Article

Method to Assess and Enhance Vulnerable Road User Safety during Impact Loading

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Abstract: Every year approximately 1.35 million people die as a consequence of road accidents. Almost 50% of road fatalities are vulnerable road users (VRUs). This research reviews the history of traffic safety for VRUs, presents an interesting insight into the statistics and evaluates the current legislation in Europe for pedestrians, cyclists, children on bicycle-mounted seats and motorcyclists in terms of impact situations and applied criteria. This enabled the author to have a better perspective on how the VRUs' safety is currently verified. Furthermore, the VRU safety requirements are contrasted with the author's research, which is mainly focused on VRU's head biomechanics and kinematics. Finally, a new coherent method is presented, which encompasses the sub-groups of VRUs and proposes some improvements to both the regulations as well as technical countermeasures to mitigate the injuries during an impact. This study highlights the importance of numerical methods, which can serve as a powerful tool to study VRUs' head injuries and kinematics.

1. Introduction

Vulnerable road user (VRU) safety is affected by many crucial factors such as vehicle design, its frontal aggressiveness, road and pavement layout, legislation (e.g., speed limitations), active and passive safety systems such as a car's camera/LIDAR/RADAR or bicyclist's helmet, to name a few. Vulnerable road users are defined as "non-motorized road users, such as pedestrians and cyclists as well as motor-cyclists and persons with disabilities or reduced mobility and orientation" [1]. Thus, the road users—who have a high casualty rate and should be given special attention in road safety policy—are often referred to as 'vulnerable road users'. The lack of external protection or absence of a protective 'cage' around the traffic participant is also an indicator for pedestrians, cyclists and motorcyclists [2,3]. In the literature, car drivers and occupants are most often excluded from the definition of VRU [1,4]. Interestingly, some reports indicate that in the future connected transport system, VRU or "vulnerability" could be more related to non-connected users and people unable to fully use the potential of the Information and Communications Technologies (ICT) services offered to mobility [5].

It should be noted that due to traffic accidents, about 1.35 million people die each year [6]. The burden of road traffic injuries and deaths is disproportionately borne by vulnerable road users, who contribute to half of all victims. The World Health Organization (WHO) predicts that by the year 2020 road accidents will become the leading cause of premature death [7]. It proves that irrespective of numerous pedestrian/cyclist crossings, sidewalks/roads and effort made to separate VRUs from vehicles, the danger of death as a victim of a road accident is much higher in a city, mainly due to traffic density and complexity. It is reported that among people killed on city streets, on average

73% are pedestrians, cyclists and motorcyclists [6,8]. As Figure 1 depicts, for high-density population cities—such as Paris—of all fatalities on roads, VRUs make up 90%.
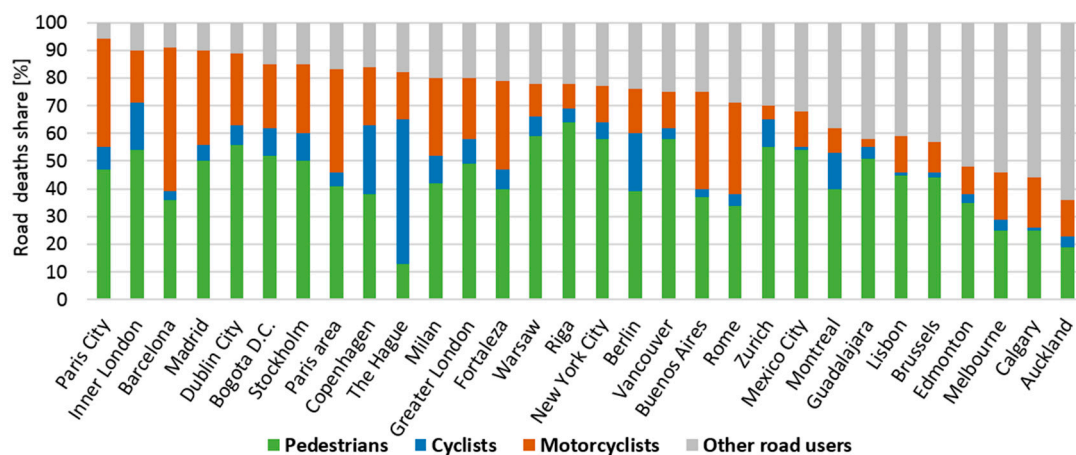

Figure 1. Vulnerable road users' (VRUs') road deaths [%] by city in 2013–2015—based on data from Reference [8].

In Figure 2, the author presented the data reported for 24 European Union (EU) members, with an additional EU average, for the share of pedestrians and cyclists of all who died on EU roads. The percentage of cyclists killed correlates strongly with countries' bicycle traditions and proper infrastructure, which encourages inhabitants to choose a bicycle as a mean of transport. Thus, higher than average shares are reported in the Netherlands and Denmark. On the other hand, the high share of pedestrian fatalities distinguishes relatively new EU member states such as Romania, Latvia, Poland and Lithuania where pedestrians contribute to more than 30% of all road deaths [9,10]. However, an interesting correlation forms as we compare the road safety level in various countries (fatality rate per million inhabitants) with the pedestrian deaths on roads. For the majority of countries, the lower the overall fatality rate, the lower the pedestrians' fatality contribution [11]—namely, the percentage of pedestrians who are killed on the country's roads may provide an approximate idea of the general country road safety.
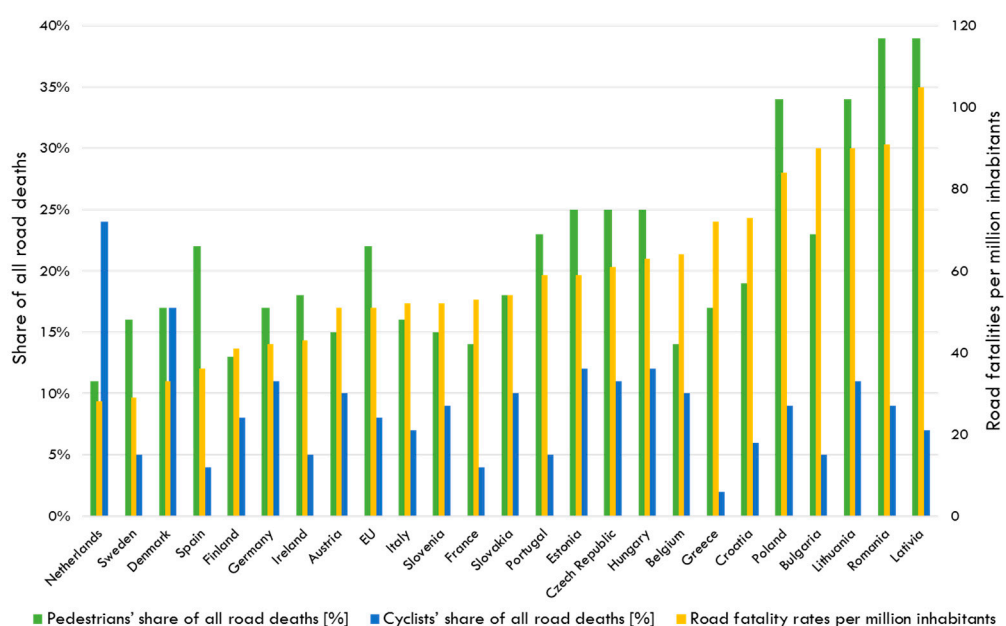

Figure 2. Pedestrians' and cyclists' share of all road deaths [%] in contrast to road fatality rates per million inhabitants [ ] in European Union in 2014—based on data from [9,12].

The problem of unprotected road users first appeared in the literature in the 1950s [13,14]. In the late 1970s, pedestrian collision statistics investigated the vehicle front as a major problem for pedestrian injuries. However, until the 1980s, it was not taken into account by designers, engineers or governments, which in fact had the power to exert sufficient pressure on vehicle manufacturers. Less than 70 years ago, there was still no detailed research in this area as it was commonly claimed that a pedestrian has little chance of survival in a collision with a much heavier and stiffer vehicle. This statement can be complemented by an excerpt from Fisher and Hall [15], who summed up in 1971: "it would appear that pedestrians and vehicles are just not compatible". Full-scale tests were carried out with post mortem human subjects (PMHS) and test dummies. Although the first proposal for a test procedure was defined in 1982, the repeatability of the head impact kinematics was identified as one of the major difficulties of a full-scale procedure [8]. Additionally, VRU-oriented improvements often conflict with design considerations, such as styling, manufacturing expenses and safety standards for low-speed crashes and rollovers. For years, road design standards and practice have been focused on needs of car occupants, whereas the needs of VRUs have been neglected or limited. However, deployable passive safety systems, such as pop-up hoods and windshield airbags and active safety designs that is, brake-assist systems, cameras, radars, LIDARs and autonomous-braking systems, have confirmed significant benefits for reducing VRUs injuries. Thus, integrated passive and active systems are recommended for a further enhancement of VRUs protection [3,16–19].

In this publication, the author presents each group of vulnerable road users—i.e., pedestrians, cyclists, children transported on the bicycle-mounted seats and motorcyclists—in the context of current norms and regulations, which are now in force in Europe. The present requirements are contrasted with the author's research which is mainly focused on VRUs' head biomechanics and kinematics. Finally, the author's new method is presented, which encompasses the sub-groups of VRUs and proposes some improvements to both the regulations as well as the technical system to mitigate injuries during impact. Moreover, some important conclusions are drawn, which may be taken into consideration during the process of new legislation formulation. The research implies that proper policies and enforcement, public awareness campaigns and smart road design may save a great number of lives over the coming decades.

2. Materials and Methods

The methods for testing the safety of VRUs against criteria set out in the regulations might seem surprising. It would seem that the procedures might be similar to safety tests carried out, among others, by the EuroNCAP organization, where different biomechanical parameters are examined using a full-scale dummy [20]. However, testing of, for example, a vehicle front-end for pedestrian issues, based on a collision with a full-scale dummy is more of a qualitative study for manufacturers rather than the data for type approval. This is because a single collision between a vehicle and a dummy is expensive and requires extensive organizational preparation. Assuming that the front-end of the vehicle shall be tested fully in terms of its geometry, there should be at least a dozen crash tests using a dummy.

Therefore, for VRU safety the working groups decided to replace the dummy with a series of tests with impactors. The models of human body parts, called impactors, significantly reduce the cost of research, and, on the other hand, allow the test procedure to be normalized. Herein, the author presented the current norms and regulations for pedestrians, cyclists, children transported on the bicycle-mounted seats and motorcyclists. This will enable to have a better perspective on how the VRU's safety state is currently verified. Moreover, some limitations of current regulations are highlighted.

2.1. Pedestrian Safety Regulations

Since the 1960s, the enhancement in vehicle safety was not only a marketing trick but more importantly, was required by relevant standards and regulations. Twenty years later the first actions

were taken to stop the growing number of fatal road accidents involving pedestrians [21,22]. The legal aspects of vehicle collisions with pedestrians were first dealt with by the European Experimental Vehicle Committee (EEVC) in the 1980s. In 1988 the so-called Working Group 10 (later renamed to Working Group 17) was established under the EEVC, whose objective was to develop methods and define limits on biomechanical values for a case when a pedestrian is struck by the front of a vehicle [23]. In 2009, based on the experience of the EEVC, the Parliament of the European Union issued Regulation (EC) 78/2009 amending Directive 2005/66/EC on the type-approval of motor vehicles with regard to pedestrian safety [24]. In order to validate the parameters established in Regulation (EC) 78/2009, certified impactors should be used, which reflect those parts of the human body that are crucial during collision.

Regulation (EC) 631/2009, which specifies the (EC) 78/2009, distinguishes two types of headform impactor models: a child/small adult model and an adult model, which have the form of a rigid aluminium sphere, with a diameter of 165 mm, half of which is covered with a 14.0 mm thick synthetic skin. The total mass of the headform impactor, including instrumentation, is 3.5 kg for the child model and 4.5 kg for the adult model [25]. In order to validate the parameters established in Regulation (EC) 78/2009 it is mandatory to use certified impactors which reflect those parts of the human body that are critical in terms of injuries.

The simulation of the collision is performed at impact speeds of 35 or 40 km/h and includes the following tests (Figure 3a):

■ A legform impactor representing the adult lower limb;
■ An upper legform impactor representing the adult upper leg and pelvis;
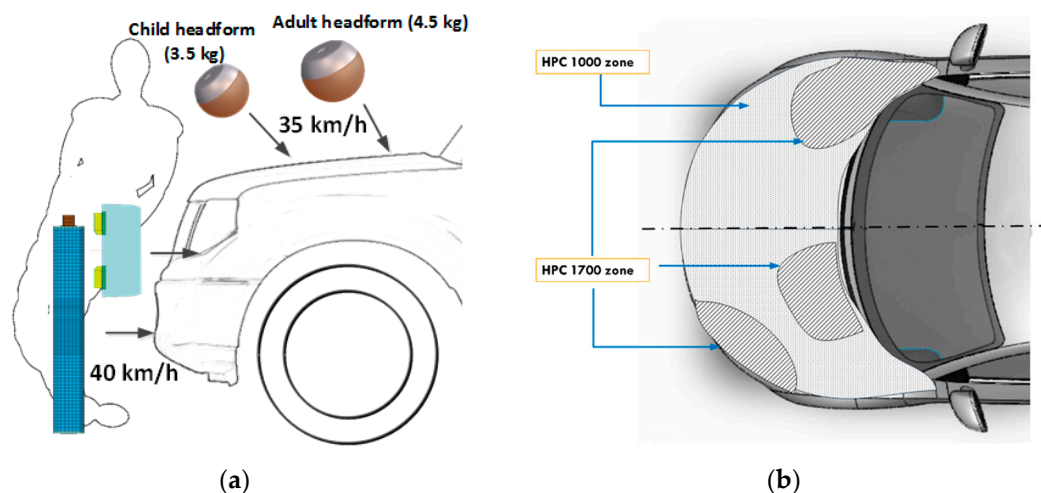■ Child and adult headform impactors.

(**a**)   (**b**)

Figure 3. (**a**) Visualization of a vehicle-to-pedestrian accident and the use of impactors that represent critical parts of the human body; (**b**) determination of head impact zone—according to Regulation (EC) 78/2009, phase II.

As far as head injuries are concerned, to obtain the type-approval for the tested vehicle the HPC (Head Performance Criterion) shall not exceed 1000 over one half of the child headform test area and, in addition, shall not exceed 1000 over 2/3 of the combined child and adult headform test areas. The head impact zone was depicted in Figure 4a. The HPC for the remaining areas shall not exceed 1700 for both headforms [24]. The HPC Equation (1) is the same as for HIC (Head Injury Criterion), thus:

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

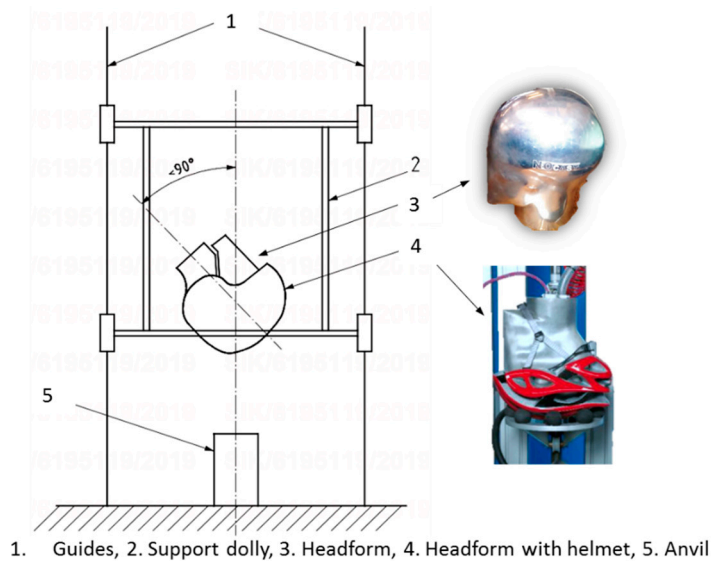1. Guides, 2. Support dolly, 3. Headform, 4. Headform with helmet, 5. Anvil

Figure 4. The test rig for the guided free fall impact test in accordance with the EN 1078 and using EN 960 magnesium headform.

The magnitude of the linear acceleration observed at the centre of mass of the dummy head during the impact is described by a(t). The resultant acceleration [g] is of duration t and t_1 and t_2 are two time points [s] during the impact, $0 \leq t_1 < t_2 \leq t$. HPC or HIC considers only the linear, translational acceleration over this previously defined time window. For (EC) 78/2009 time interval greater than 15 ms is ignored thus we can name it as HPC(15).

A study of the literature concerning pedestrian safety indicates that the biofidelity of the used impactors for (EC) 78/2099 has not been definitively resolved. It has been proven that the impactors used in tests cannot reliably assess the safety of vehicles with a high-bumper and bonnet reference line (SUVs). Using the impactor raises many doubts and questions [26,27]. The currently used impactors are not reliable in assessing the safety of SUVs for vulnerable road users. Moreover, it should be noted that the limit values of HPC parameters are not related to the mechanisms of injury.

2.2. Cyclist Helmet Regulations

In recent years, environmental awareness has gained strength and popularity especially in high-income countries [6]. Not only hybrid or electric vehicles are frequently used but also bicycles more often replace cars as the main mean of transport. Except for its undisputed ecological value, the economical aspect comes to the fore [28]. Nowadays, due to traffic jams in cities, a bicycle as a mean of transport allows its user to save time. As the ecological, economical, time saving and health improving form of transport, the tendency with all likelihood will increase the participation of cyclists in traffic. In low-income countries, the key aspect for cycling is the availability, ease of access and low expense of vehicle maintenance. Usually, there is no need for dedicated infrastructure and this contributes to the convenience of using this form of transport, especially in places that are hard to reach by other means of transport.

Nevertheless, the main burden for a bicyclist comes from the high probability of injury, especially in cases of impacts with motor vehicles. The most exposed body regions in the case of cyclists during road accidents are the upper extremities and head, which is injured in 42% of cases [29]. The frequency of injuries to the cyclist's body region is presented in Table 1. It was also reported that cyclists who died as a result of an impact usually did not wear helmets [30].

Table 1. Injury frequency of cyclist's body region, adapted from [4,29].

Body Region	Frequency [%]
Head	42
Neck	6
Thorax	21
Upper extremity	44
Abdomen	5
Pelvis	11
Thigh	7
Knee	25
Lower leg	15
Foot	13

To protect the cyclist's head from potential injuries the EN 1078 standard was introduced 1997 in the European Committee for Standardization (CEN) member states. EN 1078 applies to helmets for adults and children. However, to prevent young children being trapped by a helmet during some activities (e.g., play in the playground), which may lead to strangulation, the EN 1080 was put forward. Although EN 1078 and EN 1080 requires from a helmet the same shock absorption performance (<250 g), the EN 1080 requires from a helmet manufacturer to provide a retention system with a self-release mechanism—which opens by a force of 90–160 N—to minimize the risk of child strangulation. The author of this paper highlights that these two standards cannot be applied interchangeably, when it comes to young cyclists, as some literature may indicate [31].

According to EN 1078 a helmet should protect the user in the way that the peak acceleration shall not exceed 250 g for the velocity of 5.42 m/s (drop height 1497 mm) on a flat anvil and 4.57 m/s on the kerbstone anvil (drop height of 1064 mm). The test rig and the magnesium headform (size 575—type J), which complies with EN 960, for helmet testing are depicted in Figure 4. The measured peak linear acceleration according to EN 1078 shall not exceed 250 g.

2.3. Child on Bicycle-Mounted Seat Restrain Regulations

The transport of children by bicycle has been popular in America since the late 1970s [32]. It is also described by the Australian National Cycling Strategy 2011–2016 (NCS) as a safe, viable and enjoyable mode of transport and recreation and enabling families to cycle safely [33,34]. However, road injuries are the leading cause of death for children—this is a clear signal for the current child health agenda. Car seats designed for children are highly effective in reducing injury to child occupants. It has been reported that a proper child restrain can lead to approximately 60% of the reduction in deaths [35–37]. Yet, little attention has been drawn to the VRUs who are children transported in child seats mounted on the bicycle [38].

Bicycle-mounted child seats consist generally of a horizontal platform supported by vertical struts, which are connected to the bike's frame—the mounting configurations are visualized in Figure 5. Safety features include spoke guards, reflectors, seat belt or harness and on some models a grab bar which acts as a front restraint [39].

Figure 5. Mounting configurations of bicycle-mounted seat—rear-rack (**left**), rear-frame (**middle**), front (**right**).

The different baby carrier models offer the possibility to transport up to a mass of 22 kg. Baby carriers have to match the demands of DIN EN 14344 [40] to be sold as such a device on the European Union market. In terms of child safety, there is a requirement in DIN EN 14344, which is related to the restrain system test. The test method for effectiveness of the restraint system (roll-over test) states that a test dummy shall be placed centrally on the seat against the backrest. The test dummy is to be made of rigid material with a smooth surface finish. The mass is to be 9 kg. Its technical drawing is illustrated in Figure 6. A means of rotation is used to rotate the product smoothly through 360° at a rotational speed of (4 ± 0.5) RPM in a forward and reverse direction for a total of 3 forward and 3 reverse rotations. The dummy shall not completely fall out of the restraint system. However, partial movement of the test dummy is not considered a failure [40].
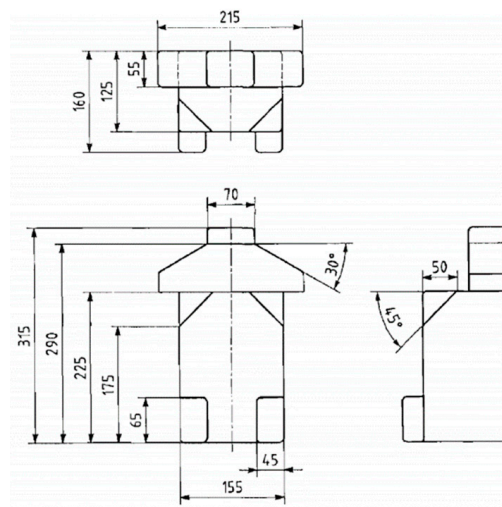

Figure 6. Test dummy with its dimensions [mm] for child seat roll-over test [40].

Some research done by Ptak et al. [38] highlighted the problem of a child slipping out of the bicycle seat during a crash. Consequently, it has been proven that the crashworthiness of a child seat is very low [41].

2.4. Motorcyclist Helemet Regulations

Motorcyclists are about 27 times more likely to die in a traffic crash than car occupants and about 6 times more likely to be injured. This means that crashes and their consequences are a significant problem in society [42,43]. The most frequent injuries experienced by two-wheelers include injuries to the lower limbs (31.8%), upper limbs (23.9%) and head (18.4%). For passengers, also the greatest number of injuries were injuries to the lower limbs (32.3%), while a higher share of head injuries was recorded, that is, 24.2%. Moreover, it the human's torso with the spine is also a vulnerable part of the human body during accidents—thereby the researchers attention have been focused on this issue [44–47]. The number of injuries to individual parts for drivers and passengers is shown in Figure 7. Besides, head injuries are the leading cause of death and trauma for motor vehicle users [48].
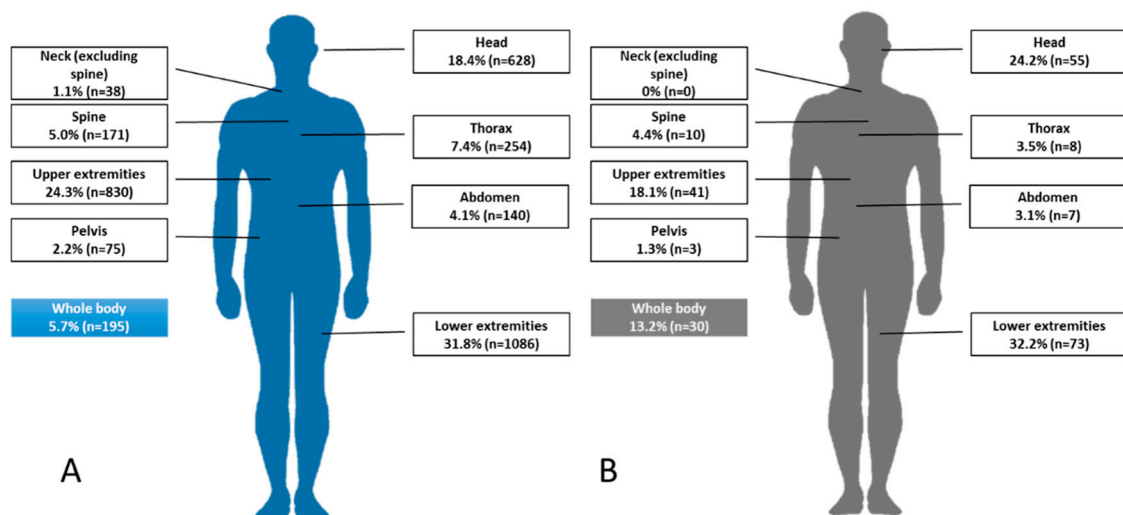
Figure 7. The number of injuries to body parts for a: (**A**) motorcycle driver; (**B**) passenger [49].

According to the ECE 22.05 standard, the helmet-headform system is dropped without any restriction against an anvil with a velocity of 7.5 m/s for points B, P, R, X and 5.5 m/s for point S—see Figure 8.
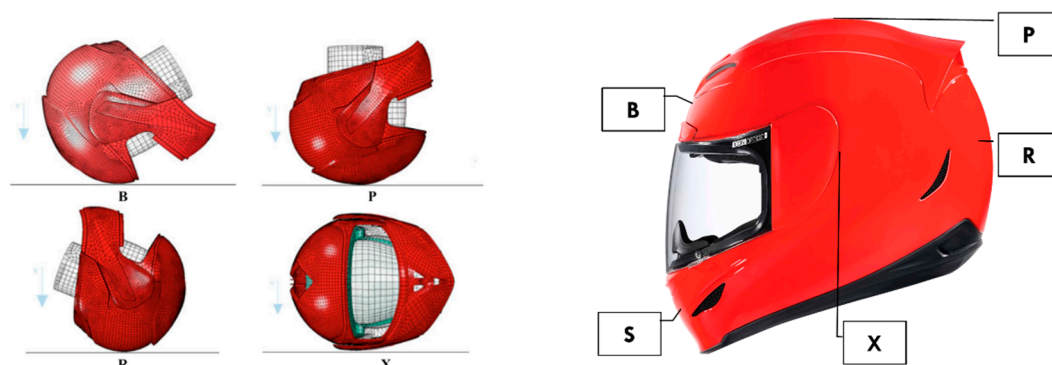

Figure 8. Impact configurations according to ECE R22.05 and marked points for testing.

The absorption efficiency shall be considered sufficient when the resultant acceleration measured at the centre of gravity (CoG) of the EN 960 headform (the same as for EN 1078) does not exceed 275 g and the HIC does not exceed 2400 [50].

The use of helmets has indicated the reduction of fatal and serious head injuries by between 20% and 45% among motorized two-wheelers users [6]. However, a low quality helmet might give the rider a false sense of protection. In case of a crash, a rider using a poor quality helmet could get more severely injured or even killed, sending the false message that all helmets are useless [42].

2.5. Author's Research Methodology

It needs to be highlighted that the best solution for the analysis of human body structure degradation is the research on human preparations [51,52]. Nevertheless, obtaining the preparations to investigate for example, tissues immediately after death is significantly impeded. Therefore, currently one of the best ways to identify structure responses to forces is numerical modelling. In particular, the finite element method (FEM), which is the leading method for the analysis of dynamic phenomena [53,54]. The vast development of computational power and expansion of FEM enables broadening the possibilities and application area on the ground of VRU safety. Advanced numerical analyses have been developing simultaneously with the rapid growth of computers. Currently, their contribution to the vehicle designing and testing process is vital. When FEM and MultiBody (MB)—the

techniques used to determine the approximated solution for partial differential equations on a defined domain—were started to be used by appropriate software, the complexities of modelling, including safety issues, could be addressed [50,55,56]. Figure 9 depicts Computer-aided technology (CAx) approaches to enhance VRU safety.
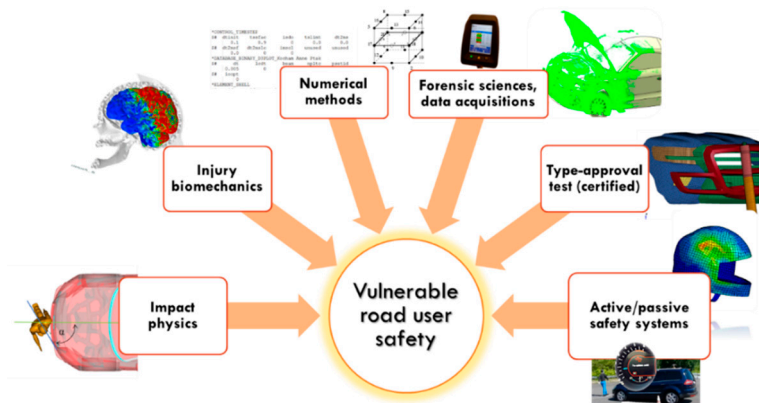

Figure 9. Computer-aided technologies (CAx) for vulnerable road user safety enhancement.

During the last two decades, the application of FEM and MB has been widely used in the field of traffic safety enhancement [57,58]. Therefore, multi-variant numerical models, which take into account the complex structures of the human body become a valuable tool for assessing safety and estimating the risk of injury and can reduce the effects of accidents through better diagnostics and the creation of preventive systems.

To assess the kinematics of an impacted VRU the author used mainly an advanced coupling method. The FE-MB coupling provides the opportunity for a user to combine, in a single numerical simulation, two different numerical codes. The author needed to combine the two products since MADYMO contains advanced, well-developed and validated dummies and LS-DYNA features accurate contact definitions and state-of-the-art material models. In the coupling, MADYMO builds a part of the FE model it receives from LS-DYNA. The MADYMO code puts forces on the nodes and display the FE model in the kinematic output files. The time step is synchronized, so the minimum of either FE or MB time step is integrated. The MB models presented in study are the 50th percentile male Hybrid III-adult dummy and a 1.5 and 3-year-old child dummy from MADYMO environment.

The author of this study has simulated hundreds of possible real-world frontal and side impact scenarios by applying a hybrid finite element-multibody framework. The geometrical models of vehicle, baby seat and motorcycle were created mainly by using a 3D scanner and advanced photogrammetry method to obtain realistic point clouds that were subsequently transformed into finite element models. The implementation of an original bicycle model and biofidelic multibody dummy models allowed the author to evaluate the influence of the transport-modes to the resulting kinematics. The constitutive material models were also investigated through destructive and non-destructive tests—more details can be found in References [11,59]. Finally, some parts of numerical models were validated during experimental research.

The last part of the presented authors' methodology is focused on safety gears and pro-active measuring systems. Moreover, the author presents, among others natural energy-absorbing materials—including cork—which, due to the adequate crashworthiness, may in the future replace commonly used polystyrene, for example, in motorcycle helmet liners [59–61].

3. Results

The current experimental test methods described in paragraph 2 used to assess the safety of VRUs do not allow the researcher to have a full insight into either the human kinematics nor the body response, especially brain tissues, resulting from excessive loads. Currently, the described physical

models (impactors such as a headform) are used to assess VRU safety thanks to which for example, HIC or HIP is verified. However, usually the current trauma criteria only estimate the risk of external injuries caused by mechanical acceleration. The HIC criterion, among the others, only takes into account linear acceleration, while neglecting the influence of angular acceleration [62]. In fact, there is rarely an impact that is purely rotational or linear in the real world [63].

The author of the publication solves the research problem by linking, usually separately considered, issues from the mechanics, biomechanics, medical imaging and neurosurgery as well as computational methods. Thanks to the study of the properties of the brain structure through experimental and computational research, the precise input data for numerical models was obtained. Thus, after a proper validation, it was feasible to carry out robust numerical simulations of the structural destruction of the brain tissues and to verify the injuries of other parts of the human body under the influence of physical loads. By using numerical simulations, it was possible to compute for example, stress, strain and intracranial pressure, which would be unfeasible while measuring in vivo. Variables such as strain or intracranial pressure have been pointed out as better injury indicators than externally measured linear or angular acceleration [63]. Accordingly, based on MADYMO dummy's head velocity registration the author implement the boundary conditions such as velocity components, for the simulations in LS-DYNA or ABAQUS. The post-processed data aided in assessing the severity of head injury. The FE head models were developed, validated and descripted in details in author's publications [64–66]. The multi-scale approach carried out for VRU safety assessment is presented in Table 2. Unlike the other presented models, the child's head model has not been validated so far—thus the author refrained of showing any results, which might be not robust.

Table 2. The multi-scale vulnerable road user numerical approach to assess safety.
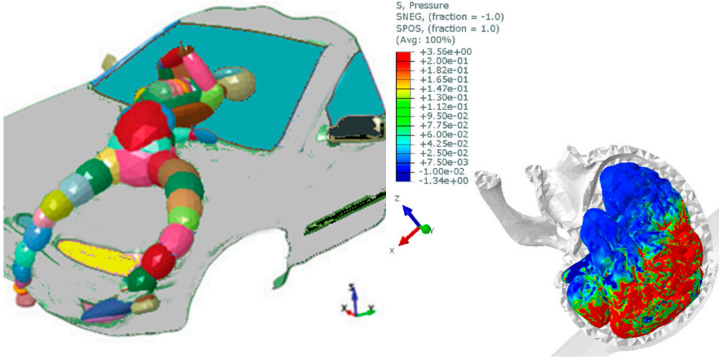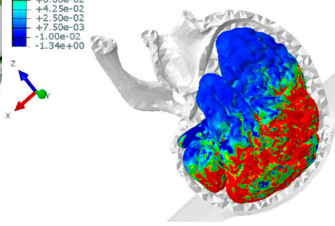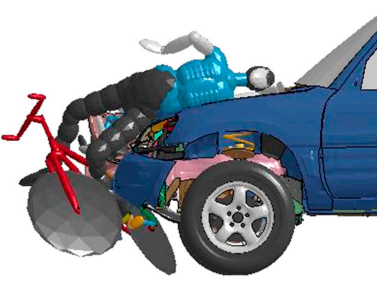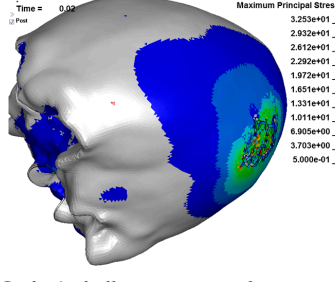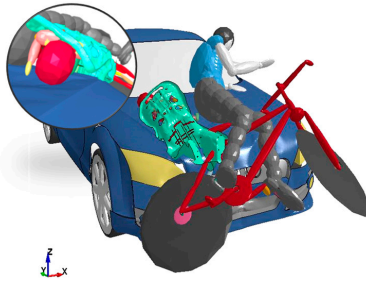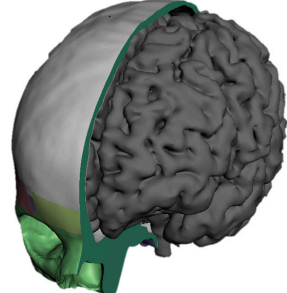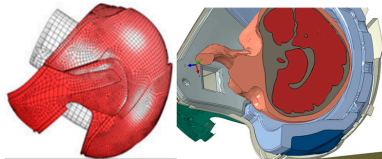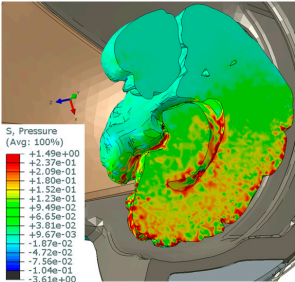
VRU Case Study	Numerical Approach	In-Depth Numerical Study
Pedestrian accident—windshield impact at 72 km/h. The sustained injuries in brain tissues are assessed to be critical—cerebral contusion.	50th-percentile male MB pedestrian model coupled with a FE compact car.	Hydrostatic pressure in the brain [MPa].
Cyclist accident—SUV impacts at 40 km/h. Skull fractures can be clearly validated during autopsy or CT medical examination. Research important for cyclist's helmet optimization and forensic science.	50th-percentile male on a MB bicycle model, coupled with a FE SUV.	Cyclist's skull—max principal stress and fracture pattern on periosteum and endosteum [MPa].

Table 2. *Cont.*

VRU Case Study	Numerical Approach	In-Depth Numerical Study
Child on bicycle-mounted seat—compact car impacts at 40 km/h. The child slips out from seat belts and impacts the bonnet. The child's seat crashworthiness is assessed.	50th-percentile male and 1.5-year-old child MB models coupled with a FE SUV—the head bonnet contact magnified.	Child's head numerical model.
Motorcyclist—the helmet test according to ECE R22.05 (point B) with an advanced head model to compare HIC registered on the standard headform with cerebral pressure on FE model.	EN 960 headform test published in Reference [50] (left): HIC = 1876 and a_{max} = 213 g vs. the helmet with advanced head model (right—sagittal section through the head and helmet).	Hydrostatic pressure in the brain [MPa]—sagittal section view, left hemisphere visible.

Nowadays, numerical systems can improve biomechanical criteria as well as head-protective systems, facilitating forensic sciences and the reconstruction of accidents, diagnosis and prediction of injuries and enables researchers to gain knowledge in the field of head injuries. The use of numerical systems has contributed to reduction of VRU injuries—these aspects were presented by eminent researchers in References [62,67–70]. Therefore, the author put forward a coherent methodology, based on numerical and experimental achievements and proposed some technical countermeasures to improve road safety for VRUs.

The method depicted in Figure 10 consists of the six steps. Whereas the stages 1–3 already exist, the stages 4–6 are added by the author to contribute towards VRUs safety enhancement:

1. *Norms and regulations* encompassing the safety requirements for a VRU during an impact. They are formed on biomechanical criteria—often established based on empirical data—and, on the other hand, limited by technical and economic aspects.

2. *Experimental tests* carried out according to detailed requirements for each group of VRUs, which were described in Section 2.

3. *Standard criteria* setting out thresholds such as HIC or acceleration limits related to VRU safety—they depend solely on the time history of the translational acceleration of a head CoG and do not evaluate whole body kinematics (pedestrian) nor the crashworthiness of a safety system (a bicycle-mounted seat).

4. *Numerical simulations* to verify the injuries/kinematics of a VRU by having an insight into VRU's biomechanics by the use of the state-of-the-art numerical models. This tier may involve:

    4.1　Coupling (4.1) that is, combining more than one numerical code;

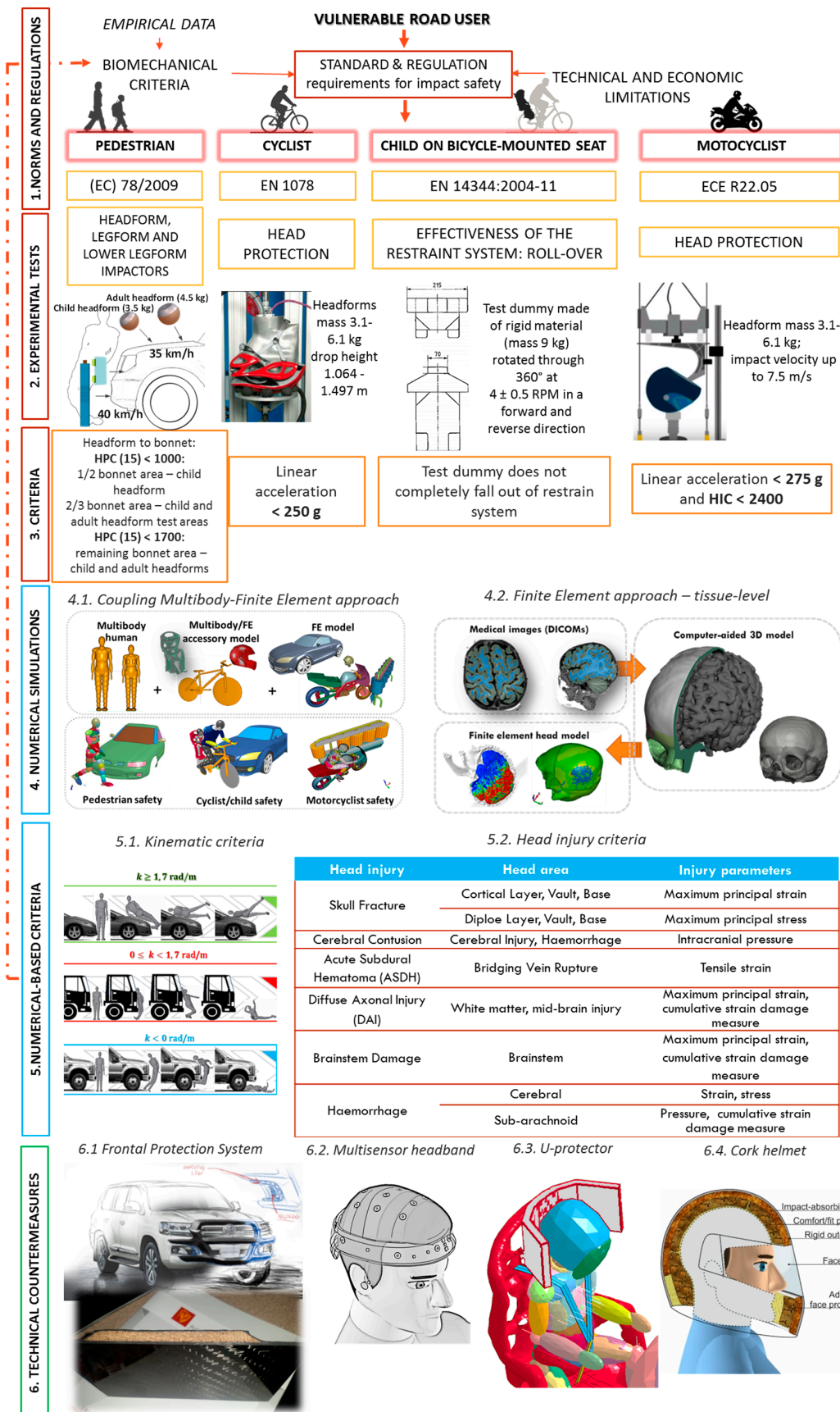   4.1　Single numerical code approach for example, finite element analysis for tissue-level simulations (4.2).

1. NORMS AND REGULATIONS

EMPIRICAL DATA

VULNERABLE ROAD USER

BIOMECHANICAL CRITERIA

STANDARD & REGULATION requirements for impact safety

TECHNICAL AND ECONOMIC LIMITATIONS

PEDESTRIAN	CYCLIST	CHILD ON BICYCLE-MOUNTED SEAT	MOTOCYCLIST
(EC) 78/2009	EN 1078	EN 14344:2004-11	ECE R22.05

2. EXPERIMENTAL TESTS

HEADFORM, LEGFORM AND LOWER LEGFORM IMPACTORS

HEAD PROTECTION

EFFECTIVENESS OF THE RESTRAINT SYSTEM: ROLL-OVER

HEAD PROTECTION

Child headform (3.5 kg)
Adult headform (4.5 kg)
35 km/h
40 km/h

Headforms mass 3.1-6.1 kg drop height 1.064 - 1.497 m

215
70

Test dummy made of rigid material (mass 9 kg) rotated through 360° at 4 ± 0.5 RPM in a forward and reverse direction

Headform mass 3.1-6.1 kg; impact velocity up to 7.5 m/s

3. CRITERIA

Headform to bonnet:
HPC (15) < 1000:
1/2 bonnet area – child headform
2/3 bonnet area – child and adult headform test areas
HPC (15) < 1700:
remaining bonnet area – child and adult headforms

Linear acceleration **< 250 g**

Test dummy does not completely fall out of restrain system

Linear acceleration **< 275 g** and **HIC < 2400**

4. NUMERICAL SIMULATIONS

4.1. Coupling Multibody-Finite Element approach

Multibody human
Multibody/FE accessory model
FE model
+
+
Pedestrian safety
Cyclist/child safety
Motocyclist safety

4.2. Finite Element approach – tissue-level

Medical images (DICOMs)
Computer-aided 3D model
Finite element head model

5. NUMERICAL-BASED CRITERIA

5.1. Kinematic criteria

$k \geq 1.7$ rad/m

$0 \leq k < 1.7$ rad/m

$k < 0$ rad/m

5.2. Head injury criteria

Head injury	Head area	Injury parameters
Skull Fracture	Cortical Layer, Vault, Base	Maximum principal strain
	Diploe Layer, Vault, Base	Maximum principal stress
Cerebral Contusion	Cerebral Injury, Haemorrhage	Intracranial pressure
Acute Subdural Hematoma (ASDH)	Bridging Vein Rupture	Tensile strain
Diffuse Axonal Injury (DAI)	White matter, mid-brain injury	Maximum principal strain, cumulative strain damage measure
Brainstem Damage	Brainstem	Maximum principal strain, cumulative strain damage measure
Haemorrhage	Cerebral	Strain, stress
	Sub-arachnoid	Pressure, cumulative strain damage measure

6. TECHNICAL COUNTERMEASURES

6.1 Frontal Protection System

6.2. Multisensor headband

6.3. U-protector

6.4. Cork helmet

Impact-absorbing liner
Comfort/fit padding
Rigid outer shell
Face shield
Additional face protection

Figure 10. A method to assess and enhance the vulnerable road user safety during impact.

Moreover, the multi-scale modelling is also feasible as presented in Table 2.

5   *Numerical-based criteria* based on biomechanical studies combined with numerical simulations and full human body analysis. This stage shall contribute in improving the biomechanical criteria in stage 1—this is highlighted by a dashed line, joining the steps 5 and 1, in Figure 10. The mechanically relevant responses related to VRU's:

    5.1   Kinematics—such as the *k parameter*, which can determinate the geometric property of the pedestrian body movement after a collision. This criterion is thoroughly described in the author's publication [71].

    5.2   Acceleration, intracranial pressure, stress and strain, which have been postulated as head injury mechanisms and thereby may be used as predictions of various head injuries.

6   *Technical countermeasures* to enhance VRU safety when the standard (stage #3) and numerical criteria (stage #5) are not met. The author has already proposed these countermeasures for each group of VRUs:

    6.1   The Composite Frontal Protection System—made of cork and carbon fibres to reduce injuries sustained by a pedestrian and optimize the kinematics after a vehicle impact—the approach is described in References [72,73] and patented [74].

    6.2   The multisensor headband, which can be worn under a helmet to gain the data about the VRU. The system enables registering complex dynamic characteristics of a human head during situations in which the head is exposed to mechanical impact and it is able to measure bioelectrical brain activity (electroencephalography)—patent pending [75]. The detection of the respective pathomechanism in cases of destructed brain structures is extremely important in terms of prevention and treatment.

    6.3   The U-protector designed to increase the safety of a child, who is transported in a bicycle-mounted seat. The attachable device helps to protect the child's head during the impact of a vehicle or bicycle fall over [41].

    6.4   The motorcycle helmet made of cork, where the padding is made of agglomerated cork or cork composite (agglomerated cork joined with expanded cork). The cork material improves the overall performance and capacity to withstand multi-impacts comparing to the standard synthetic padding. The device was introduced and evaluated in References [76,77].

4. Discussion

Numerical models along with tests on human cadavers and specialized physical pedestrian dummies play a pivotal role to reflect the VRU impact situations. It has been highlighted that in VRUs impacts, head injuries are one of the most common injury types. A number of publications noted that brain deformation or strain is a principal mechanism of the head injury [60,77]. From the biomechanical perspective, head injuries are regarded as the consequence of a series of mechanical interactions of the complex multi-layered scalp-skull-meninges-CSF-BVs-brain system; the CSF is cerebrospinal fluid and BVs is the abbreviation of bridging veins. However, measuring strain, especially in vivo, during an impact is a big challenge, which also implies ethical issues. Therefore, numerical analysis allowed the authors to verify, among others, VRU head injuries after a collision. This was possible as the head injury criteria are available for FE head models. Some injury tolerance thresholds, which were put forward for the state-of-the-art finite element human model GHBMC (Global Human Body Models Consortium) are presented in Table 3 [78]. A proper understanding of the injury mechanism is of uttermost importance for studying injury prevention. Without knowing the proper injury mechanism, the associated injury criteria and thresholds, it is not possible to use numerical models to predict the type, location and severity of head injuries. Beside the criteria presented, there are other injury tolerances thresholds to other biomechanical responses in the literature [79–81].

Head Injury	Criteria	Threshold
Bone (skull) fracture	Maximum principal stress (diploe layer)	20 MPa
	Maximum principal strain (cortical layer)	0.42%
Bone (facial/nose) fracture	Effective plastic strain (cortical layer)	1.2%
	Effective plastic strain (trabecular layer)	4.5%
Acute Subdural Hematoma (ASDH)	Strain in bridging veins. ASDH due to bridging vein rupture.	25%
Cerebral contusion	Intracranial pressure in region of interest (Coup)	237 kPa
	Intracranial pressure in region of interest (Contrecoup)	−104 kPa
Diffuse axonal injury	Average maximum principal strain in ROI	48%

The presented study helped to understand the VRU kinematics and head injuries at the tissue/bone level but also is advices appropriate passive safety devices. The models not only enabled the author to assess the risk to injury in vehicle impacts but also are to optimize the VRU in the early stages of the vehicle or safety gear design process at relatively low costs. The comprehension of the factors and variables, which influence the accident would not only help in accident reconstruction but also allow improving the vehicle construction in terms of safety enhancement for VRUs.

The process of contact for the VRU involves a combination of slide, roll and bounce to rest—yet the overall injury severity is largely determined on both linear and angular acceleration, which challenges the current HIC/HPC criteria. As it was presented in Section 2, these criteria, which were developed from the Wayne State Tolerance Curve (WSTC), depend exclusively on the translational acceleration without taking rotational acceleration into account [83,84]. As a result, both revealed peak acceleration and calculated HIC need to be below a threshold, which is defined by regulations for testing or certification of safety devices. Exemplarily, in the presented ECE R22.05 the maximum value of HIC = 2400 is stated, while the peak acceleration needs to be limited to 275 g [85]. Base on the state of the art, the representation of a threshold of severe but not life-threatening injuries HIC(36) = 1000 is widely accepted as an empirical predictor for head injury [86]. The results presented in Table 2 supports these findings. It turned out that for an ECE R22.05 type-approved motorcyclist helmet [50] the intracranial pressure in region of interest (compare Table 3) are much above the threshold. The calculated pressure (>1 MPa) may lead to sever brain injuries.

Regardless if the procedure is described by legislation or testing regulation: the background of establishing these thresholds is to avoid Traumatic Brain Injuries (TBI) or skull fractures by the appropriate performance of passive safety devices. Nonetheless, Diffuse Axonal Injury (DAI) and Subdural Hematoma (SDH) are the types of head injuries commonly occurring for the impacted VRUs. DAI is the most common cause of post-traumatic coma and may cause a vegetative state and severe disabilities [87–89]. As initially remarked, HIC is not considering rotational components of acceleration. In terms of their injury mechanism, DAI as well as SDH are connected to these components of acceleration, which are present during a direct cranial impact scenario and cause a relative movement of brain to skull, white to grey matter respectively. In case of SDH, relative motion between skull and brain causes tearing or failure of the bridging veins of the subdural space. The DAI may also arise out of relative motion but due to relative motion of white and grey matter. This relative motion affects the integrity of neuronal axons, which are connecting both parts of the brain tissue. The axons might get swollen due to this event, which leads consequently to the secondary severe effects of DAI. Nonetheless, these injuries may also arise below the HIC-threshold of safety criteria. Thus, the aspects of head movement are gaining importance in the assessment of the overall VRU safety during an impact scenario [90]. Moreover, the biomechanical response of the skull structures during traffic accidents is not fully understood. In order to construct head protection systems and criteria for damage to not only the head structures but also the other human body parts, the research need to be intensified. Therefore, the author proposed to include numerical modelling as the further step to assess and improve VRU's safety.

Limitations of the Study

As in every research method—including numerical simulations—there is an issue with assessing the reliability of the obtained results. The problem is to determine the mechanical properties of human's body parts, including tissues, which constitute to the analysed part of a person. This stage can be determined in experimental studies, during which there is also uncertainty of measurements. Consequently, it is the author's opinion that the used numerical models needs to demonstrate the proper validation. It also needs to be acknowledged as the limitation that the presented numerical thresholds are not necessarily universally valid for all population and related phenomena. The author believes that mechanism of injuries requires further investigation.

Moreover, most of numerical models consider only the adult head and brain structures and usually—due to lack of data—a scaled adult version for six or even three years old children is considered. Nevertheless, even if the general density of information within these models has increased noticeable over the last decades, the scaling and interpretation of the gathered results is still controversial. This gets highlighted especially concerning the usage of general accepted (or at least practically used) thresholds such as HIC(36) = 1000 for the occurrence of severe but not life-threatening injuries. The literature reveals a variety of studies [91], that tend in a conclusion toward using these adult values. However, the question is still not conclusively answered for very young children and babies. Additional work is needed to consolidate the proposed criteria for predicting head injury risk. To achieve this goal, well-documented head trauma cases are needed—which also implies ethical issues. Consequently, the author refrained of showing results for a FE child's head, as the results may be not credible.

5. Conclusions

Pedestrians, cyclists and motorcyclists form a group called vulnerable road users. More than half of global road traffic fatalities are VRUs, who tend to be negated in road traffic system design in majority of countries. This group contributes to 73% of road users killed in city traffic. Nearly half of road fatalities in cities are pedestrians—for whom the risk of fatality is ten times higher than for car occupants [8]. The detection of the respective pathomechanism in cases of human body structures is extremely important in terms of prevention and treatment. Consequently, it ensures the safety of modern society. It has been demonstrated that the numerical analysis can serve as a powerful tool to study VRUs head injuries and kinematics.

The study presents a six-stage method of assessing and improving the safety of vulnerable road users, that is, pedestrian, cyclist—along with a child on a seat—and a motorcyclist. The author presented the current European legislation for VRU safety. Furthermore, based on the numerical outcome it was proposed to extend the criteria—by the use of advanced numerical models. By means of experimental and numerical research, the technical solutions that help to reduce injuries of VRU are proposed in last stage of the methodology.

Numerical and experimental methods have been continuously improved in order to provide better analysis of accident scenarios, evaluate their outcomes and provide effective frameworks for their prevention. The progress in VRU safety enhancement can be achieved through an integrated approach that includes effective counter-measures such as improved safety standards and regulations—with the space for numerical methods—and legislation to mitigate high-risk behaviour such as speeding or giving way to VRUs. However, as it was stated, without the knowledge of the magnitude and risk of the injuries, the ability to implement biomechanical thresholds is limited. In Reference [67] King wrote about the GHBMC vehicle occupant model: "after the global model becomes functional, the entire US automotive industry will use the model for vehicle design in much the same way the Hybrid III dummy is being used currently for this purpose." According to the author and as it was presented herein, to the development of numerical methods may affect not only vehicle occupants but also the unprotected group outside the cars—vulnerable road users.

This paper sets out how the virtual testing and FE-impactors can contribute in VRU safety improvements. The utilization of virtual simulations is continuously evolving, yet it still requires some accuracy enhancements, particularly in impactor and material modelling. The relative lack of data for cyclist accidents and the frequently conflicting data on pedestrian injuries means that further widespread accident data collection is required. Although the physical validation of a test tends to be costly, it assesses whether potential development can be made in terms of safety enhancement. The accident data determines the quality of the accident reconstructions, which in turn lays the foundations for the evaluation of FE models.

The problem of safety of the VRUs is critical and global. The available resources shall be used to reduce the fatalities and injuries on roads. Thus, this research addresses a gap in current state of the art by holistically investigating the safety of vulnerable road user groups. As there is the room for improvement in the field of VRU safety, this publication supports the statement that the presented standards and regulations can include the numerical methods, such a finite element analysis, in the near future.

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