Towards the Development of Injury Matrix: Preliminary Analysis Through Multi-body Codes for Vulnerable Users

Mauro D'Apuzzo[1], Sofia Nardoianni[1](✉), Giuseppe Cappelli[1,2], and Vittorio Nicolosi[3]

[1] University of Cassino and Southern Lazio, Via G. Di Biasio 43, 03043 Cassino, Italy
{dapuzzo,sofia.nardoianni,giuseppe.cappelli1}@unicas.it, giuseppe.cappelli@iusspavia.it
[2] University School for Advanced Studies, IUSS, Piazza della Vittoria n.15, 27100 Pavia, Italy
[3] University of Rome "Tor Vergata" Via del Politecnico, 1, 00133, Rome, Italy
nicolosi@uniroma2.it

Abstract. In an era where cities worldwide advocate for walking and cycling as sustainable modes of transportation, concerns over the safety of pedestrians, cyclists, and e-scooter riders have intensified. This paper delves into the pressing issue of pedestrian accidents, which continue to pose significant challenges despite legislative and technological advancements. Drawing from a study conducted in literature, data analysis reveals a heightened risk of collisions between pedestrians and cyclists. Such collisions often result in severe injuries or fatalities for pedestrians, underscoring the urgent need for further research and interventions to mitigate these risks. Parameters such as peak head velocity, Head Injury Criterion (HIC) values, and vehicle stiffness play pivotal roles in evaluating the severity of injuries sustained in such collisions. As cities strive to promote active transportation, addressing the safety concerns arising from pedestrian-cyclist-scooter drivers' interactions remains paramount for enhancing road safety and fostering sustainable urban mobility.

The aim of this research is to investigate the injuries suffered by vulnerable road users due to accidents and to provide prediction models that can be used in the new design criteria of transport infrastructures.

Keywords: Sustainable mobility · Vulnerable users · Pedestrian · Collision

1 Introduction

Cities around the world are increasingly trying to promote walking and cycling as healthy and sustainable modes of travel [1, 2]. While such activities are suitable for exercise and reducing greenhouse gas emissions, their growing role leads to concerns for the safety of pedestrians, cyclists, and e-scooter riders.

These users, either because are not protected by external structures (bodywork) or because are mainly made up of children and the elderly, are more exposed to the risks

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deriving from road traffic and these risks can lead, in most cases, to serious injuries or fatalities as a result of road accidents [3, 4].

Despite new legislative efforts and technical improvements, research still needs to address the problem of pedestrian accidents, an issue that still has a heavy negative impact [5].

A study of literature [6] led to the analysis of some data derived from a survey carried out on the population of some Finnish cities. The data collected were used to assess close accidents and/or collisions between pedestrians and cyclists, to assess the frequency of such accidents and to assess the sense of safety of the population. Cycling on pedestrian paths has been found to increase the likelihood of a collision between pedestrians and cyclists. In fact, many studies confirm that sharing space between pedestrians and cyclists can be particularly dangerous [7]. Collisions between these two road users can cause serious injury to the pedestrian, especially due to the secondary impact between the skull of the user concerned and the road surface. In severe cases, this type of impact can even lead to death. Parameters of peak head velocity, HIC values [8–11], and likelihood of severe head trauma can be evaluated. These values are all a function of the speed at which the scooter rider is going and the angle of impact of the accident. As far as the impact with vehicles is concerned, the characteristics of the vehicle itself also become important. Some parts of cars are stiffer than others according to some EuroNCAP [12] motor vehicle safety standards and this aspect of stiffness plays a key parameter in scooter-to-vehicle impacts.

When examining road infrastructure, it is necessary to apply the principles of road safety from a multidisciplinary perspective, thus taking into account all possible road users. In urban areas a very important aspect is to make roads safe, especially for vulnerable users (pedestrians, cyclists and scooter drivers) to encourage sustainable mobility. Very often these users share the space with motorized vehicular traffic or even with each other and this can cause different accidents between the various types of users. Talking about vulnerability and therefore risk is equivalent to talking about an event that intervenes in the Vehicle – Driver – Environment system. Once the risk factors have been identified, it is necessary to assess the number, severity and recurrence of accidental events, as well as the severity of the physical consequences due to the impacts. To do this, it is necessary to have detailed data on the location and dynamics of accidents and the harmful and fatal consequences that are encountered by users. Many times, this data is difficult to find. Therefore, it is necessary to carry out a vulnerability study that sees the definition of the results of an impact and the examination of the phase following it.

The research aims to analyze the dynamics of a vulnerable user's collision, for this purpose, numerical simulations were conducted, through the use of Virtual Crash software, taking into account a pedestrian model with a multi-body system structure, and the vehicle represented as a rigid body. A general presentation of the methodology used for crash simulation is presented. An insight on Multi-Body concepts is reported as it constitutes the mathematical structure for the numerical simulations and a calibration of the methodology is showed. Later on, an extensive sensitivity analysis is showed and obtained results are analysed and commented providing the basis for the development of a vulnerability prediction model.

2 Method

Most accident reconstructions are based on mathematical models, which can provide quantitative results and are able to cover multiple scenarios in a more cost-effectively.

There are several types of pedestrian kinematic estimation:

- Projectile models: in which a pedestrian is assumed to be a point mass;
- Empirical models: described by single-argument regression equations that are based on the statistical approximation of the results of fictitious experiments or analysis of real accidents;
- Two- and three-segment 2D analytical models: the pedestrian body is composed of rigid segments connected with a hinge joint;
- Numerical models;

Empirical and projectile models are the easiest to use, as they are described by single-variable equations that are easily solved. The equations describe the relationship between the speed of impact and the distance of the pedestrian's throw.

Two- and three-segment models are limited to 2D cases and have found limited application in traffic accident analysis.

Numerical modeling, on the other hand, has found ample space in the reconstruction of road accidents and can be used to study impacts under various conditions.

2.1 Multi-body Models

The most common approach to pedestrian modeling is multi-body. The basic principle is to model mechanical systems as kinematic chains consisting of rigid and non-deformable bodies, connected to each other by kinematic torques (kinematic constraints or joints).

The history of multi-body models began in the 1960s when the first numerical simulations of vehicle occupants were created. Currently, the most widely used multi-body bodies are MADYMOs. They are special multi-body simulators mainly used in the automotive industry. There are two types of MADYMO solvers available in commercial distribution. The first is the ellipsoidal model and the second is the faceted model of multi-body rigid bodies. Faceted models are represented by a rigid mesh of faceted surfaces covering rigid bodies with contact forces calculated using the standard multi-body body. Faceted models do not come with controllers and are not scalable, unlike MADYMO multi-body bodies which can be scaled and allow the body to be shaped following human muscles.

Many traffic accident reconstruction and commercial vehicle dynamics programs are equipped with multi-body models of the human body such as: HVE, PC-Crash, Virtual Crash and Cybim V-Sim. The mentioned solvers use a contact algorithm similar to MADYMO, i.e. an algorithm based on the calculation of penetration depth. Multi-body forensic models are simpler than MADYMO models, the main advantage being that they can be scaled to any height and mass. The user can integrate the data collected at the scene during an investigation into the software, create a digital environment of the accident site and simulate the dynamics of vehicle movement using mathematical models of the vehicle's subsystems.

2.2 Virtual Crash

Virtual Crash software [13] has been used as a tool to simulate collisions between e-scooter and pedestrians in different scenarios. Virtual Crash is a well-known impulse moment-based crash reconstruction software that has been widely used in car accident research and by law enforcement agencies in Europe and America. The software is based on Kudlich–Slibar rigid body impulse models [14] and uses mixed Euler and Runge-Kutta numerical integration methods [15]. It is possible to import different models such as CAD of vehicles, pedestrians, terrain and obstacles to be able to reconstruct the working environment in the best way.

The software uses 13 ellipsoidal objects connected by joints to create a ragdoll model of cyclists and pedestrians in which shape, size and weight are adjustable. It is possible to change mechanical properties such as joint stiffness, damping, and postures to create a realistic human model. The models have been adapted to replicate the postures of e-scooter riders and pedestrians.

This software allows to develop a sensitivity analysis with a low computational burden, for this reason it was used for the present research.

2.3 Calibration of the Model Through Literature Data

As a first step, it was decided to replicate studies in the literature in order to calibrate the model and proceed with new simulations.

To reconstruct the vulnerable user's collision phenomena, numerical analyses have been carried out using a pedestrian model based on the multi-body system, while the vehicle has been modelled as a rigid body. The simulations' plan to be undertaken is conveniently reported in Fig. 1. Before commencing the simulations data related to the vehicle characteristics (such as type, speed, trajectory, weight) and to the pedestrian features (such as age, height, mass, speed and initial position about the vehicle) should be primarily evaluated and implemented in the models.

	E-scooter	Pedestrian	Bike	Car
E-scooter		X		X
Pedestrian			X	
Bike				
Car				

Fig. 1. Matrix of simulations carried out.

As far as the pedestrian is concerned, the profiles with the various characteristics are reported in Table 1.

Impact conditions may play a remarkable role in the outcome of a collision. Therefore, according to aforementioned technical literature [16] different impact conditions (namely, angles of impact) were evaluated:

– 0° = frontal impact;

– 0° off-center = off-center frontal impact;
– 90° = side impact;
– 180° = rear impact;
– 180° off-center = off-center rear impact.

Table 1. Anthropometric data for the dummies models used as pedestrian [16].

Profile	Weights (kg)	Height (m)	Body Width (m)	COG Height (m)
Child	34.7	1.367	0.365	0.862
Adult	69.2	1.73	0.460	1.094
Elder	63.2	1.647	0.440	1.035

2.4 Calibration Scenario: E-scooter – SUV

In this analysis, the scenario in which an E-scooter crashes into a car was evaluated. In the analysis, the points of impact against the car, the speed of the scooter, and the posture of the scooter driver were varied. The study by Ptak et al. [17] was followed since the aim of the work is to compare the results obtained by a refined calculation software used by the previously mentioned author and software that uses multi-body models such as VirtualCrash.

In the study, an aluminium scooter model was used, a typical scooter of sharing companies, with a mass of 14 kg.

The rider was modelled as an adult with a height of 174 cm and a mass of 75.7 kg.

The vehicle used for the impact assessment (see Fig. 2.) was defined as an SUV (Sport Utility Vehicle) with an overall mass of 1266 kg.



Fig. 2. Type of vehicle used (SUV).

The first scenario described is that of a side impact between the vehicle and the electric scooter. In this impact, an electric scooter hitting the front of the vehicle laterally on the bonnet was simulated.

In the second and third scenarios, the side impact in the pillar of the vehicle have been evaluated. This configuration was chosen because the side pillar of the vehicle is the most rigid part of it. This scenario has been divided into two positions acquired by the manikin, the first in which the manikin has a fully upright position, and in the second the manikin assumes a slightly bent position.

In the fourth and final scenario, a frontal impact was assessed.

In the first three scenarios, the speed of the electric scooter is assumed to be 25 km/h, while in the last scenario, the speed is reduced to 21.6 km/h. These specific speed values have been established in such way since it is assumed that in side impacts the scooter driver does not notice the arrival of the vehicle, while in frontal impact the speed decreases assuming braking i.e. evasive manoeuvres to avoid the impact with the vehicle by the rider.

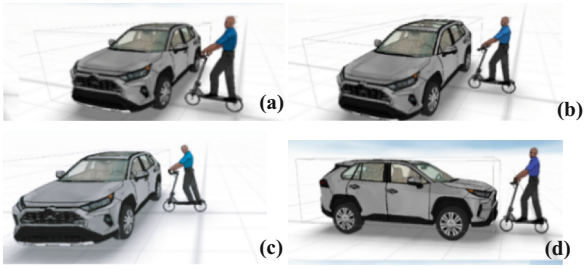


Fig. 3. E-scooter - SUV bonnet Impact a), E-scooter -SUV Side Impact in standing b), E-scooter - SUV Side Impact in folded c) and E-scooter - SUV Frontal Impact d).

In the side impact on the bonnet scenario (see Fig. 3a), the first rider-vehicle contact takes place in the centre of gravity of the dummy. The point of contact between the scooter and the vehicle acts as a pivot point.

In the side impact scenario on the mast in an upright position, (see Fig. 3b), the main contact is between the dummy's legs and the vehicle. The head-neck system is the part that impacts the vehicle with the highest energy, but since the scooter-rider system has a greater height than the vehicle, the rider's head hits the roof of the vehicle and not the pillar.

In the side impact on the pillar in a slightly bent position scenario (see Fig. 3c), contrary to what has been highlighted above, the main impact occurs between the head and the pillar of the vehicle, while the rest of the body has the same behaviour as in the analysis mentioned above.

In frontal scenario (see Fig. 3d), the user maintains kinetic energy and is projected forward. The point of contact between the scooter and the vehicle acts as the dummy's temporary axis of rotation. The dummy rotates around this axis until it reaches the centre of the bonnet where it impacts with its head. However, it can be seen that the main impact is with the rider's torso; then, thanks to this main contact, the head hits the bonnet at a later time.

From the following figures, it is possible to evaluate the head acceleration data and it can be seen that the impact with the pillar in the bent position is the most dangerous compared to bonnet impact (see Fig. 4), side impact in standing (see Fig. 5) and frontal impact (see Fig. 6) because the acceleration of the head reaches values of 900 m/s^2 (see Fig. 7). In this case the handlebars of the scooter act as a pivot point for the rider and provide the reason for increased acceleration by the head when impacting the vehicle.

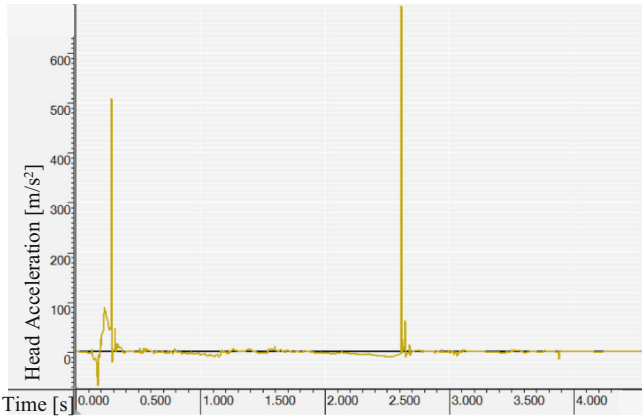


Fig. 4. Head acceleration of e-scooter rider in e-scooter - SUV bonnet impact.

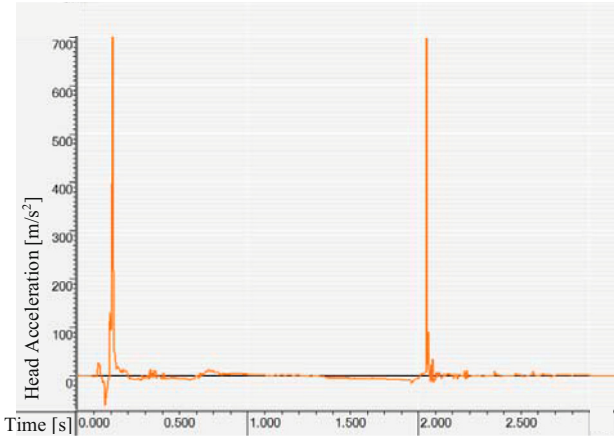


Fig. 5. Head acceleration of e-scooter rider in e-scooter - SUV side impact in standing.

A comparison has been carried out between e the data obtained from the Virtual Crash simulation and the results obtained by Ptak et al. [17] with Madymo in terms of maximum accelerations.

It has to be reminded that the VirtualCrash software uses a multi-body approach whereas the model used by Ptak et al. [17] employs a combined multi-body and finite element numerical model that it is able to take into account for a more realistic deformation in contact area. A question therefore arises whether this different modelling approach may affect the reliability of the results obtained by Virtual Crash.

As can see from the value of Pearson (P) (see Fig. 8) evaluated on the simulations carried out, the calibration is somehow satisfying, so the results obtained with the Virtual Crash software appear to be very similar to those obtained with a more refined numerical

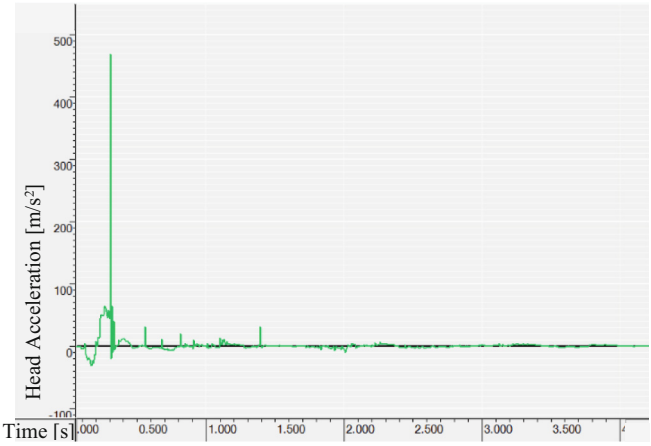


Fig. 6. Head acceleration of e-scooter rider in e-scooter - SUV frontal impact.

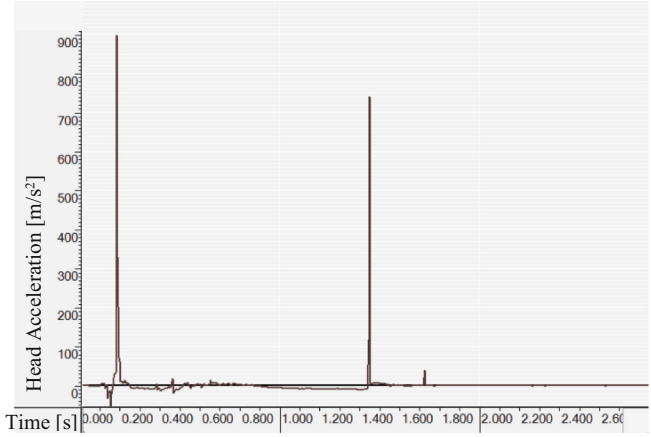


Fig. 7. Head acceleration of e-scooter rider in e-scooter – SUV side impact in folded.

approach (Madymo). As a matter of fact, as regards frontal impact, b-pillar (squat) and b-pillar (upright) impact scenarios (depicted by black circles), the results are comparable. The collision scenario that leads a dramatic decrease of Pearson statistics (down to 0.464) and appears somehow erratic compared with the aforementioned results is that pertaining the impact against the bonnet (see the red circle in Fig. 8). This is probably due to a problem with the car model that is modelled as a rigid body in Virtual Crash unlike what happens in Madymo where deformation of the car bodywork is taken into account. In frontal impact, when the rider hits the bonnet, this latter should deform and plasticize thus allow energy to be dissipated, whereas in the rigid a significant increase in the acceleration suffered by the e-scooter's rider can be registered. On the other hand, this problem does not occur for the other impact scenarios as they occur at points of the car that are already much less deformable by themselves.

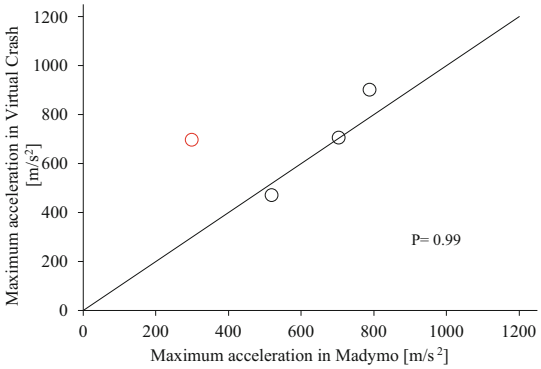


Fig. 8. Calibration between Maximum acceleration in Virtual Crash and Madymo the Pearson coefficient value, P, for the comparison between maximum acceleration values provided by both simulation software (black dots) is also conveniently reported.

3 Simulation of E-scooter – Pedestrian Accident

Soft mobility is implying an increasing interaction with various traffic components, including pedestrians and scooter riders. Therefore, it was decided to investigate the dynamics of collisions between these two vulnerable road users. In the technical literature the most relevant parameter used to determine the injury suffered by the pedestrian is the HIC (Head Impact Criterion, or Criterion of Traumatic Brain Injury) [8–11].

This criterion for assessing head injuries, which are the most serious compared to other parts of the body, following an accident between a pedestrian and a vehicle is based on the evaluation of the actual deceleration of the braincase following an impact, by means of the following relationship:

$$HIC = \max\left[(t_2 - t_1) \cdot \left(\frac{\int_{t1}^{t2} a(t)dt}{t_2 - t_1}\right)^{2.5}\right] \tag{1}$$

where:

- a represents the acceleration over the time interval;
- t_2 e t_1 represent the time interval that maximizes the average deceleration.

The equation proposed above can be simplified as a mass-spring model [16]:

$$HIC = K * V^{2.5} \tag{2}$$

Where:

- K is a constant of proportionality equal to 33.93;
- V is the maximum velocity of impact (m/s);

HIC values (dimensionless) can be converted to assess the likelihood of serious injury using the AIS scale. This probability can be assessed through the following relationship for AIS4:

$$Probability\ of\ \ injur = \frac{1}{\left[1 + exp\left(\left(\frac{4{,}9+200}{HIC}\right) - 0,\ 00351 \cdot HIC\right)\right]} \tag{3}$$

This relationship uses the maximum head-to-ground impact velocity from crash test simulations to estimate HIC values. The HIC values are then used to estimate the likelihood of severe TBI (Traumatic Brain Injuries) based on the AIS abbreviated injury scale (see Fig. 9). This establishes a relationship between the vehicle's collision speed and the likelihood of serious head injuries.

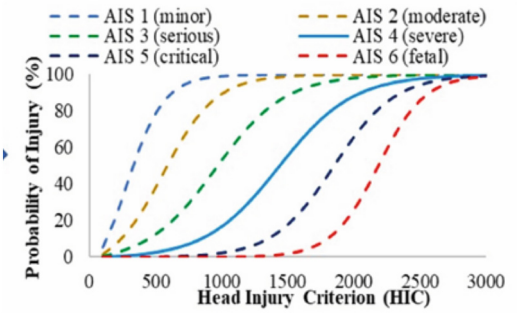


Fig. 9. Scale of AIS proposed in Prasad and Mertz and reported in Paudel et al. [16].

By varying the speed of the scooter, the pedestrian anthropometric properties, the scooter models and collision conditions an overall amount of 180 simulations were carried out.

As far as pedestrian anthropometric properties are concerned, reference is made to Table 1. The rider, on the other hand, was modelled as an adult with a height of 175 cm and a weight of 75 kg.

The angles of impact were: 0°,90°,180°,0° off,180°off.

As far as scooter models are concerned, the different technical characteristics of the scooters on the market and the scooters supplied by sharing companies have been analyzed and viewed. As far as scooters on the market are concerned, an initial classification is made based on weight and material.

They can be classified into:

1. Carbon fiber (12 kg)
2. Aluminum (15 kg)
3. Steel (20 kg)

In addition, they can also be classified according to height (measured from the ground to the handlebars). The latter can vary from 108 cm to 120 cm. Finally, they can also be classified according to the width of the handlebar, which can vary from 45 cm to 50 cm.

From the technical data sheets of the scooters, it has been found that the maximum speed reached varies from 25 km/h to 30 km/h. On the basis of these speeds and also due to the fact that scooter accidents are increasingly widespread on European area, the new Highway Code D.L. 2021 [18] has established new speeds limits on roads and in pedestrian areas. The maximum speed allowed in urban areas is 20 km/h, while in pedestrian areas this limit drops to 6 km/h.

During the simulation, no brake was applied by the rider, as it was decided to analyze the worst-case scenario that could occur, i.e. the one in which none performs evasive

and/or protective maneuvers. From the simulations, it is possible to extrapolate the launch distance and the peak velocity of the head before impact on the ground. Throw distance is defined as the distance traveled by the pedestrian's head from initial collision to the impact with the ground. Similarly, the impact velocity of the head represents the maximum speed reached by braincase.

The results obtained from these simulations were compared with those proposed by the scientific literature [16]. As can be seen from Fig. 10, the model results are again in agreement with data derived by similar studies.

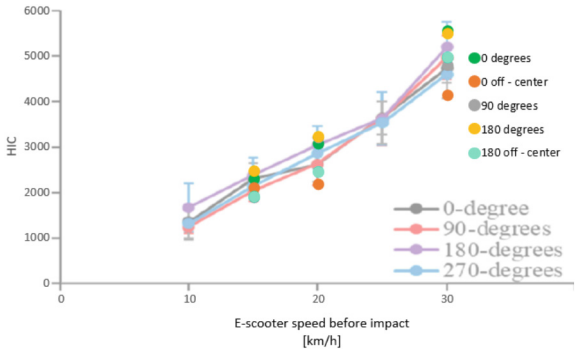


Fig. 10. E-scooter - Pedestrian Model Calibration [16].

4 Analysis and Discussion of Results

In order to better understand the physics underlying the event it could be beneficial to examine the various phases of impact between e-scooter and pedestrian.

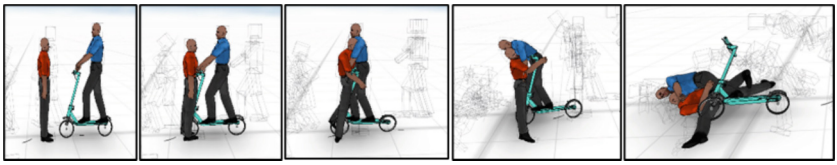


Fig. 11. Phases of E-scooter- Pedestrian impact.

As it can be observed from Fig. 11, the first impact on the pedestrian is close to the waist and comes from the handlebars of the electric scooter. Later on, the bodies of the rider and the pedestrian collide. Since the impact of both the handlebars and the collision between the driver's body and the pedestrian is above the center of mass, the pedestrian falls to the ground.

For a defined type of pedestrian profile and of e-scooter relationships between HIC and the velocity according to different impact angles can be obtained.

By way of example, the specific case involving an adult pedestrian and a 12 kg scooter is depicted in the following figure (see Fig. 12).

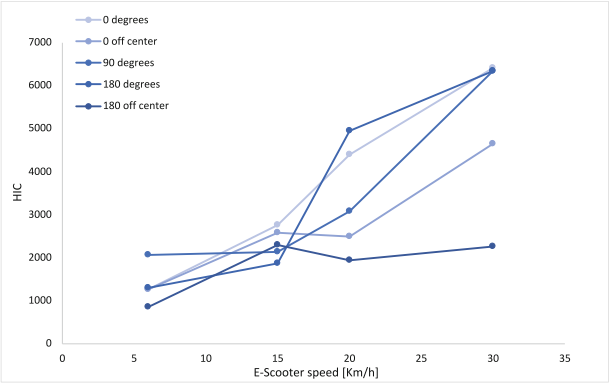


Fig. 12. HIC-speed relationship in adult for center and off -center degrees of impact with weight of E-scooter 12 kg.

As can be seen from Fig. 12, although a monotonic increasing trend can be observed HIC-velocity relationships of the centered and off-center impact angles are very different from each other's.

Following these encouraging results, by combining all impact angle values, e-scooter speed values, e-scooter types and adult pedestrian properties a general relationship HIC versus speed has been sought, that is conveniently reported in the following figure (see Fig. 13).

As can be seen from Fig. 13 and Table 2, regression statistics of the obtained mathematical model are somehow poor exhibiting an high dispersion.

Table 2. Main statistics of interest and prediction accuracy of the model.

Mod	Param.	Value	Stand. error	t-ratio	Prob(t)	Adj-R^2
$Y = a*x^b$	a	215.0203	101.4050	2.1204	0.0380	0.5618
	b	0.9542	0.1488	6.4111	0.0000	

Higher differences between results provided in centered and off-center impact scenario are probably due to an energy dissipation in the roto-translational motion that occurs in the case of impacts with off-center angles. Basing on these outcomes, a new mathematical model employing Impact Kinetic Energy as the independent variable has been proposed.

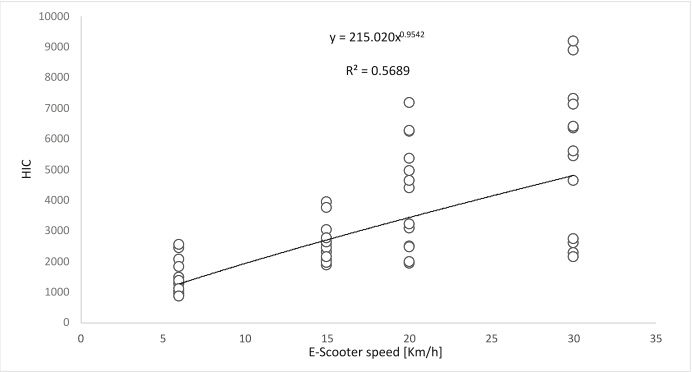


Fig. 13. Model of regression between HIC and Speed E-Scooter.

The kinetic energy for centered impact angles was then evaluated as expressed in Eq. 4.

$$E_{c,center} = \frac{1}{2}mV^2 \tag{4}$$

where:

– m is the mass of the E-scooter and the rider that impact on pedestrian;
– V is the speed of e-scooter

For off-center impact angles, kinetic energy was evaluated as expressed in Eq. 5.

$$E_{c,off-center} = \frac{1}{2}mV^2 * S_c \tag{5}$$

where:

– m is the mass of the E-scooter and the rider that impact on pedestrian;
– V is the speed of E-scooter;
– S_c is the dimensionless overlapped contact surface between the two colliding bodies that in this case is 0.347 depending on the selected off-center value.

The new regression model is conveniently reported below with relevant statistics (see Fig. 14 and Table 3).

Table 3. Main statistics of interest and prediction accuracy of the model

Mod	Param.	Value	Stand. error	t-ratio	Prob(t)	Adj-R^2
$Y = a*x^b$	a	84.8162	26.9497	3.1472	0.0025	0.8172
	b	0.5479	4.25E-02	12.8826	0.0000	

As it can be observed, by making use of kinetic energy as an independent variable, it is possible to obtain a better description of accident outcomes in term of HIC values.

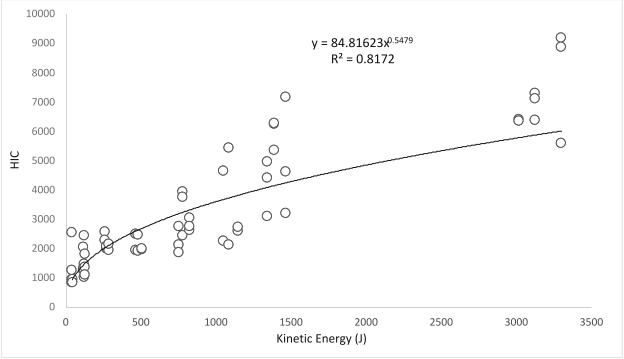


Fig. 14. Model of regression between HIC and Kinetic Energy.

4.1 Impact of Rider

Since the e-scooter rider can be also considered a road vulnerable user, it seems important to analyze the injuries suffered by the rider as a result of the impact with the pedestrian by comparing these latter with those suffered by the pedestrians themselves.

Speed Effect

Speed is again the crucial factor in a collision as the momentum and kinetic energy of the rider-scooter system is transferred to the pedestrian. The following Fig. 15 show the overall effect of the speed of the electric scooter on the rider's HIC in the case of E-scooter's mass of 12 kg.

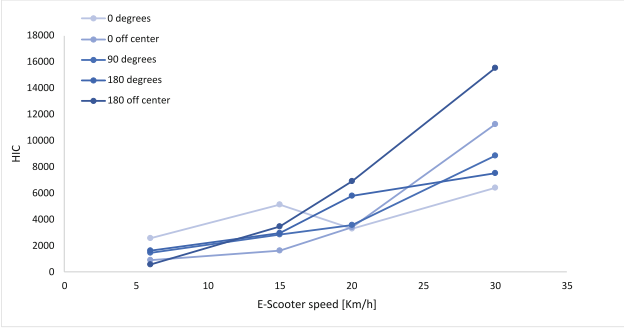


Fig. 15. HIC-Speed relationship.

The results showed an increase in the average rider's head peak speed as the speed of the scooter increased and therefore an increase in HIC and consequently an increase in the probability of severe head trauma.

For the 0-degree impact angle, a different trend occurs from the others, i.e. for a higher speed of the scooter (20 km/h) a lower HIC value is recorded than that obtained at a lower speed (15 km/h).

Analyzing the video of the two simulations, it is clear that for a higher speed of the scooter the rider tends to cushion the impact on the pedestrian and then only subsequently impact the ground, on the contrary for a lower speed this mechanism does not occur and the rider hits the ground cushioning the blow only with his shoulder.

Rider's Fall Mechanism

From the analysis of the videos of the simulations carried out, it was possible to analyze the mechanism of the rider's fall. This mechanism can be divided into three sections as shown in the following figure (Fig. 16 and Fig. 17).

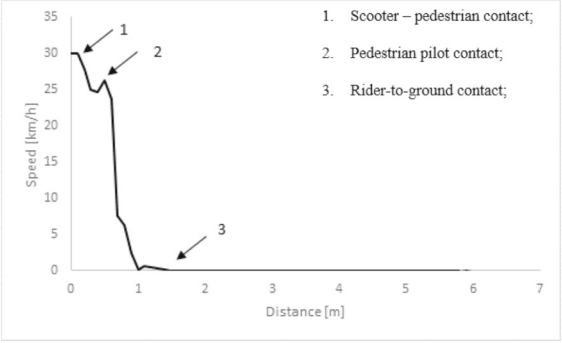


Fig. 16. Mechanism of the rider's fall.



Fig. 17. Mechanism of the rider's fall in Virtual Crash animation.

Comparison of Pedestrian - Rider Effects

It is worth to compare the HIC values of the pedestrian with those pertaining the e-scooter rider following the impacts on the ground.

The figure below (Fig. 18) shows the dispersion of the data provided by the simulations compared with the equality line.

As can be seen from Fig. 18, the relationship between pedestrian and rider in terms of HIC is highly dependent on the angles of impact.

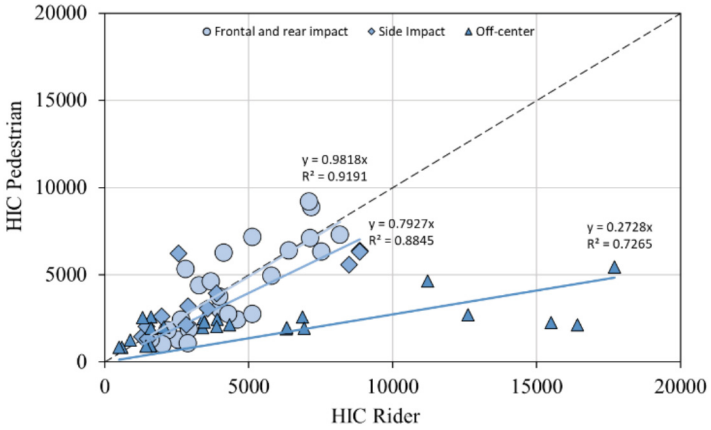


Fig. 18. Comparison of HIC values for pedestrian and rider.

For frontal and backward angles of impact, these values align on the equality line, whereas, as far as lateral angles of impact are concerned, the difference in HIC values between the two bodies are dramatically differing.

Specifically, the rider, in such an impact, undergoes to a higher head velocity than the pedestrian. From the analysis of the simulation videos, it was clear that the latter directly impacts the ground without cushioning the blow, unlike the pedestrian who, thanks to a first impact with the shoulder and arm, cushions this blow.

For off-center angles of impact, the rider suffers from a much higher speed than that pertaining the pedestrian because he only hits the latter for a small area and then hits the ground directly without being appreciably slowed down.

One aspect that should be evaluated, however, is the impact of helmet use on rider's HIC. Recent studies [19–21] try to simulate this situation and to evaluate the difference in impact with and without helmets. What is clear is that with the use of helmets acceleration is significantly reduced. As regards the HIC, it is almost comparable for low impact speed values, whereas it is significantly reduced (with the presence of the helmet), for high impact speed values.

What has been noted, however, is that this reduction does not apply to angular velocity, where the values with and without the presence of the helmet are comparable, and for low angular velocity values the case of a rider without a helmet produces a smaller impact.

5 Conclusion

The assessment of the vulnerability of vulnerable road users was carried out through analyses with multi-body codes that made it possible to define what happened to the braincase following the impact on the ground.

Electric scooters are growing more and more and are spreading faster and faster among the population due to their various advantages, such as maneuverability and low

weight, which makes them more and more transportable, not to mention the ease of recharging, and lower operating costs.

Allowing electric scooters to share pedestrian paths with pedestrians must be carefully considered as this has been seen to result in an exponential increase in scooter-to-pedestrian and scooter-to-vehicle impacts.

As evidenced in the analyses carried out, it has been shown that, most of the time, the higher the speed of electric scooters at the time of impact, the more dangerous the consequences, are because both momentum and kinetic energy increase. When a scooter collides with a pedestrian, much of the momentum is transferred to the pedestrian, leading to a longer launch distance and a higher head-to-ground impact speed, resulting in a more serious potential head injury. Similarly, the results also showed that the outcome of accidents between scooters and pedestrians depends on the direction of impact.

Regarding the post-collision fall mechanism, simulations have shown that the direction of impact and the age profile have a significant influence. For direct impacts (0°, 180°, 90°), pedestrians tend to fall forward in the direction of travel of the rider, while off-center impacts cause pedestrians to rotate as they fall on the rider's side.

What happens to the rider's head for the impact, was also analyzed. It turns out that the HIC suffered by the rider is by no means negligible and highly depends on the angles of impact. To reduce the peak speed of the head in contact with the ground, the use of a helmet is therefore strongly recommended.

The impacts analyzed seem to be able to capture the complexity of these proposed accident scenarios and provide a reliable estimate of the possible outcomes.

By extending the field of simulation scenarios to be investigated, it is believed that it will be possible to achieve a better understanding of the problem and provide prediction functions for pedestrian vulnerability. In future simulations, it will be essential to focus on the use of helmets and how they may or may not reduce HIC values.

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