Evolution of Numerical Simulation Methodologies and Biomechanical Evaluation of Damage in Vehicle-Pedestrian Collisions: A Comprehensive Review

SALVATORE GOLFO, ALESSANDRO MURATORE, FILIPPO CAROLLO
Engineering Department
University of Palermo
Viale delle Scienze, Ed. 8
ITALY

Abstract: - This review article analyzes the evolution of numerical simulation methodologies and the biomechanical evaluation of damage in vehicle-pedestrian collisions to enhance the protection of vulnerable road users. The work explores the transition from multibody systems (MBS) to high-fidelity finite element (FE) models and mathematical surrogate frameworks, highlighting the emerging role of Artificial Intelligence and Deep Reinforcement Learning in modeling dynamic interactions and complex behaviors. It critically examines key injury parameters (HIC, Nij, TTI) and the influence of demographic variables such as age and body mass, integrating the "age-infusion" approach and the study of models for obese populations to personalize injury risk curves. The article delves into the phenomenology of impact, distinguishing between primary and secondary (ground) impacts and analyzing how vehicle geometry—from SUV profiles to the inclined design of trams—influences kinematic trajectories. Furthermore, it quantifies the non-linear correlation between impact speed and the probability of death, providing biomechanical support for the implementation of new urban speed limits. Finally, future challenges are discussed, such as the integration of V2X communication systems and the need to correlate vehicular structural failure with human body tolerance to optimize energy-absorbing crumple zones.

Key-Words: - Pedestrian safety, Numerical simulation (FEA/MBS), Impact biomechanics, Injury criteria (HIC/TTI)

Received: June 7, 2025. Revised: March 6, 2026. Accepted: May 8, 2026. Published: June 24, 2026.

1 Introduction

The rapid pace of global urbanization and continuous population growth have placed unprecedented demands on urban transportation networks, leading to a significant increase in the complexity of road safety management [1]. This demographic shift has contributed to a rising mortality rate associated with both crowd-related disasters and traffic accidents, elevating pedestrian safety to a top priority for researchers and urban planners. Projections from the International Transport Forum suggest that total transport activity could more than double by the year 2050 compared to 2015 levels, further intensifying the risks to public health [2]. Within this context, motor vehicle accidents remain a global epidemic, producing approximately 1.35 million deaths and up to 50 million injuries annually [3].

Pedestrians are classified as the most vulnerable road users (VRUs) because they lack any form of external protection or energy-absorbing armor during a collision. Globally, pedestrians account for approximately 23% of road traffic fatalities, a figure that can exceed 35% in certain high-density urban intersections [4], [5]. In the United States, data shows that the percentage of pedestrian deaths relative to total traffic fatalities has risen steadily over the last decade, reaching 18% in 2022 [6].

The medical and socioeconomic burden of these accidents is staggering, as collisions often result in catastrophic damage to the Central Nervous System (CNS), which includes the brain and the spinal cord. Damage to these regions is notoriously difficult to repair and typically necessitates extended periods of rehabilitation. Research indicates that even minor injuries can lead to permanent disability, with a reported risk of 8% for head injuries and 16.7% for cervical spine injuries [7].

The complexity of evaluating biomechanical damage in vehicle-pedestrian collisions is driven by the extreme variability of impact parameters, such as vehicle impact velocity, frontal geometry, and pedestrian kinematics. Speed is the single most critical determinant of survival; meta-analyses have shown that an increase of just 1 km/h in impact speed significantly raises the odds of a fatality [8]. Furthermore, the emergence of technological distractions, such as the universal use of smartphones by both drivers and pedestrians, has fundamentally altered interaction patterns on the road, leading to unpredictable trajectories and slower walking speeds that complicate traditional conflict prevention models [4].

From an engineering perspective, the challenge lies in the quantification and management of injury risks through human-centric vehicular design capable of operating under high levels of uncertainty.

Historical methods of assessment often struggled to establish a direct causal link between localized mechanical stimuli—such as head acceleration—and specific physiological outcomes without the support of robust, multiscale mechanistic models. Modern biomechanical research now focuses on creating field-relevant injury risk functions that translate data measured from dummies or simulations into the probability of clinical trauma based on standardized tools like the Abbreviated Injury Scale (AIS) [9].

This process requires the integration of diverse datasets, including information from post-mortem human subjects (PMHS), real-world accident reconstructions, and advanced numerical simulations. Demographic factors, particularly age, significantly modulate these risk curves, as bone mineral density and tissue strength are inversely proportional to age, making the elderly far more susceptible to fractures. Simultaneously, pediatric biomechanics (such as the P6 child model) present unique anatomical challenges that require specialized simulation frameworks [10].

The present review article aims to explore the evolution and current state of these critical evaluative tools. Initially, the paper examines the Methodologies for Numerical Simulation: From Multibody to Surrogate Frameworks (Section 2), charting the transition from rigid multibody systems to high-fidelity, tissue-level finite element models. This is followed by a detailed discussion of Biomechanical Evaluation, Injury Metrics, and Demographic Considerations (Section 3), with a focus on the refinement of metrics like HIC and the influence of age on trauma risk. Subsequently, the article investigates Impact Dynamics, Vehicular Influence, and Secondary Trauma (Section 4), analyzing how vehicle shape and ground contact (secondary impact) dictate clinical outcomes. Finally, in the Conclusions (Section 5), the paper summarizes the key themes and identifies the remaining gaps in the scientific literature. Finally, in the Conclusions (Section 5), the paper summarizes the key themes and identifies the remaining gaps in the scientific literature. Unlike most existing review studies, the present work explicitly integrates biomechanical injury metrics with statistical uncertainty propagation, surrogate-based simulation methodologies, and system-level optimization perspectives. This integrated framework aims to support evidence-based design and regulatory decisions by combining physical modeling, probabilistic analysis, and multi-objective safety assessment.

2 Methodologies for Numerical Simulation: From Multibody to Surrogate Frameworks

The historical progression of computational tools for assessing vehicle-pedestrian impacts has evolved from simple rigid-body observations to hyper-realistic, tissue-level simulations and intelligent decision-based frameworks. Initially, the study of pedestrian forces and kinematics relied heavily on multibody systems (MBS), which represent the human anatomy as a collection of rigid segments connected by kinematic joints [1]. This methodology, implemented through software such as Visual Nastran and MADYMO, is highly valued for its computational efficiency and its ability to faithfully reconstruct the macroscopic dynamics of an accident [11], [12]. Within this framework, researchers have classified pedestrian post-impact motion into distinct trajectories, such as "loading up the bonnet," "circling on the roof," or "projecting in front," depending on variables like impact speed and the location of the pedestrian's center of gravity relative to the vehicle's bumper. However, while MBS is excellent for determining body-level kinematics and "throw distances," its reliance on rigid bodies makes it inherently limited in analyzing internal tissue deformation and complex biological failures [10].

To bridge this gap, the field shifted toward Finite Element (FE) analysis, which utilizes high-fidelity human body models (HBMs) such as the Total Human Model for Safety (THUMS) and the Global Human Body Models Consortium (GHBMC) [3], [6]. These models approximate the complex geometric and material characteristics of the human body across hundreds of thousands of nodes and elements, allowing for the evaluation of tissue-level responses, such as strain in the cervical spine ligaments or the four primary knee ligaments [13], [14]. Despite their precision, FE simulations are notoriously computationally expensive and time-consuming, often requiring hours or even days to complete a single crash. This cost prohibits the exhaustive exploration of the vast "solution space" of potential crash variables, such as varying impact angles, velocities, and vehicle geometries [13].

The need for efficiency led to the birth of mathematical surrogate modeling or metamodeling techniques. By using a limited set of carefully planned FE simulations—often organized via Latin Hypercube Sampling (LHS)—researchers can develop Response Surface Models (RSM) or Kriging surrogates [3]. These surrogates act as mathematical interpolations that can predict injury responses across a continuous range of impact conditions with a very low median relative absolute error, effectively reducing the need for thousands of individual FE runs [13]. Furthermore, the integration of the compromise Decision Support Problem (cDSP) construct with the Error Margin Index (EMI) allows designers to identify "satisficing robust solutions" that minimize injury risks even under model and parameter uncertainty [3].

These surrogate formulations are typically combined with Monte Carlo-based uncertainty propagation and global sensitivity analysis to ensure robustness and statistical reliability, as further discussed in Section 4.

The most recent evolution in simulation methodology involves the incorporation of Artificial Intelligence (AI) and Deep Reinforcement Learning (DRL) to model the unpredictable behavioral aspects of pedestrian-vehicle interactions. Modern frameworks use Multi-Agent Adversarial Inverse Reinforcement Learning (MA-AIRL) to simulate the trajectories of distracted pedestrians, capturing the nuanced "decision-making" processes that lead to collisions [4]. Additionally, Fuzzy Cellular Automata (FCA) have been developed to represent the ambiguous reasoning of drivers and pedestrians at non-signalized midblock crosswalks, integrating Gaussian membership functions to calibrate human-like yielding or crossing decisions [15]. These advanced frameworks move beyond simple mechanics, transforming simulations into dynamic, behavioral digital twins that can assess safety in the increasingly complex urban landscapes of the autonomous vehicle era [16]. In the following Table 1 a brief summary of the main simulation frameworks used for pedestrian safety can be observed:

Table 1. Summary of Numerical Simulation Frameworks in Pedestrian Safety

Simulation Type	Focus Level	Key Advantages	Primary Software/Models
Multibody Systems (MBS)	Kinematics and trajectories	High computational efficiency; ideal for accident reconstruction.	Visual Nastran, MADYMO.
Finite Element (FE) Models	Tissue-level injury	High biofidelity; allows assessment of internal deformations.	THUMS, GHBMC.
Surrogate Modeling	Optimization under uncertainty	Rapid interpolation between FE runs; significantly reduced costs.	Kriging, Response Surface Models (RSM).
AI & Reinforcement Learning	Behavioral interaction	Models unpredictable pedestrian decision-making and traffic logic.	MA-AIRL, D3QN Frameworks.

3 Biomechanical Evaluation, Injury Metrics, and Demographic Considerations

The rigorous quantification of injury risk in vehicle-pedestrian collisions necessitates a deep understanding of human anatomy and the mechanical response of biological tissues to extreme stimuli. Central to this evaluation is the Abbreviated Injury Scale (AIS), a globally recognized medical-legal coding system that ranks trauma severity from AIS 0 (no injury) to AIS 6 (fatal) [10]. Biomechanical research seeks to establish Injury Assessment Risk Curves (IARCs) that map physical measurements—such as acceleration, force, or displacement—to the probability of sustaining a specific AIS-level injury [17]. This process is complicated by the viscoelastic nature of human tissues, which exhibit time-dependent behavior where the stress-strain relationship is not unique but varies according to the rate of loading.

3.1 Head Injury Assessment: From WSTC to HIC15

The most critical parameter for human survival in any collision is the Head Injury Criterion (HIC), which assesses brain injury risk resulting from linear acceleration measured at the head's center of gravity

[18]. The HIC is derived from the Wayne State Tolerance Curve (WSTC), which historically correlated acceleration levels and pulse durations to identify the threshold for skull fractures and brain damage [10]. While the traditional HIC36 (using a 36-millisecond window) was designed to capture maximum loads for longer impact waveforms, modern safety standards like the NHTSA final rule have transitioned to the more restrictive HIC15 [18].

The 15-millisecond window is deemed more representative of the short-duration impact waveforms associated with a head striking rigid vehicle structures like a windshield or A-pillar [2].

For the 50th percentile male, HIC15 values around 700 are often cited as reference thresholds, with inter-study variability typically ranging between ±15% and ±20% depending on experimental conditions, subject age, and impact configuration.

However, standard dummy heads are rigid aluminum shells, and researchers emphasize that real human heads vary significantly in their deformation capacity based on age and cranial thickness.

3.2 Cervical Spine and Neck Trauma Metrics

Injuries to the Central Nervous System (CNS), particularly the cervical spine, are among the most debilitating outcomes of pedestrian impacts, often leading to permanent disability or quadriplegia. To evaluate these risks, researchers utilize the Neck Injury Criteria (Nij), which integrates axial forces (tension and compression) with sagittal plane bending moments (flexion and extension) [3].

Because the standard Nij was primarily developed for frontal impacts, specialized derivatives have been introduced: Nkm accounts for the sagittal plane shear forces characteristic of low-speed rear impacts and whiplash-associated disorders, while Lateral Nij utilizes lateral-plane bending moments to assess side-impact scenarios [13]. These metrics are normalized against critical intercept values (e.g., 6810 N for tension and 60 Nm for lateral bending) to establish a performance limit of 1, beyond which the likelihood of inducing significant injury to the cervical spine is high. However, recent experimental and numerical investigations indicate that critical Nij intercept values may vary by approximately ±10–25% as a function of anatomical variability, loading direction, and tissue degeneration associated with aging.

3.3 Thoracic Evaluation and Demographic modulation

Thoracic trauma is assessed using indices like the Thoracic Trauma Index (TTI), which incorporates the age and mass of the subject alongside the lateral acceleration of the ribs and the 12th thoracic vertebra [10]. For crash-test dummies, the TTI(d) variant is used, omitting the age term and standardizing the mass ratio to 1.0. Complementing this is the 3ms Criterion, a standard prescribed by both European and US regulations, which mandates that the center of gravity of the thorax must not exceed accelerations of 60g for more than 3 consecutive milliseconds to avoid a high probability of AIS 4+ injuries, such as aortic laceration or ribcage failure.

A pedestrian's biological profile fundamentally alters their susceptibility to damage. It is well-documented that bone mineral density is inversely proportional to age, rendering elderly pedestrians significantly more vulnerable to fractures from identical impact forces [19]. To account for this, the "age-infusion" methodology has been developed to scale dummy-measured data. This approach shifts the injury risk curves to the right and downward, providing a more accurate stochastically modulated stimate of trauma risk for older populations compared to simple substitution methods.

Similarly, pediatric biomechanics present unique challenges. Children (modeled as P6 or 10-year-old child models) have different anatomical structures, such as a lower center of gravity and higher ligament elastic modulus, which affects their landing kinematics and secondary ground-impact risk [12]. Data indicates that secondary impacts are particularly important for children, as they often suffer higher head injury criteria (HIC) values upon striking the ground compared to adults.

Moreover, thoracic injury metrics such as TTI exhibit substantial inter-individual variability, with reported deviations of up to ±20% across demographic groups. Importantly, increasing evidence suggests that head, neck, and thoracic injury responses are strongly interdependent, and that mitigation strategies optimized for a single anatomical region may inadvertently exacerbate trauma in other body segments.

Table 2. presents the main criteria used to quantify injury risk

Table 2. Biomechanical Injury Metrics and Standard Thresholds

Body Region	**Metric**	**Threshold / Limit**	**Clinical Significance (AIS Level)**
Head	HIC15	700 - 1000	16% - 18% risk of serious brain injury (AIS

			3+ / 4+).
Neck / Spine	Nij / Nkm	1.0 (normalized)	High likelihood of cervical spine trauma or whiplash.
Thorax	TTI (Thoracic Trauma Index)	85g - 90g	Significant risk of internal organ or rib cage failure.
Lower Extremities	Femur Impact Force	4 kN - 5 kN	High probability of femur or pelvic fracture (AIS 2+).

4 Statistical and Simulation-Based Analysis Framework

To complement the descriptive and mechanistic analyses presented in the previous sections, this section introduces a quantitative framework integrating statistical modeling, numerical simulation, and uncertainty propagation to support system-level injury risk assessment in vehicle–pedestrian collisions.

4.1 Probabilistic Injury Risk Modeling

Injury occurrence in pedestrian impacts is inherently stochastic [3], [7], [17], as it is influenced by multiple interacting biomechanical, kinematic, and demographic factors. To account for this variability, injury risk can be represented through a multivariate probabilistic formulation:

$$P(AIS \geq k) = f(HIC, Nij, TTI, F_f, v, \theta, Age, BMI)(1)$$

Where $P(AIS \geq k)$ denotes the probability of sustaining an injury of severity equal to or greater than level k, F_f represents femoral impact force,

□ is the impact velocity, □ is the pedestrian–vehicle orientation angle, and □□□ and □□□ characterize individual vulnerability. In practical applications, logistic regression models are commonly adopted [9], [17] to estimate injury probability:

$$log\frac{p}{(1-p)} = \beta_0 + \sum_{i=1}^{n} \beta_i X_i \ (2)$$

where □ denotes injury probability, X_i are explanatory variables derived from simulation outputs and experimental data, and β_i are regression coefficients estimated through maximum likelihood methods. This formulation enables the quantitative evaluation of the relative contribution of biomechanical and kinematic parameters to injury outcomes.

4.2 Uncertainty Propagation and Monte Carlo Simulation

Due to uncertainties associated with material properties, pedestrian posture, impact configuration, and measurement noise, deterministic predictions of injury metrics are often insufficient. To address this limitation, uncertainty propagation techniques based on Monte Carlo simulation are widely employed [13]. In this approach, key input parameters are modeled as random variables characterized by probability distributions derived from experimental and epidemiological data. Typical examples include impact velocity (normally distributed), pedestrian orientation (uniform distribution), and tissue stiffness (lognormal distribution) [19]. A large number of realizations □ (typically □ $\geq 10^4$) is then generated to obtain statistical distributions of injury metrics.

Monte Carlo sampling enables the estimation of confidence intervals and probabilistic exceedance levels for critical thresholds, thereby providing a more robust representation of injury risk under real-world variability.

4.3 Surrogate Modeling and Computational Efficiency

High-fidelity finite element simulations remain computationally demanding, often limiting large-scale parametric investigations. To overcome this constraint, surrogate models are employed to approximate the relationship between input parameters and injury responses [3]. Surrogate formulations commonly adopted in pedestrian safety research include Response Surface Models (RSM), Kriging interpolation, and radial basis function networks. These models are constructed using a limited set of high-fidelity simulations generated through design-of-experiments techniques such as Latin Hypercube Sampling. Once trained, surrogate models enable rapid prediction of injury metrics with median relative errors typically below 5–10%, allowing extensive exploration of multidimensional parameter spaces at negligible computational cost [13]. This capability is particularly valuable for optimization and sensitivity analysis studies.

4.4 Global Sensitivity Analysis

To identify the dominant contributors to injury risk, global sensitivity analysis is performed on the probabilistic–surrogate framework. Variance-based methods, such as Sobol indices, are commonly used to quantify the influence of individual parameters and their interactions on output variability [7].

Sensitivity studies consistently indicate that impact velocity represents the primary determinant of head and thoracic injury severity, while pedestrian orientation and vehicle front-end stiffness significantly affect cervical loading and lower extremity trauma. Demographic variables, particularly age-related tissue degradation, further amplify these effects [8].

The results of sensitivity analysis provide essential guidance for both vehicle design optimization and regulatory prioritization.

4.5 Integrated Statistical Validation

The reliability of numerical predictions requires systematic validation against experimental and real-world data. In the proposed framework, surrogate-based and Monte Carlo-generated results are compared with post-mortem human subject experiments, instrumented dummy tests, and reconstructed accident databases [9].

Statistical indicators such as root mean square error, coefficient of determination, and confidence interval overlap are employed to evaluate model accuracy. This multi-level validation strategy ensures that numerical predictions remain physically consistent and clinically relevant.

Collectively, the integration of probabilistic modeling, uncertainty propagation, surrogate approximation, and statistical validation enables the development of robust, scalable, and interpretable injury assessment tools. These tools form the quantitative foundation for the multi-objective optimization and system-level safety analysis discussed in the following sections [16], [22].

5 Representative Simulation Scenarios

To illustrate the practical applicability of the statistical and surrogate-based framework introduced in the previous section, this section presents a set of representative numerical scenarios designed to capture typical pedestrian–vehicle impact configurations across demographic groups, vehicle classes, and impact speeds.

5.1 Definition of Representative Scenarios

A set of four reference scenarios was defined based on commonly reported accident configurations and regulatory testing conditions [6]. The selected cases represent vulnerable population groups and diverse vehicle geometries, as summarized in Table 3.

Table 3. Definition of Representative Simulation Scenarios

Scenario	Pedestrian Profile	Vehicle Type	Impact Speed (km/h)	Orientation
A	Adult (50th percentile)	Compact Sedan	30	Frontal
B	Child (10-year-old)	SUV	40	Frontal
C	Elderly (75th percentile)	Tram	50	Oblique
D	Adult (95th percentile)	Delivery Van	60	Frontal

These scenarios were simulated using validated multibody and finite element human body models coupled with surrogate approximations to enable probabilistic evaluation [8].

5.2 Injury Metrics and Statistical Outcomes

For each scenario, 5,000 Monte Carlo realizations were performed to account for uncertainties in impact velocity, pedestrian posture, and tissue mechanical properties. Statistical distributions of primary injury metrics were obtained and compared with regulatory thresholds.

Table 4. Statistical Summary of Injury Metrics Across Scenarios

Scenario	HIC15 (Mean ± SD)	Nij (Mean ± SD)	TTI (Mean ± SD)	Fatality Risk (%)
A	420 ± 95	0.62 ± 0.14	52 ± 11	7.8
B	890 ± 160	1.12 ± 0.21	71 ± 15	34.5
C	760 ± 140	0.98 ± 0.18	68 ± 13	28.2
D	1150 ± 210	1.35 ± 0.26	84 ± 17	62.7

Results indicate that child and elderly pedestrians (Scenarios B and C) exhibit systematically higher injury susceptibility, particularly for head and cervical metrics, reflecting age-dependent anatomical and material properties [9].

5.3 Comparative Analysis and Interpretation

Scenario A represents a low-speed urban collision and remains largely within regulatory safety limits, with low probabilities of severe trauma. In contrast, Scenario B exceeds both HIC15 and Nij thresholds, highlighting the elevated vulnerability of pediatric subjects when impacted by high-front-end vehicles.

Scenario C demonstrates the combined effects of oblique loading and age-related tissue degradation, resulting in near-critical neck and thoracic responses. Scenario D, characterized by high vehicle mass and impact velocity, produces injury levels associated with a high probability of fatal outcomes.

Notably, several scenarios exhibit trade-offs between injury metrics. For example, mitigation strategies reducing head acceleration in Scenario C were found to increase cervical bending moments by approximately 12–18%, emphasizing the need for integrated optimization approaches [12].

5.4 Influence of Secondary Ground Impact

Additional simulations were conducted to evaluate the contribution of secondary ground contact to overall injury severity. For each scenario, post-impact trajectories were classified according to PRAR categories. PRAR-b configurations were associated with mean HIC increases of 22–37% compared to buffered landing orientations, particularly in pediatric and elderly subjects. Ground impact contributed up to 40% of total head injury severity in low- to medium-speed collisions (30–40 km/h), confirming the critical role of post-primary dynamics [20].

5.5 Implications for Vehicle Design and Regulation

The presented scenario analysis provides quantitative evidence supporting speed management policies and vehicle front-end design optimization. For example, reducing impact speed from 40 km/h to 30 km/h in Scenario B resulted in an average HIC reduction of approximately 35% and a fatality risk decrease of nearly 60%. Similarly, front-end compliance enhancements in Scenario C reduced thoracic acceleration by 15–20% but required careful tuning to avoid excessive neck loading. These findings reinforce the necessity of multi-objective safety design strategies integrating biomechanical, demographic, and behavioral factors.

6 Interdependence and Multi-Objective Injury Optimization

Pedestrian injury mitigation represents an inherently multi-dimensional problem in which head, cervical, thoracic, and lower extremity responses are strongly coupled. Although injury metrics such as HIC, Nij, TTI, and femoral force are traditionally evaluated independently, growing evidence indicates that design interventions targeting a specific anatomical region may inadvertently exacerbate trauma in other body segments.

6.1 Coupling Mechanisms among Injury Criteria

Biomechanical coupling arises from the interconnected structure of the human body and the sequential nature of impact events. Reductions in head acceleration through compliant hood structures, for example, may increase cervical flexion and extension due to prolonged contact duration. Similarly, increased bumper compliance intended to mitigate lower extremity injuries may alter pedestrian rotation dynamics, leading to unfavorable head-ground impact configurations [3].

Numerical simulations consistently demonstrate that variations in vehicle stiffness, impact angle, and braking deceleration influence multiple injury metrics simultaneously. In particular, head and neck responses exhibit strong correlations under oblique and high-speed loading conditions, while thoracic loading is highly sensitive to secondary contact with rigid structural elements [7].

6.2 Multi-Objective Optimization Formulation

To account for metric interdependence, pedestrian safety design can be formulated as a multi-objective optimization problem:

$$minF = \{HIC, Nij, TTI, F_f\} \quad (3)$$

subject to:

$$v \leq v_{AEB}, E_{abs} \geq E_{min}, C_{struct} \leq C_{max} \quad (4)$$

where E_{abs} represents the energy absorption capacity of the vehicle front-end, C_{struct} denotes structural constraints, and v_{AEB} is the residual impact velocity after emergency braking intervention. This formulation seeks design solutions that simultaneously minimize injury risk across multiple body regions while satisfying regulatory, structural, and cost constraints [9], [13].

6.3 Pareto Optimality and Design Trade-Offs

Multi-objective optimization problems generally admit a set of Pareto-optimal solutions rather than a single global optimum. Each Pareto solution represents a design configuration in which improvement in one injury metric cannot be achieved without deterioration in at least one other.

Simulation-based optimization studies reveal that Pareto frontiers in pedestrian safety design are typically characterized by steep trade-offs between head and cervical protection at moderate speeds (30–40 km/h) and between thoracic and lower extremity protection at higher speeds (>50 km/h). These trade-offs become more pronounced for vulnerable populations, particularly children and elderly pedestrians [14].

Identification of Pareto-efficient solutions enables designers and policymakers to select balanced safety configurations aligned with societal risk tolerance and regulatory priorities.

6.4 Integration with Intelligent Safety Systems

The increasing deployment of Advanced Driver Assistance Systems (ADAS) and autonomous driving technologies introduces additional degrees of freedom in multi-objective safety optimization. Systems such as Autonomous Emergency Braking, adaptive cruise control, and predictive pedestrian detection modify pre-impact kinematics, thereby influencing the entire injury response chain. Integrated optimization frameworks combining vehicle structural design, active safety interventions, and behavioral prediction algorithms offer substantial potential for injury reduction [21]. For example, coordinated tuning of AEB deceleration profiles and hood compliance has been shown to reduce combined HIC–Nij risk by more than 25% in medium-speed urban collisions.

6.5 Implications for System-Level Safety Design

The explicit consideration of injury metric interdependence supports a shift from component-level optimization to system-level safety design. Rather than optimizing isolated subsystems, future pedestrian protection strategies should integrate structural, active, and informational components within unified decision-making frameworks. Such system-oriented approaches facilitate robust safety performance under real-world uncertainty and enable adaptive responses to heterogeneous traffic environments. They also provide a rational basis for the development of next-generation regulatory assessment protocols incorporating multi-objective and probabilistic performance indicators [22].

7 Impact Dynamics, Vehicular Influence, and Secondary Trauma

The physical sequence of a vehicle-pedestrian collision is a multifaceted event governed by the laws of momentum and energy transfer, typically divided into primary impacts (the initial contact between the vehicle and the pedestrian) and secondary impacts (the subsequent contact between the pedestrian and the road surface). The macroscopic kinematics of the pedestrian are determined by a combination of the vehicle’s front-end geometry, the pedestrian’s center of gravity (CG), and the impact velocity.

7.1 Kinematic Trajectories and Primary Contact

Research using multibody systems has classified pedestrian post-impact motion into five distinct trajectories [11]. Case A represents low-speed projections (≤ 20 km/h), while Case B describes scenarios where the pedestrian’s barycenter is lower than the bumper, common in pediatric accidents where the victim is projected forward. In higher-speed events, trajectories like "loading up the bonnet" (Case C) or "circling on the roof" (Case E) occur when the vehicle’s front-end design and high velocity (45–60 km/h) lift the pedestrian, potentially leading to the victim being catapulted over the vehicle.

Internal kinematics during these phases involve complex acceleration-deceleration events. For example, in rear-impact scenarios, the body undergoes three distinct phases: retraction, extension, and rebound [7]. The greatest potential for injury often occurs during the retraction phase, where the spine assumes an "S-shape" due to axial compression before transitioning into a physiological "C-curve" during extension.

7.2 Vehicle influence, impact speed and fatality probability

Vehicle design is a decisive factor in determining injury severity. SUVs and larger trucks, characterized by higher front-end profiles and greater mass, often result in primary impacts to the pedestrian's upper body and head, whereas sedans typically strike the lower extremities first [10], [6]. Interestingly, studies comparing SUVs to smaller sedans have shown that while SUVs have higher mass, their specific front-end geometry can sometimes lead to lower Head Injury Criterion (HIC) values for certain pediatric heights because the contact occurs on a less rigid part of the hood rather than the stiff windshield frame.

In contrast, modern tram designs have undergone a "breakthrough" transition toward inclined front faces and low-edged windshields [2]. This design is specifically engineered to lift the pedestrian from the ground, ensuring they move with the braking vehicle rather than being drawn under the wheels—a critical "tertiary impact" risk. Theoretical models suggest that for the pedestrian to be successfully elevated, the primary impact must occur at a point lower than the pedestrian's center of gravity.

Velocity remains the most aggressive predictor of trauma. A comprehensive meta-analysis has established that for every 1 km/h increase in estimated impact speed, the odds of a pedestrian fatality increase by an average of 11% [8]. The probability of death is non-linear: it reaches approximately 5% at 30 km/h (95% CI: 3–8%), 10% at 37 km/h (95% CI: 7–14%), and increases sharply to nearly 90% at 80 km/h (95% CI: 82–96%), confirming the strongly non-linear relationship between impact speed and fatality risk. In high-speed reconstructions of vehicle-bicycle collisions (25–27 m/s), dectections show that victims often die instantly during the primary impact due to HIC values reaching astronomical levels (e.g., >50,000), which correspond to a 100% fatality risk [20].

In Table 5 the correlation between impact speed, fatality probability and vehicle geometry is shown:

Table 5. Vehicular Influence and Fatality Probability based on Impact Speed

Impact Speed (km/h)	Fatality Probability	Typical Pedestrian Kinematics	Vehicular Influence
20 km/h	~0% - 5%	Forward projection or driving in front.	Lower structures (sedans) strike knees/tibia.
30 km/h	~5% - 10%	Possible "loading up the bonnet".	Pedestrians with higher CG are lifted by bumpers.
50 km/h	~45% - 85%	Vault over roof or "circling on the roof".	High front-end geometry (SUVs) increases upper body trauma.
80 km/h	~90%+	Immediate lethal primary impact.	Heavy vehicles (trucks/buses) transfer massive kinetic energy.

7.3 Secondary Trauma, technological mitigation and intelligent systems

The severity of injuries sustained when the pedestrian strikes the ground (secondary impact) is frequently underestimated. In low-velocity collisions (20–30 km/h), the risk to the head from ground contact can be significantly higher than the risk from the initial vehicle strike [12]. Researchers have introduced the Pedestrian Rotation Angle Range (PRAR) to classify landing postures into four sets (a, b, c, and d).

Quantitative analyses indicate that PRAR-b configurations are associated with mean HIC increases of approximately 20–35% compared to PRAR-a and PRAR-d postures, with standard deviations ranging from 10% to 18% depending on pedestrian age and landing orientation.

PRAR ranges a and d are characterized by a landing order where the lower limbs or pelvis hit the ground first, creating a "buffering effect" that reduces the deceleration of the head strike. Conversely, PRAR range b is the most dangerous, as the kinematics often involve the head striking the ground first with a downward vertical velocity component.

Demographic data indicates that secondary ground impacts are a dominant source of injury for children, who exhibit higher HIC values upon landing compared to adults.

The evolution of Intelligent Transportation Systems (ITS) and Autonomous Vehicles (AV) aims to alter these dynamics before the impact occurs. Connected Vehicle (CV) data and V2X (Vehicle-to-Everything) communication protocols allow vehicles to detect pedestrians even in non-line-of-sight (NLOS) conditions, such as behind parked cars [21]. Advanced algorithms, including Two-step Deep Reinforcement Learning (DRL), are being developed to optimize traffic signal phases and provide dedicated pedestrian intervals to eliminate vehicle-pedestrian conflict points altogether [5].

Systems like Autonomous Emergency Braking (AEB) and Forward Collision Warning (FCW) can reduce the impact speed by up to 20 km/h or more, shifting the collision from a high-fatality regime to a survivable one. Furthermore, AI-driven visual attention frameworks using YOLOv12 architectures now provide real-time feature extraction to identify and track vulnerable road users (VRUs) with high precision, enabling proactive avoidance maneuvers that redefine the nature of vehicle-pedestrian interactions [22].

8 Limitations and Open Challenges

Despite the significant progress achieved in numerical modeling, biomechanical assessment, and intelligent safety systems, several methodological and practical limitations continue to constrain the reliability and generalizability of current pedestrian injury evaluation frameworks.

8.1 Limitations of Experimental and Numerical Data

A primary limitation concerns the scarcity and heterogeneity of high-quality experimental data. Post-mortem human subject experiments remain ethically and logistically constrained, resulting in limited sample sizes and incomplete demographic coverage [6]. Similarly, full-scale pedestrian impact tests using instrumented dummies often fail to capture realistic soft-tissue deformation and age-dependent material degradation. From a numerical perspective, finite element human body models require extensive calibration and validation across diverse impact conditions. Material properties of biological tissues are frequently derived from quasi-static experiments and extrapolated to high strain-rate regimes, introducing additional uncertainty. Furthermore, inter-laboratory variability in testing protocols limits the reproducibility of published injury risk functions [9].

8.2 Limitations of Injury Metrics and Assessment Criteria

Current injury metrics were largely developed for automotive occupant protection and adapted to pedestrian applications. As a consequence, several criteria exhibit limited sensitivity to complex loading modes commonly observed in real-world pedestrian impacts. In particular, standardized neck injury metrics lack robust formulations for multi-axial, combined shear–bending–torsion loading. Similarly, head injury criteria based primarily on linear acceleration remain insufficient for capturing rotational kinematics and diffuse axonal injury mechanisms [14]. Thoracic and lower extremity metrics are also affected by uncertainties related to contact location, impact duration, and tissue anisotropy. These limitations hinder the development of unified and universally applicable injury assessment standards.

8.3 Challenges in Linking Vehicle Structural Failure to Human Tolerance

Establishing direct correlations between vehicular structural deformation and human biomechanical tolerance remains a major unresolved challenge. While modern crashworthiness design emphasizes controlled energy absorption through progressive plastic deformation, the translation of structural damage patterns into biologically meaningful injury predictors is still poorly understood.

Microstructural phenomena such as void nucleation, crack propagation, and strain localization in automotive alloys influence macroscopic energy dissipation, yet their relationship with tissue-level stress transmission is rarely quantified. Bridging this gap requires multi-scale modeling frameworks integrating material science, structural mechanics, and human biomechanics.

8.4 Validation of Intelligent and Autonomous Safety Systems

The rapid deployment of connected and autonomous vehicle technologies introduces new validation challenges for pedestrian safety assessment. Simulation-based evaluations of perception, prediction, and decision-making algorithms often rely on simplified behavioral models and limited real-world datasets. Machine learning systems may exhibit performance degradation under rare or adversarial scenarios, such as occluded pedestrians, atypical postures, or complex multi-agent interactions. The lack of standardized benchmarking protocols and open validation databases further complicates comparative performance assessment. Ensuring the reliability of AI-driven safety systems therefore requires continuous real-world monitoring, transparent reporting practices, and regulatory oversight mechanisms [21].

8.5 Data Integration and Interoperability Challenges

Pedestrian safety research increasingly relies on heterogeneous data sources, including accident databases, sensor recordings, experimental measurements, and large-scale simulations. However, inconsistencies in data formats, annotation standards, and privacy regulations limit effective integration and cross-study comparison. The absence of interoperable digital infrastructures hinders the development of comprehensive injury prediction platforms and digital twin ecosystems. Addressing these issues necessitates coordinated international efforts toward standardized data-sharing frameworks and ethical governance models [22].

9 Conclusions

This comprehensive review has examined the progressive evolution of numerical simulation methodologies and biomechanical injury assessment techniques in the context of vehicle–pedestrian collisions. The field has transitioned from simplified multibody formulations primarily focused on macroscopic kinematics to high-fidelity finite element human body models capable of resolving tissue-level responses. The integration of surrogate modeling and probabilistic frameworks has further enabled scalable and robust injury risk evaluation under real-world uncertainty [3]. By incorporating statistical uncertainty propagation, representative simulation scenarios, and multi-objective optimization principles, this work extends traditional descriptive reviews toward a system-level analytical perspective. The quantitative framework presented in Sections 4 and 5 demonstrates how injury metrics, demographic factors, and vehicle characteristics can be jointly analyzed to support evidence-based safety design and regulatory decision-making. The results highlight that pedestrian injury mitigation cannot be effectively addressed through isolated optimization of individual metrics. Strong interdependencies among head, cervical, thoracic, and lower extremity responses necessitate integrated design strategies accounting for biomechanical coupling and trade-offs. The multi-objective formulation discussed in Section 6 provides a rational foundation for balancing these competing safety objectives within practical engineering constraints [13]. Despite substantial methodological advances, significant challenges remain. Limitations in experimental data availability, incomplete validation of human body models under complex loading conditions, and the lack of standardized assessment protocols for multi-axial injury mechanisms continue to restrict predictive accuracy. Furthermore, establishing reliable links between vehicular structural deformation and human tolerance thresholds represents an open research frontier requiring interdisciplinary collaboration. The growing deployment of intelligent transportation systems and autonomous driving technologies introduces both opportunities and risks for pedestrian protection. While advanced perception and emergency intervention systems can substantially reduce impact severity, their performance under rare and highly dynamic scenarios remains insufficiently validated [16], [22]. Ensuring the safety of AI-driven mobility systems therefore demands transparent benchmarking frameworks and continuous real-world monitoring. In this perspective, future investigations should prioritize the development of hybrid digital twin platforms integrating real-time sensor data with high-fidelity biomechanical models. In addition, large-scale experimental validation campaigns, standardized injury assessment protocols for multi-axial loading, and real-time surrogate-based optimization frameworks will be required to support next-generation pedestrian protection systems in connected and autonomous mobility environments. Collectively, the analytical, methodological, and conceptual contributions presented in this review aim to support the transition toward human-centric, data-driven, and system-integrated pedestrian safety paradigms capable of addressing the increasing complexity of modern urban mobility.

References:

[1] Zhao, R, Rahman, A, Wei, B, Li, C, Ma, Y, Cai, Y & Han, L 2024, A literature review of contacting force measurement methods for pedestrian crowds, Heliyon, vol. 10, no. 21, p. e39755.

[2] Frantisek Lopot, Lubos Tomsovsky, Marsik, F, Masek, J, Petr Kubovy, Jezdik, R, Sorfova, M, Barbora Hajkova, Dita Hylmarova, Havlicek, M, Ondrej Stocek, Doubek, M, Tikkanen, T, Svoboda, M & Jelen, K 2023, Pedestrian Safety in Frontal Tram Collision, Part 1: Historical Overview and Experimental-Data-Based Biomechanical Study of Head Clashing in Frontal and Side Impacts, Sensors, vol. 23, Multidisciplinary Digital Publishing Institute, no. 21, pp. 8819–8819, viewed 25 October 2024, https://www.mdpi.com/1424-8220/23/21/8819

[3] Nellippallil, AB, Berthelson, PR, Peterson, L & Prabhu, RK 2022, A Computational Framework for Human-Centric Vehicular Crashworthiness Design and Decision-Making Under Uncertainty, ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part B: Mechanical Engineering, vol. 8, no. 2.

[4] Alsharif, T, Lanzaro, G & Sayed, T 2024, Distracted Walking: Does it impact pedestrian-vehicle interaction behavior? Accident Analysis & Prevention, vol. 208, Pergamon, p. 107789.

[5] Ren, AD, Zhang, BG, Chang, CF & Huang, DH 2025, Two-step deep reinforcement learning for traffic signal control to improve pedestrian safety using connected vehicle data, Accident Analysis & Prevention, vol. 222, Elsevier BV, pp. 108161–108161.

[6] Hu, J, Lin, Y-S, Boyle, K, Bonifas, A, Lin, C-H, Tatem, W & Martin, P 2025, Predicting head impact conditions in vehicle-to-pedestrian impacts through computational

human modeling, Traffic Injury Prevention, vol. 26, no. sup1.

[7] Kohles, SS & McClaren, JW 2022, A stochastic model validated with human test data causally associating target vehicle Delta V, occupant cervicocranial biomechanics, and injury during rear-impact crashes, Journal of Forensic and Legal Medicine, vol. 91, Elsevier BV, pp. 102431–102431.

[8] Hussain, Q, Feng, H, Grzebieta, R, Brijs, T & Olivier, J 2019, The relationship between impact speed and the probability of pedestrian fatality during a vehicle-pedestrian crash: A systematic review and meta-analysis, Accident Analysis & Prevention, vol. 129, pp. 241–249.

[9] Prasad, P, Mertz, H, Augenstein, J & Digges, K 2010, 0S-44 Evaluation of the Field Relevance of Several Injury Risk Functions, Stapp Car Crash Journal, vol. 54.

[10] Golfo, S 2021, Analisi della gravità delle lesioni nellimpatto veicolo-pedone.

[11] Mariotti Virzì, G 2009, MULTIBODY NUMERICAL SIMULATION FOR VEHICLE – PEDESTRIAN CRASH TEST, vol. 62, pp. 40–49.

[12] Shi, L, Han, Y, Huang, H, Li, Q, Wang, B & Mizuno, K 2018, Analysis of pedestrian-to-ground impact injury risk in vehicle-to-pedestrian collisions based on rotation angles, Journal of Safety Research, vol. 64, pp. 37–47, viewed 6 December 2019, <https://www.sciencedirect.com/science/article/pii/S0022437517303705>.

[13] Berthelson, PR, Ghassemi, P, Wood, JW, Liu, Y, Al-Graitti, AJ, Jones, MD, Chowdhury, S & Prabhu, RK 2021, Evaluation of occupant neck injury response to varied impact conditions using a finite element-mathematical surrogate modeling approach, International Journal of Crashworthiness, vol. 27, no. 6, pp. 1726–1742.

[14] Nusia, J, Xu, J-C, Knälmann, J, Sjöblom, R & Kleiven, S 2023, Injury risk functions for the four primary knee ligaments, Frontiers in Bioengineering and Biotechnology, vol. 11, p. 1228922, viewed 27 November 2023, https://pubmed.ncbi.nlm.nih.gov/37860626/

[15] Li, C, Liu, S & Cen, X 2021, Safety and efficiency impact of pedestrian–vehicle conflicts at non signalized midblock crosswalks based on fuzzy cellular automata, Physica A Statistical Mechanics and its Applications, vol. 572, Elsevier BV, pp. 125871–125871.

[16] Lee, MB, Lee, CT, Abas, MA & Chong, WWF 2025, Advancing pedestrian safety in the era of autonomous vehicles: A bibliometric analysis and pathway to effective regulations, Journal of Traffic and Transportation Engineering (English Edition), Elsevier.

[17] J.A., P 2012, Development Process of Injury Risk Curves, viewed 28 December 2025, https://www.researchgate.net/publication/287059557_Development_process_of_injury_risk_curves

[18] Mariotti Virzì, G 2019, Head Injury Criterion: Mini Review, American Journal of Biomedical Science & Research, vol. 5, no. 5, pp. 406–407.

[19] Narayan Yoganandan, Banerjee, A & Pintar, FA 2015, Age-Infusion Approach to Derive Injury Risk Curves for Dummies from Human Cadaver Tests, Frontiers in Bioengineering and Biotechnology, vol. 3, Frontiers Media, viewed 19 May 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC4677537/

[20] Virzi Mariotti, G, Golfo, S, Carollo, F & Scalici, E 2021, Study of an impact vehicle-bike at high speed, Academia Letters.

[21] Adnan Yusuf, S, Khan, A & Souissi, R 2024, Vehicle-to-everything (V2X) in the autonomous vehicles domain – A technical review of communication, sensor, and AI technologies for road user safety, Transportation Research Interdisciplinary Perspectives, vol. 23, no. 2590-1982, p. 100980.

[22] Unar, S, Nazar, M, Khokhar, S, Ahmed, A, Su, Y & Elkhalil, A 2026, Artificial Intelligence-driven visual attention framework for vehicle–pedestrian interaction in Intelligent Transportation System, Engineering Applications of Artificial Intelligence, vol. 165, p. 113455.

Declaration of Generative AI and AI-assisted
Technologies in the Writing Process
During the preparation of this work the authors used NotebookLM in order to be assisted with structuring the literature review and brainstorming initial research questions. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)
The authors equally contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself
No funding was received for conducting this study.

Conflict of Interest
The authors have no conflicts of interest to declare that are relevant to the content of this article.