Towards a Better Understanding of Vulnerability in Pedestrian-Vehicle Collision

Mauro D'Apuzzo[1], Daniela Santilli[1](✉), Azzurra Evangelisti[1], Luca Di Cosmo[1], and Vittorio Nicolosi[2]

[1] Department of Civil and Mechanical Engineering DICEM, University of Cassino and Southern Lazio, Cassino, Italy
{dapuzzo,daniela.santilli}@unicas.it

[2] Department of Enterprise Engineering "Mario Lucertini", University of Rome "Tor Vergata", Rome, Italy
nicolosi@uniroma2.it

Abstract. The road is a transport infrastructure intended for the movement of users, such as vehicles and pedestrians. These interact with each other following rules that guarantee safety and security. Unfortunately, however, traffic safety does not depend solely on compliance with the rules but is affected by a series of factors, such as inattention by users or malfunctioning due to a particular environmental condition, etc. Although the accident data in Italy show a reduction in the mortality of motorists, thanks to the new on-board technologies, an increase in the number of victims among pedestrians is observed. To increase the safety of vulnerable users, several projects have been developed in order to define the correlation between the severity of the accident, the response of the vehicle and the stresses that can be tolerated without serious risks to the occupant's life. However, this requires detailed accident and user injury data. Often without this information, it is not possible to predict the accident situations of a site and the related consequences. The aim of this study is to enrich the existing vulnerability functions by correlating the objective kinematic parameters (acceleration, speed, etc.) with user injuries through multi-body simulations.

Keywords: Head Injury Criterion · Pedestrian injury · AIS

1 Introduction

In recent decades, the need to improve road safety has been increasingly felting both on vehicles equipped with innovative technological means (in terms of active and passive safety) and on the infrastructure. In fact, the European Union has drawn up a set of laws to obtain a coherent and complete system of measures aimed at improving road safety (cf. the recent European Directive 2008/96/EC); but also by promoting and financing programs and initiatives that have fostered both greater awareness and, consequently, consumer demand for safer vehicles (thanks to the EuroNCAP scoring system). Road safety requires an articulated approach capable of integrating multiple aspects, from

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the most purely technical to the psychological ones that govern user behaviour. The adoption of measures in favour of safety presupposes that one is able to recognize and evaluate the risk conditions that accompany a specific infrastructural configuration. The preventive safety analyzes of existing infrastructures (defined internationally with the term Road Safety Review) can help to identify, in a road layout, the presence of situations of potential risk for traffic, addressing the problem from the point of view of users and trying to investigate how they perceive, interpret and use street space. During the examination of the infrastructure, it is necessary to apply the principles of road safety according to a multidisciplinary perspective; that is, taking into account all types of users: motorists, motorcyclists, cyclists, pedestrians, the elderly, children, etc.

Especially in urban areas, a very important aspect is to make roads safe, especially for vulnerable users (pedestrians and cyclists), who often shared the space with motorized vehicle traffic, in order to encourage sustainable mobility (zero pollution). To focus attention on this type of user, it is advisable to identify the points or sections of the road network where it is most urgent to proceed with engineering investigations and safety analyzes for the assessment of risk factors. Talking about a risk factor means considering an event, or a condition, which intervenes in the Vehicle-Driver-Environment (VDE) system and modifies its correct functioning, thus constituting a probable trigger for a possible accident. Once the risk factors have been identified, it is necessary to evaluate the number, severity and recurrence of accidental events [1, 2] as well as the severity of the consequences to people. The objective is to determine the priorities of the interventions to be implemented, maximizing their effectiveness and optimizing the financial resources available.

To do this, it is necessary to have detailed data on the localization and dynamics of the accident as well as the harmful/fatal consequences that are encountered on users. Such data are often difficult to find and the ISTAT database is not useful since it does not provide a detailed location of the accident or a precise description of the dynamics.

In many European countries, in-depth accident databases [3, 4] are already available to help understand the mechanisms of injury and tolerance of the human body so as to provide an operational framework for investigating pedestrian accident scenarios in the real world [5–9].

These data together with the biomechanical knowledge (with which it is possible to know the tolerance of the human body to stresses and to attribute criteria that classify the injuries suffered by the occupants of the vehicle) have allowed starting studies whose purpose was to define the vulnerability prediction functions [10].

Evaluating vulnerability means defining the results of an impact, this means examining what in the reconstruction of an accident is called the post-impact phase. Numerical analyzes based on empirical formulations are usually used for the reconstruction of accidents involving pedestrians, even if the use of software that makes use of multi-body simulation is increasingly widespread. By means of the multi-body simulation codes, once the initial conditions have been imposed, it is possible to describe the motion of the bodies involved and, as a function of the dynamics, allowing to evaluate induced damage.

In this paper a new methodology aimed at enriching the existing pedestrian vulnerability prediction functions by the information on kinematic (acceleration, speed, etc.)

and mechanical (moments, cuts, normal stresses, etc.) outcomes provided by multi-body simulation codes is proposed.

2 Dynamic Vehicle-Pedestrian Collisions

Reconstructing the dynamics of the pedestrian-vehicle collision is not a simple task. In fact this depends on the concatenation of many factors such as: physical ones of the vehicle (type, speed, etc.), physical ones of the pedestrian (size, a position assumed at the moment of impact, age, etc.), the atmospheric, urban, legislative, psycho-physical ones of the driver etc.

2.1 Pedestrian Vehicle Collisions

Kinematics and pedestrian injuries in vehicle accidents are affected by numerous factors such as impact speed, vehicle type, stiffness and shape of the vehicle front (such as bumper height, hood height and length, windshield frame), age and build of pedestrians, as well as the pedestrian's initial posture relative to the front of the vehicle [11].

In this work for the reconstruction of accidents, reference was made to "free trajectories". These allow to model the collision between vehicle-pedestrian and the subsequent motion of the pedestrian in a series of successive phases (contact, acceleration, loading, projection, rolling or sliding on the ground).

Basically, it is possible to distinguish two types of free trajectories:

- *Forward projection:* in which the height of the centre of gravity of the pedestrian "hcg" is placed below the height of the upper edge of the front of the vehicle "Hc". It is substantially realized in all those cases in which the pedestrian is hit in full, or the impact occurs in the central area of the front of the vehicle.
- *Wrap* o with wrapping: which has three sub-categories (Fender Vault, Roof Vault and Somersoult). The centre of gravity of the pedestrian is greater than that of the height of the upper edge of the front of the vehicle. By schematizing the pedestrian as a rigid body, the motion that is given to it following the impact is a horizontal translation and a rotation around the centre of mass. Consequently, the pedestrian wraps around the hood of the vehicle with a subsequent impact of the head on it or on the windscreen. In this regard, a fundamental parameter is introduced, the WAD (Wrap Around Distance).

The WAD is defined as the distance from the point of contact with the front of the bumper to any point on the front structure of the vehicle. This parameter is influenced by the impact speed of the vehicle, the length of the hood and the height of the pedestrian. With the same shape of the front of the vehicle and the height of the pedestrian, the higher the speed, the greater the WAD.

Given the variability of each influencing parameter in each phase, it is more convenient to classify the types of impact on the basis of the overall trajectories (pre-impact, impact, post-impact). As already mentioned, this work mainly dealt with the post-impact

phase which is influenced by the characteristics of the impact phase such as: the geometry of the front of the vehicle related to the height, position and motion of the pedestrian in the pre-impact phase, the braking characteristics of the vehicle and the impact speed.

2.2 Vehicle Characteristics

As far as the vehicles characteristics are concerned, three fundamental geometric parameters are used to define the shape of the vehicle's front (Fig. 1):

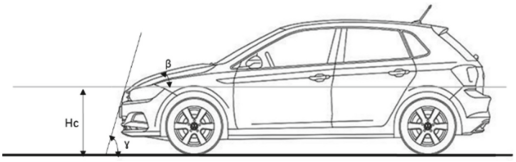


Fig. 1. Geometric parameters for defining the front of the vehicle

- γ = "Lead Angle" loading angle which determines the amount of vertical thrust on the pedestrian in the primary impact;
- β = "Bonnet Angle" influences both the loading and the launch direction of the pedestrian, as well as the way in which the pedestrian hits the bonnet in the secondary impact;
- Hc = Height of the front edge of the "Lead Edge" hood which together with the height of the centre of gravity of the pedestrian determines the arm of the rotary moment (ω).

According to the relationship between the height of the pedestrian and the front of the vehicle, three types of front are identified:

- *Low Front Vehicles,* which the height h of the frontal is less than 0.55 m, that is the value corresponding to the 50% percentile of the knee height of the adult population;
- *High Front Vehicles,* such as the height of the front h is between 0.55 m and 1.05 m; that is the value corresponding to the 50% percentile of the height of the center of gravity of the adult population;
- *Vertical front vehicles,* whose front height h is greater than 1.05 m.

The height of the front edge of the hood and its combination with other parameters affect the head or torso injuries of the vulnerable user. In fact, increasing the height of the front edge of the hood can potentially reduce the risk of head injuries.

Further consideration should be made on the profile of the front of the vehicle seen from above which can be rectangular, triangular or arched.

This latter classification has a considerable influence on the speed component of the pedestrian positioned transversely with respect to the direction of the vehicle. In fact, for rectangular type fronts, the speed remains unchanged, with a consequent variation

of the momentum of the pedestrian in the direction of advancement of the vehicle itself, neglecting the friction during contact. While for triangular or arched fronts, the transverse motion of the pedestrian can undergo a deceleration or acceleration depending on the area in which the impact occurs. According to Han et al. [12] the hood therefore affects:

- the loading phase;
- the extent of the vaulting during the loading phase, since it depends on the height from the ground of the upper edge of the bonnet (this is greater for low edges, lower for high edges);
- the parts of the body that impact the front of the vehicle vary according to the height from the ground of the front edge of the bonnet and the length of the bonnet.

2.3 Pedestrian's Characteristics

Pedestrians are characterized according to their age, their size, but a not marginal factor is their position relative to the vehicle at the moment of impact. In fact, based on the position and the angle of impact there is a different sequence of the parts of the body that collide with the vehicle and therefore of the related injuries [13, 14].

As regards the pedestrian rest position, if the vehicle starts braking immediately after the primary impact, it is placed in front of the stop position of the same, otherwise, it is placed in a rearward and lateral position (Fig. 2).

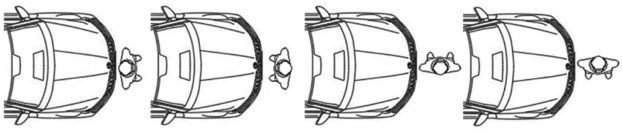


Fig. 2. Different position of the pedestrian relative to the vehicle

By further increasing the vehicle's impact speed, i.e. greater than 60 km/h, the somersault-like trajectory of the is passed, which differs from the Roof Vault in that the secondary impact does not occur since the pedestrian undergoes a greater vertical thrust with a flight phase and the vehicle moves much faster under the pedestrian in flight. In this case, the final resting position of the pedestrian is always behind the vehicle stop position.

In fact, many studies [15, 16] confirm that the frontal position is more dangerous than the lateral one because the contact of the head and the thorax occurs directly on the hood; while the pedestrian in the lateral position hits the hood with the shoulder, this limits the injuries to the fatal parts. The above is confirmed by the analysis of the data on accidents.

3 Proposed Methodology for Pedestrian Injuries Evaluation

To determine the pedestrian injuries, both in terms of location and severity, following an impact, several factors must be considered. They never occur individually but combined with each other.

In order to identify the outcomes of the impact, vulnerability functions are often used. These, however, consider only two parameters, not allowing to take into account the mechanical behavior of the bodies during the impact. To make the results of the analyzes more realistic, once the various factors have been defined, a model can be built and then multi-body simulations can be started, from which the mechanical or kinematic parameters useful for defining the lesions will be obtained (Fig. 3).

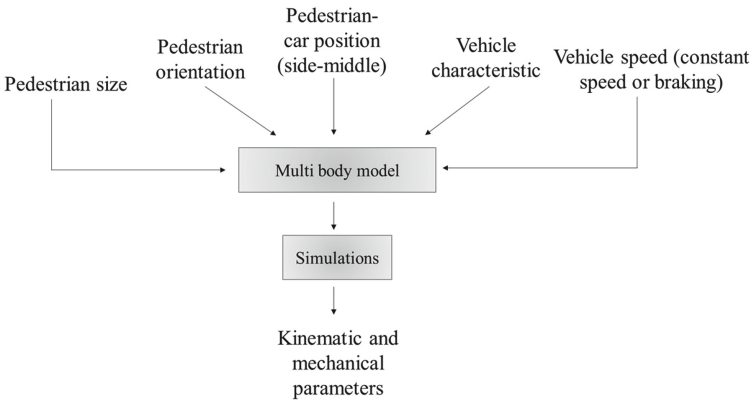


Fig. 3. Conceptual scheme adopted in the numerical simulations

The vehicle-pedestrian collision generates damages of a different nature, due to the primary impact, the secondary impact and finally those due to the impact on the ground. In this work, the focus was on the injuries suffered by a pedestrian in the primary impact. Usually, in these cases, there are bruises, fractures, or trauma and they vary according to the speed of the vehicle and the pedestrian and whether it is an adult or a child (Fig. 4).

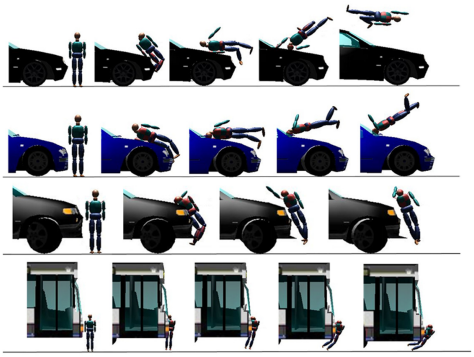


Fig. 4. Pedestrian kinematics after various vehicle impacts

This is easily found by observing the different frames of the multibody simulations. In fact, in these, it is clearly visible that when the front of the vehicle and the respective

shape vary, there are impact conditions and therefore different outcomes and injuries in the different parts of the body.

Nowadays pedestrian-vehicle impact outcome in terms of injury level can be evaluated by means of vulnerability prediction functions employing a logistic approach [32]. Logistic models are stochastic models that do not allow us to know the outcome of an accident but only to estimate the probability of a certain degree of injury and they are calibrated on detailed accident data collected within in-depth accident databases [3, 4]. Unfortunately, most of the existing vulnerability logistic models (VLM) is based on few statistically significant explanatory variables (namely, vehicle speed and pedestrian age) since the size of the in-depth accident database is very limited.

However, in order to analyses pedestrian safety according to a risk-based approach a better understanding of how pre-impact conditions (in term of pedestrian, vehicle and site characteristics and possible evasive maneuvres) may affect accident outcome is needed. The basic idea underlining this work is therefore to develop and calibrate a multi-body pedestrian-vehicle model. The aim is to provide an additional analysis tool that may complement the prediction yield by VLM by producing reliable synthetic accident data to enrich VLM with additional and new explanatory variables.

In order to accomplish this task, the following procedure has been pursued:

1) review of existing relationships between kinematic and mechanical quantities provided by multibody/fem accident numerical simulations and pedestrian injury scales;
2) assessment of numerical reliability of the developed multibody model by calibration with scientific literature data;
3) experimental calibration of the proposed methodology by comparison with results provided by existing VLM based on real accident data.

3.1 Injury Scales

Based on the type and severity of the lesions, they are classified with different scales based on the area of use. The main ones can be grouped into three sets:

- anatomical scales: classify the lesion in terms of anatomical location, type and severity. These scales assess the extent of the injury rather than the long-term consequences. The most famous and widespread of these scales is the “Abbreviated Injury Scale” (AIS);
- physiological scales: they describe the physiological state of the patient based on the change in function caused by the lesion. The status and its numerical rating may vary during the period of care. This type of scale is widely used in the clinical setting;
- scales based on damage, disability and social cost. In this case, the long-term consequences and the influence that the injuries have on the patient’s quality of life are assessed.

The first two types are medical, biomechanics is concerned with the scales that belong to the third group.

Abbreviated Injury Scale

The most common injury scale worldwide is the Abbreviated Injury Scale (AIS). This is commonly used to assess the severity and describe types of injuries. Starting from the patients' medical records assigns a score from 0 to 6 [17] as a function of injury severity, as described in international literature [16, 18–20].

For each level, there is [21] different damage to different parts of the body.

In reality, other scales are used to take into account the injuries involving the different parts of the body, including the Injury Severity Score (ISS) [22–24]. To determine the ISS it is necessary to evaluate the AIS of six body regions (head, face, chest, abdomen, upper and lower limbs) and then sum the squares of the three highest AIS indices. The ISS score, therefore, assumes values ranging from 0 to 75 (where 1 represents the presence of moderate injuries while 75 represents a fatal injury). By definition, if a region of the body has an AIS of 6, it automatically has an ISS of 75.

This is an anatomical scoring system that correlates linearly with mortality, hospital stay, and other measures of severity [25].

To define these scales it is, so, appropriate to estimate the lesions for the different parts of the body with the corresponding parameters.

Head Injury Criterion

In this report, statistical data was used to identify relationships between the injury criteria and the probability that it will occur. Several studies [26–28] have shown that the parts of the body that are most injured following an accident are the head and legs.

It is difficult to define a criterion that is able to take into account all the different modes of injury. But the international literature comes in support by providing various risk criteria [16, 19].

The most used criterion for head injuries in impact with the various areas of the vehicle is the Head Injury Criterion (HIC), also known as Head Performance Criterion (HPC).

The modification of the formula leads to the definition of the Head Injury Criterion:

$$\mathrm{HIC} = \max\{(t_2 - t_1)[\frac{1}{(t_2 - t_1)} \int_{t_1}^{t_2} a(t)dt]^{2.5}\} \quad (1)$$

where:

- a(t) is the resultant of the acceleration evaluated in the center of gravity of the head[g];
- t_1 and t_2 are two points on the time axis which, during impact, maximize the HIC[seconds];
- the exponent 2.5 is the slope of the curve in bilogarithmic coordinates.

Therefore the Head Injury Criterion indicates the threshold beyond which the individual undergoes fatal injuries by inversely correlating the intensity of the acceleration and its duration; but the HIC does not provide any information regarding the extent of the injury. This is precisely why the HIC-AIS correlation is used.

Thoracic Trauma Index

For the evaluation of thoracic trauma, one of the most common injury criteria, especially for lateral impact cases, is the Thoracic Trauma Index (TTI). This is evaluated as expressed in the following Eq. (2):

$$\mathrm{TTI} = 1.4 * \mathrm{age} + 0.5 * (\mathrm{RIBy} + \mathrm{T12y}) * \frac{m_c}{M_{std}} \tag{2}$$

where:

age is the age of the pedestrian;

$\mathrm{RIB_y}$ is the maximum lateral acceleration of the abdominal spine (12th spinal segment) [g];

$\mathrm{T_{12y}}$ is the maximum lateral acceleration of the 12th thoracic vertebra [g];

mc is the mass of the pedestrian [Kg];

Mstd is the standard mass equal to 75 kg.

In the case under examination, having a simplified model of a dummy, the vertebral and thoracic accelerations are hypothesized to be similar to the resulting acceleration in the chest.

Spine Injury Criterion

Another injury found recurrently in accidents is that of the spine; although the injured in most cases make a full recovery within short periods, there are prolonged medical problems. So the socio-economic cost of these injuries is enormous.

The part of the spine most involved in collisions is the cervical one. In this, the stresses are due to the contact forces acting on the head or to inertial forces related to the mass of the same. Therefore, several combined loads must be considered to estimate neck injuries [29, 30] between them so that these do not exceed certain limits.

In this preliminary phase, the spinal injuries are assimilated to those of the torso.

Conversion of Injury Thresholds to AIS Scale

Not having available complete data that would allow evaluating the precise AIS values, starting from the relationship between AIS and the different lesion parameters present in the literature, the level of the lesion was assessed. For example, I notice that the HIC has entered the range and assigned an AIS level [31] (Table 1)

Table 1. HIC-AIS relationship

HIC	AIS	Brain and head injury level
135–519	1	Headache or dizziness
520–899	2	Loss of consciousness for less than 1 h - linear fracture
900–1254	3	Loss of consciousness from 1 to 6 h - depressed fracture
1255–1574	4	Loss of consciousness from 1 to 24 h - open fracture
1575–1859	5	Loss of consciousness for more than 25 h - diffuse hematoma
>1860	6	Not survivable

Similarly it is done for the other injury parameters. After evaluating the AIS for the different parts of the body, the three maximum values are taken and the ISS is estimated (3):

$$\mathrm{ISS} = \mathrm{AIS}_1^2 + \mathrm{AIS}_2^2 + \mathrm{AIS}_3^2 \tag{3}$$

The next step is to define the probability of having an injury using both deterministic and stochastic models.

3.2 Calibration of Numerical Multi-body Model for the Reconstructions of Vehicle-Pedestrian Impacts

In order to reconstruct the vehicle-pedestrian collision phenomena, numerical analyzes are started using a pedestrian model based on the multibody system, while the vehicle is schematized as a rigid body.

In order to start the simulations, the initial conditions of the vehicle (speed, trajectory, braking), the pedestrian (age, height, weight, position with respect to the car) and the type of simulation to be started (kinetics or kinematics).

Starting from the study conducted by Corallo F. et al. [16] which considers the reconstruction of an impact with multibody modelling between a teen pedestrian and an SUV/sedan, the model is calibrated. Having known the pedestrian's positions, its physical characteristics as well as the dimensions and speeds of the vehicle, the simulations are started from which the maximum acceleration values to the head and chest are extrapolated (Fig. 5).

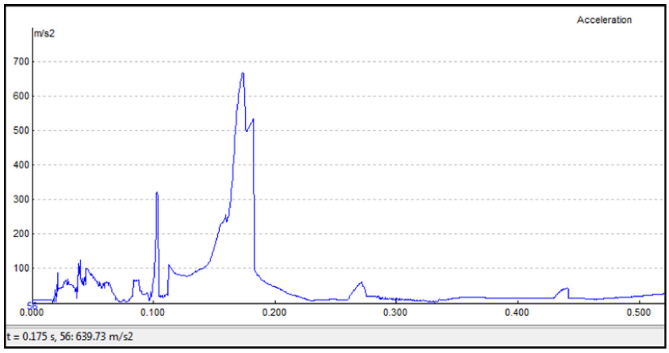


Fig. 5. Graphic-analytical determination of the head's accelerations provided by the numerical simulation

Once these maximum accelerations relating to the primary impact are obtained, the injury parameters are evaluated.

These simulation parameters are then compared with those in [16] and it can be observed a fairly good correlation with Pearsons values equal to 0.93 with the SUV and to 0.88 for the sedan, whereas those for HICs seems lower (0.77 for the SUV and 0.87 for the sedan) (Figs. 6 and 7).

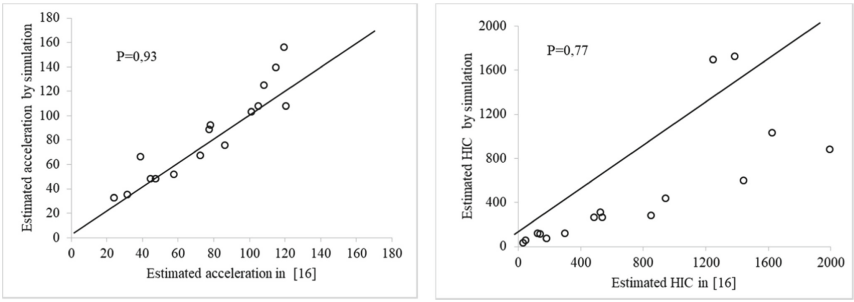


Fig. 6. Comparison of data from simulation and those reported in [16] (teenager-SUV)

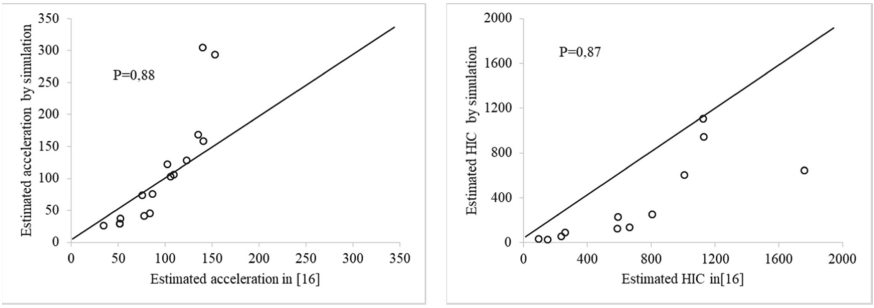


Fig. 7. Comparison of the simulation results with those reported in [16] (teenager-sedan)

This allows to say that the results obtained are not very dissimilar from each other, therefore it follows that the model has been calibrated correctly and the differences can be attributed to the different software used.

Once the software is calibrated, numerous simulations are carried out in which the following are varied:

- vehicle speed between 20 and 50 km/h (with a step of 10 km/h, as proposed by EuroNCAP) assuming both the absence and the presence of braking;
- different vehicles: suv, sedan, coupé, van and bus;
- pedestrians of different age groups and different sizes (30-year-old adult with normal build, strong 50-year-old adult, 15-year-old teenager and 6-year-old child);
- position of the front or side pedestrian with respect to the bonnet of the vehicle.

From the various simulations, the acceleration parameters are obtained with which the extent of the injury suffered by the pedestrian is assessed, therefore the corresponding AIS and ISS are evaluated for the various scenarios.

3.3 Evaluation of Injury Level by Existing Prediction Function

To define the injury risk functions, logistic models are used, obtained as a result of laboratory experiments, with which it is possible to determine the biomechanical response

and the level of tolerance to injuries. Logistic regression models, which are used to estimate the effect of one or more factors on the probability of injury, are binary.

$$\mathrm{Pi} = \frac{1}{1 + \exp\left(a + b \cdot Y_{ped} + c \cdot V\right)} \tag{4}$$

where:

Pi, probability of a specific injury level;
a, b, c are the calibration parameters;
Y_{ped} is the age of the pedestrian;
V the speed of the car (considered constant).

Therefore by means of these function it is possible to estimate the probability that following an injury the pedestrian can reach or exceed a certain level of severity. Starting from the vulnerability functions for assigned ISS [32], implemented on GIDAS data [3], the five degrees of severity of the injury and the respective probability estimates are identified, as shown in the Table 2.

Table 2. Probability of injury based on severity

Severity of the injury	ISS range	P (ISS)
Minor	0–8	1 - P (ISS_{9+})
Mild	9–15	P (ISS_{9+}) - P (ISS_{16+})
Moderate	16–25	P (ISS_{16+}) - P (ISS_{25+})
Serious	26–75	P (ISS_{25+})
Not survivable	>75	P (fatalities)

These models estimate the probability of an injury considering two explanatory variables, namely the age of the pedestrian and the speed of the car.

Starting from these models, the probabilities associated with the different levels of injury were assessed (Fig. 8).

From this for each age-speed pair the expected value is obtained as:

$$ISS_{\text{vulnerability model}} = \sum P(ISS) * ISS_{average\ of\ the\ interval} \tag{5}$$

Then different input parameters such as the age of the pedestrian and the travel speed of the car (steady mode), the position of the pedestrian (front or side with respect to the bonnet of the car) and the type of car (SUV, sedan, cabrio) have been changed. Then a overall ISS average value, $ISS_{average}$ has been evaluated to be compared with that provided by the vulnerability prediction functions, $ISS_{vulnerability\ model}$. The comparison between the two ISS, taking into consideration an adult pedestrian of 30 years and a 15-year-old teenager is reported below for several vehicle (steady) speed values (Table 3 and Fig. 9).

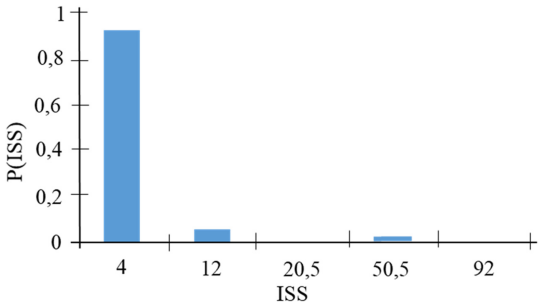


Fig. 8. Example of ISS probability distribution derived from vulnerability prediction functions

Table 3. ISS vulnerability model-ISS average comparison

Pedestrian's age	V (Km/h)	ISS vulnerability model	ISSaverage
15	20	5.16	3.07
	30	6.40	5.4
	40	8.84	12.3
	50	13.44	27.72
30	20	5.76	0.85
	30	7.35	1.9
	40	10.79	7.35
	50	17.32	25.075

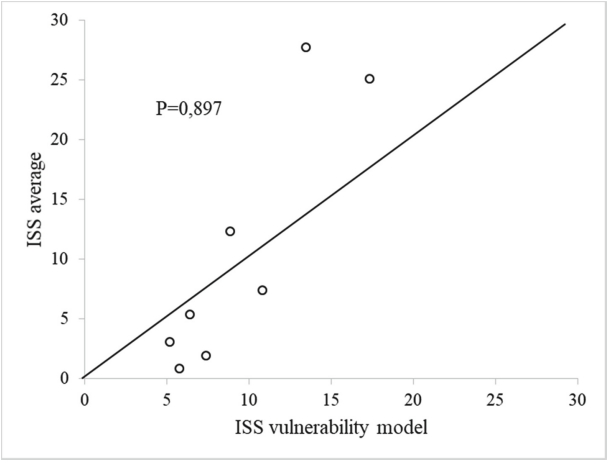


Fig. 9. ISS vulnerability model-ISSaverage comparison (teenager-adult pedestrian)

The agreement between the average outcome provided by the simulation models and that derived from vulnerability prediction functions seem fairly acceptable. However further simulations are needed in order to improve it.

4 Conclusions

The aim of the work is to analyze the vehicle-pedestrian impact dynamics, as recent national and international accident reports provide evidence for an increase of crashes involving pedestrians. In this connection, refined pedestrian vulnerability prediction tool are needed to help road safety engineers. It is believed that multibody accident reconstruction models may offer a significant contribution in improving existing pedestrian vulnerability predictions functions.

To this purpose, a multibody pedestrian vehicle impact model has been developed. Following an initial calibration by a comparison with data provided by technical and scientific literature, a parametric analysis has been carried out by varying several pedestrian and vehicle related impact parameters. From kinematic and mechanical results obtained by numerical simulations, injury level evaluation has been performed and an estimation of an average values of ISS has been derived. This value obtained for several vehicle speed and pedestrian type has been compared with an average ISS value derived from existing pedestrian vulnerability prediction functions that have been calibrated on real accident data collected in a German in-depth accident database (GIDAS).

The comparison is fairly acceptable and more simulations are needed in order improve the modelling framework. However, basing on these preliminary results, the multibody pedestrian-vehicle impact developed seems to be able to capture the complexity of this accident scenario and to provide a reliable estimation of possible outcomes. By an extensive use of this model it is believed that it will be possible to add a better understanding of the complex kinematic of impacted pedestrians and provide more significant explanatory variables in the existing pedestrian vulnerability prediction functions.

This will allow safety engineers to highlight site conditions affecting the initial pedestrian-vehicle impact parameters and therefore to study mitigations countermeasures.

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