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Problems of modelling a pedestrian collision – selected aspects

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ABSTRACT

The article studies modelling a collision of a pedestrian with a car and the components of road infrastructure. With the study of the course of the road accident, there are analysed the possibilities of using a human body multi-solid model and the kinematic model for impact parameters reconstruction. The study also considers the possibilities of applying an analytic approach and road incidents databases, supplementary to computer simulation, offered by modern software used in road accident reconstruction. The study results demonstrate an application potential, and they can be used for road traffic safety enhancement. The effects of collisions with unprotected road traffic participants are most tragic and very expensive, hence considering the problem is this article is very important also for socioeconomic reasons.

Keywords: car accidents, collision modelling, pedestrian, road traffic safety.

INTRODUCTION

The article's data concerning the number of accidents and their kinds and effects have been taken from the elaborations of the National Council of Road Traffic Safety [1], the report by the Main Command of the Police [2] and paper [3].

The year 2023 ended up with 20,936 road accidents reported, with 24,125 injured and 1893 fatalities (Fig. 1). However, only inconsiderable decreases are noted, as compared with the year 2022, which points to a need of a further road traffic safety improvement. Most incidents were qualified as collision of vehicles in motion; in 2023 – 11,107. It accounted for 53% of the total accidents in which 840 people died, which accounted for 44.4% of all the deaths and 13,811 injured, which accounted for 57.2% of all the injured.

The second most frequent kind of road accident in 2023 was an incident qualified as hitting a pedestrian. A total of 4 787 such accidents were notified, which accounted for 22.9% of the total accidents with 447 fatalities, which accounted for as much as 23.6% of fatalities in total, and 4 609 injured, which, in turn, accounted for 19.1% of the victims of such road accidents. Road safety is still a critical issue in Poland, especially for pedestrians. An example of improving safety for these road users is presented in the work [4].

In Poland the total costs of road accidents accounts for 1.75% GDP, namely PLN 52 bn., and the costs of road accidents are PLN 37.9 bn. Table 1 breaks down the unit costs for the year 2022. We, therefore, face a very serious socioeconomic problem, especially that first material losses are considered and not personal injuries, which are deferred, however they generate the most serious losses. For that reason, the actions of experts performing analyses to reconstruct the parameters of impact on the pedestrian, which is a springboard for road accident reconstruction, are becoming especially significant. And, further, the results of such analyses frequently directly affect court decisions.

The analysis of a collision of vehicles, vehicles with obstacles, or a vehicle collision with a pedestrian can be made using programs

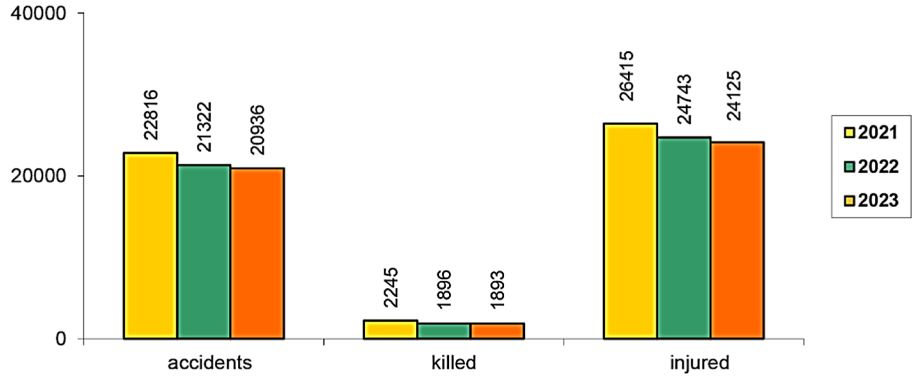

Figure 1. Comparison of the number of road accidents and the subsequent personal injuries in 2021–2023 [2, 3]

modelling the course of the collision with the finite element method (FEM) or applying simpler models; multi body system (MBS) / multi body dynamic (MBD). Examples of approaching the impact analysis using FEM are presented, e.g., in other papers [5–12]. Today, the numerical analysis of the collisions of vehicles, vehicles with obstacles and with pedestrians for accidents reconstruction involves MBS / MBD programs, which is demonstrated, e.g., in [13, 14]. Such programs include, e.g., V-SIM, PC-Crash, Virtual Crash, which offer much less time-consuming computations with reasonable parameters and a high number of numerical vehicle models, as compared with FEM programs. They also allow for the collision analysis to use the impact collision model, in which the forces acting between the collision participants develop continuously from the first contact to the final separation and the traditional impulse-based model, in which, on the other hand, the exchange of force impulses occurs in the same selected time. On top of that, those IT tools facilitate the simulation objects performing many tasks during computations, e.g., for vehicles: gear change, acceleration, turning manoeuvres, or various functions and cases of braking, which has been described in other papers, e.g. [15]. The tasks of wheel blocking, displacement or decrease in tyre compressed air pressure are also feasible, while the full vehicle modelling was shown in the paper [16]. For a kinematic simulation object, e.g., a pedestrian, the tasks of change in velocity, acceleration and deceleration as well as revolutions can be performed. The same simulation program tasks can be also carried out for the human multibody model. Those advantages of the MBS/MBD programs have made them dominate the applications of accident reconstruction for impact parameters. However, simpler modelling in those programs, as compared with FEM, also poses threats the expert must consider, especially making an adequate selection, considering the accident reality, of the impact model and collision detection as well as introducing control parameters, as mentioned in this article. In those programs, thanks to optimisers applying, e.g., the Monte Carlo method, random sampling of the solution space is possible, thanks to which one can receive the optimal solution of the problem, and not to base on a single simulation performed, which has been described in [17].

Table 1. Unit costs of road accidents in Poland in 2022 [1]

Unit cost	Value in PLN
Accident fatalities	2 574 672
Seriously injured in the accident	4 203 244
Slightly injured in the accident	54 558
Material losses	19 004

MATERIALS AND METHODS

Vehicle model

The simulation study involved a use of a program representing the MBS group, applied for road accident reconstruction and road engineering; V-SIM ver. 6.0.21 [18]. In that program, the numerical model of the passenger car has ten degrees of freedom. The resultants of the position of the centre of mass and moments of inertia determined in the program also consider a specific distribution of passengers and load in the vehicle. In the model there have been applied a progressive characteristics of an independent wheel suspension and the stiffness of stabilizer bars. The dynamics of the wheels rotation is independently analysed, and the steering system considers malleability. The vehicle's brake system model considers the function of anti-lock braking system (ABS) and the electronic stability program (ESP). Each object simulated has its own coordinate system (`) the centre of which is located in the centre of mass, and the motion environment is defined by the program operator. Fig. 2 demonstrates the described-above vehicle model in a global frame of reference.

The program provides two collision detection models to choose from. The 2D model (Fig. 3) detects geometrical simulation objects overlapping in a 2D plane and the 3D model (Fig. 4) reduced to a voxel from 2 cm to 8 cm in size. Collision detection involves the program verifying which points of the object's network interior are found in the other one.

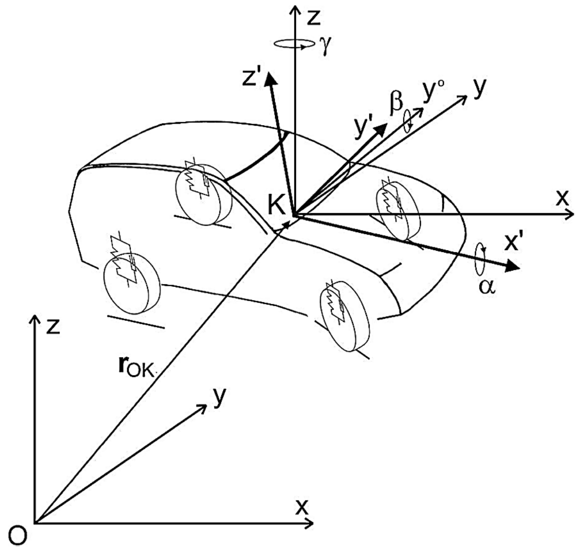

Figure 2. Vehicle model in the program with frames of reference [18]

Pedestrian model

The kinematic pedestrian model facilitates considering the mass, centre of mass and the moments of inertia as well as performing tasks, e.g., a change in velocity, a change in trajectory (Fig. 5). It is one of the simplest pedestrian body models. A pedestrian body model which is much more advanced is a multi-body model; multi body (MB) (Fig. 6). In the V-SIM the model is made up of 15 body segments joined with kinematic pairs with three degrees of freedom.

Motion environment modelling

In the program, simulation objects motion environment modelling allows for defining the state and the kind of the road surface, assuming the values of the grip index and rolling resistance coefficient. In the program the elements of the motion environment have been divided into passive and active. The passive ones include, e.g., symbols of the elements of the horizontal markings of the roads, railway tracks and many ready objects from the program library, whereas the active environment elements include, e.g., a section of the road together with the kind of the road surface and roadsides as well as the poles which can be an element of road infrastructure providing an obstacle with specific dimensions and material stiffness coefficients at the phase of compression and restitution. The program interface facilitates generating the motion environment modelled in a form of a scaled site plan, which is applied for the accident analysis and reconstruction of the impact

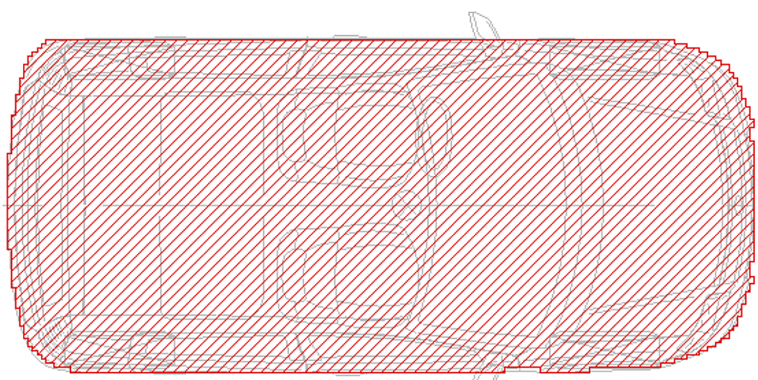

Figure 3. 2D Collision detection model

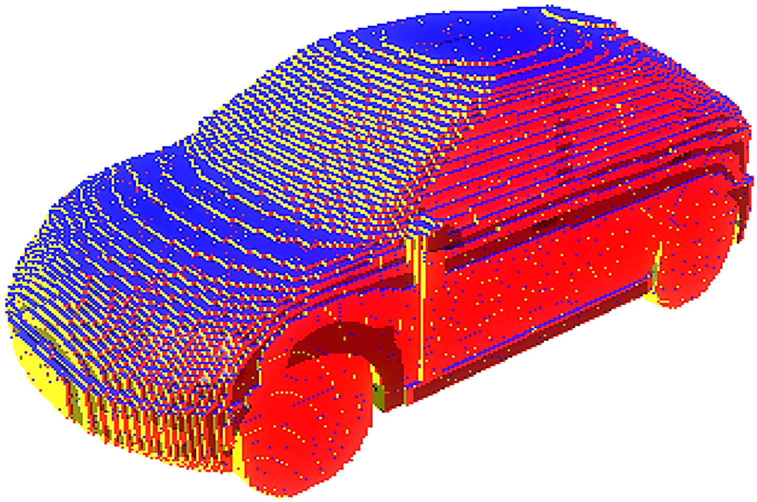

Figure 4. 3D Volumetric collision detection model with voxels

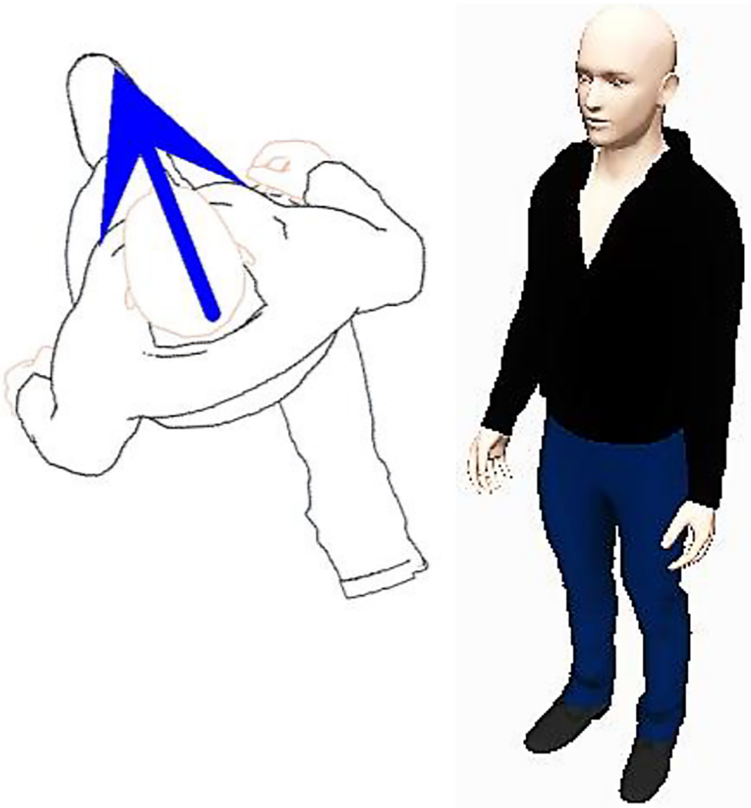

Figure 5. Graphic view of the kinematic human body model in a 2D and a 3D plane

parameters. The 2D site plan developed for the analysis is demonstrated in Figure 7.

Case study own research

The accident involved a passenger car and a pedestrian; their parameters used in the computations are provided in Table 2; the motion environment parameters are given in Table 3, while Table 4 specifies the simulation objects settings. The circumstances of the accident which happened at night involved the car hitting the pedestrian running across the road from the left to the right considering the direction of the car travel and, after hitting the car, the pedestrian hit the lamppost on the pavement, on the right. The free-flight motion of the pedestrian's body was and so the reconstruction of the car impact velocity parameters

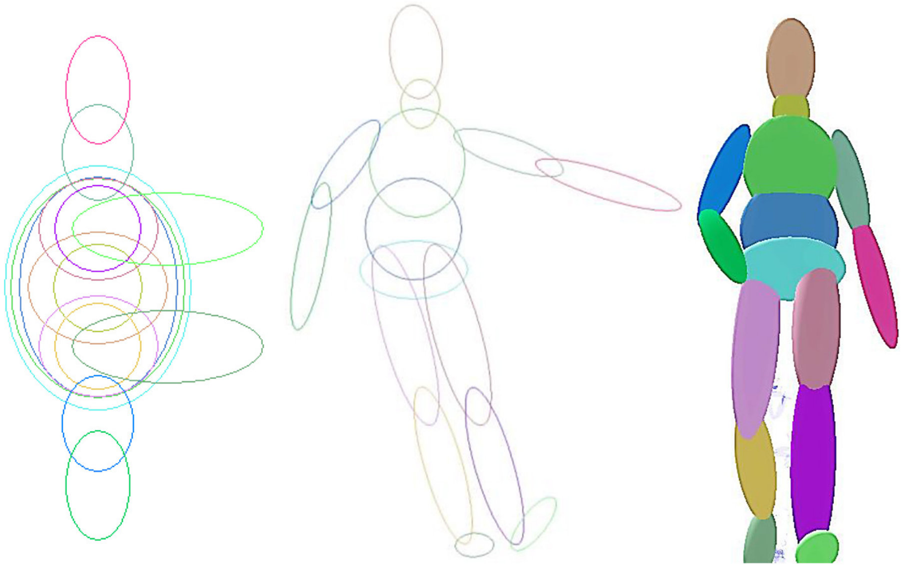

Figure 6. Graphic view of a multi-solid human body model in a 2D and a 3D plane

is a problem, and thus the selection of the model which would be adequate to the case considered and the control parameters is getting very crucial.

The shape of the front part of the car body determines the qualification according to the following parameters [19].

- wedge body; the height of the front bonnet edge ≤ 0.7 m from the ground, and the angle between the bonnet and the horizontal ≤ 20°,
- trapezoid body; for a flat bonnet, the angle between the front wall plane and the horizontal ≤ 70 °, and the angle between the bonnet plane and the horizontal ≤ 20°,
- trapezoid body; for a steep bonnet, the angle between the front wall plane and the horizontal ≤ 70°, and the angle between the bonnet plane and the horizontal > 20°,
- trapezoid body; in case of the elliptical shape of the front bonnet, the radius of its front part > 0.25 m,
- pontoon styling; the angle between the front wall plane and the horizontal > 70°,
- box body; it has a vertical front wall.

Such car body division is provided for in the German DIN 75204-1:1992-05 standard norm and the examples developed using vehicles' vector shapes [20] are given in Figure 8.

A vehicle hitting a pedestrian most often results in the pedestrian's bounce in the car travel direction. Literature refers to this phenomenon as pedestrian's bounce. The pedestrian's longitudinal bounce has been defined as the distance between the place where the pedestrian was hit by a vehicle and the position of the pedestrian's body and the place where the body finally stopped after the accident, measured in the car travel direction. The term should not be confused with the phase of flying or sliding of the pedestrian's body after the fall to the road. The flying phase is a distance made by the pedestrian once the pedestrian got separated from the vehicle which hit him/her to the place of the first fall to the road. The sliding distance is the distance between the place of the first contact of the pedestrian's body with the ground after the fall,

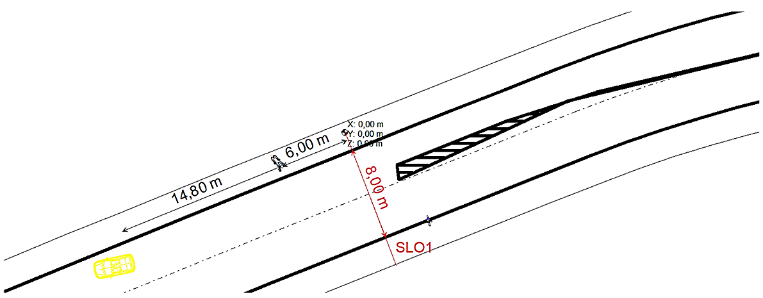

Figure 7. Accident site plan used for impact parameters reconstruction

Table 2. Vehicle technical parameters and pedestrian parameters

Parameter	Value
Pedestrian weight / height	75 kg / 1.70 m
Pole diameter / height	0.23 m / 5.0 m
Stiffness of the pole material	Nondeformable
Driver weight	78 kg
Total vehicle weight	1 013 kg
Vehicle length / width / height	3.538 m / 1.578 m / 1.540 m
Car wheelbase	2.299 m
Track axle 1–2	1.366 m / 1.357 m
Tire size front axle / rear axle	165/70 R14 / 175/65 R14
ABS system	Yes
ESP system	No

and the final position of the body after the accident. Below, Figure 9 presents the diagram of the pedestrian body's longitudinal bounce.

Searching for the impact velocity, there have been used the car damage and its post-accident position as well as the pedestrian-bounce-related parameters. Figure 10 shows a position of both accident participants crashing at the moment of contact.

To estimate the car impact velocity, there was first applied a comparative method with the data provided in equivalent energy speed (EES), which presents the vehicle's damage the equivalent impact velocity has been determined for. Fig. 11 demonstrates the vehicle's damage after hitting a pedestrian from a database of vehicles [21] the range of which is very similar to the damage of the car taking part in the accident. The data points to the car impact velocity of 50 km/h.

Table 3. Movement environment

Parameter	Value
Road surface type	Wet asphalt
Pavement surface	Wet concrete
Adhesive / slip friction coefficient	0.60 / 0.50
Vehicle/human friction coefficient	0.70 / 0.50
Road width / slope	8.00 m / 0°

The next step involved searching for the successive methods to verify the impact velocity. With crash test dummies, with known impact velocity, the distances from the place of the objects' first contact to the final (post-accident) position of the dummy's centre of mass were measured. It was found that for the impact velocity ranging from 5 to 14 m/s, the pedestrian's bounce can be described with the equations [19]:

$$S_O = 1{,}5 \cdot v_k - 6 \tag{1}$$

$$S_O = 0{,}034 \cdot v_k^2 + 0{,}45 \cdot v_k + 1{,}1 \tag{2}$$

where: S_o – pedestrian's longitudinal bounce,
v_k – vehicle's impact velocity.

However, as earlier indicated, a free-flying of the pedestrian's body was interrupted by hitting the pole. With the place of impact and trajectory of the pedestrian established, to verify the above value of impact velocity, it was verified whether it would correspond to the impact velocity as a function of bounce with the assumption that flying

Table 4. Tasks modelled for vehicle and pedestrian

Parameter	Value
Initial linear speed of the car	13.89 m/s
Vehicle controls	60° steering wheel 4.6 s in time
Braking	Press on brake pedal 100% 4.90 s in time
Brake action time	0.35 s
Initial pedestrian speed (76 age)	Running 1.66 m/s
Multibody activation	4.18 s in time

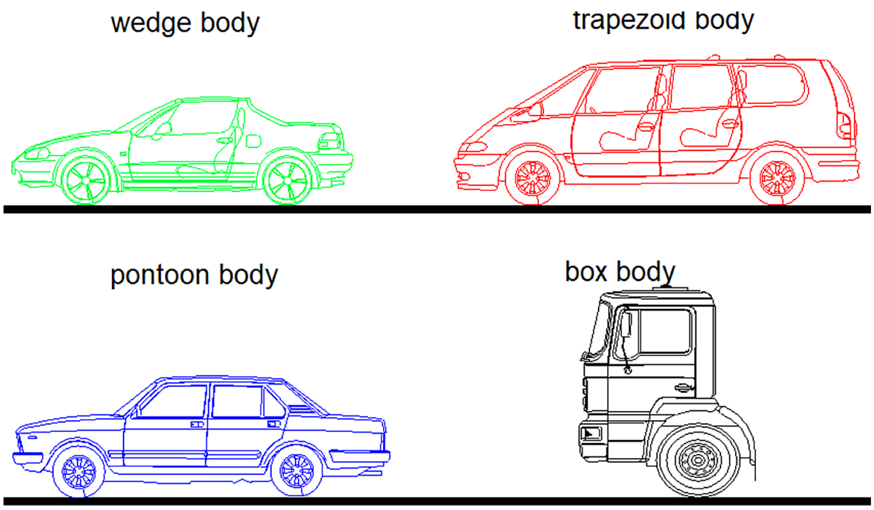

Figure 8. Car bodies assumed for accident reconstruction

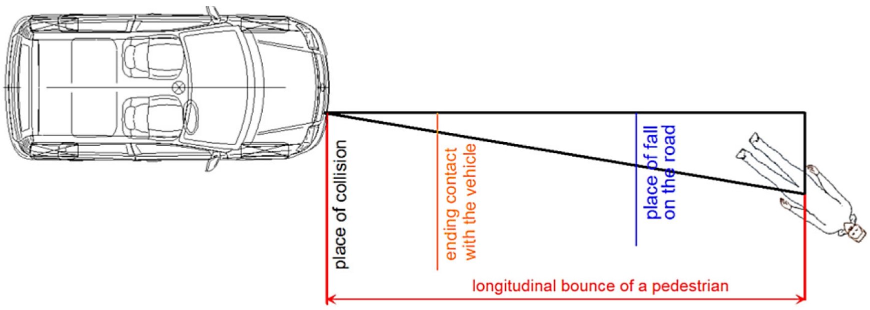

Figure 9. Longitudinal bounce of a pedestrian

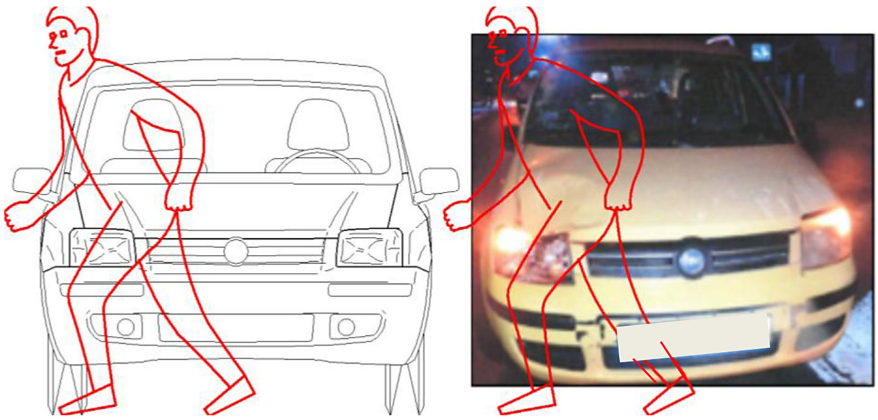

Figure 10. Position of the pedestrian crashing with the car at the moment of contact

Figure 11. EES data [21] for a comparative method

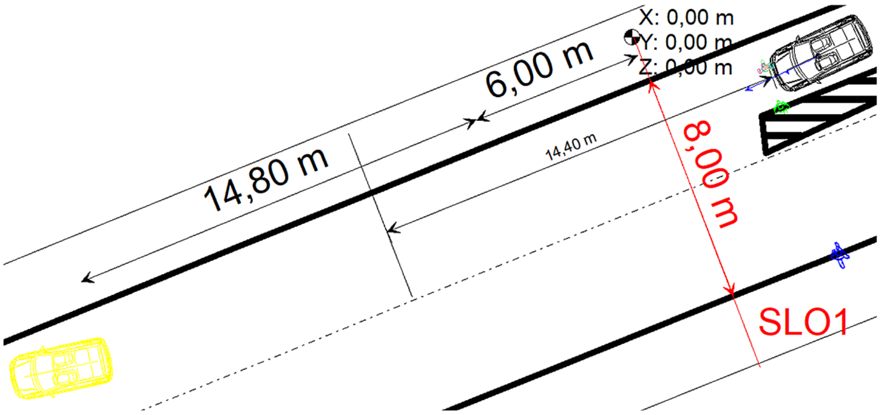

Figure 12. Impact of the pedestrian's crash with the vehicle

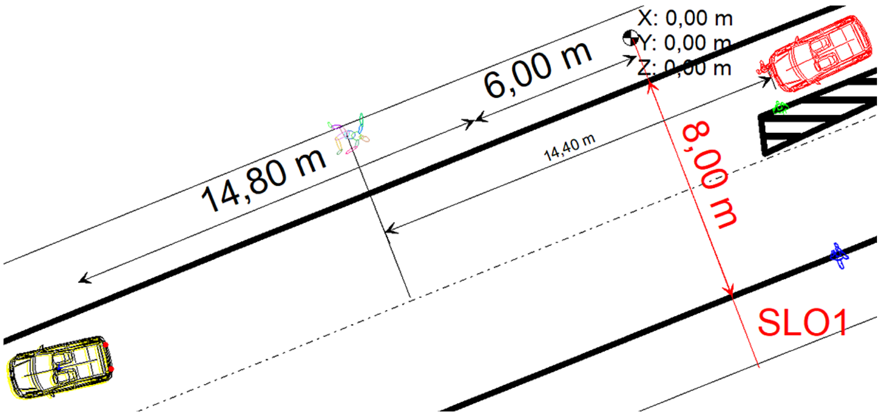

Figure 13. Final positions of the vehicle and the pedestrian after the accident

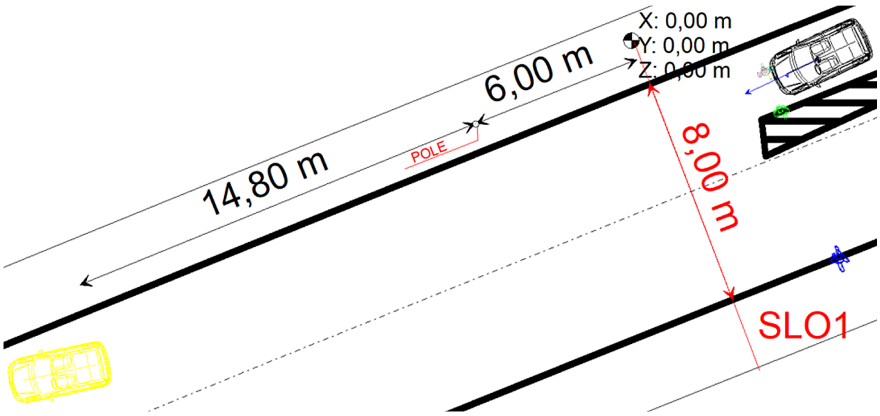

Figure 14. Reconstructed pedestrian's crashing into the vehicle

of the pedestrian's body would be free. Therefore, supporting the simulation methods with an analytical approach becomes indispensable, which is also described, e.g., in [22, 23].

For the impact velocity established earlier, applying the above relations, an averaged pedestrian bounce would be 14.40 m. In further study, an impact simulation aimed at verifying whether the bounce value would be corresponding. Figure 12 shows an impact, and Figure 13 – the post-accident positions of the simulation objects. In the simulation with a use of the human multibody model for the impact velocity of 50 km/h, the pedestrian's post-accident position complied with that resulting from the experiments [19] and with the vehicle's post-accident position, which is represented by the yellow and black images overlapping (Fig. 12 and Fig.13).

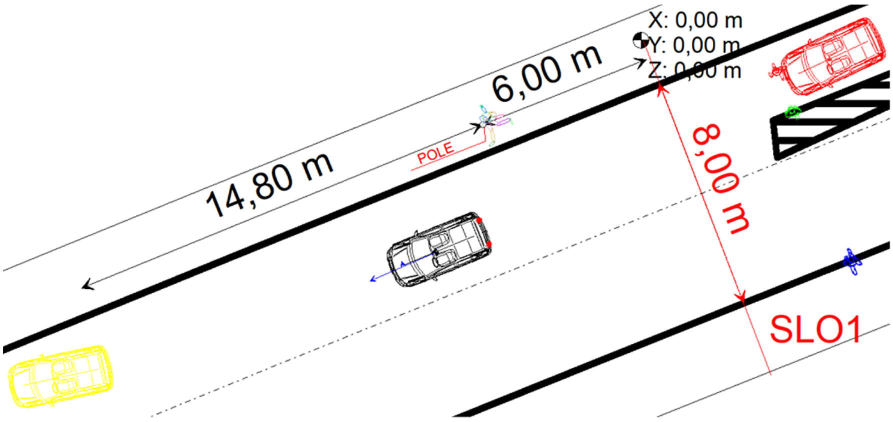

Figure 15. Reconstructed pedestrian's crashing into the pole

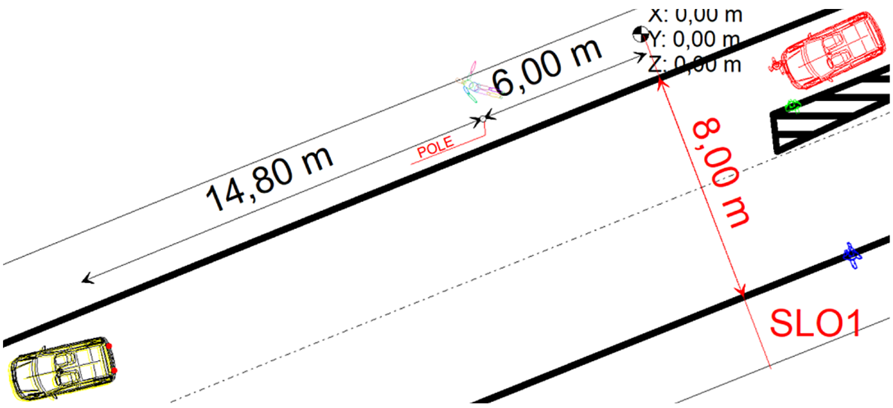

Figure 16. Overlapping final positions of the vehicle and the pedestrian in the simulation and after the accident

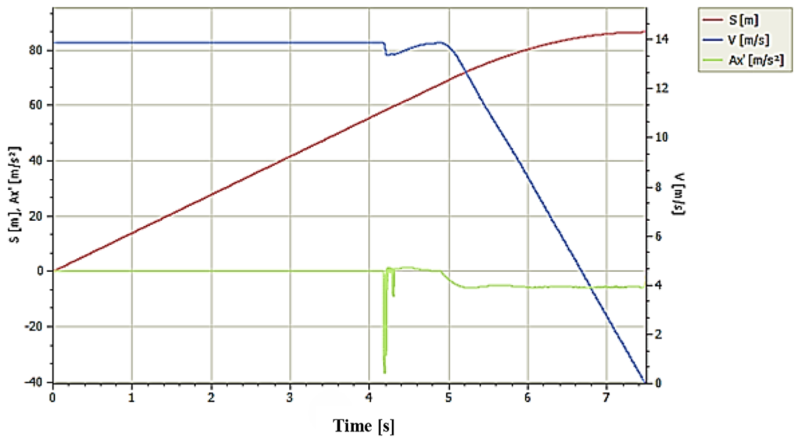

Figure 17. Time course of the changes in the vehicle's linear velocity, acceleration and the distance covered

The kinematic pedestrian model turns out hardly useful for such verification as it does not make it possible to simulate the pedestrian's bounce after being hit by the car. However, thanks to the research procedure presented in the article, it is possible to reconstruct the parameters of the vehicle hitting the pedestrian and the pedestrian crashing into the pole, which is demonstrated in Figures 14–16.

Figure 17 shows the patterns of changes in velocity, deceleration and the distance covered as a function of time of the vehicle, and Figure 18 – changes in the pedestrian's linear velocity as a function of time. The simulation objects got into

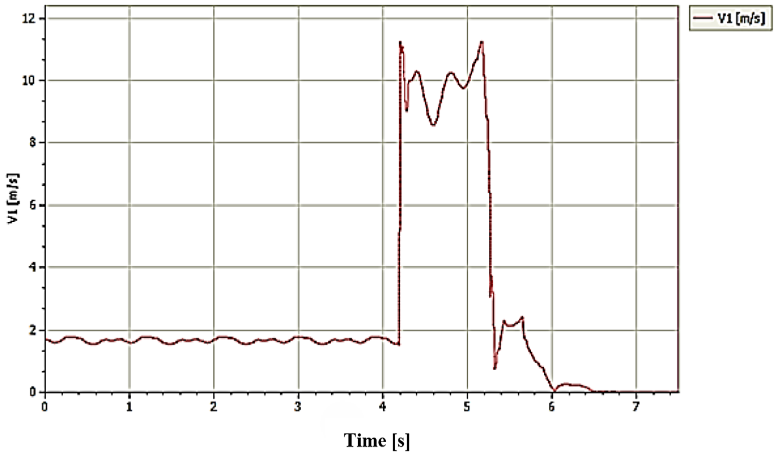

Figure 18. Time course of the changes in the pedestrian's linear velocity

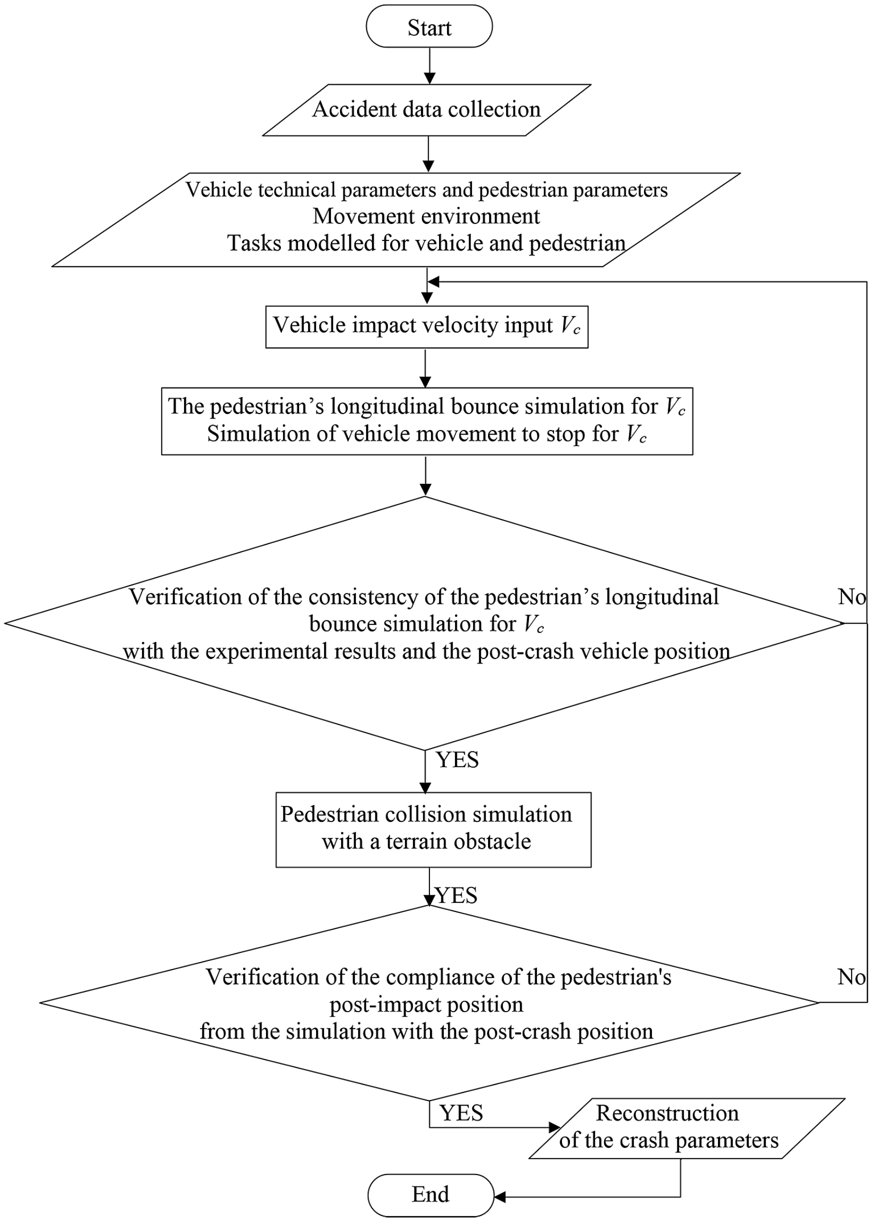

Figure 19. Schematic diagram of the reconstruction of the parameters of a vehicle-pedestrian collision and a pedestrian-road infrastructure element or terrain obstacle collision

contact at time $t = 4.18$ s for the car's resultant linear velocity of $V = 13.88$ m/s and the pedestrian's $V = 1.66$ m/s. The impact resulted in the vehicle's momentary deceleration $Ax' = 18.7$ m/s^2 at time $t = 4.19$ s and a rapid increase in the value of the pedestrian's velocity up to $V_1 = 11.2$ m/s. After the flying phase at time $t = 5.30$ s, the pedestrian hit the pole with a similar velocity, which resulted in a rapid stop of the pedestrian's body and a fall at the pole base.

CONCLUSIONS

The present study provides tangible results and conclusions which offer an application value and Fig. 19 shows the developed procedure in the form of a diagram:

- the research procedure developed and presented in this article facilitates the reconstruction of the parameters of the vehicle hitting the pedestrian with elements of road infrastructure or with an obstacle,
- thanks to the research procedure developed, which allows for determining the pedestrian's velocity, as a resultant value, it is possible to establish the pedestrian's motion by referring the value received to the literature data for pedestrian velocity ranges,
- the kinematic pedestrian model should have limited applications and the analysis without a use of the human multibody model and the bounce must be considered uncertain.

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