Research Trends in Pedestrian Safety: Topics, Methodologies, Techniques, and Data Insights

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Abstract. This research has been carried out to make a thorough examination of the existing literature on the subject of pedestrian safety, more in detail on the construction of vulnerability curves. Emphasis was placed on key methodologies such as impact testing, finite element modelling, and predictive analysis needed to define risk mitigation measures for vulnerable road users, particularly in research such as pedestrians. Pedestrian safety has become an increasingly important area of research in recent decades, due to the increase in accidents where pedestrians are injured and/or die, especially as regards the urban environment. Understanding the main factors that influence accidents involving pediatricians is therefore essential to define mitigations to reduce this problem, which today has an increasing impact. The consultation of 93 key studies aims to highlight the latest advances in pedestrian safety research, assessing innovations to be undertaken in vehicle design, urban planning, and policy development.

Keywords: Pedestrian Safety · Biomechanical Evaluations · Experimental data · Vulnerability curves

1 Introduction

With the increasing number of accidents involving vulnerable road users, especially pedestrians, transport research is increasingly focusing on analysing the safety of such users. Globally, according to the World Health Organisation (WHO), pedestrians account for about 22% of road deaths, with an estimated 270,000 deaths per year [1]. The latest update by the National Highway Traffic Safety Administration (NHTSA) reports 12,330 deaths from speeding in 2021, an 8% increase compared to 2020 [2]. In Italy, 485 pedestrians died in 2023, a stable figure compared to 2022, which saw an increase of 3.2% compared to the previous year [3, 4].

As the data therefore show, there is a need to analyse and define effective measures to improve road safety and protect vulnerable users. Although vehicle safety technologies have made significant progress, the study of pedestrian-vehicle impacts requires further investigation, in particular about factors such as road design, vehicle speed, the behaviour

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of the driver, and the actions of pedestrians [5, 6]. Sever-al scientific methodologies, including crash tests [7, 8], finite element modeling (FEM) [9–23], predictive modeling [7, 8], and the integration of emerging technologies, have been developed to improve pedestrian safety [24, 25]. The purpose of this review is to investigate innovations in impact testing, vehicle design, and urban planning that have contributed to creating a safer environment for pedestrians, with a focus on the significance of a multidisciplinary approach. By this, the focus concerns the in-depth study of all the phases necessary for the definition of pedestrian-vehicle vulnerability curves that describe, based on impact parameters, what are the probabilities of the pedestrian suffering more or less serious damage as a result of the impact. It also seeks to explore how artificial intelligence, machine learning, and other advanced technologies can be used to predict, identify, and mitigate pedestrian risk in real time [26, 30]. Initial studies focused on understanding the basic mechanics of vehicle-pedestrian collisions through simple kinematic models to analyze injury outcomes, such as head trauma, leg fractures, and chest injuries. However, these studies lacked the detailed biomechanical understanding necessary to design effective countermeasures. A turning point in research occurred in the 1990s with the introduction of finite element modeling (FEM) [9–23]. These computational methods allowed for more realistic simulations of collisions, deepening the understanding of the biomechanics involved and simulating a range of impact scenarios to assess injuries based on the forces involved. This advancement facilitated the development of new vehicle design methodologies, including energy-absorbing bumpers, crumple zones, and pedestrian-friendly bonnets, which have been credited with reducing the severity of injuries in real-world pedestrian accidents [26–30].

These developments have opened new avenues for improving pedestrian safety, such as advanced driver assistance systems (ADAS), real-time hazard detection, and predictive traffic management systems [26–28, 32]. This paper aims to define the process of defining vulnerability curves, from the collection of simulation data to that relating to real accidents, and to investigate the crucial aspects of pedestrian safety.

The structure of the paper includes a Section 1 in which an overview of the focus of the case study is made, a Section 2 where the methodology adopted is illustrated, a Section 3 where the Numerical simulations are analyzed, a Section 4 that explains the experimental data, a Section 5 in which the real accident databases are described, a Section 6 in which the several statics methods to realize vulnerability curves are investigated, a Section 7 in which the vulnerability curves procedure is explained, a Section 8 in which risk factors are indicated, a Section 9 in which the effectiveness of safety systems are described and at the end, in Sect. 10 there are the conclusions.

2 Methodologies in Pedestrian Safety Research

To investigate the aspects concerning the implementation of vulnerability curves, 93 scientific papers were reviewed.

The selection was based on keywords such as “pedestrian vulnerability”, “vulnerability curves”, “injury severity models”, and was made through the consultation of databases such as Scopus, Web Science, and Google Scholar.

Purely theoretical or descriptive papers that do not highlight simulation and/or statistical models and/or incidental data necessary for the construction of vulnerability curves

have not been considered. Instead, papers concerning the impact of pedestrians and vehicles have been selected, written in English, and do not have a particular restriction in terms of time.

From the analysis of the 93 articles, it was possible to evaluate the main methodologies for data collection and data processing pedestrian vulnerability curves to improve the latter's safety (see Table 1).

Table 1. Methodologies adopted for the assessment of pedestrian safety

Methodologies	Percentage
Numerical simulations	35.71%
Experimental data	19.04%
Real accident database	33.33%
Statistical analysis	11.90%

From Table 1, it can be deduced that the methodology concerning numerical simulations is the most widespread in the literature, probably because, within impact reconstruction software, it is possible to implement a wide variety of scenarios by considering different impact conditions. Then follow the data of real accidents, which certainly represent an important source for what concerns the calibration of vulnerability curves, in order to obtain results as close as possible to real conditions. On the other hand, experimental data, such as crash tests or reproduction of impacts in controlled environments, are also useful for calibrating vulnerability curves but are probably less used than real accident data, as they involve high costs and ethical limitations. Finally, more or less advanced statistical analyses are used to define the correlation between the impact variables and the risk of injuries suffered.

By virtue of this, it was possible to classify the articles according to macro-categories (see Fig. 1).

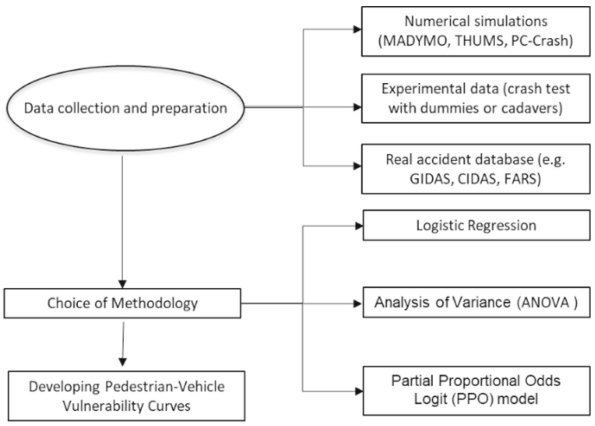

Fig. 1. Development of vulnerability curves

Figure 1 shows the necessary process that leads to the definition of vulnerability curves. The main steps are, first of all, the reconstruction of the impacts in simulation software that allows for investigating the variables and defining those that most affect the outcome of the impact.

However, these analyses require calibration, and to do this, both experimental data, obtained from crash tests and the like, and databases of real accidents can be used.

Everything converges in the choice of the statistical analysis to be carried out to identify risk factors and estimate the probability of post-impact injury.

3 Numerical Simulations: Biomechanical Evaluations

Biomechanical assessments analyze human body responses during impact, helping to understand injury dynamics and risk. Mathematical models and simulations evaluate force, acceleration, and tissue deformation, aiding in the improvement of safety devices and standards. PC-Crash is widely used for accident reconstruction and impact analysis [33–38]. Several studies have used this software to evaluate key parameters influencing pedestrian injuries. For example, Martínez et al. [33] used PC-Crash for sensitivity analysis, identifying key factors like pedestrian height, collision angle, hood height, and pedestrian-road friction. Their regression model predicted impact velocity with less than 10% deviation from real-world reconstructions, confirming the relevance of these factors in pedestrian-vehicle collisions. Similarly, Xiaoyun et al. [39] analyzed biomechanical friction in pedestrian accident reconstruction, conducting numerical simulations to improve accuracy. Validated with a real-world bus-pedestrian collision, their study showed that friction significantly affects post-impact pedestrian throw distance. Errors in friction estimation can lead to major discrepancies, while their methodology enhances simulation reliability for forensic applications. To enhance injury prediction capabilities, several studies have combined PC-Crash with biomechanical models. Portal et al. [40] used PC-Crash and biomechanical models to reconstruct a pedestrian accident, analyzing injuries based on AIS, HIC, and TTI criteria. The pedestrian, struck at approximately 80 km/h, sustained severe injuries. The study accurately estimated impact speed by assessing the pedestrian's final position and vehicle damage. Simulations also helped verify or refute witness statements, highlighting biomechanics' crucial role in forensic analysis. Additionally, Chen et al. [34] evaluated automatic emergency braking (AEB) effectiveness using PC-Crash and the CIDAS database, analyzing 358 pedestrian accidents in China. Simulations showed that activating AEB one second before impact could prevent over 20% of collisions, reducing average impact speed from 39 km/h to 24 km/h, and enhancing pedestrian safety. This study underscores the importance of AEB adoption in mitigating pedestrian-vehicle collisions. Additionally, PC-Crash simulations improve injury severity assessments by analyzing vehicle speed and impact angle, offering greater reconstruction accuracy than traditional methods [41]. Gu et al. [37] used PC-Crash simulations to analyze "second collision" accidents, finding a sharp increase in fatality risk above 50 km/h, emphasizing the need for improved detection systems. Han et al. [38] applied orthogonal analysis with PC-Crash, identifying hood height and vehicle speed as key factors affecting pedestrian projection distance and injury severity. Similarly, Richardson et al. [42] analyzed the relationship between pedestrian impact

speed and projection distance using PC-Crash. Testing nine vehicle types at speeds from 20 to 80 km/h, they found that the pedestrian throw distance is heavily influenced by vehicle front-end geometry, with taller vehicles projecting pedestrians higher and farther. Their results suggest that traditional impact speed estimation formulas may be inaccurate depending on vehicle type, highlighting the need for refined models. MADYMO is another key simulation software for impact dynamics, incorporating rate-dependent deformation [5, 20, 21]. These simulations enhance biomechanical response analysis, improving injury risk predictions. Collision speed is a key parameter that influences the outcome of the collision between a pedestrian and a vehicle. This parameter was investigated [20], implementing simulations in MADYMO, in relation to the deformation rate of the vehicle. It was found that it is important to evaluate the response of materials to different collision speeds, as it influences the outcome of the impact. To more accurately investigate the post-impact pedestrian kinematics, it is possible to use the PC-Crash and MADYMO modeling software in combination [17, 23]. This makes it possible to understand more precisely the parameters that play a crucial role in the dynamics of impact, among these, the point of contact between pedestrian and vehicle [17] is identified, and consequently, also the type and shape of the vehicle itself. For example, it has been found that cars with a higher height, such as Sport Utility Vehicles, cause more serious head injuries than cars with a lower profile. Analyzing the impact dynamics through the modeling reconstruction in FEM software is certainly not enough to obtain accurate results, it is necessary to compare these outcomes with datasets of real accidents to calibrate the models developed [5, 21, 43]. From the calibration of the results obtained from software such as MADYMO and real accident data, it is possible to create algorithms that allow for the obtaining of more accurate and realistic estimates of impact parameters, including speed, as output from the model [43]. Untaroiu et al. [43] have shown that the best-performing algorithm, among those analyzed, is the genetic algorithm. It takes into account the characteristics of the pedestrian, in particular posture and position.

Therefore, the characteristics related to the pawn play a crucial role in the dynamics of impact, confirming that the study by Guo et al. [5] defines the center of gravity of the pawn as a key parameter. Silicone dummy blocks with human-like biomechanical properties are also used in simulations to emulate pedestrian impacts, providing an ethical and cost-effective alternative to human testing [44].

SimWise simulates SUV-adolescent pedestrian impacts, assessing injury criteria such as Head Injury Criterion (HIC) and Thoracic Trauma Index (TTI) [45], offering insights into collision risks and safety measures. Multibody system (MBS) and finite element (FE) models are essential for analyzing cranial dynamics and limb injuries during impacts [10, 43, 46–49], aiding in injury mechanism understanding and safety development. Bose et al. [9] used FE leg models to assess knee injury thresholds, informing safer vehicle design. Similarly, Liu and Yang [50] developed four mathematical child pedestrian models (ages 3, 6, 9, and 15) using biomechanical scaling of adult models. Liu and Yang [50] validated their child pedestrian models by reconstructing two real-world accidents, accurately replicating impact dynamics. Their study confirmed the effectiveness of biomechanical scaling, enhancing predictive capabilities in pedestrian safety simulations and aiding vehicle design improvements to reduce child pedestrian injuries.

Another critical aspect of pedestrian safety research is the role of vehicle geometry in injury risk. Huang et al. [10] used MBS and FE analysis to study cranial dynamics in windshield impacts, identifying brain pressure thresholds for AIS 2+ and AIS 3+ injuries. They found that 50% of severe brain injuries occur above 227 kPa, providing critical data for head injury risk reduction in pedestrian-vehicle collisions.

Li et al. [48] applied the THUMS FE model to analyze upper limb fractures in truck-pedestrian accidents, confirming flexion as the primary injury mechanism. Ito et al. [47] validated a child pedestrian lower limb FE model, improving impact simulation accuracy and proposing new safety criteria. Chai Xianghai et al. [49] developed a numerical model for predicting skull fractures, while silicone dummy block tests showed that even low-speed collisions can generate significant impact forces, increasing chest and head injury risks [44]. These findings underscore the need for comprehensive safety measures, even at lower speeds. Verma and Repa [51] conducted 3D pedestrian impact simulations using experimentally measured geometric and stiffness parameters. They identified bumper stiffness, height, and protrusion as key injury severity factors. While some design changes reduced adult injuries, they increased risks for children, emphasizing the need for vehicle optimizations that account for age-related differences.

3D laser scanners are used to analyze windshield deformation and estimate impact velocity [18, 52, 53]. Xu et al. [53] developed a mathematical model based on laminated windshield deformation, achieving higher accuracy than traditional projection-based methods. Chen et al. [52] confirmed that deformation correlates with vehicle speed, reinforcing 3D laser scanning as a valuable tool for accident reconstruction. Genetic algorithms and optimization methods enhance vehicle hood designs [54] and refine pedestrian AEB test scenarios [26]. Gholamjafari et al. [26] optimized AEB test scenarios, reducing costs while maintaining real-world accuracy. Ji et al. [54] applied genetic algorithms to improve hood designs, reducing brain trauma risk through controlled panel deformation. Cao et al. [55] used an uncertain inverse method based on Sequential First-Order Second Moment (FOSM) to estimate pre-collision vehicle parameters, improving crash reconstruction efficiency.

4 Experimental Data

Experimental tests are crucial for validating severity curves and refining injury risk assessments. Through crash tests with dummies, biomechanical simulations, and post-crash analyses, researchers can enhance theoretical models and identify critical injury thresholds, contributing to safer vehicle designs and improved pedestrian protection measures.

Anthropomorphic test devices (ATDs) and human cadavers are used to measure accelerations and assess injuries at various impact speeds [8, 56–58]. However, significant differences exist between dummies and human biomechanics. Kallieris and Schmidt [56] used cadavers and Hybrid II-P dummies, revealing that high-speed collisions cause multiple lower limb fractures and that head impact locations differ between cadavers and dummies, underscoring ATD limitations in replicating human biomechanics. Similarly, Bacon and Wilson [8] tested adult and child dummies, finding that higher bumpers increase femur fracture risk by directly impacting the knee.

Beyond full-body testing, component-level impact tests have been instrumental in assessing the energy absorption capacity of specific vehicle structures, such as bumpers and hoods [8, 59]. MacLaughlin and Kessler [59] developed a test procedure for pedestrian head impacts on the hood, demonstrating that increased under-hood space reduces the likelihood of severe head trauma. Similarly, Matsui et al. [60] employed a TRL leg-form impactor to evaluate vehicle leg protection performance, demonstrating that knee and tibia injuries depend on vehicle shape.

Finite element modeling has further refined these analyses. Li [61] developed an algorithm using finite element simulations to identify high-risk zones on car hoods. The model accurately pinpointed critical head injury areas, later validated through real crash tests by calculating the Head Injury Criterion (HIC) based on structural rigidity and secondary impact point distance.

Validated crash test results allow for identifying the areas of the vehicle that cause a more serious head injury to the pedestrian who impacts it, thus providing input on appropriate countermeasures to be adopted on the vehicle design [62]. Similarly, autopsy and medico-legal studies are important to validate the injury thresholds described in the vulnerability curves. These data allow for to definition of different types of injuries at specific impact speeds and to investigate how the individual characteristics of the pedestrian can influence the outcome of the impact [6, 63–66]. For example, Schmidt et al. [63] were able to define the direction of impact from the knowledge of the Messerer fracture recorded by the pedestrian, which allowed them to reconstruct the impact dynamics. At the same time, Gorrie et al. [6] derived a relationship between cognitive decline and the types of impacts in which these pedestrians are involved, while Williams et al. [65] derived a relationship between the severity of injuries and the state of intoxication of pedestrians.

5 Real Accident Data

Databases such as GIDAS [67, 68], CIDAS [69], GES [26, 70], FARS [26, 70], and PCDS [73] provide essential data for analyzing accident characteristics and identifying risk factors, supporting the development of targeted safety measures.

In addition to accident databases, hospital records serve as a valuable data source. Eck et al. [71] highlighted the role of road conditions, such as slippery surfaces, in pedestrian accidents, emphasizing the need to address environmental factors in pedestrian safety efforts. EDR (Event Data Recorder) data is also used to estimate post-impact speed and is compared with traditional accident reconstruction methods. Su et al. [72] found that EDR data provides a more reliable post-crash speed estimate, improving accident reconstruction accuracy.

Observational studies have further contributed to understanding injury mechanisms in pedestrian-vehicle collisions. Schmucker et al. [73] conducted an observational study in Berlin, identifying head injuries as the primary mortality risk in pedestrian-vehicle accidents, with a significant increase above 40 km/h. Meanwhile, Schneider and Beier [74] compared dummy test results with real pedestrian accidents, noting that dummy tests tend to underestimate actual injuries and that vehicle design significantly influences injury distribution.

Recent studies have also explored the role of vehicle technology in pedestrian risk. Mizuno et al. [11] demonstrated that impact orientation affects pedestrian post-collision movement. Hong et al. [75] found that quiet electric vehicles reduce auditory recognition distance, increasing pedestrian collision risk. Meanwhile, Badea-Romero et al. [76] reconstructed real-world accidents, confirming that Brake Assist Systems (BAS) reduce impact severity.

6 Statistical Analysis and Modeling

Statistical analysis is essential for predicting pedestrian vulnerability in vehicle collisions by identifying injury patterns based on speed, impact point, and pedestrian characteristics.

Regression analysis develops vulnerability curves to estimate injury probability and severity across different scenarios. Logistic regression quantifies the influence of vehicle front-end geometry on pedestrian injury risk [22, 67, 68] and examines the relationship between impact speed and mortality risk [69]. For instance, Li et al. [67] found that bumper height and depth affect leg injuries, while hood leading edge height correlates with femur and pelvis injuries, providing key insights for vehicle design improvements aimed at minimizing pedestrian injuries. Similarly, Wang et al. [68] used logistic regression to quantify the impact of vehicle geometry on pedestrian injury risk while Zhang et al. [69] confirmed that mortality risk increases exponentially with impact speed, with flat-fronted vehicles posing the highest fatality rates and long-bodied cars the lowest, emphasizing the need for speed reduction in pedestrian areas. Zegeer and Bushell [77] conducted a global analysis of pedestrian accidents, identifying speed as the primary factor in injury severity. Their study found over 400,000 annual pedestrian fatalities, with 50% occurring in low-income countries. Key mitigation measures include safer crossings, urban speed reduction, and improved street lighting. Among the statistical methods adopted in the literature, there is certainly the analysis of variance (ANOVA). A study [68] showed that, using this statistical method, it was concluded that the most serious injuries are suffered by elderly pedestrians and individuals with a high BMI.

However, there are more accurate models in the literature that allow us to identify, more precisely, the factors that influence the severity of injuries. Among these is the PPO (Partial Proportional Odds Logit) [78]. In the study by Sasidharan et al. [78], it is clear that PPO models outperform logit models in terms of predictive accuracy, identifying vehicle speed and pedestrian age as the most influential factors. This highlights the importance of advanced statistical methods to improve injury risk predictions.

7 Developing Pedestrian-Vehicle Vulnerability Curves

Vulnerability curves make it possible to identify the severity of the injuries suffered by users involved in the impact by varying the most significant parameters.

Statistical models allow for the derivation of correlations between impact velocity and the severity of the injuries suffered [67, 68], allowing for the definition of the outcome of the collision based on the representative impact parameters. Simulations with MBS and FE models, on the other hand, allow for the obtaining of data on biomechanical

variables related to the risk of injury [10]. These simulations provide detailed insights into the mechanisms of injury, informing the development of targeted safety measures.

Some studies focus on identifying injury thresholds for parameters such as brain pressure [10] and impact forces. Establishing these thresholds is fundamental for designing vehicle components and safety systems aimed at minimizing injury risks.

Huang et al. [10] identified cerebral injury thresholds. This study provides valuable data for the development of vehicle designs that can reduce the risk of head injuries in pedestrian-vehicle collisions. Similarly, Matsui [31] developed risk curves for femoral and pelvic injuries, correlating injury occurrence with impact forces surpassing 7.4 kN and bending moments exceeding 500 Nm. These curves provide a framework for assessing the risk of specific types of injuries based on impact parameters, informing the design of targeted safety measures.

Beyond direct vehicle-pedestrian impact, recent research has highlighted the importance of secondary impacts, particularly ground contact injuries. Shang et al. [79] analyzed ground contact injuries, noting they account for a significant percentage of severe pedestrian injuries, while Tamura [13–15] identified ground impact as the leading cause of traumatic brain injuries in pedestrian-vehicle collisions.

In addition to biomechanical and statistical approaches, alternative modeling techniques have emerged. Xu et al. [53] introduced a model that estimates impact speed based on windshield deflection, providing a novel method for post-crash analysis and injury prediction. Such methodologies highlight the growing role of computational models in forensic crash reconstruction, improving the accuracy of injury assessments.

Limitations and Future Directions Despite significant progress, research in pedestrian safety continues to encounter several challenges:

- Complexity of Human Biomechanics: The biomechanical response of the human body to impacts is highly complex, necessitating ongoing refinements in simulation models [14, 80]. More precise and detailed models are essential to accurately replicate human reactions to impact forces.
- Data Availability: Reliable accident data is essential for accurate vulnerability curves [67, 68]. Access to comprehensive and high-quality data is critical for conducting meaningful research and developing effective safety measures.
- Integration of Human Factors: Human behavior should be integrated into simulation models and statistical analyses [81–83]. Understanding how pedestrians and drivers behave in different situations is essential for developing effective safety measures.
- Advancement of Safety Systems: The ongoing evolution of both active and passive safety technologies remains crucial [24, 84, 85].

Continued innovation in safety technology is essential for reducing the risk of pedestrian-vehicle collisions and mitigating the severity of injuries when they do occur.

8 Risk Factors and Accident Characteristics

The analysis of the literature identified several key risk factors associated with accident characteristics.

Vehicle speed is a major determinant of pedestrian injury severity, with higher speeds exponentially increasing mortality risk [20, 22, 86]. Zhang et al. [86] confirmed that

mortality risk rises exponentially with impact speed, emphasizing the need for speed reduction measures in pedestrian-dense areas. Nie et al. [22] found that mortality risk doubles at 50 km/h compared to 40 km/h and quintuples compared to 30 km/h.

Vehicle design also plays a crucial role in pedestrian safety, particularly the front-end structure [7, 87]. Ashton [7] concluded that modifying vehicle front structures is the most effective way to mitigate pedestrian injuries, highlighting the importance of incorporating pedestrian safety into vehicle design.

Peng et al. [10, 88, 89] established a relationship between Abbreviated Injury Scale (AIS) scores and impact speed, reporting that AIS2+ injuries occur in 50% of cases at 38.87 km/h, while AIS3+ injuries reach the same probability at 54.39 km/h. Sturtz [90] analyzed 310 real-world pedestrian accidents and found that both vehicle aggressiveness (based on injury costs) and front-end shape significantly influence injury severity. The study confirmed that taller, more rigid vehicle fronts are associated with more severe injuries, particularly for vulnerable pedestrian groups.

Pedestrian age plays a crucial role in determining injury severity, with elderly and child pedestrians being particularly vulnerable due to their physical and cognitive characteristics. Gorrie et al. [6] analyzed forensic data from elderly pedestrian fatalities, showing that cognitive decline increases collision risks, reinforcing the need for targeted safety measures. Similarly, Serre et al. [91] demonstrated that head injuries depend heavily on vehicle geometry and impact location, with windshield pillar impacts being especially dangerous. Lam et al. [92] applied a GIS-based 3D time-space analysis to assess pedestrian crash risks in Hong Kong, identifying central districts during afternoon peak hours as the most dangerous areas. The study highlighted the correlation between pedestrian density and crash frequency, emphasizing the necessity of interventions in high-risk zones.

Environmental conditions also play a significant role, as poor lighting has been found to increase pedestrian accident risks [93]. Enhancing street lighting can effectively reduce nighttime pedestrian-vehicle collisions. Pedestrian behavior further influences accident outcomes, with Zou et al. [94, 95] demonstrating that crossing speed and direction impact post-impact throw distance, ultimately affecting injury severity. Additionally, Williams et al. [65] found that alcohol intoxication increases injury severity and decreases post-impact survival times, underscoring the importance of addressing alcohol consumption in pedestrian safety strategies.

Finally, driver awareness and pedestrian visibility are also critical factors. Hamdane et al. [96] revealed that only 30% of pedestrians were visible to drivers one second before impact, highlighting the limitations of current detection systems and the need for improved visibility measures to enhance pedestrian safety.

9 Effectiveness of Safety Systems

AEB (Automatic Emergency Braking) and BAS (Brake Assist System) can significantly reduce impact speed and injury severity [75, 84, 85]. These systems can automatically apply the brakes to avoid or mitigate collisions, reducing the risk of severe pedestrian injuries.

Several studies have demonstrated the effectiveness of AEB in accident prevention. Barrios et al. [84] analyzed real accidents and simulated scenarios, demonstrating that

pedestrian detection systems with automatic braking potentially avoided 48% of accidents in the simulation. This study highlights the potential of AEB systems in preventing pedestrian-vehicle collisions. Similarly, Good et al. [85] reported that AEB implementation resulted in a 30% reduction in pedestrian accidents, confirming its role as a vital tool in urban safety strategies. However, while these systems effectively decrease collision severity, they may also introduce unintended consequences. Badea-Romero et al. [75] found that although BAS successfully reduces impact speed, it may shift the collision point to more rigid vehicle structures, potentially altering injury patterns rather than eliminating them. Ong and Lachapelle [97] found that GNSS (Global Navigation Satellite System) technology can provide at least one second of warning for pedestrian collisions.

Beyond braking technologies, other sensor-based safety innovations are being explored to enhance pedestrian protection. Global Navigation Satellite System (GNSS) technologies, as investigated by Ong and Lachapelle [97], have shown promise in providing at least one second of warning before an impending pedestrian collision, which could significantly improve driver and pedestrian reaction times.

Additionally, Pressure-Based Pedestrian Safety Systems (PPS pSAT) have been developed to detect pedestrian impacts and trigger passive safety mechanisms, such as external airbags, to reduce injury severity [24]. Feser et al. [24] demonstrated that such sensors can reliably identify pedestrian collisions, ensuring a rapid response to mitigate trauma.

Another emerging approach is Vehicle-to-Pedestrian (V2P) communication, which aims to enhance pedestrian safety by enabling real-time data exchange between vehicles and vulnerable road users. Sewalkar et al. [32] found that V2P communication systems can significantly improve driver reaction times. However, these systems still face challenges related to network congestion, which can delay critical alerts in high-density urban environments.

10 Conclusion

In the present research, we have investigated the different methodologies used in the literature for the construction of pedestrian vulnerability curves, highlighting the main techniques used in road safety. The review of 93 studies confirmed the importance of finite element modelling (FEM) and multi-body simulations (MBS) to predict collisions and optimise vehicle design and the urban environment. Statistical models are essential tools for analysing accident data and developing more effective mitigation measures. It is recognised that the risk of collision and the severity of injuries can be significantly reduced by technologies, including advanced driving assistance systems (ADAS) and intelligent sensors. The increasingly accurate definition of vulnerability curves is certainly useful to administrations and/or public authorities about the design of safer pedestrian infrastructures, thus reducing the risk of accidents; not only that, vehicle manufacturers could also provide themselves with such models to optimize the design of the vehicles themselves. However, it is important to improve the quality of experimental data and refine biomechanical models to take into account different categories of pedestrians. However, some limitations remain, including the variability of experimental data, the difficulty of accurately modelling human behaviour, and the need to

test new methodologies in more diverse real-life scenarios. In addition, the integration of different approaches, such as combining numerical simulations with real data, needs to be further developed to improve the reliability of vulnerability curves.

Future research should focus on advancing artificial intelligence applications to improve the predictive capabilities of models and refine risk mitigation strategies. The creation of standardized global databases and the adoption of uniform international regulations will facilitate better application of the acquired knowledge.

Furthermore, the review of literature articles concerns vulnerability curves that describe the post-impact injury between pedestrian and vehicle, what we want to do is to free ourselves from this condition and evaluate vulnerability curves that also take into account other types of impact that involve vulnerable road users such as pedestrian – e-scooter rider or pedestrian – cyclist.

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