Micro-Simulation Model for Assessing the Risk of Car-Pedestrian Road Accidents

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ABSTRACT

The data on traffic accidents clearly points to "Black Spots" that continually cause a high rate of accidents. However, road safety research is still far from understanding why this particular place on a road is risky. The reason is the deficit of knowledge of how pedestrians and drivers interact when facing a potentially dangerous traffic situation, and in the lack of an integrated framework that relates the data on human behavior to real-world traffic situations. We tackle the problem by developing SAFEPED, a multi-agent microscopic 3D simulation of cars' and pedestrians' dynamics at the black spot. SAFEPAD is a test platform for evaluating experimentally estimated drivers' and pedestrians' behavioral rules and estimating accident risks in different traffic situations. It aims to analyze disadvantageous design of the Black Spot and to assess alternative architectural solutions.

Categories and Subject Descriptors

I.6.5 Computing Methodologies, Simulation and Modeling, Model Development

General Terms

Algorithms, Design, Reliability, Experimentation, Human Factors, Standardization

Keywords

Traffic accidents, Black Spot, agent-based modeling, spatially-explicit modeling

1. INTRODUCTION

1.1 Micro-simulation of road accidents between the cars and pedestrians: from static to dynamics view

Accident statistics reveal factors of risk and establish the dependencies of accident rates on the characteristics and parameters of roads, cars, pedestrians, traffic and the environment of the accident location [1, 2, 3]. However, statistical models are inherently static and, thus, unable to reflect the chain of events that cause an accident [4]. The static view of the accident may explain the persistent fraction of the "black spot" - seemingly regular road locations with an unexpectedly high and stable accident rate [5] – but cannot be used for assessing the consequences of changes in the infrastructure or traffic conditions at the location.

Treatment of a specific black spot is typically based on an engineers' insight of the local conditions. The effectiveness of the safety measures is confirmed by comparing the accident rates before and after the implementation of safety measures. Successful implementations are usually reported, such as the installation of the several hundred countdown signals at the crossings in San Francisco, that reduced the number of pedestrian injuries caused by crashes with vehicles by 52% [6]; or the system for detecting pedestrians approaching a crosswalk zone and warning the drivers of pedestrian presence [7].

However, failures are often not reported. Traffic engineers lack tools for assessing the proposed safety measures, and say nothing about their economic justification. Safety measures are costly, while their success is not guaranteed. As a result, urban decision-makers have essential difficulties when deciding on changes in traffic regulations and infrastructure, even when the location is identified as a black spot.

The development of a dynamic simulation model of traffic accidents at a black spot provides a solution to this problem. Using this model, the chain of events (based on the behavior of the vehicles and pedestrians) that caused the accident can be investigated. This paper presents the pilot version of such a model.

1.2 Field studies of the accident micro-dynamics

Last decade a series of large-scale studies aimed at developing reliable indicators of vehicle pre-crash conditions were performed within the framework of the Intelligent Transportation Systems program of the U.S. Department of Transportation. The research focused on "last second" urgent maneuvering, and resulted in significant amounts of data collected during real-time observations of driver behavior and car movement [8, 9, 10, 11], as well as during simulator-based driving [12, 13]. On-road data includes kinematic characteristics of the vehicle, real-time measurements of the distance to the other objects, and video of driver's behavior. Laboratory experiments aimed to study drivers' behavior in potential accident scenarios, such as a lane-change maneuver.

The above studies provided important information on vehicle-vehicle interaction in pre-accident and accident situations. However, vehicle – pedestrian interaction were beyond the focus of the program, therefore the recorded number of vehicle –

pedestrian incidents and behavior of the participants, was low [10, 12].

In parallel, computer-based analysis of the videos taken on the roads became popular and provided essential knowledge on pedestrian decision-making when cars were approaching, as well as in more complex situations. These studies are employed for developing static, discreet choice models that describe the probability of road crossing or other action based on the distance to approaching car, or its velocity and road geometry [14, 15, 16, 17, 18]

1.3 Modeling car-pedestrian conflict

Usually agent-based (AB) models focus on either vehicle or pedestrian traffic and avoid combining these two flows within the same model. The major reasons are inherent behavioral differences between pedestrians and drivers in regard to route choice and compliance with traffic regulations. Popular models of car traffic, such as VISSIM, PARAMICS, SUMO or Aimsun [19] use an intentionally simplified view of pedestrians. Models of crowding specify pedestrian interactions but ignore details of vehicle traffic [15].

The model of pedestrians' disobedience to traffic laws at the crosswalks [20] is a rare example of a dynamic model of car-pedestrian interactions. It is based on Cellular Automata and combines the vehicle flow sub-model of Nagel-Schreckenberg [21] with the pedestrian sub-model. However, Cellular Automata's view of space inherently restricts agents' movement to relatively large cells introduced for describing vehicle flows and is too rough for microscopic representation of pedestrian motion.

In this paper, we propose SAFEPAD – a high-resolution, spatially explicit dynamic simulation model as a tool for forecasting the effects of changes in traffic environments. SAFEPAD is based on the continuous representation of space and the objects' movements, and in this respect follows the recent approaches and achievements in robotic algorithms for motion planning and collision avoidance. It is a spatially-explicit agent-based model that explicitly represents spot infrastructure and moving objects in fine 3D detail, and operates at a time resolution of 1/20 of a second. Behavioral rules of SAFEPAD agents – vehicles and pedestrians – are based, when possible, on the experimental data.

2. SAFEPED, the Agent-Based model of car-pedestrian interactions

AB techniques provide the basis for modeling vehicular-pedestrian conflict [22, 23]. By dynamically simulating the behavior of every car and pedestrian (represented by the precise 3D models) within a precise 3D model of the spot infrastructure, the researcher is able to record agents' actions and their outcome (e.g., an accident). This model identifies risk factors and investigates the effectiveness of proposed safety measures.

The advantages of the AB approach for modeling and studying traffic accidents are numerous. Results of experiments on the behavior of participants can be directly interpreted in terms of agents' behavioral rules, which can be used by the simulation model to assess an infinite number of scenarios with different numbers of cars and pedestrians of various kinds, and behaviors and in various environmental and architectural settings. The frequency and severity of accidents can then be quantitatively projected for any situation. The goal of our research is to develop the AB model of car-pedestrian interaction at a specific spot as a tool for assessing, planning and engineering decisions of road safety. The user of SAFEPED can change the 3D geometry of the spot and characteristics of the traffic flow, and then assess whether the proposed changes will decrease accident rate and severity.

The motion behavior rules of the SAFEPED agents follow the robotic approach to real-time motion planning and maneuvering for vehicles and pedestrians. These rules account for basic imperfections of human visual perception, limitations in pedestrian locomotion and car mobility, and are based on the robotic algorithms of motion in a dynamic environment proposed by Fiorini and Shiller [24].

SAFEPED is a working prototype that works at a high time resolution of 1/20 of a second. At each time step, agents, considered in a random order or priority, decide on their motion behavior for the next time step and perform it.

2.1 The 3D presentation of the spot

SAFEPED is built on precise 3D representation of the Black spot's land surface and infrastructure including road borders, parked cars, pedestrian crossings, buildings, trees, traffic lights and signs (Figure 1). Combined with the orthophoto, this provides realistic representation of the spot geometry.

Figure 1: SAFEPAD model scene showing agents' trajectories

2.2 SAFEPED agents and their behavior

SAFEPED simulates movement of both drivers and pedestrians, acting in a 3D environment. Drivers and pedestrians behave autonomously according to a set of probabilistic behavioral rules. Each agent, driver or pedestrian, is assigned an agent's profile that includes height, width, velocity, steering and acceleration/deceleration capabilities.

2.2.1 Agents' motion at a macro-level:

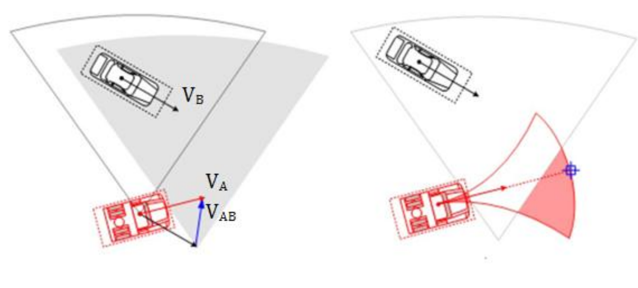
Each SAFEPAD agent tries to maintain the desired velocity, and aims to follow a predefined trajectory, shown in Figure 1 as a blue dashed line for a vehicle and red dashed line for pedestrian. However, it is often impossible to follow the trajectory because of other moving and stationary objects. In this example, driver and pedestrian agents react, not necessarily adequately, to the behavior of the other autonomous agents when they see them. The agent, driver or pedestrian, decides whether to deviate from the trajectory to the left or to the right, accelerate, decelerate or even stop, and returns to the trajectory should the road conditions make it possible.

We choose the trajectory-based approach in order to reduce generating accident situations in which drivers or pedestrians follow potentially dangerous paths. An agent enters the site at the end of one of the predefined trajectories and follows it, trying to maintain the desired velocity while taking into account the other agents and environmental elements (Figure 1). In addition, at every intersection of agents' trajectories, SAFEPED makes it possible to set decision-making priorities that reflect traffic rules and agreements. An agent moving along the continuous green path has priority over an agent moving along the continuous red path (Figure 1). When two agents, one on the continuous green path and the other on the continuous red path, approach the point of intersection of their trajectories and take account of each other (according to their movement decision rules), *both agents know* that an agent on the green path would act before the agent on the red path. Note that this includes the case when the agent on the green path decides that the agent on the red path is moving too fast, and rather than risk a potential collision, the agent on the green path decides to stop and give a way to the other agent. If the trajectories of two agents intersect and priorities are not assigned, both agents know there are no priorities (i.e. the order of their actions in the simulation will be random).

2.2.2 Agents' micro-behavior behavior in conflict situations

Road safety demands motion planning in dynamic environments, where cars and pedestrians should avoid dynamic and static obstacles. This is far more complex than the static problem and, in this case, robotics uses velocity space instead of the standard 3D space (referred to as "configuration space" in robotics). The problem of avoiding one or many mobile or immobile obstacles is treated directly in the velocity space, providing the trajectory which satisfies an optimization criterion. In our model, agents, drivers, and pedestrians follow robotic motion planning algorithms for dynamic environments. We employ the version of this algorithm that is proposed by Fiorini and Shiller [24]. One of the advantages of this algorithm is its applicability to a set of objects that essentially vary in their inherent velocities, vehicles and pedestrians in our case.

The algorithm considers Velocity Obstacle (VO) - the set of all velocities of a moving object that will result in a collision with another moving object at some moment in time, assuming that the other object maintains its current velocity. In our model, the concept of VO is applied for computation of avoidance maneuvers; accelerating/decelerating cars, and pedestrians that follow curvilinear trajectories (Figure 2).



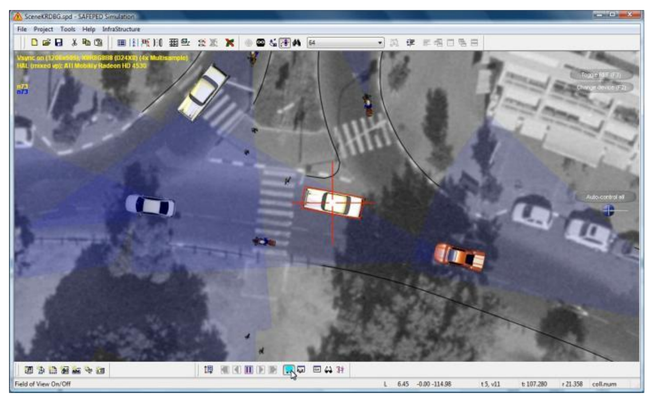
(a) (b)

Figure 2: An example of the avoidance maneuver algorithm as implemented in SAFEPED.

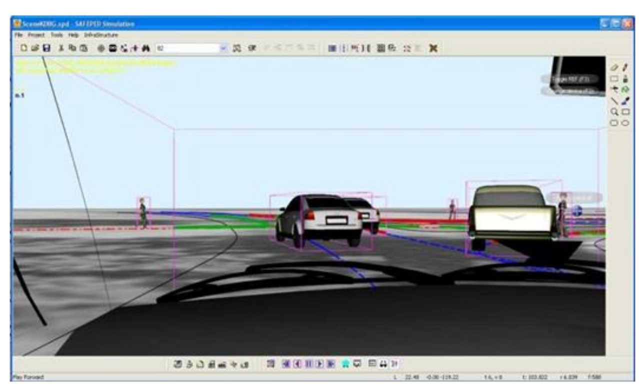
In Figure 2a, the red car is moving at a velocity of V_A, the black car at V_B and the red car is trying to avoid collision with the black car by changing its velocity. The white sector in Figure 2a denotes the set of *relative* velocities V_{AB} of the red car relative to the black car that will result in a collision. The white sector is constructed in the configuration space, taking into consideration the physical dimensions of each car (represented by the radius of the circumference circles of each car). The gray sector denotes the domain of the *absolute* velocities of the red car that leads to collision with the black car. The gray sector is a simple transformation of the white sector along V_B. In Figure 2b, the red domain denotes the set of available velocities of the red car, constrained by maximal possible acceleration of the car that guarantees no collision. This sector is constructed by subtracting the velocity obstacle domain that results in a collision (the gray sector) from the domain of all possible maneuvers of the red car. The blue point denotes a safe avoidance velocity for the red car that does not require a change in the car direction. If accident avoidance demands acceleration or deceleration that is beyond the human and car abilities, the red domain vanishes, and accident occurs.

2.2.3 Agents' vision

SAFEPED agents see the 3D environment within the "view cone" of up to 180^o angle (Figure 3a). In the pilot version of SAFEPED, agents are unaware of traffic lights, and this feature has yet to be added. We interpret the human visual system as a pinhole camera. The 3D shape (currently minimal 3D box) of each object within the view cone is projected on the retinal plan of the agent's "eye" (Figure 3b).



(a)



(b)

Figure 3: SAFEPED scene with the agents' view cones (blue); the car marked by cross is chosen for follow up (a); 3D visibility in the SAFEPED, the driver's view from the car (b).

Based on this information, an agent detects objects close to the line of sight, defines which objects are obscured by others, and to what degree. Objects that are fully obscured for 3 seconds become invisible to the agent, and the agent does not react to them. These objects are currently represented by parallelepipeds; a more precise representation of the objects by mesh technique is currently in development.

2.3 SAFEPED output and performance

All agents' actions are continuously recorded at every time step, and can be replayed. Possible types of accidents (head-on collision, one-sided collision, car-pedestrian collision, etc.) are defined and instantaneously checked. The model keeps track of agents' location, set of available velocities, eyesight behavior, decisions on velocity, distance to other agents, and acceleration/deceleration.

SAFEPED analysis of a typical site considers up to a hundred simultaneously moving agents. Even at a finest resolution of the spot and the agents' 3D geometry, we did not encounter any computational difficulties with the pilot version of the SAFEPED.

The first version of the SAFEPAD is ready for evaluation. For a general view see http://www.youtube.com/watch?v=ia3W8oiTVYw&feature=related. Our formalization of visibility is given by http://www.youtube.com/watch?v=6KFcfFRElt8&feature=related, and http://www.youtube.com/watch?v=axWEGNetpM0 illustrates a traffic accident.

3. Experiment with an obscured car

Following is an experiment with SAFEPAD that aims at testing agents' micro-motion algorithm in potentially risky situations.

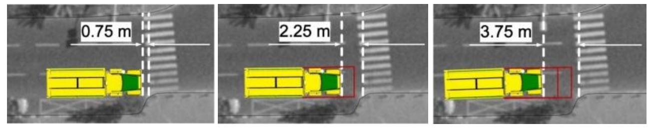
3.1 Experimental setup

The experimental setup is presented in Figure 4: the pedestrian crosses a multi-lane street on a non-regulated crossing.

Figure 4: Experimental setup: high truck A is stopped in the lane adjacent to the sidewalk and obscures the view of both the pedestrian and of approaching car B

High truck A is stopped in the lane closest to the sidewalk and obscures the pedestrian's view. Vehicle B approaches the crosswalk from the second lane and the view of the driver is obscured too. US Transportation Agency publication describes this situation as follows: "The pedestrian entered the traffic lane at midblock in front of standing or stopped traffic and was struck by another vehicle moving in the same direction as the stopped traffic" [25]. According to [3] multiple threat crashes comprise 17.6 percent of pedestrian crashes on marked crosswalks.

The actual road crossing between Weizmann St. and Moshe Sharet St. in Tel Aviv, Israel was chosen for constructing the 3D representation of a junction infrastructure. We investigate the emergence of the accident situations for three different locations of the obscuring high truck: at a distance of 0.75, 2.25 and 3.75 m from the crosswalk (Figure 5).



(a) (b) (c)

Figure 5: Three experimental situations: high truck parks at a distance of 0.75m (a), 2.25m (b) and 3.75m (c) from the crosswalk

We investigated the risk of contact between the car and the pedestrian, such as the pedestrian being hit by the car's right fender (Figure 6), as dependent on velocities and attention times of the car and pedestrian. According to [26] we set the pedestrian reaction time as 0.28 ±0.07 sec and driver reaction time as 0.70-0.75 sec. [27]. This includes all components of reaction, e.g. movement time of ~0.2 sec required to lift the foot from the accelerator and then to touch the brake pedal.

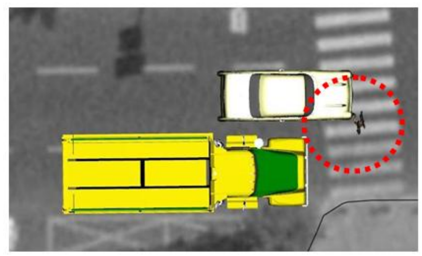


Figure 6: Car's right fender hits pedestrian when truck parks at 0.75m distance from the crosswalk.

3.2 When can each participant avoid the accident on its own?

Let us investigate the conditions in which pedestrian and driver may take control of the situation and are capable of avoiding a collision, even if the other participant chooses the worst line of action.

We start with a pedestrian that does not look around and crosses the street at a high speed of 6km/h (Table 1). In case of a truck stopped at 0.75 m form the crosswalk, the driver succeeds in noticing the pedestrian and stops safely when the truck's speed is lower than 12 km/h in case the pedestrian reacts slowly, and 13 km/h in case the pedestrian reacts fast. The reaction time of the pedestrian is based on estimates presented in [26] - 0.28 ±0.07 sec, and we used 0.28 - 0.07 = 0.21 sec and 0.28 + 0.07 = 0.35 sec as a reaction time for "fast" and "slow" pedestrian. Similarly, when the truck is located 2.25m and 3.75m from the crosswalk, the driver is able to stop if his/her speed is below 24-28km/h.

Table 1. Driver full control speed in case of inattentive pedestrian crossing at 6 km/h

Pedestrian's Reaction	Distance between truck and crosswalk		
	0.75 m	2.25 m	3.75 m
Slow	12 km/h	24 km/h	26 km/h
Fast	13 km/h	25 km/h	28 km/h

Let us now consider an ignorant driver driving at a speed of 50 km/h. To avoid an accident in case of a truck at 0.75 m, a slow reacting pedestrian must walk at 3.7 km/h or slower, while a fast reacting pedestrian can walk at speeds up to 4.6 km/h (Table 2).

For the two other positions of obscuring truck, a pedestrian walking at any reasonable speed is capable of detecting the car and stopping.

Table 2. Pedestrian full control speed in case of inattentive driver at 50 km/h

Pedestrian's Reaction	Distance between truck and crosswalk		
	0.75 m	2.25 m	3.75 m
Slow	3.7 km/h	5.1 km/h	Above 6.0 km/h
Fast	4.6 km/h	6.0 km/h	Above 6.0 km/h

Let us now focus on the most dangerous situation of close-by obscuring truck and investigate the case when, in order to avoid an accident, both the driver and pedestrian have to react to each other, i.e., when the driver's speed is above 12-13 km/h.

3.3 The situation in which both participants have to be careful

Figure 7 presents the maximal safe speeds for the car and pedestrian in the case of inattentive and attentive agents, as obtained in the model for the obscuring truck at a distance 0.75 m. As can be seen from the chart, attentive agents can move faster and avoid the accident. Pedestrian reaction is very important in this case. Slowly-reacting attentive pedestrian will be in danger if the car's speed is above 20 km/h, while the fast-reacting pedestrian is in danger if the car's speed is above 35 km/h. Note that to avoid a crash regardless of the car's speed, the pedestrian should not walk faster than 2 km/h.

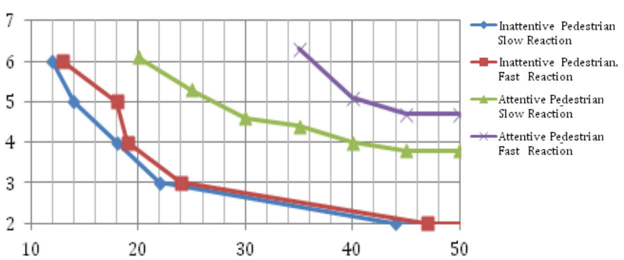


Figure 7: Maximal safe speeds for car and pedestrian with obscuring truck at a 0.75m distance

The crash is a qualitative event and, to be really safe, one needs to include essential margins to the estimates presented in Tables 1, 2 and in Figure 7. Let us estimate these margins.

3.4 Safe avoidance of crash

The situation in which the driver and pedestrian successfully avoided an accident by passing each other at a distance of 5 cm can be hardly considered safe. The human view of safe resolution of the accident demands a significant distance between the car and pedestrian during the entire period of their interaction.

In our experiments with SAFEPAD we have chosen 0.5 m as "minimal safe" distance between the car and pedestrian. We investigate only the case of a truck at 0.75 m, and present the worst case for a slowly reacting pedestrian. As can be seen from Table 3, the safe speeds are essentially lower than those that are required in order to avoid the accident.

To conclude, our model study confirms the importance of advanced stop lines on the road before crosswalk as an accident prevention measure. The simulations demonstrate that the distance between the advanced stop line and the crosswalk should be about 2m, higher than the intuitive estimate of the 1.5 m as proposed by [28].

Table 3. Minimal distance between the car and slowly reacting pedestrian, truck at the distance of 0.75m from the crosswalk

Pedestrian's speed, km/h	Car's speed, km/h						
	50	45	40	35	30	25	20
5.5	crash	crash	crash	crash	crash	crash	0.17
5.0	crash	crash	crash	crash	crash	0.06	0.16
4.5	crash	crash	crash	crash	0.10	0.19	0.29
4.0	crash	crash	crash	0.08	0.08	0.26	0.36
3.5	0.04	0.04	0.06	0.10	0.18	0.28	*0.47*
3.0	0.10	0.09	0.11	0.20	0.26	0.36	*0.45*
2.5	0.22	0.20	0.47	0.71	1.05	1.08	*0.47*
2.0	0.94	1.14	1.00	0.99	1.01	1.02	*0.42*
Shaded cells – unsafe speeds *Italic* – pedestrian can stop and avoid accident on his/her own							

4. Discussion

The proposed SAFEPED model is unlimited in "measuring" vehicular-pedestrian interaction in scenarios with a wide range of agents' behavior. High temporal and spatial resolution of the SAFEPAD, similar to that of driver simulators and real-time in-car equipment, provides high potential for combining it with field studies [8, 9, 10, 11, 12, 13]. SAFEPED can serve as a tool for assessing accident risks at specific spots, and can identify measures to decrease these risks.

By direct assignment of human-based behavioral rules to the model agents, SAFEPED is capable of implementing arbitrarily cognitive-perceptual parameters of drivers' and pedestrians' behavior, including strategic and tactical behavioral components.

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