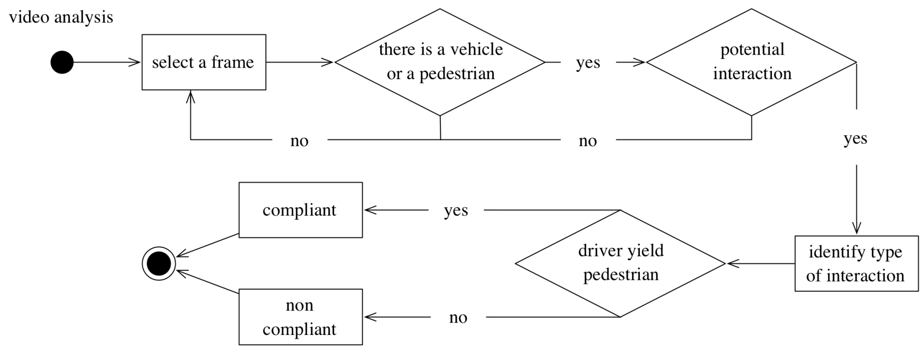


Fig. 2. The work flow for selecting of crossing episodes from the video frames.

hicles, 18.89 vehicles per minute) and pedestrian flows (585 crossing pedestrians, 8.01 pedestrians per minute). The estimation of pedestrians' age has been performed through the visual inspection of the video by considering a set of locomotion and physical indicators (e.g., walking pace, gait, posture, clothing, use of artefact for walking). Results showed that elderlies were a significant portion of the total counted pedestrians (24%).

A series of time stamping activities were aimed at measuring the Level of Service (LOS) [11], as an important indicator of the efficiency and safety of an intersection. The LOS has been estimated by time stamping the delay of vehicles due to vehicular and pedestrian traffic conditions (time for deceleration, queue, stopped delay, acceleration), and the delay of crossing pedestrians due to drivers' non compliance to pedestrian right of way (waiting, start-up delay). Results showed that both the average delay of vehicles (3.20 s/vehicle $\pm$ 2.73 sd) and the average delay of pedestrians (1.29 s/pedestrian $\pm$ .21 sd) corresponded to LOS A. In conclusion, the results about LOS showed that nearly all drivers found freedom of operation and that no pedestrians crossed irregularly, with low risk-taking crossing behaviour.

Then, a sample of 812 crossing episodes have been selected (see Fig. 2) and analysed to evaluate the overall compliance of drivers with crossing pedestrians. The episodes have been selected considering the direct interaction between one vehicle and one or more crossing pedestrians, and then classified to the type of interaction: (*i*) pedestrian approaching the cross-walk, (*ii*) pedestrian waiting to cross at the curb, (*iii*) pedestrian crossing on the zebra-striped, (*iv*) pedestrian approaching or waiting or crossing from the far lane. Results (see Tab. 1) showed that the 52% of drivers were compliant with pedestrians, stopping or slowing down to give way to them. The 48% of drivers were non compliant with the right of way of pedestrian; 6 episodes (1%) were characterized by non compliant drivers with pedestrians already occupying the zebra-striped crossing, with potentially risky interactions.

Table 1. Results about drivers' compliance to pedestrians' right of way at the observed non-signalized intersection.

Typologies of interactions	Compliant drivers	Non-compliant drivers
Pedestrians from the near side-walk	191 (46.14%)	223 (53.86%)
Pedestrians from the far side-walk	230 (57.79%)	168 (42.21%)
Total (812 crossing episodes)	421 (51.85%)	391 (48.15%)

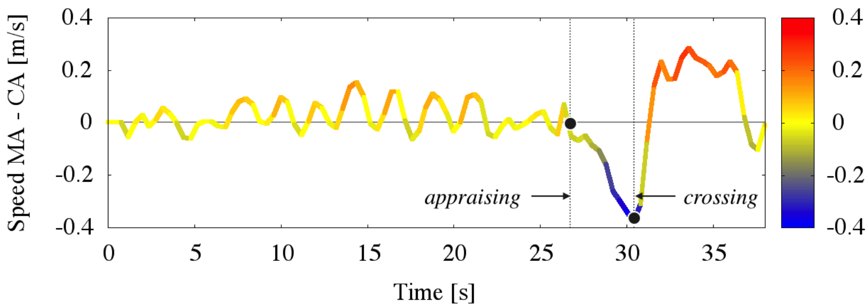


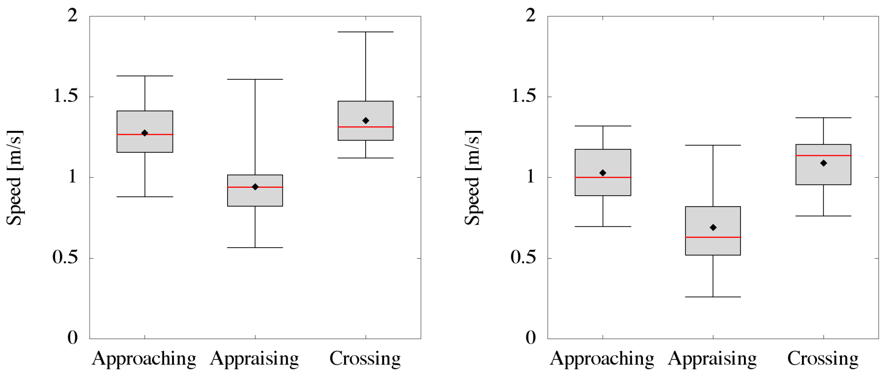
Fig. 3. An exemplification of the trend analysis performed on the time series of speeds. The starting time of the appraising and crossing phases are highlighted with black dots.

2.2 Pedestrian Speeds and Crossing Phases

A video tracking analysis has been performed considering a sub-sample of 50 pedestrians (27 adults, from about 18 y.o. until about 65 y.o.; 23 elderly, from about 65 y.o.), which were selected avoiding situations influencing the direct interaction between the pedestrian and the driver. Part of the selected episodes was characterised by the multiple interaction between the pedestrian and two vehicles oncoming from the near and the far lane. Moreover, the episodes have been sampled considering the impact of pedestrians' age and the effect of the different spatial layout of crossing points A and B.

The speed of pedestrians has been analysed among the time series of video frames (i.e. *trend analysis*). According to results, we defined a parametric description of crossing behaviour as composed of three distinctive phases (see Figure 3):

1. Approaching phase: the pedestrian travels on the side-walk with a relatively stable speed (Speed MA - CA $\simeq 0$);
2. Appraising phase: the pedestrian approaching the cross-walk decelerates to evaluate the distance and speed of oncoming vehicles (decision making). We decided to consider that this phase starts with the first value of a long-term deceleration trend (Speed MA - CA < 0);
3. Crossing phase: the pedestrian decides to cross and speeds up. The crossing phase starts from the frame following the one with the lowest value of speed before a long-term acceleration trend (Speed min).



(a) Adult Pedestrians (b) Elderly Pedestrians

Fig. 4. The speed of adult and elderly pedestrians among the crossing phases. The Box and Whisker plot reports: local maximum value, 75^{th} percentile, mean, median (highlighted in red), the 25^{th} percentile and the local minimum value.

A two-factors analysis of variance (two-way ANOVA) showed a significant difference among the speeds of pedestrians while approaching, appraising and crossing [F(2,144) = 61.944, $p < 0.0001$], and a significant effect of pedestrian' age on results [F(1,144) = 63.751, $p < 0.0001$] (see Tab. 2). A series of post hoc Tukey test showed a non significant difference between the speeds of pedestrians while approaching and crossing, considering both adults and elderlies ($p > 0.05$). The difference between the speed of adults and elderlies was significant among all the three crossing phases ($p < 0.0001$). A one-factor analysis of variance (one-way ANOVA) showed that there was no a significant effect of gender on the speeds of pedestrians while approaching ($p > 0.05$), appraising ($p > 0.05$) and crossing ($p > 0.05$) (see Tab. 2).

In conclusion, results (see Fig. 4) demonstrated that pedestrian crossing behaviour is based on a significant deceleration in proximity of the curb (appraising phase) to evaluate the distance and speed of oncoming vehicles and safely cross. A further consideration, concerns the need to embed heterogeneous features of pedestrians into computer-based simulation about crossing phenomenon: results showed also that elderlies walked in average 22% slower than adults among the three crossing phases, and they decelerated 6% more than adults while appraising. This demonstrated the impact of ageing on crossing behaviour in terms of motor skills decline.

2.3 Crossing Decision and Accepted Time Gap

Now we use the term *accepted time gap* to denote the ratio between the pedestrians's evaluation of the distance of an approaching vehicle and its average speed (not taking into account acceleration/deceleration trends) to decide to pass safely avoiding collision. Results are based on the estimation of the distance and speed of vehicles when pedestrians decide to cross and speed up (i.e. starting time of crossing phase, from

Table 2. The speeds of adult and elderly pedestrians among the three phases: approaching, appraising, crossing.

Phases	**Speed of adult pedestrians**	**Speed of elderly pedestrians**
Approaching phase	1.28 m/s ± 0.18 sd	1.03 m/s ± 0.18 sd
Appraising phase	0.94 m/s ± 0.21 sd	0.69 m/s ± 0.23 sd
Crossing phase	1.35 m/s ± 0.18 sd	1.09 m/s ± 0.17 sd

the frame after the one with the lowest value of speed before a long-term acceleration trend).

Results take into account the impact of several factors potentially influencing pedestrians' crossing decision. First of all, we compared results considering the lane occupied by the oncoming vehicle (oncoming from near lane or far lane). Then, focused on single and multiple pedestrian/vehicle interactions (one pedestrian interacting with only one vehicle or two vehicles oncoming from the near and the far lanes). Finally, we tested the impact of pedestrians' age on results.

A series of independent samples t-tests showed that crossing pedestrians did not discriminate between the distances and speeds of vehicles oncoming from the near (accepted time gap = 4.10 s ± 2.43 sd) and the far lanes (accepted time gap = 4.39 s ± 1.92 sd). Data analysis showed also that there was not a significant difference ($p > 0.05$) between the accepted time gaps in a situation comprising one vehicle approaching from the near lane (4.12 s ± 2.45 sd) or two vehicles respectively oncoming from the near and far lane (4.20 s ± 2.24 sd). A series of two-way ANOVA showed the non significant impact of the factors *age* ($p > 0.05$) and *gender* ($p > 0.05$) on results. The accepted time gaps of adult (3.98 s ± 2.55 sd) and elderly pedestrians (4.49 s ± 1.77 sd) did not differ significantly in any of the tested crossing typologies.

In conclusion, data analysis showed the average time gap accepted by pedestrians corresponded to 4.20 s ± 2.24 sd (average distance of vehicle = 16.83 ± 8.71 sd; average speed of vehicles = 15.93 ± 7.02 km/h). However, further data analysis on age-driven crossing decision have been performed, showing a significant difference between the time duration of the appraising phase among elderly (4.12 s ± 2.54 sd) and adult pedestrians (2.79 s ± 1.47 sd), $t(48) = 2.40658$, $p = 0.012$. Although pedestrians have the right of way on zebra-striped, elderly were found to be more cautious than adults: 57% of them gave way to at least one approaching vehicle, compared to 30% of adults. This result suggested that, when elderly pedestrians decided to cross, they were able to regulate their behaviour by adapting the accepted time gap to their own crossing capacities (lower walking speed).

3 Model Description

The model presented here extends the work proposed in [4]. In this paper we will provide a brief description of its core components, supporting the evaluation of results presented in the next section. For a complete and thorough discussion, we refer to [7].

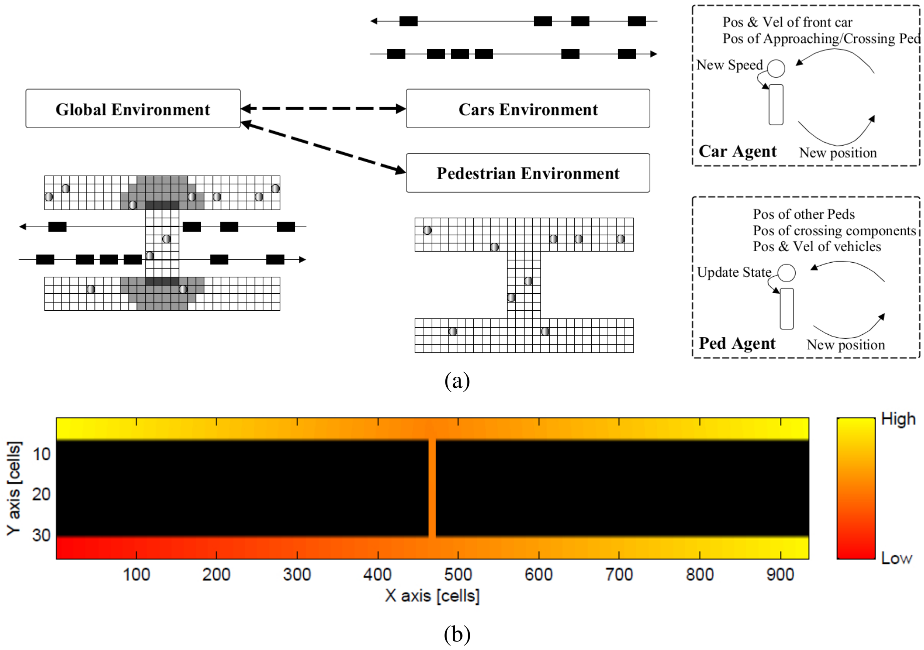


Fig. 5. (a) Schematic representation of the environments and agents. (b) Example of a floor field spread in the simulated scenario of the crossing.

The model supports the simulation of non-signalized pedestrian crossing by means of heterogeneous agents, namely pedestrians and vehicles. The two types are hosted in different environments, which grant an effective reproduction of the two different but coupled dynamics considered in the simulation.

As shown in Figure 5(a), the model is based on the integration of two independent models for the simulation of vehicles, moving in continuous lanes, and pedestrians, moving in a 2-dimensional discrete environment. The two environments are superimposed, and car-agents perceive pedestrian-agents while they are crossing or in the nearby of the curb (grey cells in Fig. 5(a)) and vice-versa. The interactions between them are described in Figure 5(b). Pedestrian-agents consider the speed and distance of cars to avoid collisions, giving way to non-compliant vehicles. The compliance of car-agents is mainly influenced by the necessary braking distance. On the other hand, according to a fixed probability that will be set on the collected data on compliance, car-agents can deliberately avoid to stop even if the braking distance is sufficient, requiring pedestrian-agents to yield.

3.1 The Behaviour of Car and Pedestrian-Agents

The motion of cars is based on the car-following model by Gipps [8], in which the speed of each vehicle is updated considering, firstly, internal parameters of the agent:

(i) maximum acceleration for each time-step of the simulation; (ii) maximum breaking capabilities; (iii) speed limit of the road. The presence of a vehicle ahead of the updating one affects its next speed according to a safe speed v_{safe}. v_{safe} is calculated based on the distance between the two vehicles and their breaking capabilities. In this way, possible collisions between cars are simply avoided in this model since they are not subject of investigation.

If the car-agent perceives a pedestrian, which is already crossing, then v_{safe} is calculated in order to let the car stop in correspondence of the zebra cross. Given the rules of the interaction also on the pedestrian-agent side, in this case the car-agent will always be able to stop before the crossing. On the other hand, if the pedestrian is approaching or waiting to cross the street, the car-agent will yield to the pedestrian if both there is enough space, according to its current speed, and the car-agent chooses to be *compliant*.

The behaviour pedestrian-agents is modelled on the basis of the classic *floor field model* [3]. When activated, pedestrian agents can move in the 8 cells surrounding their position in the grid (i.e. Moore neighbourhood). By considering the assumed side of cells and the time-step duration of the car model, the instantaneous speed of the agent is computable as $0.4/0.1 = 4.0$ m/s, which is rather high for pedestrian walking. A different time-step duration of 0.3s is then assumed to simulate the pedestrian motion, in order to get a maximum speed of pedestrians of about 1.3 m/s.

To simulate the three phases of crossing behaviour, as well as the observed differences in the speeds of adult and elderly pedestrians (see Sec. 2), the activation of pedestrian-agents for movement at the beginning of the time-step is managed in a probabilistic fashion, similar to [2]. In order to trigger a specific behaviour for the appraising phase, we exploited the intrinsic nature of the floor field generated by the curb close to the zebra crossing: since it indicates the distance from the cells generating it, its low value will trigger a specific set of actions to decide about crossing timing. In particular, when the pedestrian agent is nearby the curb, it will evaluate the safety gap from oncoming vehicles, which describes the time needed by the incoming car-agent c_i to reach the pedestrian-agent position, considering the current speed v_{c_i}.

4 Discussion about Simulation Results

The present paper has introduced a model for the simulation of pedestrian-vehicles interactions at non-signalized road crossings. The model is based on already existing approaches extended to grant the different actors the possibility to interact and coordinate their behaviours. The model has been defined according to the results of an observation, which was focused on studying the crossing behaviour of elderly pedestrians. The results of the observation have been employed to calibrate and perform an initial validation of the model in a reference scenario.

Simulation results are based on the arrival rate empirically observed for both pedestrian and vehicle traffic flows: 5.52 pedestrians per min; 16.53 vehicles/km. The speed limit was set to 35 km/h, based on the empirically observed velocities: despite the speed limit of 50 km/h, drivers were not able to approach this velocity due to the presence of additional intersections roughly 150 m before and after the modelled crossing.

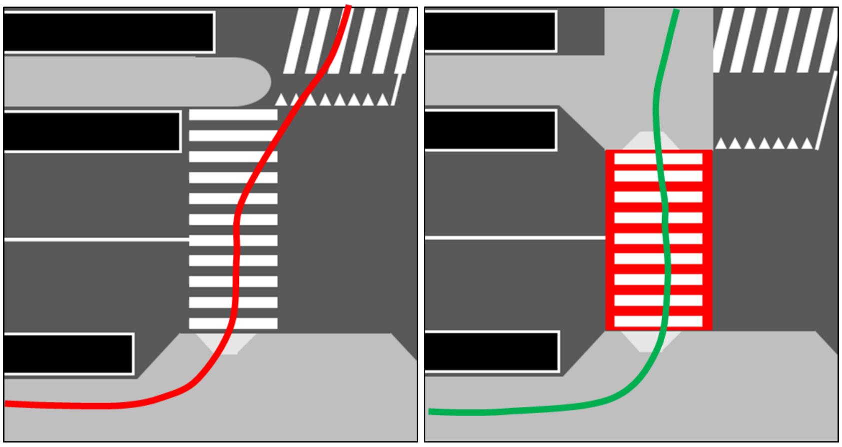
Table 3. Assignment of the calibration parameters regarding the operational level model.

Pedestrian features	*Value*
Adult walking speed (mean)	1.30 m/s
Adult walking speed (variance)	0.20 m/s
Elderly walking speed (mean)	1.05 m/s
Elderly walking speed (variance)	0.20 m/s
Acceleration	0.30 m/s^2
Deceleration	0.50 m/s^2
Crossing behaviour	*Value*
Appraising distance	3.0 m
Accepted gap adult (mean)	4.0 s
Accepted gap adult (variance)	2.5 s
Accepted gap elderly (mean)	4.5 s
Accepted gap elderly (variance)	1.8 s
Minimum accepted gap	1.0 s

The model improves the results of previous works in this area, with reference to the introduction of: (*i*) the non-compliance of drivers to pedestrians' right of way at zebra crossing; (*ii*) the observed appraising phase of pedestrians to evaluate the safety gap from oncoming vehicles to safely cross; (*iii*) the heterogeneous speeds of pedestrian-agents comparing adults and elderlies. With these features we introduced the heterogeneity among adult and elderly pedestrians, as described by the parameters shown in Table 3.

The *compliance* of drivers has been modelled in a static way: car-agents are configured as either compliant or not at their generation and they will keep this behaviour for all the simulation run. The probability of generating a compliant car-agent is then assigned to 0.5, in accordance to the observation. Moreover, since the results of the observation showed that there was no significant difference between the average time gap of adult and elderly pedestrians, the *accepted time gap* for all pedestrian agents in the simulation has been normally distributed with $\mu = 4$s and $\sigma = 2$s.

The results achieved through the simulation campaign are in tune with the empirical evidences of the presented observation, highlighting the validity of the model. Simulations can be already used to test the effects of different traffic conditions on the performance of the road infrastructure (e.g., travel time, LOS). In particular, the simulation results presented in [6] are based on an experimental evaluation of the risk of the crossing by considering: (i) different proportions between adult / elderly pedestrians; (ii) different traffic conditions; (iii) the possibility of distraction for both crossing people and drivers. On the other hand, the model currently allows few modifications to the tested environment, which now defines the surrounding –of configurable width– of a pedestrian intersection in a two-lanes road. It is already possible to simulate a longer road with more crossings by linking the borders of multiple environments with respect to this definition, but what is now lacking in the model and that will be part of future works is a component to manage arbitrary road intersections and more complex ge-



(a) (b)

Fig. 6. (a) Schematic representation of the observed cross-walk and possible alternative layout which could guarantee to pedestrians enough room for evaluating distance and speed of oncoming vehicles and take decision to cross in a more safe manner.

ometries of the setting. This would allow to enlarge the analysis to a larger area (e.g., a neighbourhood of a city), verifying possible propagations of jams due to mixed car-pedestrian traffic conditions, but also to test alternative spatial layout to avoid pedestrian jaywalking (see Fig. 6).

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