Vehicle-pedestrian collisions – Aspects regarding pedestrian kinematics, dynamics and biomechanics

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Abstract. Vehicle-pedestrian collisions result in a substantial number of pedestrian fatalities and injuries worldwide. Concern continues to limit and reduce the tragic consequences suffered by pedestrians involved in road accidents, caused the vehicle-pedestrian accident reconstruction become an important area and distinctly outlined in the reconstruction of road incidents involving vehicle. This paper analyzes the dynamics of vehicle-pedestrian impact influence over pedestrian biomechanics, which is directly connected with the severity of injury after contact with the vehicle profile and with the place where the pedestrian is projected. The main goal of this paper is to highlight some features of reconstruction of road accidents involving pedestrian, looking at the kinematics and dynamics of pedestrian impact for a better understanding of the phenomena that occur. The study on the dynamics and biomechanics of the pedestrian hit by the vehicle is useful in order to understand how the injuries, including the lethal ones, are generated in the collision, what is essential in road accidents reconstruction.

1. Introduction

Pedestrians are the most vulnerable road users in traffic crashes. On road accidents the impact between pedestrian and motor vehicle generates, in most situations, severe injuries and even deaths among pedestrians.

During the last twenty years pedestrian safety has been widely studied [1; 2; 5; 7] and pedestrian protection becomes of increasing concern of the world, especially in the EU. Currently the pedestrian protection at accidents considers one of the most important challenges in automotive industry everywhere in the world due to the large number records of death, and severe injuries occurred for the pedestrians in road accidents.

This paper refers to significant aspects regarding the frontal collision between motor vehicles and pedestrians, being used real-world collisions (car-to-pedestrian collision filmed in real time) and analytical methods with numerical solving that allow computer-based reconstitution of the vehicle-pedestrian impact. In order to report the results of multibody numerical simulation of a vehicle crash with the pedestrian has been used specialized software PC-Crash 10.1. The results are analysed by calculating the values of the head injury criterion and the combined thoracic index. The pedestrian injuries are known from the medico-legal report and the theoretical results are assessed according to the real pedestrian injuries, emphasizing certain phases of the pedestrian projection movement on which the severity of injury in pedestrian depends.

2. Reconstruction of the specific parameters of the vehicle-pedestrian traffic accident

2.1. Circumstances of the traffic accident

The accident occurred on str. Mihai Bravu, in Bucharest, and was filmed by a video surveillance camera that records at a 150 fps frequency, with a frame size of 1920 x 1080 pixels. The camera was located on the side of the street with the sidewalk where the pedestrian had started to cross the road. The accident involved a VW Golf vehicle and a pedestrian, male, aged 50, with a height of 1.72 m and a weight of 78 kg.

Figure 1 shows the area where the accident occurred, the direction of the vehicle and that of the pedestrian, respectively.

Figure 1. View of the area where the accident occurred

The pedestrian crossed the street on the red color of the pedestrian traffic light and he entered the lane of the VW vehicle from the right side, as shown in figure 2.

Figure 2. The pedestrian enters the lane of the VW vehicle from the right side

The pedestrian was hit by the mid frontal area of the vehicle as illustrated in figure 3 and he is struck by the hood and windshield, and ends up falling down on the road in front of the VW vehicle as it can be seen in figure 4.

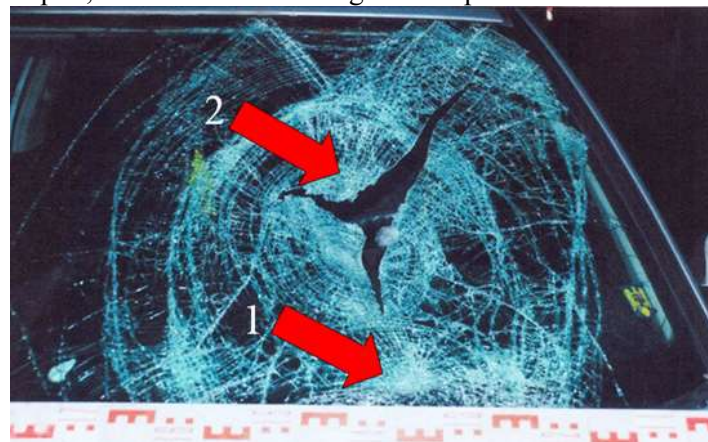**Figure 3.** The pedestrian was hit by the mid frontal area of the VW vehicle

Figure 4. The pedestrian ends up falling down on the road in front of the VW vehicle

The damage caused to the VW vehicle are shown in figure 5, which reads: A - deformed license plate; B - frontal grids between headlights is broken; C - traces of deformation of the engine bonnet; D - damage to the left side of the windscreen.

Figure 5. The damage caused to the VW vehicle after the impact with pedestrian

The configuration of the windshield damages presented in figure 6 show the existence of two damage areas, one of which is more pronounced, which can be corroborated with the video recording of the accident, and which indicates the fact that there wasn't only one, but two impacts of the pedestrian with this car part, as also resulted during the computer reconstruction of the accident.

Figure 6. The configuration of the windshield damages

The consequences of the accident suffered by pedestrian are highlighted by the forensic findings, as follows:
- severe head trauma with multiple neurocranium and viscerocranium fractures on the right side, and cerebral hemorrhage;
- fracture of both bones in the left lower leg;
- chest trauma with left pulmonary contusion.

The real-time recording of the traffic accident provided the opportunity to establish the way it occurred, determining the time and place of the impact, as well as the momentums and the final positions when both vehicle and pedestrian stopped on the roadway, also allowing to ascertain the post-impact trajectory of the pedestrian and the relative position between the pedestrian and the vehicle on initial impact. The total duration of the accident was accurately determined at 3.5 s from the initial moment of the impact until the pedestrian and the VW vehicle stopped on the roadway.
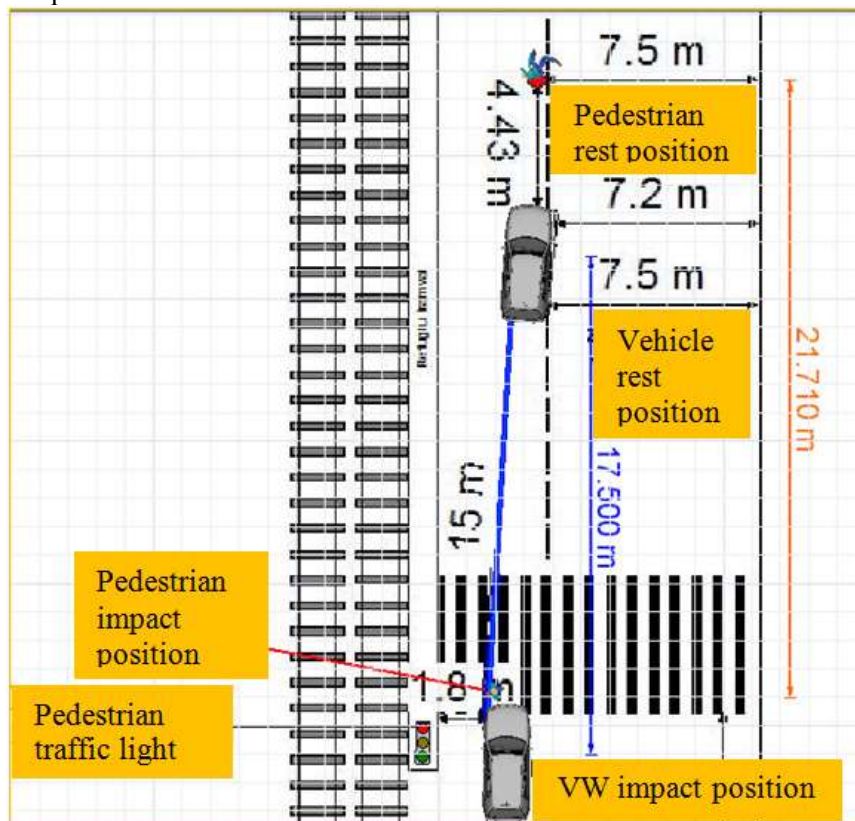
2.2. Reconstruction of the specific parameters of the vehicle-pedestrian traffic accident using analytical methods with numerical solutions

In order to reconstruct the kinematics parameters specific to this traffic accident, it was used the compute-based collision reconstruction method, with the help of the PC-Crash software, version 10.1. With PC-Crash can be reconstruct complex accidents, using multibody dynamics formulations [4].

The dimensional parameters, as a whole, of the road section where the accident occurred and the positions where both the vehicle and the pedestrian stopped after the impact were identified by the measurements taken by the police at the accident site.

A sketch of the accident site is shown in figure 7. It contains the measurements taken by the police at the accident site, as well as the impact position and the final positions, on the roadway, of the vehicle and of the pedestrian.
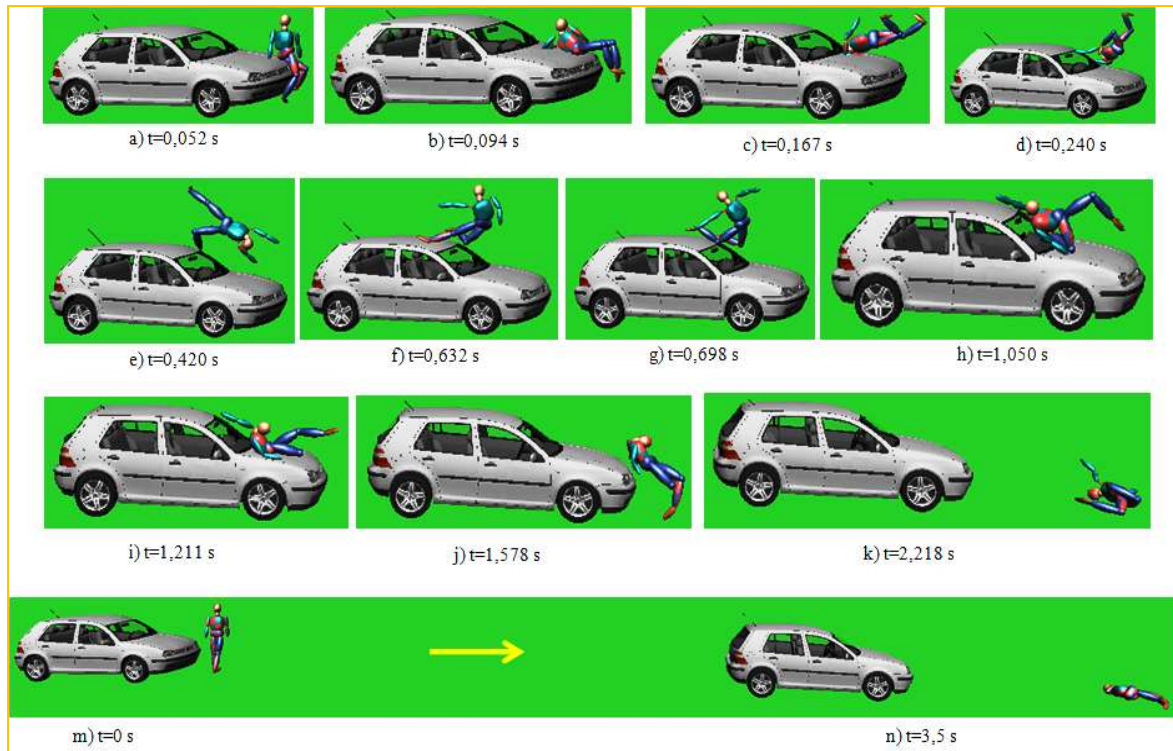

Figure 7. The sketch of the accident site

The distance between the impact position and the final position of the vehicle (relative to the centre of gravity of the vehicle) is of 17.50 m, and the distance between the impact position and the final position of the pedestrian (relative to the centre of gravity of the pedestrian) is of 21.71 m.

In the simulation generated using the computer-based reconstruction method, the impact speed of the vehicle was of 44 km/h and the pedestrian speed was of 6 km/h, given de fact that the vehicle and the pedestrian stopped, in the simulation, in the positions recorded by the police in their on-site investigation; the initial positions and trajectories of the vehicle and of the pedestrian are similar to those shown in the video recording.

The dynamics of the vehicle-pedestrian impact, achieved using the computer-generated reconstruction of the collision, provided by the PC-Crash software, are shown in figure 8.
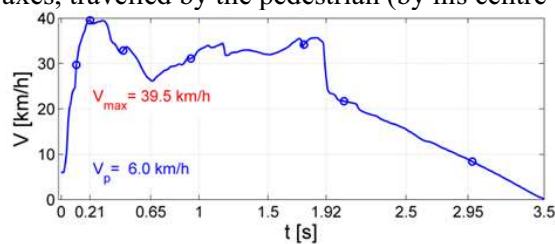
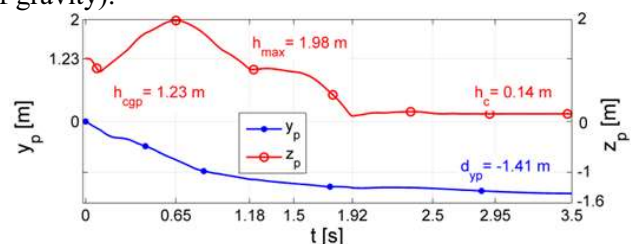**Figure 8.** The dynamics of the vehicle-pedestrian impact

2.3. Pedestrian kinematics and biomechanics

Concerning the pedestrian biomechanics, below are shown the results obtained through the computer reconstruction of the collision.
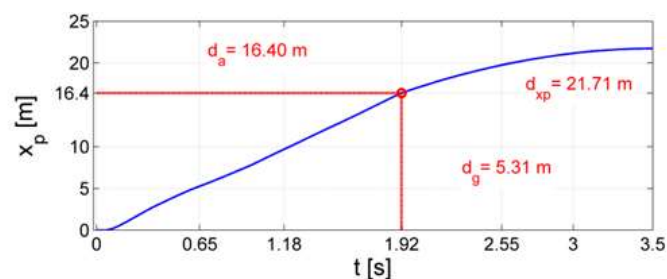
Figure 9 shows the speed of the pedestrian, and figures 10 and 11 show the distances relative to the axes, travelled by the pedestrian (by his centre of gravity).

Figure 9. The speed of the pedestrian

Figure 10. The distances on the Oy and Oz axes, travelled by the pedestrian (by his centre of gravity)
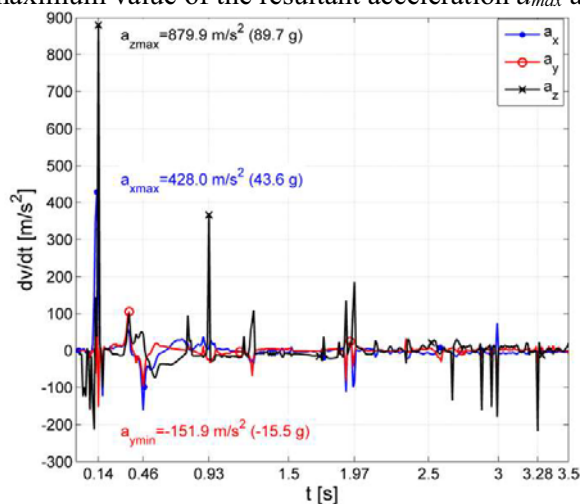

Figure 11. The distance on the Ox axis, travelled by the pedestrian (by his centre of gravity)

From the graphic presented in figure 9 can be ascertained that from the impact speed of the pedestrian, 6 km/h, the speed of the pedestrian after impact grew up to the value of 39.5 km/h, at time t=0.21 s.
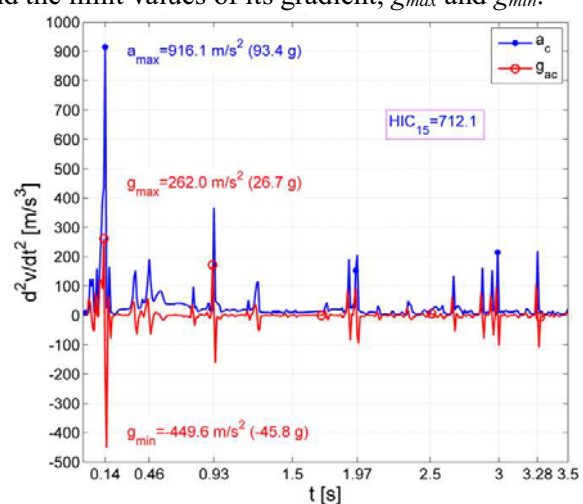
From figure 10 it can be also ascertained that at time t=0.65 s, the pedestrian reached the maximum throwing height h_{max}=1.98 m. Because starting from this moment on the speed of the pedestrian increases (figure 9), results that after the pedestrian was thrown into air, he crashed again into the automobile, from which it absorbed another quantity of energy. From figure 10 can be ascertained that at time t=1.92 s the pedestrian fell down on the road, because the height z_p is minimum. Therefore, from this moment on and until stopping (at t=3.5 s), the pedestrian falls on the road. As results from figure 10 the falling of the pedestrian on the road lasts for 1.58 s and the distance travelled during this period of time is d_g =5.31 m. From the moment of the initial vehicle-pedestrian impact, until the pedestrian reached the road, has passed a period of time of 1.92 s, and the distance travelled in this period of time is d_a=16.4 m.

From figure 11 results that the distance travelled by the pedestrian on the Ox axle direction is d_{xp}=21.71 m, value that was also shown in figure 7.

In figure 12 are shown the values on the three coordinate axes of the accelerations/decelerations of the head (a_x, a_y and a_z), and in figure 13 is shown the value of the resultant and its gradient. In figure 12 are also shown the maximum levels of the accelerations values on the three axes through absolute values and through values related to the gravitational acceleration g. Also, in figure 13 are shown the maximum value of the resultant acceleration a_{max} and the limit values of its gradient, g_{max} and g_{min}.

Figure 12. The derivatives speeds of the head (accelerations/decelerations), values on the three coordinate axes

Figure 13. The resultant and gradient of pedestrian head acceleration

As it can be seen in figure 12 the longitudinal acceleration of the head a_x exceeds the maximum tolerated acceleration (43.6>30 g [3]), and the lateral acceleration a_y is lower than the acceleration tolerated by a human being (15.5>9 g [3]).

Therefore, the head of the pedestrian is under accelerations higher than the ones tolerated. Moreover, in figure 13 can be observed that the value of the HIC$_{15}$ criterion is higher than the maximum tolerated one (712.1>700). For the persons aged six years and older is accepted the fact that the maximum limit of tolerance is HIC$_{15}$=700 [3].

Exceeding the tolerance criteria justifies the trauma suffered by the head of the pedestrian as they were highlighted in the consequences of the traffic accident (paragraph 2.1).
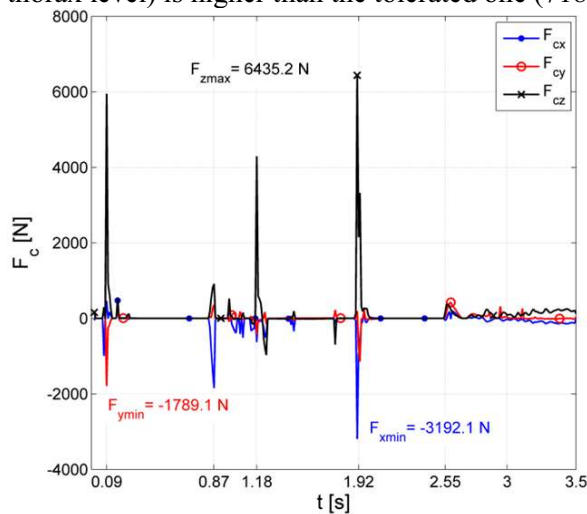
As known in the specialty literature [6], in order to appreciate the severity of the head injuries the most used criterion is the one named HIC (Head Injury Criteria), which is expressed through the relation:

$$\mathrm{HIC} = \left[\left(\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a_{rez} \mathrm{d}t \right)^{2,5} \cdot (t_2 - t_1) \right]_{max} \tag{1}$$
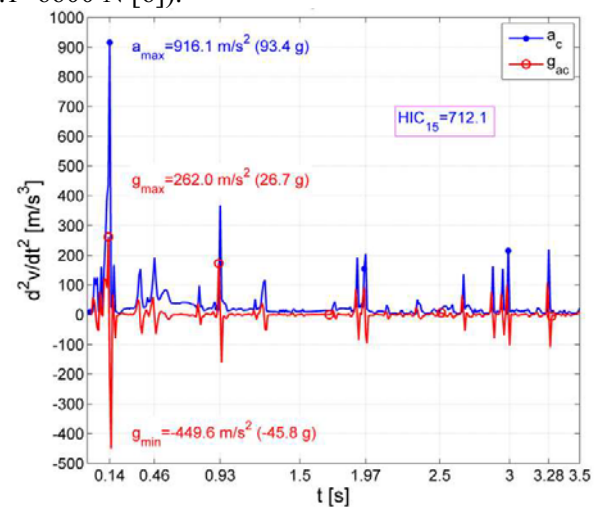
in which t_1 and t_2 are the limits of the period of time considered, and a_{rez} represents the resultant of the instant acceleration/deceleration related to the gravitational acceleration g.

The risk of fracturing the skull bones refers to the period of time t_2-t_1=15 ms and it's marked with HIC_{15}.

In figure 14 are shown the contact forces of the thorax (torso) of the pedestrian. From figure 15 results that in the thorax area there are rib fractures, because the contact force (the resultant force at the thorax level) is higher than the tolerated one (7186.1>6600 N [6]).

Figure 14. The contact forces of the thorax (torso) of the pedestrian, values on the three coordinate axes

Figure 15. The resultant force at the thorax level of pedestrian

The contact force at the thorax level which is higher than the tolerated contact force justifies the existence of the thorax trauma with a left pulmonary contusion mentioned in the forensic findings and highlighted in the consequences of the traffic accident involving the pedestrian (paragraph 2.1).

Also, from figure 15 results that this trauma may have appeared at time t=1.92 s, namely when the pedestrian, after the separation from the vehicle, hit the road surface and started slipping on it (figure 10). The presence of the trauma at the moment of impact with the vehicle (at t=0.09 s) is less probable, because the contact force value is lower than the tolerated value (6226.9<6600 N [7]).

3. Conclusions

The current research methods can assess the level of human body damage, considered in its entirety. The assessment of kinematic and dynamic parameters for a **certain component or organ** inclined to be affected during the manifestation of certain reactions specific to the type of dynamic load and the comparative analysis related to the human tolerance at the force applied to the human body during traffic accidents, generate a **higher level of accuracy for the car accident reconstruction, including concerning how pedestrian injuries are occurring.**

The results obtained after analyzing the parameters related to the pedestrian kinematic and dynamic show that during the impact significant values of the contact forces and the accelerations were displayed in the thorax and head area, these values being superior to the ones tolerated by the human body. The size of the accelerations and the contact forces, as well as the duration of the impact represent the main factors that generate the severity of the lesions suffered by the victims. **The secondary impact with the ground proved to be another important factor that generated severe**

trauma.

The assessment methods of the kinematic and dynamic parameters on components seem to represent the best solutions for evaluating the potential for pedestrian injury resulted in the car accident, during the impact between the vehicle and the victim, as well as during the impact of the pedestrian with the ground.

The paper is the result of the research conducted during the preparation of the PhD thesis within the "Automotive Engineering" doctoral studies section of the Faculty of Engineering and Technology - University of Pitești.

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