

# Accident simulation and reconstruction for enhancing pedestrian safety: issues and challenges

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**Abstract** - The enhancement of pedestrian safety represents a major challenge in traffic accidents. This study allows a better understanding of the issues in pedestrian protection. It highlights the potential of in-depth studies in identifying relevant crash parameters interfering in the pedestrian safety. A computational simulation tool was developed to reconstruct pedestrian real-world crashes. A sample of 100 in-depth accident cases was reconstructed from two sources: 40 crashes provided by IFSTTAR-LMA and 60 crashes from CASR. To exemplify the methodology, two accident cases from each database were illustrated.

A description of the sample of crashes was presented including the travel and impact speed of the vehicle, the driver reaction, the pedestrian walking speed, the scene configuration with the eventual obstacles, etc. This detailed description is pointing to the major factors affecting the limits of pedestrian safety systems.

## NOTATION

$t_0$	Beginning of crash sequence (s)	$S$	Travel distance of the vehicle (m)
$t_{bi}$	time at beginning of braking (s)	$\gamma$	Jerk due to the deceleration ( $m/s^3$ )
$t_b$	time at full braking (s)	$V_{impact}$	Impact speed of the vehicle (m/s)
$t_c$	time of collision (s)	$\mu$	Coefficient of tire/road friction
$T$	time interval of the simulation (s)	$g$	Acceleration due to gravity ( $m/s^2$ )
$d$	distance from start of skid marks to point of impact (m)	$L$	Percentage of kinematic energy loss prior to full braking
$a$	Deceleration of the vehicle ( $m/s^2$ )		
$V$	Speed of the vehicle (m/s)		

## INTRODUCTION

Each year, more than 270.000 pedestrians are killed on the world's road and millions are non-fatally injured covering a range of severities [1]. Pedestrian safety is a world-wide issue and represents a key challenge to decrease road traffic accidents involving these vulnerable users.

Several studies were performed to enhance pedestrian safety. Accordingly to these studies, measures and interventions have been established encompassing several fields as engineering, enforcement and education. Considerable safety-based technologies have been designed to prevent pedestrian crashes using Intelligent Transportation Systems [2]. These systems allow monitoring in particular the motion of pedestrians (e.g. the European project PUVAME [3], SAVE-U project [4] and WATCH-OVER project [5]). To develop such systems, there is a need to investigate in in-depth crash studies in order to reconstruct crashes and simulate the interaction between pedestrians, vehicles and the road environment.

Researches based on numerical simulation have been explored to assess the performance of safety systems. Some approaches are focusing on identifying typical crash scenarios from in-depth data [6]–[8]. Due to the complexity of driving situations, a considerable number of factors have to be addressed. Rather than synthesizing accidents into common scenarios, other researches were using probabilistic methods like the Monte Carlo method to compute many complex crash configurations [9], [10]. Factors like visibility constraint are not yet covered enough in these methods. So the objective of this research is to reconstruct real accident configuration including factors interfering in pedestrian safety.

This paper presents a method to reconstruct real accidents scenarios using computational simulation. A sample of 100 accident cases involving pedestrians has been reconstructed. To illustrate the method,

only two cases were detailed. Finally, the characteristics of the selected crashes were described as fields of interest with respect to pedestrian primary safety.

## **MATERIALS AND METHODS**

This research is based on the reconstruction of 100 real-world crashes involving a pedestrian and vehicle. A computational simulation tool is developed to reproduce the crash sequences displaying the interaction between the vehicle, pedestrian and the crash environment including obstacles. These two steps are described in the following sections.

### **Accident database**

A sample of hundred crashes was provided by two in-depth databases: IFSTTAR-LMA (the laboratory of accident mechanism analysis of the French institute of science and technology for transport, development and networks, France) and CASR (Centre for Automotive Safety Research, University of Adelaide, Australia). Both of these centres proceed in a similar way to perform in-depth investigations as it is respectively described by [11] and [12].

Extensive data are collected from on-scene accidents and are clustered in files as follows:

- Photographs and videos of the crash scene and vehicles involved;
- Statements of people involved in the crash, witnesses, and police;
- Details of the road environment, involved vehicles and pedestrians;
- Details of injuries from medical records;
- A site diagram of the accident drawing to scale including the marks observed on the scene (skid, debris, blood, etc.), the final position of the vehicle and the pedestrian, the estimated impact location and the estimated trajectories of the different subjects involved in the crash.

The hundred cases used for this study were selected corresponding to the available information from the crash database as the estimated impact location drawn on the site diagram of the accident and the assessed impact speed of the vehicle.

A subset of 40 cases was compiled from the IFSTTAR-LMA crash database. These crashes were investigated around the township of Salon-de-Provence, covering a wide period of 1995-2011. The remaining 60 cases were provided by CASR which investigated in the Adelaide Metropolitan Area in the period April 2002 to October 2005.

### **Accident modeling**

To emulate a crash scenario, required input variables are compiled from the crash databases. These variables are clustered in spreadsheets with accordance to the crash components: the environment, the vehicle and the pedestrian.

The site diagram of the accident is used as a background for the crash simulation. The scale of the diagram expressed in pixel/meter is extracted and saved as a variable. This variable allows getting from the diagram any data with the appropriate dimensions identical to their counterparts in the real world. These data extracted from the diagram are the impact location picked as a reference point, the length of the skid marks – if there is –, and the width of the driving lane from the reference point. Obstacles that may obscure the visibility of the pedestrian are spotted on the diagram. Other data describing the road environment of the crash are extracted from the in-depth database. Some of these data are required for the crash simulation like the tire/road friction coefficient and some are complementary information such as light conditions and traffic flow.

For the vehicle, its dimensions are requested as well as the measured impact location provided by the in-depth database. Using the pre-defined reference point, all these dimensions are set to locate and

draw the vehicle on the diagram at the impact. An estimated trajectory is then extracted from the diagram and converted from pixel coordinates (2D) to curvilinear distances or travel distances in meters (1D). These space coordinates are overlapped with the kinematic of the vehicle computed through the equations of motion. These equations are associated to the pre-crash sequence depending on whether the driver did brake or not (Figure 1). For cases with no braking maneuver, the vehicle is assumed to drive under a constant speed (the impact speed) described by Equation 1. For cases where the brakes are triggered, the vehicle goes through different motions: a motion presumed to have a constant speed, a transition phase and a uniform deceleration (Figure 1). Each phase is represented by the appropriate equation of motion (Equation 1-9). The parameters of these equations are retrieved from the estimated impact speed of the vehicle, the length of the skid marks, the time for the braking system to lock the wheels and time interval of the simulation. The time to lock the wheels is the time elapsed for the vehicle to travel from the application of the brakes to the wheels locking and producing visible skid marks. This time interval depends on the braking system of the vehicle: for Brake Assistant Systems or equivalent, this time characteristic is assumed to be 0.2secs, and for normal brakes, it is 0.5secs as defined by [13]. During this time interval, there is a loss of kinetic energy of 80%. The sequences of the vehicle motion are finally modeled in a spatiotemporal continuum.

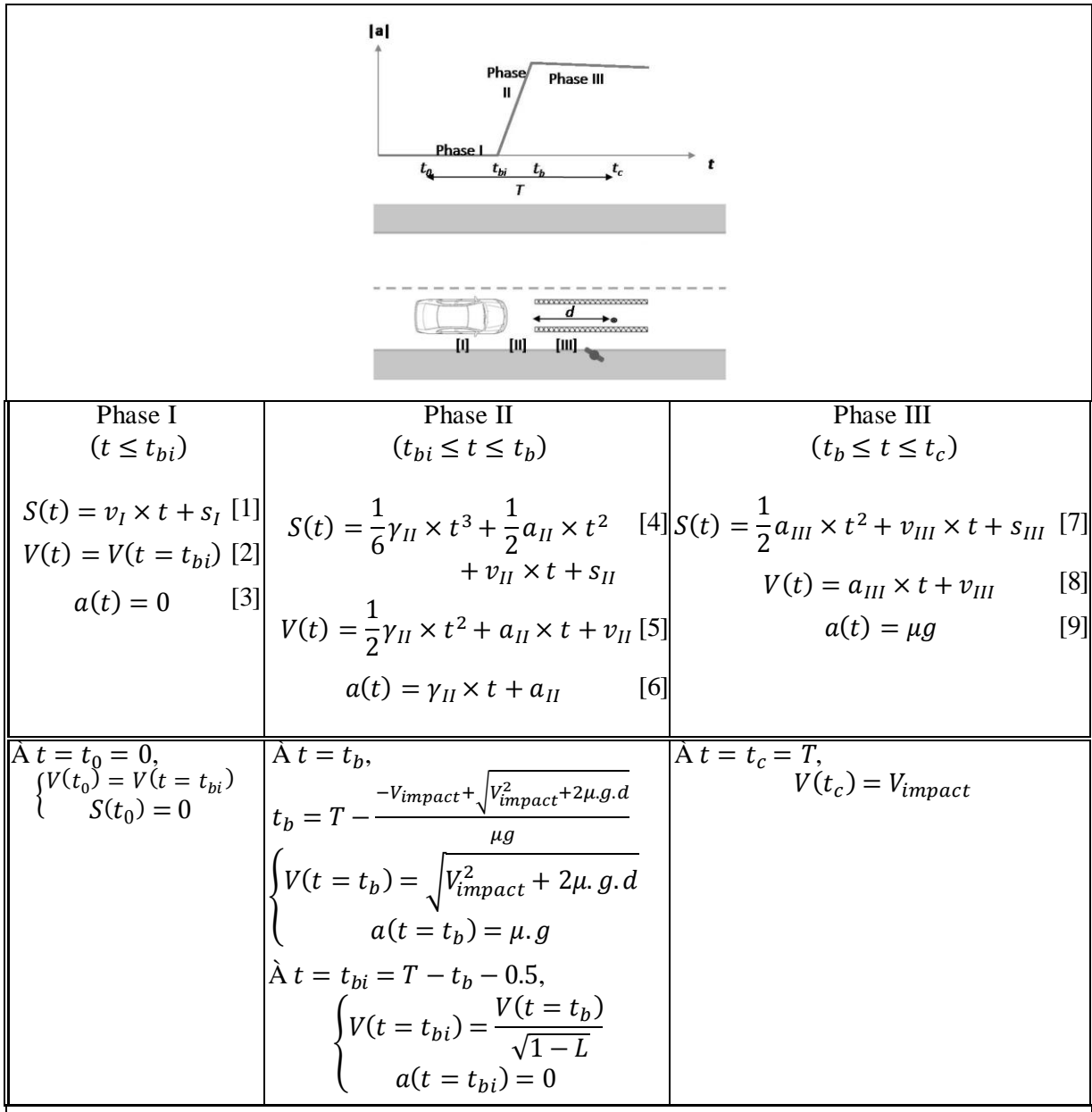


Figure 1. Brake model for the crash reconstruction

For the pedestrian, the trajectory is also extracted from the site diagram. Its kinematic is assumed to be at constant velocity. Since it is missing in in-depth databases, the speed of pedestrians is estimated based on the work of [14]. This speed is the mean of the normal speed distribution related to the pace and age of the pedestrians (Table 1). At the end, the trajectory is combined to the kinematic parameters to locate in space and time the pedestrian all along the accident scenario.

**Table 1**  
**Pedestrian speed estimation**

Age	50% speed (m/s)	
	Walking	Running
5-9	1.83	3.94
10-14	1.68	4.20
15-19	1.65	4.20
20-29	1.62	3.54
30-39	1.62	3.35
40-44	1.62	2.90
45-49	1.52	2.90
50-54	1.52	2.83
55-59	1.46	2.83
60-64	1.46	2.47
65+	1.28	2.47

## RESULTS

### Examples of accident reconstruction

The method of accident reconstruction is illustrated here by two cases: one case from IFSTTAR-LMA database and another from CASR.

#### *Example 1*

On a rainy day in the morning, a 2004 MY Citroen C3 took the first exit at a roundabout. In the middle of the lane, the vehicle struck two kids on a pedestrian crossing. The 6 and 10 years old boys were holding their hands while running to cross the road. After a vehicle stopped to give them way to cross, the pedestrians run across the road without paying attention to the oncoming vehicles. Although there was a pavement separating the lanes, the visibility of the pedestrians was masked by a sign of 2.4m wide but with low height. The driver of the Citroen C3 declared that he didn't see the kids crossing due to the heavy rain. The youngest child was struck approximately in the center of the vehicle and has been forwarded straight ahead, while the other child was hit by the right front edge of the vehicle and thrown on the right side of the road. The driver did not stop the vehicle and continued his itinerary as he didn't notice that a collision occurred (according to the driver's statement).

The 10 years old boy was not injured. Concerning the other kid, after been thrown straight forward to the vehicle path, he found himself trapped underneath the vehicle and carried for approximately 1km. He suffered from multiple lacerations. He has been transferred to the hospital.

The driver did not react. There was no evidence of pre-impact or post-impact braking, so the travelling speed and impact speed of the vehicle has been considered as the same. This speed was assessed at 25 km/h from the thrown distance of the pedestrian estimated at 4m. This speed was also consistent with the measured speed of the vehicles driving through that section of the road.

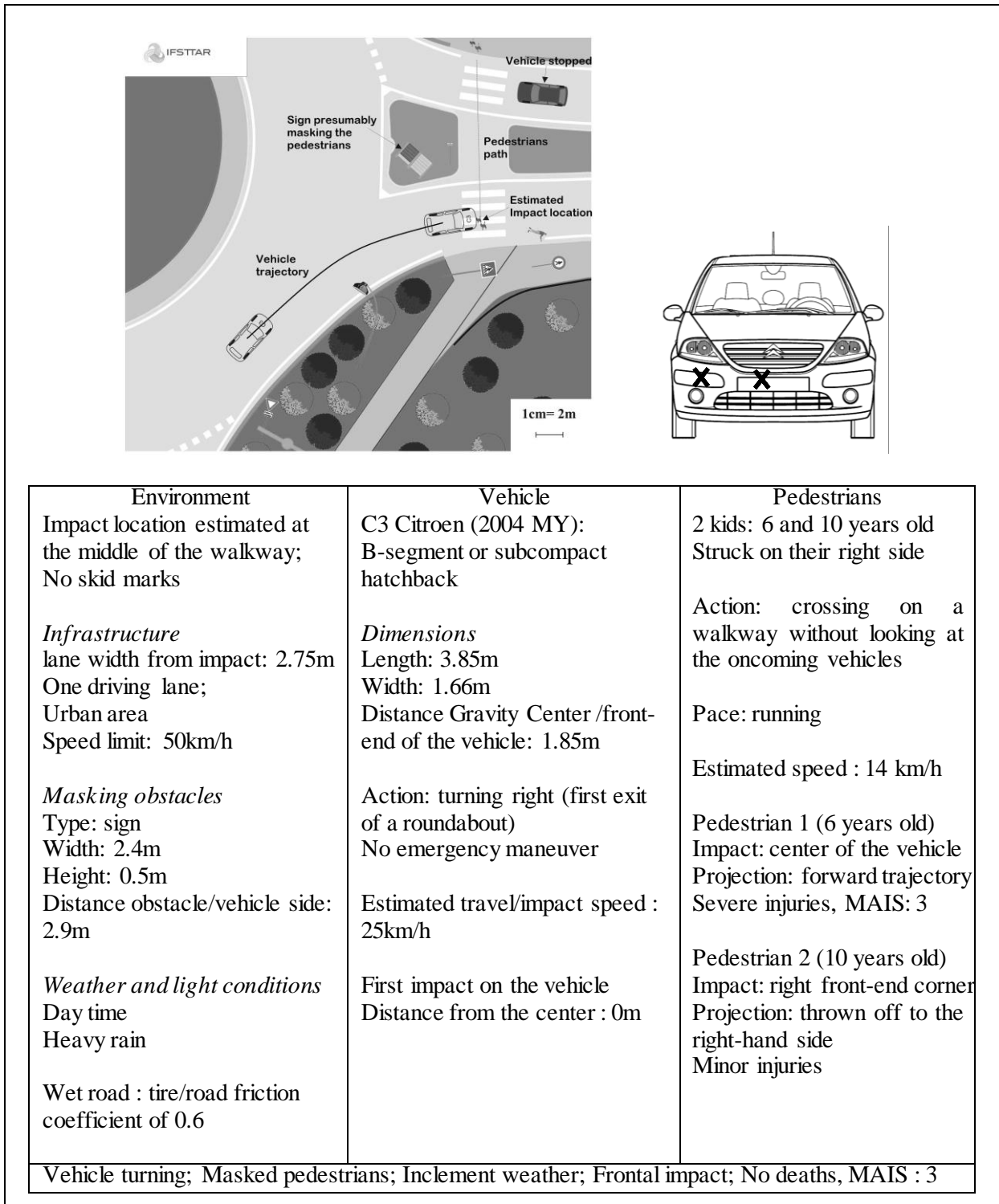


Figure 2. Example case 1

### Example 2

On a clear day, a Toyota Corolla® (Sedan MY2002) was heading west in left lane of a 3 lane highway. A 58 years old pedestrian was crossing (jaywalking) the highway, walking between vehicles stopped due to traffic. The driver of the Toyota saw the pedestrian previously masked by a stationary van type vehicle, and then applied the brakes locking them up. Unfortunately, the crash happened even if the vehicle swerves to the left. The pedestrian struck with the right front of the vehicle.

The pedestrian was admitted to the hospital for 2 days. A laceration and hematoma to the occipital region of the scalp, a comminuted fracture of the right clavicle with contusion and a fracture to the right fibula head/neck were recorded.

From the skid marks left on the dry road (9.6 and 13.28m long), the traveling speed of the vehicle was estimated at 55 km/h. The impact point was assessed based on a compromise between the results of the impact speed from the formula of Searle and Searle (1983) and the equation of a uniform deceleration. Hence, the post impact skid marks was evaluated at 2.25m, the throw distance of the pedestrian was about 3.2m and the impact speed was estimated at 20 km/h.

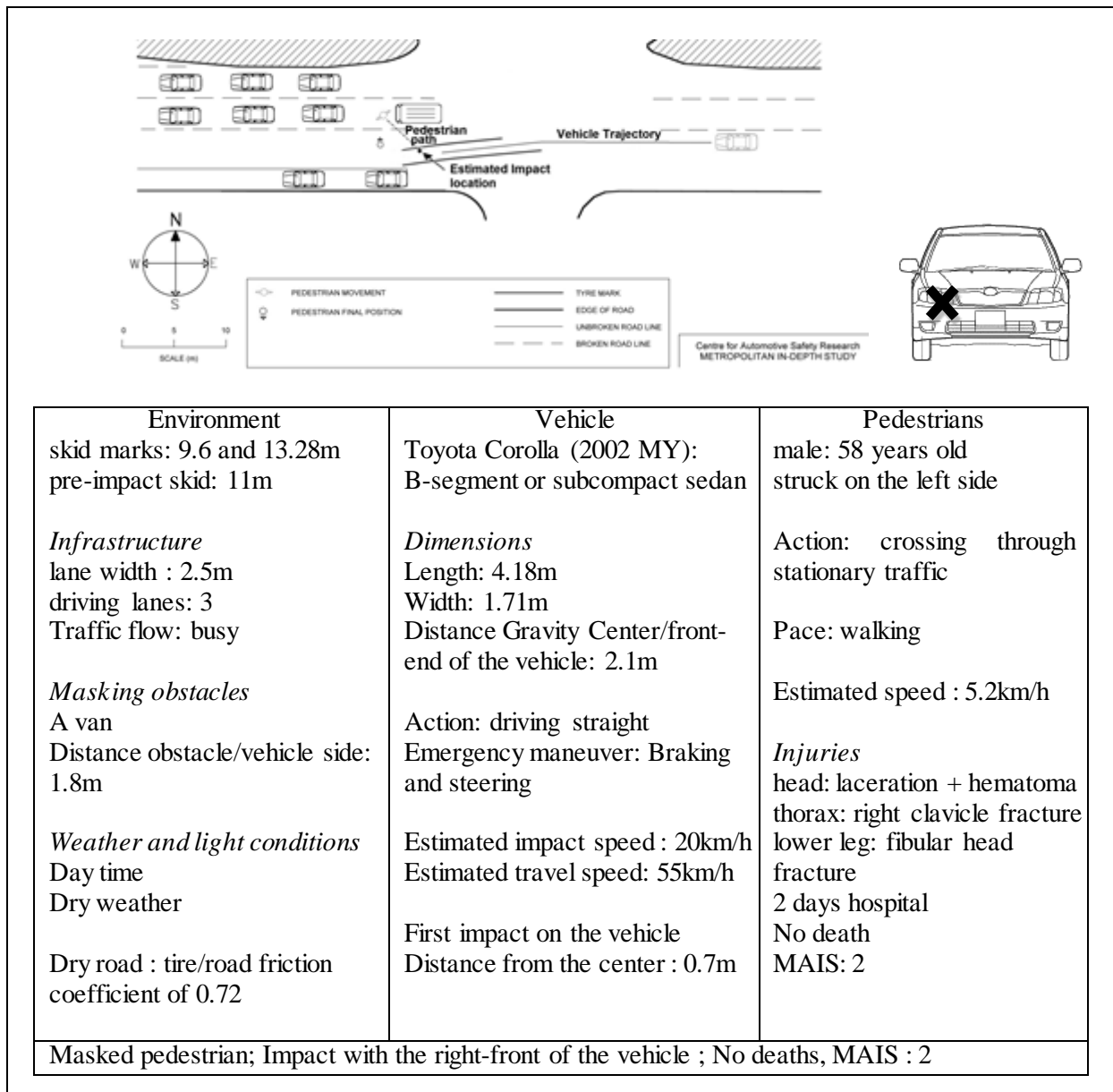


Figure 3. Example case 2

### Description of the crash set

During the process of crash reconstruction, a set of data was constituted. An analysis of this data is presented in this section and clustered with accordance to the different components of a crash: The road environment, the driver, the vehicle and the pedestrian.

### Road environment

The majority of the accident cases happened during the day (83%). Among these cases, inclement weather and bad light conditions are observed: heavy rain (4%) and dazzling light (7%).

The road curvature is also considered in this analysis. There are 18% of cases where the vehicles involved in the crashes were turning.

Finally, there is a major concern in this set about obstacles. In 22% of cases, pedestrians were masked by obstacles which are mainly parked vehicles or stopped due to traffic (Figure 4). In 80% of cases where the pedestrians are masked, the lateral distance between vehicles involved in crashes and obstacles is above 1m (Figure 5). All the pedestrians are visible (there is no more obstacle) when they are located at half a meter from the side of the vehicles.

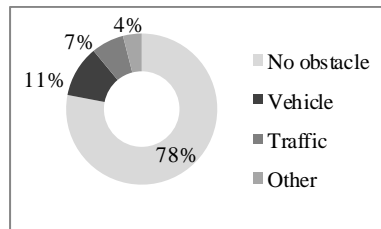


Figure 4. Rates of masked pedestrians by obstacles

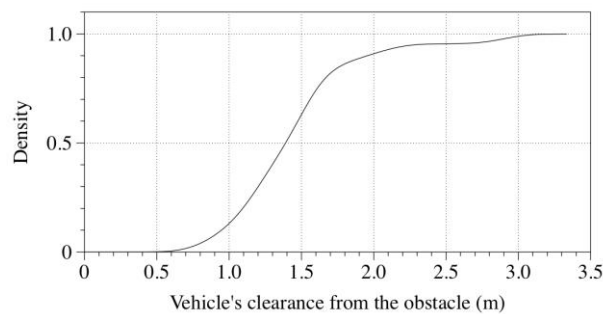


Figure 5. Cumulative distribution function of the vehicle's clearance from obstacles

### Driver reaction

The driver's reaction according to the crash sequences is described. The different emergency maneuvers applied by the driver are rated in Figure 6. This chart brings out two main groups: cases "with braking maneuvers" representing 33% of the dataset and cases "without braking".

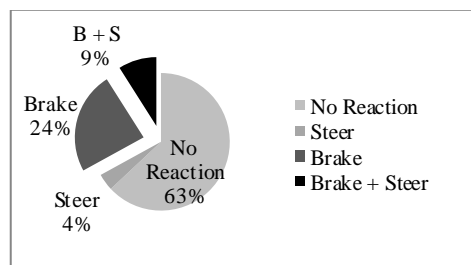


Figure 6. Emergency manoeuvre distribution

### Vehicle speed distribution

The interesting parameters relative to the vehicle involved in the crash are the travel speed and the impact speed. Figure 7 shows the distribution of both speeds through the whole set of crashes. 95% of

the vehicle travel speeds are distributed along a wide range from 20 to 60 km/h, with a peak around 40 km/h, while the average vehicle impact speed is 32 km/h.

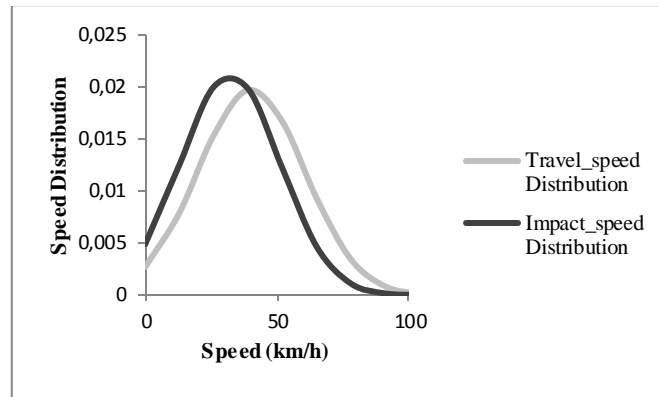


Figure 7. Travel and impact speed distribution of the vehicle

### *Pedestrian pace*

Two different distributions are displayed corresponding to the pace of the pedestrian (Figure 8). In fact, there are 25% of cases where the pedestrian is running with an average speed of 3.5m/s (~12.6km/h). For walking pedestrians, their average speed is 1.4m/s (~ 5km/h).

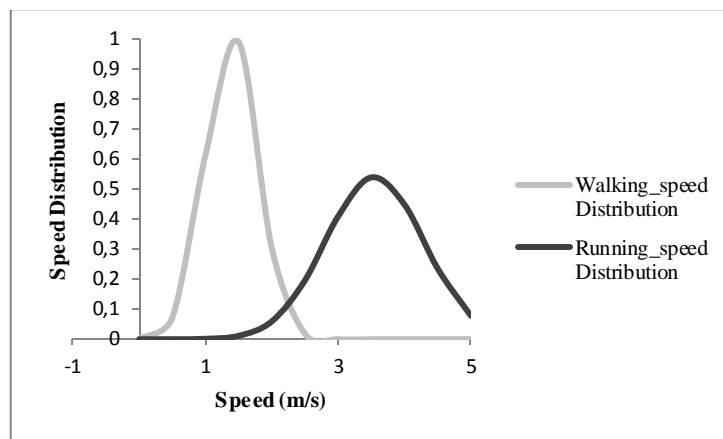


Figure 8. Pedestrian speed distribution according to the pace

### *Crash Configuration*

The crash configuration analysis combines the trajectory of the pedestrian with the impact location on the vehicle according to the timeline of the crash. The objective is on one hand to determine if the collision of the pedestrian happened at the beginning, mid or end of his crossing, and on the other hand to identify if the pedestrian was coming straight from the curb or already crossing from off-side the road (Figure 9). 6 scenarios are established from these combinations. There are as many cases of pedestrians coming from the near side (the curb) as those crossing a lane. The remaining 2% are static pedestrians. The most occurred scenario representing a quarter of the sample is pedestrian struck straight away after stepping from the curb.



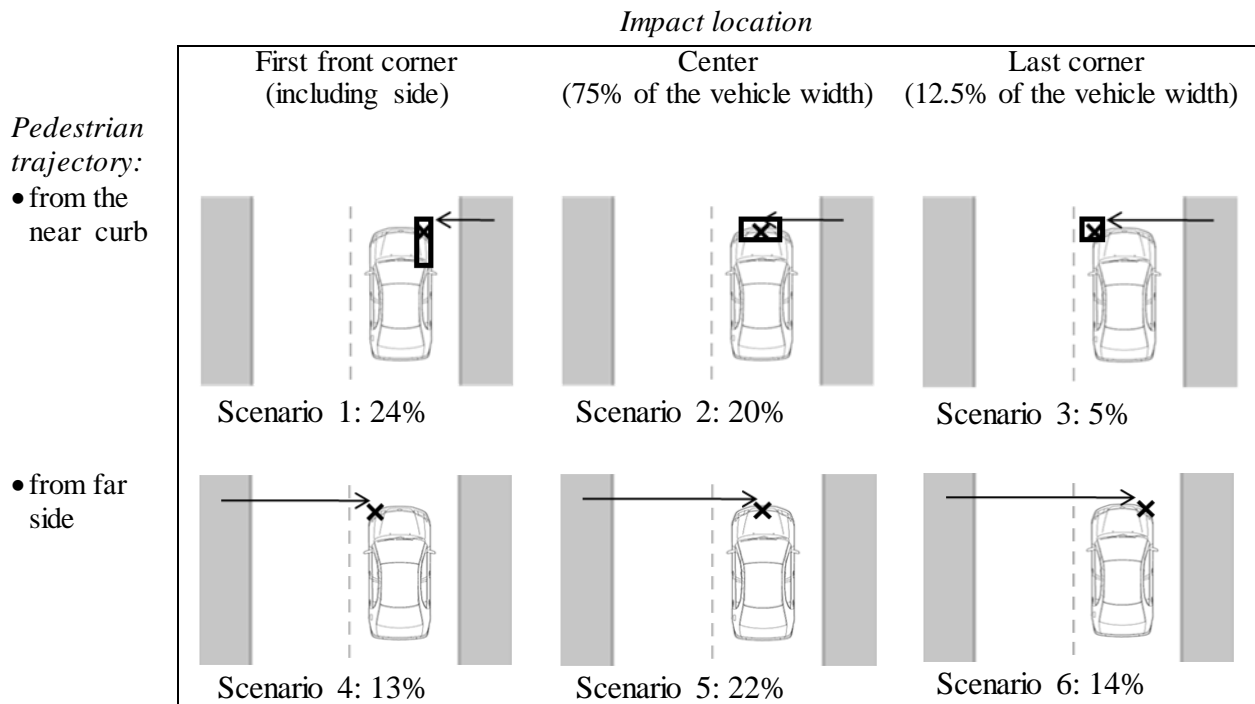


Figure 9. Description of the configuration of the crash dataset

## DISCUSSION

Detailed in-depth investigation and reconstruction of crashes involving pedestrians is required as data sources to understand issues in pedestrian active safety. Considering real accident scenarios, it allows identifying factors that interfere in pedestrian safety. These factors are related to the components that model a crash scenario: the road environment, the driver, the vehicle and the pedestrian.

The road environment factors are considered as influencing in the perception of pedestrians. Systems based on sensors that monitor the road to detect any pedestrian are subjected to these factors. Despite their performance, sensors are affected by light and weather conditions such as night time or heavy rain and dazzling light. These constraining conditions cannot be modeled in the simulation of crashes. Yet, researchers working within the ASPECSS project are trying to perform lab test in night conditions [15].

Furthermore, it is presumably challenging for on-board systems to detect a pedestrian while the vehicle is turning.

In the literature, the most studied factor from the road environment factors consists of the impact of road side obstacles in hazard perception [16]. In fact, this factor leads to a late detection of the pedestrian and thus, constrains the safety system to react in limited time and space. It is then important to consider this factor particularly since it is not complicated to model it in the crash simulation. These obstacles can be differentiate and classified into different crash scenarios as described by Brenac et al. [17].

Other factors from the road environment have also an influence in the situation analysis and decision making relative to active safety systems fitted in vehicles. These systems employ emergency braking and some may possibly employ emergency steering as a countermeasure to avoid an imminent crash [18]. Braking as well as steering depends on the road state expressed through the tire/road friction model. Moreover, steering maneuver is restricted by a considerable number of additional factors such as the traffic situation and it is parameterized according to the road boundaries (road width) and other features related to the vehicle.

Regarding the driver, information on emergency situation control before impact is relevant to the effectiveness of safety systems. In 63% of the studied cases, the driver did not react before the collision occurs. It is then interesting to understand the driver alertness and to justify the use of warning systems. On another hand, driver's behavior can annihilate the deployment of an autonomous steering system. So, active systems have to consider the attitude of the driver in emergency driving situation.

When referring to vehicle factors, the speed is the most studied in assessing risk. It is an important parameter interfering in the situation analysis and crash prediction. 95% of the travel speed of vehicles involved in pedestrian crashes range up to 60 km/h. Although the studied crashes are from two different sources (Australian and French crash databases), the speed distribution remains the same and it is similar to the survey of the GIDAS database [15]. Other factors from the vehicle are not covered in this study but are relevant in particular for parameterize steering maneuver. These factors are the lateral acceleration, steering angle and yaw rate.

Concerning the pedestrian, the most influential factor is the walking speed. As the vehicle speed, this factor is also considered in the process of situation analysis and crash prediction. In the crash database developed in this study, most of the pedestrians were walking normally (75%) with an average speed of 5 km/h. This walking speed is comparable to those found in literature [19]. However, the average speed of pedestrians who were running is higher than expected (12.6 km/h).

Considering the trajectory of the pedestrian and the impact location on the vehicle, the performance of active systems may be affected. For example, under certain circumstances, steering maneuver can be appropriate to avoid a particular crash configuration: a pedestrian coming from the curb and striking the nearest front corner or the side of the vehicle. Braking maneuver in this case is limited due to a late detection of the pedestrian leading to a short time available for deployment. This crash scenario is frequently repeated representing 24% of the whole set of studied crashes in this research. This scenario is also significant according to the GIDAS database [10]. The potential performance of steering maneuver as countermeasure in crash avoidance is thus more favorable than braking in particular crash scenarios.

Concerning the crash reconstruction, detailed information are required like the impact location, the trajectories and velocities of the parts involved in the collision, the vehicle features and the location of eventual obstacles that masks the visibility of the pedestrian. All of the crashes reconstructed in this study were selected according to the availability of most of the required data aforementioned. Some data remains missing such as pedestrian speed and some are fuzzy like the approach speed of the vehicle during the pre-crash events. It is clear that assumptions are needed to complete the reconstruction of a crash. Extensive work is necessary to fill these gaps. The use of Event Data Recorder with or without video sensors provides promising data to study pre-crash scenarios [20].

## **CONCLUSION**

The enhancement of pedestrian safety represents a major challenge in traffic accidents. It appears important to pursue in-depth studies of crashes involving pedestrians. These studies allow a better understanding of the issues in pedestrian protection.

A computational simulation tool was developed to reconstruct 100 real-world crashes involving vehicles and pedestrians. The simulation tool reproduces the crash sequences displaying the interaction between the four components: driver, vehicle, pedestrian and the environment including obstacles. The objective of the crash reconstruction was to provide a comprehensive set of data describing the crash sequences.

These detailed descriptions are pointing to the major issues concerning the development of Active Safety System and also identify their limits. In particular, it appeared important to take into consideration the speed of the pedestrian, its trajectory, the obstacles, the driver reactions, etc.

With the designed tool for computational simulation, it is possible to implement active systems like Autonomous Emergency Braking systems in order to assess their safety benefits. It is one of the next steps of this research: to evaluate AEB or ADAS using this accident database.

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