Collision Avoidance Dynamics among Heterogeneous Agents: The Case of Pedestrian/Vehicle Interactions

Stefania Bandini[1, 2], Luca Crociani[1], Claudio Feliciani[2], Andrea Gorrini, and Giuseppe Vizzari[1]

[1] Complex Systems and Artificial Intelligence research center, Univ. Milano - Bicocca (Italy)
[2] Research Center for Advance Science and Technology, The University of Tokyo (Japan)

Abstract. The dynamics of agent-based models and systems provides a framework to face complex issues related to the management of future cities, such as transportation and mobility. Once validated against empirical data, the use of agent-based simulations allows to envision and analyse complex phenomena, not directly accessible from the real world, in a predictive and explanatory scheme. In this paper, we apply this paradigm by proposing an agent-based simulation system focused on pedestrian/vehicle interactions at non-signalized intersections. The model has been designed based on the results gathered by means of an observation, executed at a non-signalized intersection characterized by a relevant number of pedestrian-car accidents in the past years. Manual video-tracking analyses showed that the interactions between pedestrians and vehicles at the zebra cross are generally composed of three phases: (i) the pedestrian freely walks on the side-walk *approaching* the zebra; (ii) at the proximity of the curb, he/she slows down to evaluate the safety gap from approaching cars to cross, possibly yielding to let the car pass (*appraising*); (iii) the pedestrian starts *crossing*. The overall heterogeneous system is composed of two types of agents (i.e. *vehicle* and *pedestrian* agents), defining the subjects of the interactions under investigation (i.e. *collision avoidance dynamics*). The system has been used to reproduce and stress the observed traffic conditions to analyse the potential effects of overloading the system on the comfort and safety of drivers and pedestrians.

Keywords: Agent-based Modelling, Simulation, Collision Avoidance

1 Introduction

The "*Global Status Report on Road Safety*" by WHO [17] showed that road accidents represent the eighth leading cause of death in the world population: 1.25 million people are killed on roads every year. Pedestrians are some of the most vulnerable road users: the percentage of pedestrian fatalities corresponds to 36% of the overall traffic victims in Japan, 23% in the United Kingdom, 16% in Italy and 14% in USA.

To effectively contrast the social cost of traffic accidents it is necessary to make transportation infrastructures safer, but also to design traffic policies able integrate theoretical knowledge and analytical data within an evidenced-based approach [13]. In this framework, the effort from academic research 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. From a methodological point of view this represents a challenging field of study which requires a cross-disciplinary knowledge (e.g., traffic engineering, traffic psychology, safety science, computer science).

In this context, computer-based systems for the simulation of vehicular or pedestrian traffic have been increasingly reported in the technical and scientific specialized literature, as a support to the activity of engineers and planners in the design of efficient and safe transportation networks. In particular, scientific communities started to incorporate agent-based systems to improve the expressiveness of traditional modelling approaches and to simulate the complex behaviour of traffic dynamics in urban scenarios.

The intrinsically dynamical properties of agent-based models offer indeed a research framework to face the complexity of the future cities [14], offering new possibilities to incorporate and integrate the growing presence of autonomous entities/artefacts both physical (e.g. autonomous vehicles) and virtual (e.g. data coming from heterogeneous sources: social media, distributed sensors etc.).

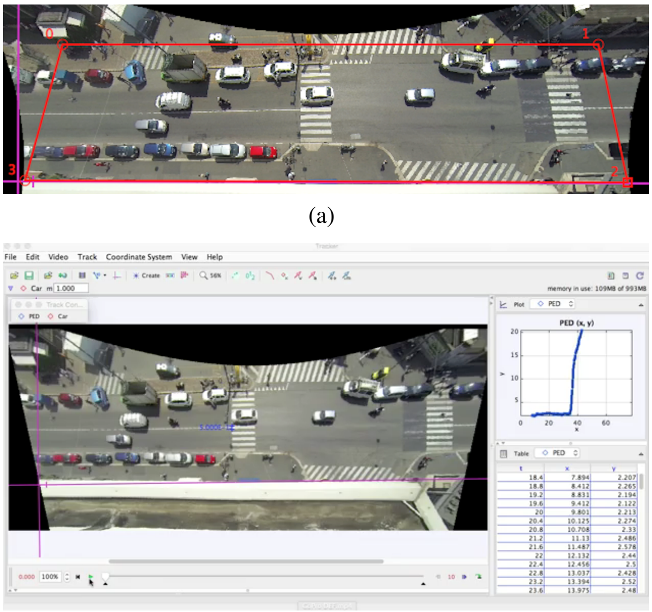
The development of plausible agent-based systems requires to test the quality of the obtained simulation results against real data [4]. Once validated, the use of simulations can support the activities of decision makers thanks to the possibility to test in advance the effects of different traffic management solutions in a predictive and explanatory scheme. In line with this general approach, the aim of this paper is to present a real case of data collection performed to: (*i*) collect empirical results about pedestrian-vehicles interactions at non-signalized intersections; (*ii*) support the development of a heterogeneous agent-based system to simulate the phenomenon.

From pioneering works, several models have been developed and applied for the simulation of pedestrian and vehicular dynamics, including both CA and particles models [8]. These two approaches have, separately and independently, produced a significant impact; efforts proposing instead an integrated 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 simplistic, narrow (i.e. targeting extremely specific situations [18]), homogeneous for the simulated entities, and they are often not validated against real data [10].

In this paper we present a novel simulation model that allows simulating pedestrian/vehicle interactions at non-signalized intersections. The model has been designed according to the results of a video-recorded observation, which focus on: (*i*) the level of compliance of drivers to traffic norms (yielding crossing pedestrians); (*ii*) pedestrians' behaviour while deciding to cross (speeds and safety gap evaluation). Thus, the model is based on the overall observed *collision avoidance* dynamics, in the context of interactions among heterogeneous agents and its implications on self-organization dynamics. In particular, we focus on the effects of a variation of the traffic conditions, described in terms of both incoming vehicles and pedestrians, on the performances of the crossing.

2 Data Collection

The video-recorded observation [11] was performed on May 18, 2015 (from 10:45 am, 73 minutes in total), at a non-signalized intersection in Milan (Italy). The intersection



t	x	y
18.4	7.894	2.207
18.8	8.412	2.265
19.2	8.831	2.194
19.6	9.412	2.122
20	9.801	2.213
20.4	10.125	2.274
20.8	10.708	2.33
21.2	11.13	2.486
21.6	11.487	2.578
22	12.132	2.44
22.4	12.456	2.5
22.8	13.037	2.428
23.2	13.394	2.52
23.6	13.975	2.48

(a)

(b)

Fig. 1. A video frame of the observed zebra crossing with an example trajectory(a). A screen shot from the tracker tool used for data analysis (b).

has been selected by means of a preliminary analysis related to the localisation of road traffic accidents. Results showed that this area is characterised by a high number of pedestrian/car accidents in the past years. The observation was performed during the peak hour of the open-air local market which is held every Monday. Weather conditions during the observation were stable and sunny.

A first phase of data analysis consisted of manual counting activities to quantify the bidirectional flows of vehicles (1379 vehicles, 18.89 vehicles per minute, 67% cars) and pedestrians (585 pedestrians, 8.01 pedestrians per minute).

The level of performance of the cross-walk has been estimated according to the Level of Service criteria (LOS) [13], which describes the degree of comfort and safety afforded to drivers and pedestrians as they travel/walk through an intersection or roadway segment (see Tab. 1). The LOS have been estimated by time stamping: (*i*) the delay of vehicles (time for deceleration, queue, stopped delay, acceleration) due to vehicular and pedestrian traffic conditions; (*ii*) the delay of crossing pedestrians (waiting, start-up delay), due to drivers' non compliance to their right of way on zebra crossings. Results showed that both the average delay of vehicles (3.20 s/vehicle ± 2.73 sd) and the average delay of pedestrians (1.29 s/pedestrian ± 0.21 sd) corresponded to LOS A.

Then, a sample of 812 crossing episodes was selected from the video in order to assess the compliance of drivers to pedestrians' right of way at non-signalized intersection (see Tab. 2). The crossing episodes have been selected considering only the cases

Table 1. The Level of Service criteria for two-way stop-controlled unsignalized intersections [13].

LOS	Description	Vehicular Delay [s/veh]	Pedestrian 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

Table 2. Results about the drivers' compliance to the right-of-way of crossing pedestrians.

Type of pedestrian/vehicle interactions	**Compliant**	**Non-compliant**
Ped. approaching/waiting/crossing from the near side-walk	191 (46.14%)	223 (53.86%)
Ped. approaching/waiting/crossing from the far side-walk	230 (57.69%)	168 (42.21%)

in which one vehicle directly interacted with one or more pedestrians and the position of pedestrians with respect to the direction of movement of the vehicle (near or the far side-walk).

Results showed that 48% of the total number of crossing episodes was characterized by non-compliant drivers with crossing pedestrians from the two side-walks. A multiple linear regression[1] was calculated to predict the percentage of non-compliant drivers per minute based on: (*i*) number of vehicles per minute (18.89 veh/min in average; $p = 0.007$, significant predictor) and (*ii*) number of crossing pedestrian per minute (8.01 ped/min in average; $p < 0.001$, significant predictor). A significant regression equation was found [$F(2,70) = 14.526$, $p < 0.001$], with R^2 of 0.293.

According to the results presented by [15], the results of the observation show that the non-compliance of drivers is determined by traffic conditions and by pedestrian flows on zebra. Despite the low level of drivers' compliance, no accidents or risky situations have been observed, thanks to the self-organization of the system based on pedestrians' yielding/collaborative behaviour to approaching cars and the observed high level of performance of the cross-walk (LOS A).

A second phase of video tracking data analysis was executed by using the software *Video Analysis and Modelling Tool*[2] (see Fig. 1), which allowed to manually track a sample of 50 pedestrians and 79 vehicles[3]. The data set (including the X, Y coordinates and the associated frames t) was exported for data analysis, aiming at measuring the

---

[1] All statistics have been conducted at the $p < .01$ level.

[2] See `www.cabrillo.edu`

[3] The sample was selected avoiding situations such as: platooning of vehicles on the roadway inhibiting a crossing episode, the joining of pedestrians already crossing, and in general situations influencing the direct interaction between the pedestrian and the drivers.

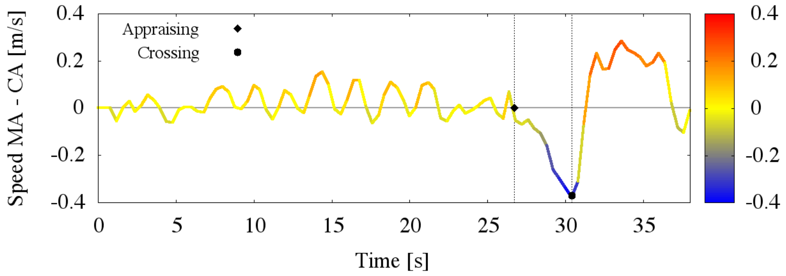


Fig. 2. An exemplification of the trend analysis performed on the time series of speeds.

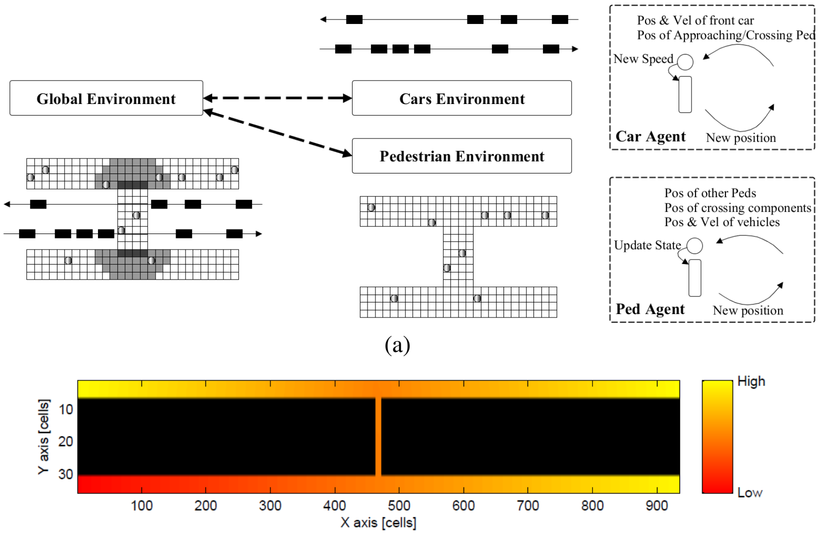
speeds of vehicles and pedestrians while interacting at the zebra crossing and the safety gap accepted by pedestrians to cross.

Pedestrian speeds have been analysed among the time series of video frames (trend analysis), as characterised by: (i) a stable trend on side-walks, (ii) a significant deceleration in proximity of the cross-walk (decision making) and (iii) an acceleration on the zebra crossing. According to results, crossing behaviour is defined as composed of three distinctive phases (see Figure 2):

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

An analysis of variance (ANOVA) showed a significant difference among the speeds of pedestrians while approaching (1.28 m/s ± 0.18 sd), appraising (0.94 m/s ± 0.21 sd) and crossing (1.35 m/s ± 0.18 sd) ([F(2,144) = 61.944, $p < 0.000$].

The term *safety gap* denotes 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). The average safety gap accepted by pedestrians corresponds to 4.20 s ± 2.24 sd (average distance of vehicle = 16.83 ± 8.71 sd; average speed of vehicles = 15.93 hm/h ± 7.02 sd). Although pedestrians have the right of way on zebra-striped, 30% of them gave way to at least one approaching vehicle. This result suggested that pedestrians were able to regulate their behaviour, by taking into account their own crossing capacities (walking speed), but also the breaking distance needed by vehicles to stop and the lack of compliance of drivers to traffic norms.



(a)

(b)

Fig. 3. (a) Schematic representation of the environments and agents. (b) Example of a floor field spread in the simulated scenario of the crossing.

3 Simulation Model

The model presented here extends the work proposed in [7]; for sake of space, we will provide a brief description of its core components, supporting the evaluation of results presented in the next section. 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.

3.1 The Multi-layered Environment

The overall environment is schematised in Fig. 3(a). Lanes of the road are represented as 1-dimensional continuous edges where car-agents can move only in one direction. The position of a car-agent is described as a point in the edge and there is no real space occupation for them: the physics of the system is ensured by means of the equations that rule their behaviour. Moreover, in order to achieve the results presented in Sec. 4 each edge is defined as toroidal, thus periodic boundary conditions are guaranteed by moving the agent to the beginning of the road once it arrives at its other extreme.

The dynamics of pedestrian is simulated with a rectangular grid of square cells whose side is assumed to be 40cm, to describe the space occupation of pedestrians [16]. Each cell can be occupied by at most one pedestrian-agent, allowing thus to reproduce the range of local densities generally observable. Cells inside the area describing the road lanes are not walkable, while the crossing is represented by cells that are walkable in case of non signalized crossing or while the traffic light is green or yellow[4].

Pedestrian-agents are moving towards their objective by means of discrete potentials called *floor fields* [3]. Each potential is spread from a set of cells describing a target in the environment. The particular scenario of the crossing is designed by means of six targets, as shown in Fig. 3(b).

Since the dynamics of pedestrians and vehicles influence each other the different environments are connected by means of a global environment supporting a mutual perception among pedestrians and vehicles according to rules that will be described in the following subsections respectively devoted to vehicle and pedestrian agents.

3.2 The Behaviour of Car-Agents

The motion of cars is based on the car-following model by Gipps [9], in which the speed of each vehicle is updated considering, firstly, internal parameters of the agent: (i) maximum acceleration a for each time-step of the simulation; (ii) maximum breaking capabilities b; (iii) speed limit of the road v_{max}. 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. The update rule of the speed $v_{c_i}(t)$, for a car-agent c_i at time-step t, is then calculated as the following:

$$v_{c_i}(t+1) = \min(v_0, v_1) + |v_0 - v_1| \cdot r$$

$$v_0 = v_1 - \varepsilon\left(v_1 - \left(v_{c_i}(t) - a\right)\right);\; v_1 = \min\left[v_{c_i}(t) + a, v_{max}, v_{safe}\right]$$

Where $r \in [0,1]$ is a random number and ε is an additional parameter of the model typically set to 0.4. v_{safe} is calculated according to the next equations:

$$v_{safe} = b\left(\alpha_{safe} + \beta_{safe}\right)$$

$$\alpha_{safe} = \left[\sqrt{2\frac{d_p+g}{b} + \frac{1}{4}} - \frac{1}{2}\right];\; \beta_{safe} = \frac{d_p+g}{(\alpha_{safe}+1)b} - \frac{\alpha_{safe}}{2}$$

Here b is the maximum deceleration of the car, g is the distance between the car ahead and d_p is the minimum breaking distance $d_p = b\left(\alpha_p\beta_p + \frac{\alpha_p(\alpha_p-1)}{2}\right)$.

With α_p and β_p respectively the integer and decimal part of the ratio v_{c_i}/b, which is the number of time-steps required to arrive at a zero speed. This original model by Gipps reliably simulates the physics of vehicular traffic by assuming the duration of a time-step of 1s. The time window described by the time-step, in fact, represents the time needed by one event to be perceived by the other agents, thus in this case it implements the *reaction time* of car drivers to a variation of the speed of an ahead car, or to

---

[4] In this particular work we will not show results related to the presence of a traffic light, but the proposed model aims at allowing a general simulation of pedestrian crossing.

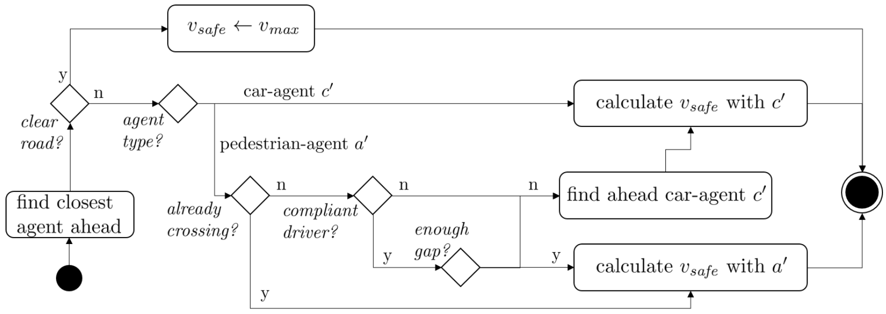


Fig. 4. The decision algorithm of car drivers.

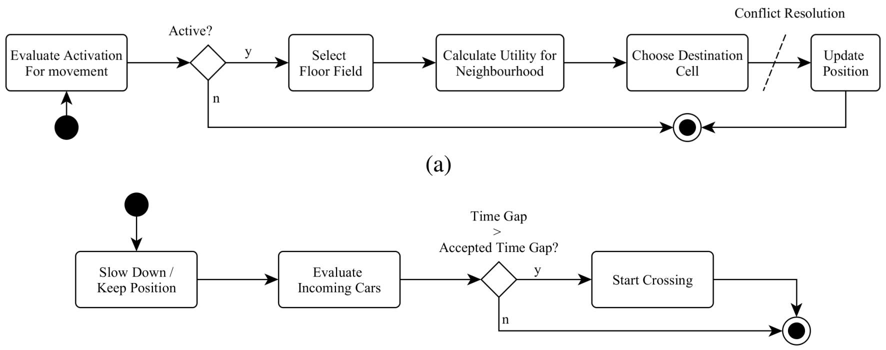
the arrival of a crossing pedestrian. By configuring a higher time resolution, that would be plausible for a situation involving pedestrians, this set of rules of the model would generate unrealistic reaction times of drivers, and the physics of the system would no longer be plausible in terms of flows of vehicles in the congested state. To solve this problem, we extended the baseline model with a gap $\hat{g}$ dependent on the assumed reaction time of the agent $t_{reaction}$ and the distance $t_{reaction} \cdot v_{car}$ that it would cover during this time: $\hat{g} = g - t_{reaction} \cdot v_{car}$.

For the simulation presented in the results section, we assumed a duration of the time-step of 0.1s and a reaction time assigned with a normal distribution with $\mu = 1.1$s and $\sigma = 0.2$s, which provides data about the density–flow relation for vehicular traffic in accordance with observations from literature.

Summarizing, car-agents simply accelerate until v_{max} if the road is free; otherwise they adjust their speed to v_{safe} in order to be always able to stop if the vehicle ahead c', moving at speed $v_{c'}$, starts breaking.

The rule defined in v_{safe} is suitable and it is used also to manage interactions with crossing or approaching pedestrians. The latter are simply considered as obstacles, just as the preceding vehicles: this choice allows employing the same rules managing the braking to avoid car accidents also to prevent accidents with crossing pedestrians.

The overall algorithm that defines the behaviour of car drivers is shown in Fig. 4. Firstly, the agent selects the closest agent ahead and, if any, checks for its type. If it is a car-agent, then the speed is updated as above discussed. If the agent is a pedestrian and 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*. For this particular work, the compliance of drivers has been simply modelled in a static way by further differentiating the agent type: 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.



(a)

(b)

Fig. 5. Algorithms to manage the movement (a) and appraising phase (b) of pedestrian-agents.

3.3 The Behaviour of Pedestrian-Agents

When activated, pedestrian agents can move in the 8 cells surrounding its 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 behaviour described in Sec. 2, among which a significant difference in the speed of pedestrians is observed, the activation of pedestrian-agents for movement at the beginning of the time-step is managed in a probabilistic fashion, similar to [2]. In particular, the probability to be activated for movement is given by $\psi = v_d/v_m$, where v_d is the *desired speed* of the agent and v_m is the *maximum speed* assumed for the simulation, calculated as explained above. By configuring v_d and also varying it during the simulation, it is therefore possible to configure differences in pedestrian type (age, gender, etc.), as well as in the phases of behaviour while crossing: when a pedestrian-agent arrives at a certain distance from the zebra, it switch to the appraising phase and it decelerates until it either reaches the curb or it evaluates the crossing to be safe. The algorithm for the movement of pedestrian-agents is then shown in Fig. 5(a).

The choice of movement is made in a probabilistic way and dependent on a simple utility function similar to the original floor field model [3], computed for cells of the neighbourhood. The function takes into account values of the floor field, possible occupation of cells by other agents and not walkable cells, and it drives pedestrian-agents towards their targets avoiding overlapping with others. In addition, possible conflicts arising from multiple choices of the same destination cell are managed with a random extraction[5] of a winner which will be allowed to move, while the others will keep their positions until their next activation.

---

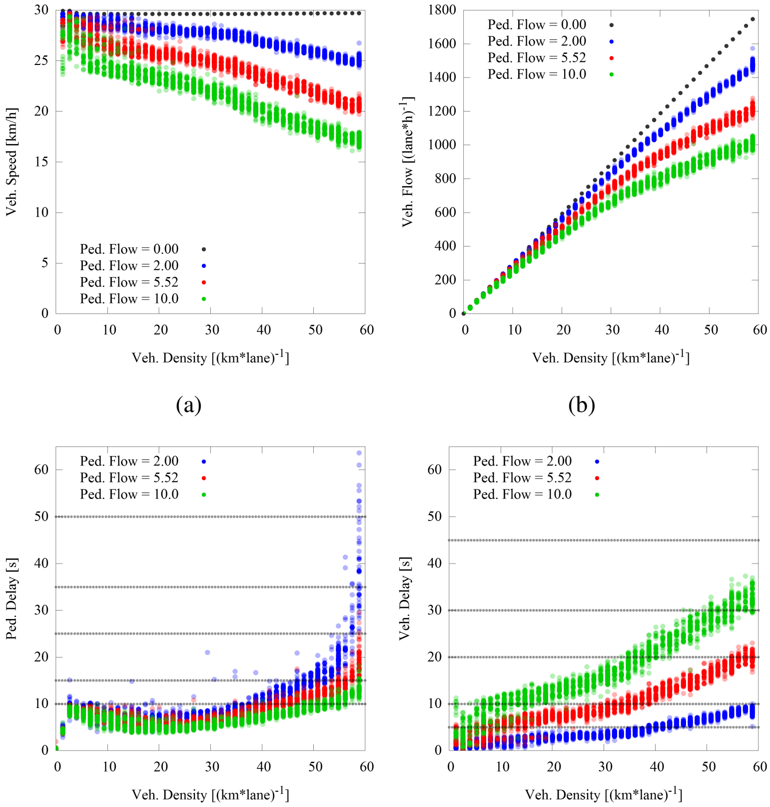
[5] With equal probabilities among the agents involved.

A more detailed representation of the pedestrian behaviour by considering proxemics and groups as in [1] has not been considered given the free-flow conditions of the pedestrian environment in the simulated scenario and the focus on the interactions with vehicles. Such level of detail will be necessary for future works, aimed at integrating the proposed model in a multi-scale one able to simulate and optimize microscopic pedestrian and vehicular traffic in urban areas [6, 5].

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 perceives the arrival at the curb, it will activate an evaluation summarized in Fig. 5(b). The algorithm is rather simple but it is based on the features recognized with the field-observation previously presented. It is founded on the concept of *time gap*, 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}. Results of the observation showed that there was no significant difference between the average time gap accepted by appraising pedestrians regarding their age, or regarding the lane of the incoming vehicles (near or far one). As empirically identified, thus, the *accepted time gap* for all pedestrian agents in the simulation has been normally distributed with $\mu = 4$s and $\sigma = 2$s. In the negative case, the pedestrian will continue slowing down –if it did not reach the curb yet– or keep its position, until either the car starts breaking to yield at the crossing or one of the following cars allows a higher time gap. Note that the compliance of car-agents does not necessarily lead to the crossing of pedestrian-agents and vice-versa: the time gap could be accepted by pedestrian-agents even if the behaviour of the car-agent is set as non-compliant. This particular situation will not lead to a collision since the non-compliant car will start to slow down as well when it will perceive the pedestrian as already crossing (see Fig. 4).

4 Simulation Results

The traditional way to evaluate the plausibility of models in the transportation area includes the generation of the so called fundamental diagram, i.e. a graph depicting the relationship between velocity or flow and the density in the simulated environment. In this context, we need to consider the impact of both vehicles and pedestrians: we chose to vary the vehicular density in a fine grained way and to consider just four situations associated to different pedestrian crossing ratios, respectively (i) no pedestrians, (ii) 2 pedestrians per minute, (iii) 5.52 pedestrians per minute (the arrival rate empirically observed) and (iv) 10 pedestrians per minute. For each value of vehicular density and pedestrian arriving flow, a set of 20 simulations iterations are run to analyse the variability of results. The simulated area is relatively short (around 400m), in order to accommodate buffer zones before and after the crossing and therefore allow the generation of different plausible vehicular densities; 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 traffic conditions at the time of the obser-



(a)

(b)

(c)

(d)

Fig. 6. On the top, fundamental diagrams in the form density–speed (a) and density–flow (b) of vehicular traffic in the investigate scenarios. On the bottom, waiting times of pedestrians (c) and vehicles (d) in relation with the density of vehicles in the simulated scenario (static grey lines marks the transitions between levels of service).

vation). We also considered a share of non-compliant vehicle drivers analogous to the observed one, that is, about 50%.

Figures 6(a) and 6(b) respectively show the trend of vehicular velocity and flow according to vehicular density and pedestrian arrival rate. The baseline result (i.e. no pedestrians) is in line with results expected in a urban road, both in terms of velocities and overall flow; as expected, higher pedestrian arrival rates reduce vehicular velocity and overall flow.

Figures 6(c) and 6(d) describe the results of the model in terms of average waiting times (one point in each picture denotes the average result for the whole simulation iteration) respectively for vehicles and pedestrians. This outcome highlights the *levels of service* of the crossing, for either pedestrians and vehicles, resulting from the simulation of each configured scenario. Both diagrams shows a monotonic growing trend of vehicle and pedestrian waiting time at the increase of the density of vehicles in the scenario. Moreover, a growth in the flow of pedestrians leads to a decrease of the level of service of the crossing for vehicles (Fig. 6(d)); at the same time, the average pedestrian delay is actually lower and with a smoother growth compared to low pedestrian density situations (Fig. 6(c)). The explanation of this phenomenon is due to the fact that pedestrian platooning in the crossing is more probable and, in addition, since it increases the probability that a pedestrian arrives at the curb in a favourable moment (i.e. with an acceptable time gap due to slow or stopped nearby vehicles, or due to very far approaching vehicles), leading vehicles to stop irrespectively of their non-compliant behaviour.

5 Conclusions

The present paper has introduced a model for the simulation of non signalized road crossings in which pedestrian and vehicular traffic meet and require a direct interaction. 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 that also produced empirical data that has been employed to calibrate and perform an initial validation of the model in a reference scenario. The model improves the results of previous works in this area especially due to the fact that an empirically observed behavioural phase for crossing pedestrians (i.e. appraisal) has been specifically considered and also since non-compliant behaviours by vehicle drivers is admitted.

Results are in tune with plausible levels of service for this kind of intersection and the model can be used to evaluate the plausible effects of different non-standard situations (e.g. exceptionally high pedestrian or vehicular densities). Future works are aimed, on one hand, at further analysing the model results to identify potential limits not visible in the presented experimentation: for instance, the growth in pedestrian delays in case of high vehicular density and low pedestrian demand seems excessive due to the lack of a cooperative behaviour by driver agents and to an overly careful behaviour by the crossing pedestrian. Finally, we aim to introduce traffic lights to evaluate the impact of their introduction and other elements for representing more realistic and complex crossing situations.

References

[1] Bandini, S., Crociani, L., Gorrini, A., Vizzari, G.: An agent-based model of pedestrian dynamics considering groups: A real world case study. In: 2014 17th IEEE International Conference on Intelligent Transportation Systems, ITSC 2014. pp. 572–577 (2014)

[2] Bandini, S., Crociani, L., Vizzari, G.: Heterogeneous pedestrian walking speed in discrete simulation models. In: Chraibi, M., Boltes, M., Schadschneider, A., Seyfried, A. (eds.) Traffic and Granular Flow ’13, pp. 273–279. Springer International Publishing (2015)

[3] Burstedde, C., Klauck, K., Schadschneider, A., Zittartz, J.: Simulation of pedestrian dynamics using a two-dimensional cellular automaton. Physica A: Statistical Mechanics and its Applications 295(3 - 4), 507–525 (2001)

[4] Campanella, M., Hoogendoorn, S., Daamen, W.: Quantitative and qualitative validation procedure for general use of pedestrian models. In: Pedestrian and Evacuation Dynamics 2012, pp. 891–905. Springer (2014)

[5] Crociani, L., Lämmel, G., Park, H.J., Vizzari, G.: Cellular automaton based simulation of large pedestrian facilities—a case study on the staten island ferry terminalse. In: Transportation Research Board (ed.) Transportation Research Board 96th Annual Meeting. pp. 17–05137. Washington DC, United States (2017)

[6] Crociani, L., Lämmel, G., Vizzari, G.: Multi-scale Simulation for Crowd Management: A Case Study in an Urban Scenario, pp. 147–162. Springer International Publishing (2016)

[7] Crociani, L., Vizzari, G.: An integrated model for the simulation of pedestrian crossings. In: Was, J., Sirakoulis, G.C., Bandini, S. (eds.) Cellular Automata - 11th International Conference on Cellular Automata for Research and Industry, ACRI 2014, Krakow, Poland, September 22-25, 2014. Proceedings. Lecture Notes in Computer Science, vol. 8751, pp. 670–679. Springer (2014), `http://dx.doi.org/10.1007/978-3-319-11520-7_71`

[8] Duives, D.C., Daamen, W., Hoogendoorn, S.P.: State-of-the-art crowd motion simulation models. Transportation research part C: emerging technologies 37, 193–209 (2013)

[9] Gipps, P.: A behavioural car-following model for computer simulation (1981)

[10] Godara, A., Lassarre, S., Banos, A.: Simulating Pedestrian-Vehicle Interaction in an Urban Network Using Cellular Automata and Multi-Agent Models. Traffic and Granular Flow'05 pp. 411–418 (2007)

[11] Gorrini, A., Vizzari, G., Bandini, S.: Towards modelling pedestrian-vehicle interactions: Empirical study on urban unsignalized intersection. In: Proceedings of the 8th International Conference on Pedestrian and Evacuation Dynamics - PED2016, Hefei, China, October 17-21, 2016 (in press, 2016)

[12] Helbing, D., Jiang, R., Treiber, M.: Analytical investigation of oscillations in intersecting flows of pedestrian and vehicle traffic. Physical Review E - Statistical, Nonlinear, and Soft Matter Physics 72(4) (2005)

[13] Highway Capacity Manual, journal=Transportation Research Board, National Research Council, Washington, DC, y.: Highway Capacity Manual

[14] Masthoff, J., Vasconcelos, W.W., Aitken, C., Correa da Silva, F.: Agent-based group modelling for ambient intelligence. In: AISB Symposium on Affective Smart Environments, Newcastle, UK (2007)

[15] Varhelyi, A.: Drivers' speed behaviour at a zebra crossing: a case study. Accident Analysis & Prevention 30(6), 731–743 (1998)

[16] Weidmann, U.: Transporttechnik der fussgänger - transporttechnische eigenschaftendes fussgängerverkehrs (literaturstudie). Literature Research 90, Institut füer Verkehrsplanung, Transporttechnik, Strassen- und Eisenbahnbau IVT an der ETH Zürich (1993)

[17] World Health Organization: Global status report on road safety 2015. World Health Organization (2015)

[18] Zeng, W., Chen, P., Nakamura, H., Iryo-Asano, M.: Application of social force model to pedestrian behavior analysis at signalized crosswalk. Transportation research part C: emerging technologies 40, 143–159 (2014)