Age-driven Crossing Behavior and Walkability: Empirical Studies towards Simulations

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Abstract. The necessity to guarantee the comfort and safety of the elderly pedestrians while walking and crossing in urban environments can be supported by the use of advanced computer-based simulations. Nowadays, simulation of vehicular and pedestrian traffic is a consolidated application domain, but integrated models considering the interactions between these two entities still lack empirical evidences to produce validated simulations. In this paper we introduce the results of two empirical studies aimed at assessing the walkability degree perceived by the elderly inhabitants of a specific area of the city of Milan, considering the impact of drivers' compliance and level of service. Then, the paper proposes an approach to the modeling of pedestrians and vehicles interactions in the area of a zebra crossing, either signalized or not. The model is subject of further improvement and validation with the outcomes of the empirical studies.

Keywords: Ageing, Pedestrian Mobility, Walkability, Crossing, Modeling

1 Introduction and Related Works

In most OECD Member Countries older adults comprise the fastest growing segment of the population (i.e. *ageing society*), due to the decline of birth rate and the increase life expectancy [17]. As highlighted by the European Chart of Pedestrian Rights[1] (1988), one of the pillars of any strategy aiming at the inclusion in the society of the elderly population is to foster the pedestrian mobility in urban environments. The concept of *Age-friendly Cities*, introduced by the World Health Organisation [18], describes 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 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 [19].

[1] see `http://goo.gl/7J8xij`

The investigation of innovative solutions to enhance the comfort and security of elderly pedestrians is becoming a mandatory requirement for Municipalities, since aged people represent a vulnerable group of the population which is more likely to face greater risks while walking in urban contexts. In particular, the examination of the variables which determinate pedestrians' behavior (whose most important examples are locomotion and speed, perceptive and cognitive abilities) has demonstrated that elderly pedestrians are more likely to die or be seriously injured in road traffic collisions than adult people [2]. This is strongly conditioned by the progressive decline in the operation of: (*i*) perceptive sensors (e.g., limited perception of light and colors, inability to tune out background noise) and (*ii*) locomotor-cognitive skills (e.g., reduced range of motion, loss of muscle strength and coordination, changes in posture, diminished attention and reaction time, spatial disorientation) [22, 24]. All these bodily changes lead to a subjective perception of physical vulnerability and a sense of fragility at the psychological level [25]. These are the reasons why elderly people are more provident in the space, they move more slowly keeping more space around themselves, and they are more exposed to risky interactions with vehicular traffic.

Facing this trend, advanced urban planning activities are shifting toward a focus on *walkability*, namely how conducive and friendly the urban environment is for walking (e.g., quality of side walks, route navigation, pedestrian-vehicular interaction) [1]. The evaluation of the walkability degree of urban areas requires the involvement of many actors, skills, and disciplines, in a global scenario: the strategic and practical solutions which will emerge will be not just a mere sum of pieces of knowledge, and only cross-disciplinary attitudes in the creation of innovative approaches will increase the possibility to succeed for the future of our style of life in the cities (e.g., urban planning, traffic engineering, health science, social science, computer science).

In this context, the role of advanced computer-based systems for the micro-simulation of pedestrian circulation dynamics have emerged and affirmed as a consolidated and successful field of research and application, thanks to the possibility to test the efficacy of alternative spatial layouts focusing on pedestrian dynamics and walkability assessment. In particular, simulations allow to import a digital representation of a determined facility (e.g., CAD files) and to populate it with a certain number of agents, which navigate the environment according to a set of behavioural rules and individual goals/preferences. Within this framework, this paper presents a twofold effort: first, it presents an analysis of the elderly users perceived walkability (in terms of walking on sidewalks as well as street crossing), both in general terms and specifically applied to a local context in the city of Milano, Italy; second, it presents an example of integrated model for the simulation of pedestrian and vehicular traffic flows, allowing either the specific evaluation of a crossing in given conditions (spatial arrangement and demands) but also the exploration of the potential effects of changes in these conditions (e.g. introduction of traffic management measures, such as traffic lights, but also different crowding conditions). A brief discussion of the most relevant related work will follow, then Section 3 will describe the results of a data collection campaign devoted assessing the walkability degree of a specific area of Milan characterized by the presence of elderly inhabitants and risky pedestrian-vehicle interactions. Section 4 will present a simulation model considering basic interactions between pedestrians and vehicles at crossings, which is currently subject of further improvement with the consideration of the observed data and behaviors achieved with the empirical study above mentioned. Conclusions will present a discussion on the possible usage of the observation in the modeled behavior.

2 Related Works

Several successful modeling approaches have been produced in the literature, comprising *discrete* approaches (floor-field Cellular Automata model [3]) and *continuous* ones (the social force model [11]). These simulation models can be employed to provide a series of analyses to evaluate key performance indicators (e.g., walkability, level of service, travel time, ...) of the considered environment, which can be improved by testing different planning hypothesis aimed at enhancing the overall walkability.

The micro-simulation of cars and vehicular traffic has been as well a prolific research area in the last decades, producing models able to provide results for the activity of traffic engineers and planners. From pioneering works, such as [15], several successful models for the simulation of different aspects of vehicular traffic have been developed and applied: see, for instance, [16] for a review of different approaches, which include both discrete models (mainly cellular automata), also applied to complicated road sections such as roundabouts [21], and continuous ones, like car-following models [12].

Whereas separately micro-simulation approaches have produced a significant impact, efforts characterized by an integrated micro-simulation model considering the simultaneous presence of cars (and other vehicular traffic like trucks or buses) and vulnerable road users (in particular pedestrians, but also bicycles) are not as frequent or advanced as isolated vehicular traffic and pedestrian models. Although observation studies of pedestrian and driver behavior in crossing can be found, both in normal conditions [9] and with respect to the presence of crossing warning systems [8], few attempts towards the modeling of this kind of scenario have been performed. With the notable exception of [10], most efforts in this direction are relatively recent, such as [6], and they just analyse simple scenarios and they are not validated against real data. The most significant and recent work in this direction is represented by [27] which adapt the social force model to this kind of scenario, considering vehicles as generators of a repulsive force for pedestrians; while this work considers real world data, the analyzed scenario is characterized by a signalized crosswalk in which only turning cars can actually interact with pedestrians and their behavior is not thoroughly analyzed.

For the design of efficient, accessible and safe road infrastructures, human factors play a determinant role in the complex interaction among vehicles and pedestrians, also considering the specific needs of vulnerable pedestrians with limited mobility, such as the elderlies. The current work is finally aimed at producing a empirically validated model for the simulation of pedestrian-vehicles interactions at non-signalized crossings, considering the different behaviors of adults and 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 [26].

In addition to supporting pedestrian studies and the design of effective (safe and comfortable) solutions for urban traffic, this kind of study is also relevant to complement studies on autonomous vehicles (see, e.g. [20]) to evaluate future intelligent transportation schemes and scenarios.

3 Empirical Studies

Data collection campaign has been performed in a particular area of the city of Milan (the intersection between Via Padova, Via Cambini and Via Cavezzali). The scenario 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 pedestrian/car accidents involving elderlies pedestrians in the past years[2]. A series of inspections of the residential area allowed to select that particular unsignalized intersection among others, considering the large amount of people which pass through it due to several point of interests (e.g., local market, public offices, bank, supermarket, Church, Islamic cultural centre).

The current work is set on a methodology composed of two main data collection techniques coming from social sciences: face-to-face interviews by using a standard questionnaire about elderly users' perceived walkability and an on field observation to achieve detailed empirical data about pedestrian crossing behavior. The results achieved with the elderly users walkability analysis will be presented in the next section. For a detailed description of the results achieved with the observation of crossing behavior, we refer to the work in [7].

3.1 Walkability Assessment

A first phase of data collection was aimed at assessing the walkability degree perceived by the elderly inhabitants of the considered area of the city of Milan. The survey has been performed by using the "Walkability Checklist: How Walkable is your Community?"[3], a standard measure which has been designed by the US Department of Transportation, United States Environmental Protection Agency, National Center for Safe Routes to School and Pedestrian and Bicycle Information Center.

The checklist has been translated into Italian language and it has been modified according to the considered setting and the target audience. Then, the checklist has been administrated on different days of May 2015 to a large sample of elderly inhabitant of the area (total 122 people, 59 males, 63 females, average age 77 years $\pm$ 6.9 sd). The questionnaire consisted of four questions which focus on the walkability degree of the area in terms of comfort and safety while walking and crossing. Participants were asked to answer each question with a rating scale from 1 to 10, and to use multiple-choice options to point out eventual critical aspects (see Fig. 1/a).

[2] See `http://aim.milano.it/en/pubblicazioni-en/archivio-pubblicazioni-en`
[3] see `http://www.walkableamerica.org/checklist-walkability.pdf`

1. *How much pleasant is to walk in this area of the neighbourhood?*
   – Rating score: 5.27 ± 1.55 sd;
   – Most cited critical aspects: danger (38%), dirt (28%), scarce greenery (26%).

2. *Is there enough space to walk on the pavements?*
   – Rating score: 6.05 ± 1.28 sd;
   – Most cited critical aspects: irregular parking (30%), bad pavements conditions (21%), cycling on the pavements (20%).

3. *Is it easy to cross the street?*
   – Rating score: 4.37 ± 1.59 sd;
   – Most cited critical aspects: absence of a traffic light (62%), insufficient time to cross the road (34%), parked cars obstructing pedestrians' view (25%).

4. *How much do you think drivers behave well toward pedestrians?*
   – Rating score: 4.30 ± 1.58 sd;
   – Most cited critical aspects: driving speed (57%), drivers not stopping near zebra crossing (56%), double-parking habit (28%).

A linear regression was calculated to predict the impact of age on the overall evaluation of the walkability degree in the considered scenario (see Fig. 1/b). The Mean Walkability Score (MWS) has been calculated as the mean of results among Question 1 to 4, which corresponds to 5.00 ± 1.11. The hypothesis was that older respondents rated the questions with lower scores. A significant regression equation was found [F (1,121) = 6.166, p = 0.014, R-square of .049; MWS = 7.941 - 0.038 * Age]. Results showed that age has a significant effect on the general walkability rating condition in the neighbourhood of reference.

In conclusion, results showed that the interviewed elderly inhabitants perceived the walkability degree of the area as medium-low, above all considering the safety in crossing due to the scarce compliance of drivers in giving to pedestrians the right of way on zebra crossing. Moreover, results highlighted that the age of respondents has an impact on the overall evaluation of the walkability degree of the area. Results confirms that it is necessary to focus more on the specific needs of the elderly people as vulnerable users of urban pedestrian facilities.

3.2 Level of Service and Drivers' Compliance

A video-recorded observation was performed on May 18, 2015 (from 11 am to 12 am) in the selected area of the city of Milan. The observation was performed during the peak hour of the open-air local market which is held every Monday in Via Cambini. Weather conditions during the observation were stable and sunny. A HD ultra wide lens camera was mounted on a light stand tripod overhung from the balcony of a private flat (at an height of about 25 m) in correspondence of the zebra crossing at the intersection between Via Padova, Via Cambini and Via Cavezzali. The hidden position of the camera allowed to not influence the behaviour of drivers and pedestrians.

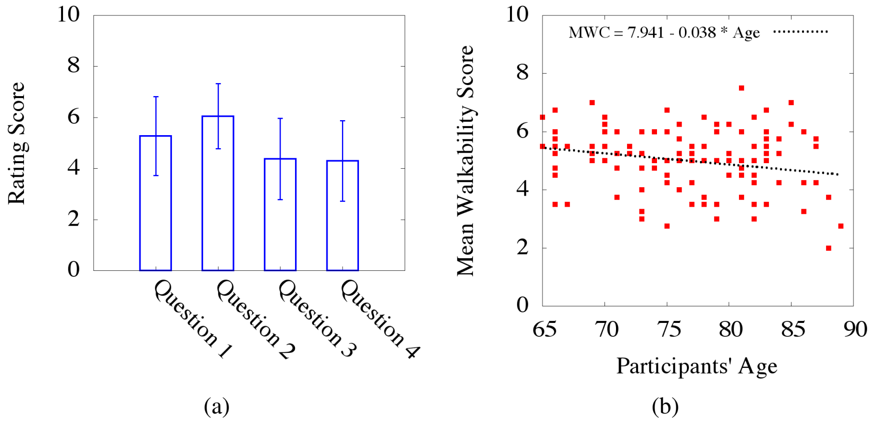

Fig. 1. Average rating score related to the each question of the walkability checklist (a). The regression scatter plot related to the impact of age on the overall evaluation of the walkability degree of the area (b).

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 vehicles, 18.89 vehicles per minute) and pedestrian flows (585 crossing pedestrians, 8.01 pedestrians per minute). An *ad hoc* checklist comprising a set of locomotion and physical indicators was used to support the annotators in profiling pedestrians' age (e.g., children, adults, elderlies). Results showed that elderlies were a significant portion of the total counted pedestrians (24%).

According to the design recommendations of [14], the measured traffic volumes (1139 vehicles/hour/both directions) were sufficiently high to hypothesize the implementation of a traffic light system for managing the observed unsignalized intersection. However, to reach an informed decision further and more extended observations should be performed, considering the potentially combined effect of peak hours and/or weather conditions on vehicular traffic volumes.

Then, a series of time stamping activities were aimed at measuring the additional travel time of experienced by drivers and pedestrians due to traffic conditions, in order to determinate the Level of Service of the observed unsignalized zebra crossing. The Level of Service (LOS) [14] standardly describe the degree of comfort and safety afforded to drivers and pedestrians as they travel/walk through an intersection or roadway segment. Six grades are used to denote the various LOS from A to F, by measuring the additional travel time (delay) experienced by drivers and pedestrians, as an important indicator of the efficiency of an intersection. At two-way stop-controlled unsignalized intersections (unsignalized zebra crossings in which pedestrians have the right-of-way) LOS E is considered to represent the minimum acceptable design standard (see Tab. 1).

The LOS have been estimated by time stamping the delay of vehicles due to vehicular and pedestrian traffic conditions (time for deceleration, queue, stopped delay,

Table 1. The Level of Service criteria for two-way stop-controlled unsignalized intersections [14].

LOS	Description	Veh. Delay [s/veh]	Ped. Delay [s/ped]
A	- Nearly all drivers find freedom of operation - Very small delay, none crossing irregularly	< 5	< 10
B	- Occasionally there is more than one vehicle in queue - Small delay, almost no one cross irregularity	5 - 10	10 - 15
C	- Many times there is more than one vehicle in queue - Small delay, very few pedestrian crossing irregularity	10 - 20	15 - 25
D	- Often there is more than one vehicle in queue - Big delay, someone start crossing irregularity	20 - 30	25 - 35
E	- Drivers find the delays approaching intolerable levels - Very big delay, many pedestrians crossing irregularity	30 - 45	35 - 50
F	- Forced flow due external operational constraints - Pedestrian cross irregularly, engaging risk-taking behaviours	> 45	> 50

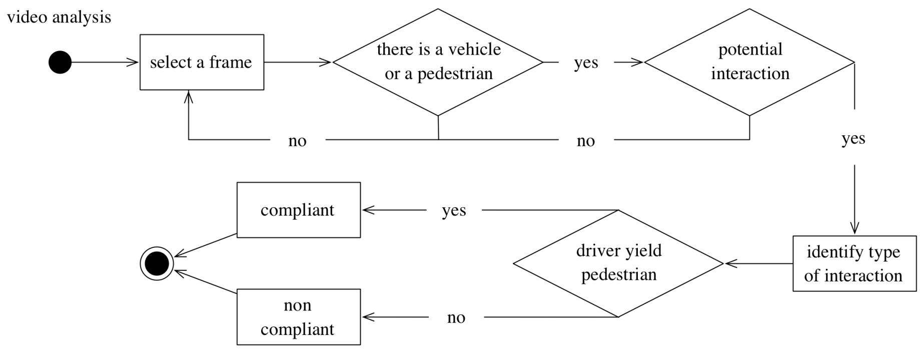

Fig. 2. The work flow for selecting of crossing episodes from the video frames.

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 analyzed 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 crosswalk, (*ii*) pedestrian waiting to cross at the at the curb, (*iii*) pedestrian crossing on the zebra-striped, (*iv*) pedestrian approaching or wait-

Table 2. The results about the compliance of drivers with crossing pedestrians.

Type of interaction	Drivers compliant	Drivers non compliant
Approaching pedestrians	11.70%	18.72%
Waiting pedestrians	8.62%	8.00%
Crossing pedestrians	3.20%	0.74%
Pedestrians from the far lane	28.33%	20.69%
Total	51.85%	48.15%

ing or crossing from the far lane. Results (see Tab. 2) 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.

4 Model Description

The simulation model proposed for the analysis of the crossing scenario refers to the one described in [4]. The system represents an integration of two independent model devoted to the simulation of respectively vehicular and pedestrian traffic. The join of the two models is made by a coordination algorithm that systematically avoid conflicts (i.e. accidents) between the two types of entities and allows a safe crossing for pedestrians by making them perceive the speed of the car. The aim of this work is to extend this model by considering the dynamics and behaviors observed in the scenario of Via Padova. The possible extensions will be discussed after a brief description of the model in object, reported to enhance the understanding and readability of the paper.

4.1 The environment

The environment is composed of different elements in a hierarchical structure (Fig. 3): the lower levels describe the sub-domains where the specific types of agents are situated; their union grants a projection of the overall dynamics. This approach is aimed at exploiting different representations (discrete and 2-dimensional for pedestrians, continuous and 1-dimensional for vehicles) allowing relatively simple behavioural specifications for the respective agents, which are hosted in independent environments with different dimensions. To allow the interaction between the two types of entity, the global environment also acts as a bridge to form a communication among the sub-domains.

The simulation scenario is modeled by annotating the global environment with the following *spatial markers*: (i) **Start area**, for the introduction of pedestrian agents in the environment, which can be done by a user-defined frequency; (ii) **End area**, representing final targets of pedestrian agents; (iii) **Street**, the portion of the space where the *cars* sub-environments are situated. Each lane of the street will instantiate one sub-environment, since lane changing and perception between cars of different lanes is not considered; (iv) **Obstacle**, to represent eventual obstacles in the sideways; (v) **Crossing**

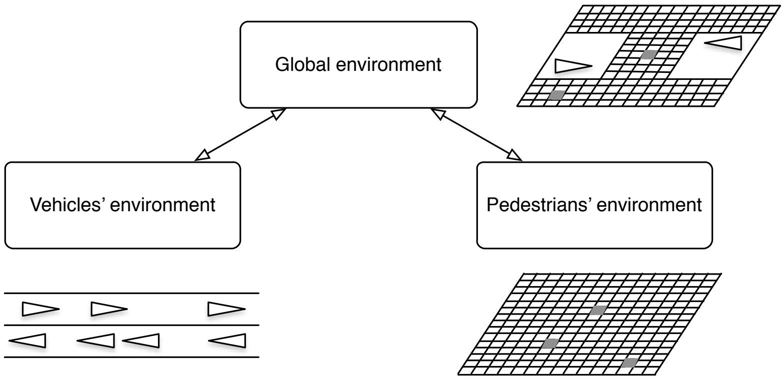

Fig. 3. Structure of the global environment composed of the vehicular and pedestrian sub-environments.

area, the shared space between the different entities; it can be *regulated* by semaphores or not.

Vehicular sub-environment The vehicular sub-domain $Street = \{q_1, \ldots, q_l\}$ is represented by the set of l continuous 1-dimensional queues, each one representing a single lane of the street. Each queue is modeled by another couple $\langle \mathrm{Dir}, V \rangle$, where Dir is the direction of the roadway and V is the set of vehicles. Each car is represented in the environment as the couple $\langle x_i,\ v_i \rangle$, which are the position and velocity of the vehicle i of the simulation.

Pedestrian sub-environment The pedestrian environment is discrete and represented by a set of grids of square cells of 40 cm side, describing the average space occupation of a person and the range of densities generally observed in the real world [23]. The main grid describes the structure of environment. The function $State(c)$ informs pedestrian type agents about cells usability at a given step: $State(c) : Cells \rightarrow \{Sidewalk$, $Street$, $ZebraCrs$, $ZebraBrd$, $Obstacle$, $Pedestrian\}$. Street, obstacles and cells already occupied by a pedestrian describe not usable spaces during the simulation. Among the usable space, the zebra crossing is specialized as *ZebraCrs*, the shared portion of the street, and *ZebraBrd* which describes its two borders. This annotation will be exploited by the interactions mechanism, supporting reciprocal perception by different entities.

Agents are driven to their targets by using the *floor field* approach [3]. This method is based on the generation of a set of additional grids, where gradients are generated starting from the cells belonging to a target. In this model only the *static floor field* is used, which contains for every cell a value of distance S_{ij} from one destination. In particular, objects of type *ZebraBrd* are also defined as targets, diffusing their own static floor field.

4.2 Vehicular Traffic Model

The behavioral model of cars has been designed on the basis of the work in [13], which describes a simplified version of the well-known Gipps car-following model [5]. We chose this continuous abstraction of traffic dynamics because it considers aspects like the *limited* acceleration and deceleration capability of a car, leading to a precise definition of a *safe* velocity per car at a given step.

The model is continuous in space and discrete in time, defining the step as the reaction time of the car drivers. It is, therefore, assumed that all the simulated drivers have the same reaction time of 1 second. The driver behavior is based on a small set of formulas which describe the speed of a car n_i at a step $t+1$ by considering three fundamental factors: (i) the current speed; (ii) the gap g between it and the preceding vehicle n_{i-1}; (iii) the speed of the preceding vehicle n_{i-1}. The last point is used to calculate the velocity which allows to maintain a safe state (i.e. to not have a collision with n_{i-1} even if it applies the maximum deceleration).

The update rule of the velocity v of a vehicle at a turn t is defined by the following equations (*ran* describe a random choice between the two elements):

$$v(t+1) = ran(v_0, v_1) \tag{1}$$

$$v_0 = min(v(t)+b,\ v_{max},\ v_{safe}) \tag{2}$$

$$v_1 = v_0 - \varepsilon \cdot \{v_0 - [v(t)-b]\} \tag{3}$$

In particular, v_0 represents two potential cases: when the vehicle has sufficient headway it can increase the velocity considering its previous value and its maximum acceleration b (that also describes the maximum deceleration) but not beyond the maximum velocity v_{max}; on the other hand, if the headway is not sufficient for maintaining or increasing the velocity, since a preceding vehicle is getting too close, the maximum safe velocity v_{safe} must be adopted. v_{safe} is computed in order to avoid a crash in the following turns even if the preceding vehicle should perform the maximum possible brake until a complete stop. Choosing the minimum value among the three assures that the most appropriate one is selected. v_1, instead, introduces a sort of small random additional drop on the adopted velocity, being essentially based on v_0 decreased by a small (potentially zero, but not negative). For the explanation of formula v_{safe} it is referred to [13].

Managing Interactions with Pedestrians While the above mechanism is conceived to manage interactions among vehicles, we have to define how interactions between vehicles and pedestrians are managed. The rationale is to adopt an altruistic attitude, from the car perspective. The function for the calculation of the highest safe speed v_{safe} is used to make vehicles calculate a speed able to avoid accidents with crossing pedestrians, as well as to stop for allowing pedestrians in the crossing nearby to proceed. The extended mechanism is shown in Fig. 4.

Car drivers are able to perceive also the position of the closest entity in front of the car, either a pedestrian or a red semaphore. The value of v_{safe}^{ped} is calculated considering the possibly perceived position of pedestrians and it describes the speed that drivers

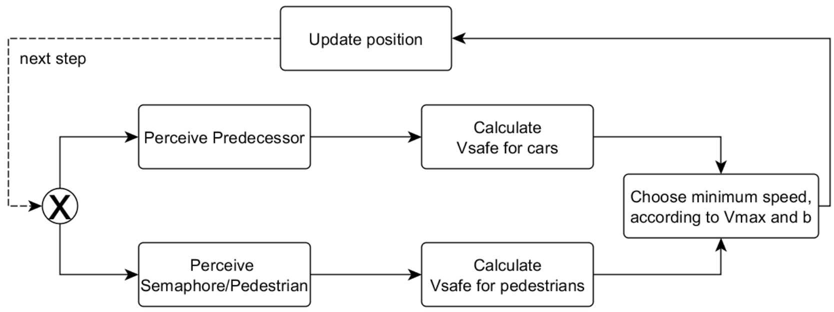

Fig. 4. Vehicles life-cycle updated to consider pedestrian presence.

can assume to avoid collisions with pedestrians and to let them cross the street. v_{safe}^{ped} is computed analogously as v_{safe}, assuming that pedestrian will mostly move along the y axis and not change the x-coordinate. In case of different values of v_{safe}^{ped} and v_{safe}, the minimum is chosen to always avoid collision and maintain a *collaborative* behavior of car drivers.

4.3 Pedestrian Behavior Model

The pedestrian behavior is described by the following two-phase life-cycle: (i) according to its final destination, each agent perceives values S_{ij} of cells of its Moore neighborhood, to understand the direction to take. With the perception phase, values ε_{ij} and $\eta_{ij} \in \{0,1\}$ are also computed, indicating respectively the presence of a not usable cell (in our case a cell c is not usable if $State(c) = Obstacle$ or $State(c) = Street$) and a cell occupied by pedestrians. Using this information, in step (ii), agents calculate the probability to choose each movement according to the function:

$$p_{ij} = N\varepsilon_{ij}\exp(\kappa_s S_{ij})(1 - \phi\eta_{ij}) \tag{4}$$

where N is a normalization factor, κ_s, $\phi \in [0,1]$ are calibration parameters. ϕ allows the usage of cells already occupied by pedestrians, leading to higher densities than the ones achievable with this configuration of the model, but since these situations are out from the scope of this work the parameter is set to $\phi = 1$. The model uses a *parallel* update strategy, so the agents firstly choose their direction of movement. This will be executed after the resolution of conflicts, ensuring $\eta_{ij} \in \{0,1\}$, $\forall\, i, j$.

Managing Interactions with Vehicles From the pedestrian point of view, interactions with vehicles are managed with the procedure shown in Fig. 5. The designed behavior is not as collaborative as for vehicles, since it is assumed that cars will stop if they are able: once the agent has reached the crossing its objective is to cross the street safely, so it has to verify that no cars are present nearby or the present ones are able to stop before the crossing. This reasoning is described by means of the following two equations (l denotes the number of lanes of the street):

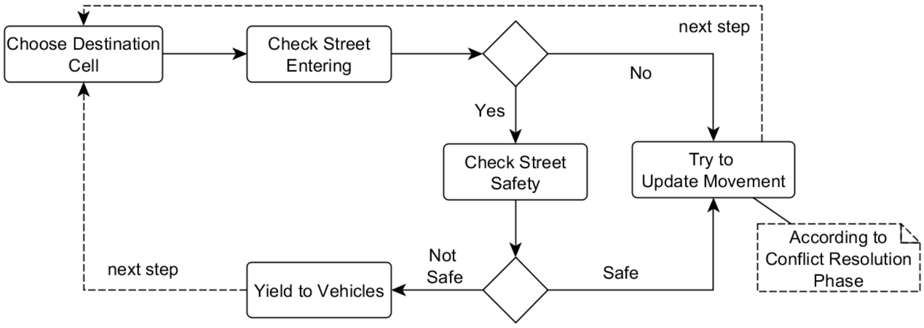

Fig. 5. Pedestrian life-cycle considering interactions with vehicles.

$$checkSE : Cells^2 \rightarrow \{\text{true, false}\} \tag{5}$$

$$checkSafety : \mathbb{R}^{l+1} \rightarrow \{\text{true, false}\} \tag{6}$$

The meaning of *checkSE* is to let agents understand that they are entering the crossing. This is formally explained by $State(p) == \text{ZebraBrd} \wedge State(d) == \text{ZebraCross}$, where p and d the cells describing position and chosen destination of the agent respectively.

Function *checkSafety* checks the speed of the closest approaching car to the crossing for each lane. Formally, $checkSafety(Street, p) = \text{true}$ iff for all not empty $q = \langle Dir, V \rangle \in Street$:

$$\exists \langle x_i, v_i \rangle \in V : \{(x_i < x_p) \wedge (\nexists \langle x_j, v_j \rangle \in V : \{x_i < x_j < x_p\}) \wedge (v_i > v^{ped}_{safe,i})\}$$

If the pedestrian *perceives* that approaching cars are not able to stop ($v_i > v^{ped}_{safe,i}$), it will yield to them. In the above formula we assume a left-right direction for each lane, but the formula for the other direction is analogous.

4.4 Modeling Regulated Interactions

Semaphores in the system are managed through the global environment, being essentially objects that can change their state given the passage of time (fixed cycle semaphores) or as a reaction to the arrival of a pedestrian (on call semaphore). In both the above cases, the semaphore is simply perceived by cars as an additional obstacle in the queue whenever the semaphore shows them the red light, causing the triggering of their braking. Similarly, whenever the semaphore shows a red light to pedestrians it is perceived as the presence of a car causing *checkSafety* to be uniformly false, independently from the actual road conditions.

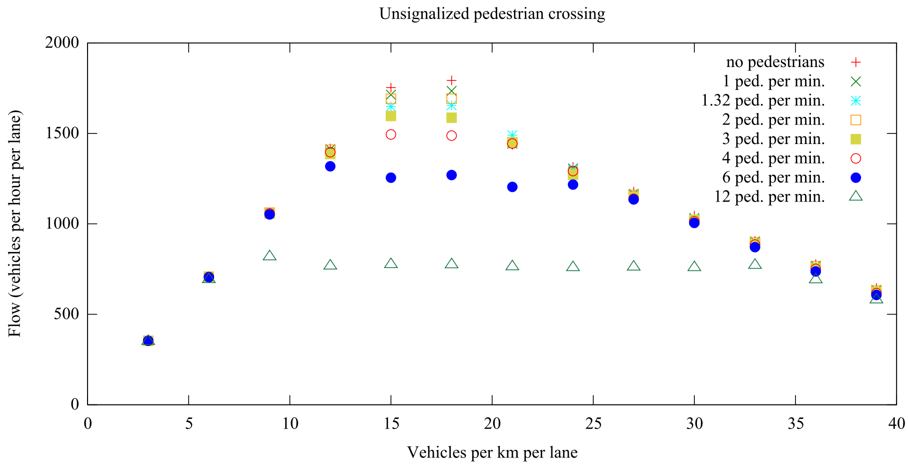

Fig. 6. Fundamental diagram of vehicle flow with different pedestrian crossing frequencies in an non signalized intersection.

4.5 Simulation Experiments

We tried to evaluate the capability of the model of generating a drop in the vehicular flow with a growing number of pedestrians trying to cross the road the above described scenario. Pedestrians are created randomly on one of the sidewalks according to a predefined frequency of generation and they try to cross the road; similarly also vehicles are initially positioned in the simulated road section (configured as a toroid) to be able to achieve a certain and stable level of vehicular density. By altering the number of cars and the frequency of pedestrian generation, we were able to achieve a fundamental diagram in which both the variation in the vehicular and pedestrian density were considered. The results are shown in Figure 6: each point is associated to one hour of simulated time and we can see that the maximum flow of vehicles drops from about 1700 vehicles per hour per lane to less than half of this value when the frequency of pedestrian generation reaches 12 pedestrians per minute (one approaching the zebra crossing every 5 seconds). Moreover, the critical density decreases with the growth of the frequency of pedestrian arrival.

A second set of experiments was conducted to evaluate the effect of the introduction of a semaphore in the scenario; in particular, we actually tested the introduction of three different types of regulations: the first two have a fixed cycle, respectively "long" (50 seconds of green light for cars, 40 for pedestrians) and short (in which both the timings are halved), and the last one is an *on call* semaphore, activated manually by an approaching pedestrian, generating a short green light period for pedestrians (25 seconds) that inhibits additional activations after its end for a similar amount of time (30 seconds). We tested the three configurations of the crossing in a similar way as the non signalized intersection, varying the vehicular traffic conditions, but actually fixing a certain rate of arrival for pedestrians. In particular, we simulated one hour in which the

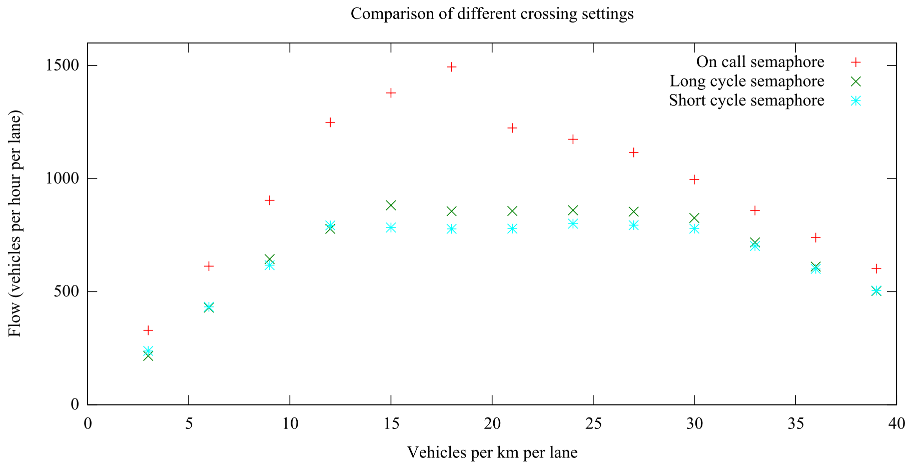

Fig. 7. Fundamental diagram of vehicle flow in different intersection configurations, respectively considering an on call semaphore, a long and short fixed cycle semaphore.

rate of arrival of pedestrians is generally low (about 3 pedestrians per minute) but for a few peak minutes in which the number of pedestrians grows to about 60 pedestrians per minute, a demand whose shape is similar to a Gaussian bell. The presence of a semaphore should reduce the impact of pedestrians on the vehicular flow while, at the same time, assuring a safe crossing possibility to the pedestrians.

The results of this experimentation are shown in Figure 7 and they are in line with our expectations: in particular, the fixed cycle semaphores cause a significant reduction of the vehicular flow and, among them, the long cycle configuration assures a slightly higher flow, granting a higher "global welfare" although at the cost of a potentially lower "local welfare" due to a higher maximum waiting time for both pedestrians and vehicles (although this data is not shown in the figure). The on call semaphore configuration, with this kind of pedestrian demand, is actually able to grant a vehicular flow only slightly lower than a situation of non signalized intersection with no pedestrians crossing the street: in fact, when very few pedestrians approach the crossing, the semaphore is rarely red for vehicles. On the other hand, when a large number of pedestrians approach the crossing, the semaphore acts as a sort of dam, accumulating pedestrians that want to cross the street in the green phase for vehicles, which is assured thanks to the 30 seconds inhibition phase following the green phase for pedestrians, arbitrating the access to the shared resource. The on call semaphore configuration, considering this model and therefore a compliant behavior of the involved stakeholders, seems able to assure a reduced impact on the vehicular traffic in case of low pedestrian presence, while at the same time providing a sense of safety to the pedestrians. On the other hand, its introduction has (one time and maintenance) costs that must be carefully considered.

5 Conclusion

A set of empirical studies has been presented for the assessment of the walkability degree in a case study scenario in Milan. The choice of the scenario is due to the significant presence of elderly inhabitants and an high number of pedestrian/car accidents involving elderlies pedestrians in the past years. The first study is based on the use of a standard checklist to evaluate the walkability degree perceived by the elderly users in terms of comfort and safety while walking and crossing. The second study is based on a series of analysis aimed at evaluating the compliance of drivers to crossing pedestrians at the non-signalized zebra crossing and its level of service.

The second part of the paper presented an integrated model for the interaction of pedestrians and vehicles in crossing situations. Existing models for the pedestrian and vehicular subsystems have been employed for the management of the ordinary behavior of the managed entities, extending them for allowing the mutual perception of the relevant entities. The interaction mechanism is still preliminary and it is based on a collaborative attitude, in which cars give way to pedestrians whenever they can actually safely brake to let them pass, and pedestrians yield whenever they perceive that the vehicle would not be able to stop in time.

Results show that this kind of model can be used to explore the impact of alternative traffic management approaches, but further work is necessary to improve and validate the crossing simulation model. In particular, this stage of the model does not consider the non-compliant behavior of drivers, which has been considerably observed. Moreover, a further detailed analysis of pedestrian crossing decision (accepted gap to cross) will be included in the model. It has been observed that the phase related to this decision needs a significant time and this time does variate among adults and elderly pedestrians, due to their limited perception capabilities. These effects are relevant for the dynamics and must also be considered in the model.

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