

Rider Injuries of Scooter – Passenger Car on Various Types of Collisions Based On PC-Crash Simulations

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Abstract: Motorcycles (MCs) are a prevalent mode of transportation in Thailand, constituting over 50% of registered vehicles, with the majority being underbone and step-through types. However, MC accidents pose significant road safety challenges, contributing to a high rate of injuries and fatalities. This study evaluates rider injuries in scooter-passenger car collisions through PC-Crash simulations, addressing the urgent need for MC test protocol specific to Thailand. Adhering to the ISO 13232-8:2005 standard for crash conditions, various collision scenarios were simulated to focus on head and chest injuries, evaluated using the Head Injury Criterion (HIC) and chest deceleration measurements, respectively. Results indicate significant variability in rider kinematics and injury patterns across different impact scenarios, highlighting severe head and chest injuries in direct perpendicular impacts. The study underscores the importance of adaptive safety measures tailored to specific collision scenarios and advocates for further research integrating real-world accident data to enhance the effectiveness of safety strategies in reducing motorcycle-related injuries and fatalities in Thailand.

Keywords: Motorcycle accident, multibody simulation, PC-Crash, injury criteria, motorcycle safety

1. Introduction

MCs are an indispensable mode of transportation in Thailand, widely favored for their maneuverability, affordability, and ease of use [1]. They constitute over 50% of all registered vehicles, with the majority being underbone and step-through models, with engine displacements below 125 cc [2]. The performance of these prevalent designs is further influenced by factors such as tire width, wheel sizes, and wheel lock characteristics [3,4]. This high prevalence, while facilitating personal mobility, also contributes to road safety challenges in the nation.

Globally, motorcycle (MC) riders account for 74% of annual road traffic deaths, predominantly in low- and middle-income countries [5,6]. Despite global initiatives like the UN's 2021–2030 Road Safety Targets, reducing MC-related injuries remains a persistent challenge [7,8]. This crisis is particularly acute in Thailand, which ranked first in Asia for traffic accidents in 2020, with MC accidents representing a primary threat to national road safety [9-12]. Statistics from 2021 reveal that collisions specifically rear-end, side, or angular impacts constitute 82.78% of these accidents, frequently resulting in severe fatalities [13-17]. Because crash severity is heavily influenced by the opposing vehicle and impact area, comprehensive research into these specific collision dynamics is essential to understanding injury mechanisms within the Thai context.

Road accidents are complex events often attributed to a combination of human factors, road conditions, and vehicle quality [18-20]. While efforts have been made to improve driver behavior and road infrastructure [21-23], advancements in vehicle safety, particularly for MCs, represent a crucial and often underexplored avenue for injury mitigation in Thailand. Unlike passenger cars, which benefit from extensive safety evaluation programs such as the New Car Assessment Programmes (NCAPs) in various regions worldwide [24,25], a standardized MC test protocol tailored to the unique accident characteristics and vehicle types prevalent in Thailand is conspicuously absent.

Building upon this critical need, this study evaluates motorcycle rider injuries in scooter-passenger car collisions to inform the development of a localized testing protocol for Thailand. Using PC-Crash simulations noted for their accuracy in modeling complex impact scenarios [26-31] the research strictly adheres to the ISO 13232-8:2005 standard for crash conditions [32]. By simulating various collision types and velocities, this paper investigates the dynamic responses of riders, focusing on key injury metrics such as the Head Injury Criterion (HIC) and chest deceleration. These findings provide a scientific foundation for adaptive safety measures and vehicle design aimed at reducing the burden of motorcycle-related fatalities in Thailand.

2. Data and Methods

2.1 Standard Compliance and Scenarios

This study strictly adheres to ISO 13232-8:2005 [32], ensuring consistent and comparable motorcycle safety research through uniform testing and analytical methods. Accordingly, seven full-scale crash configurations between a scooter and a passenger car were simulated, as illustrated in Figure 1 and Table 1.

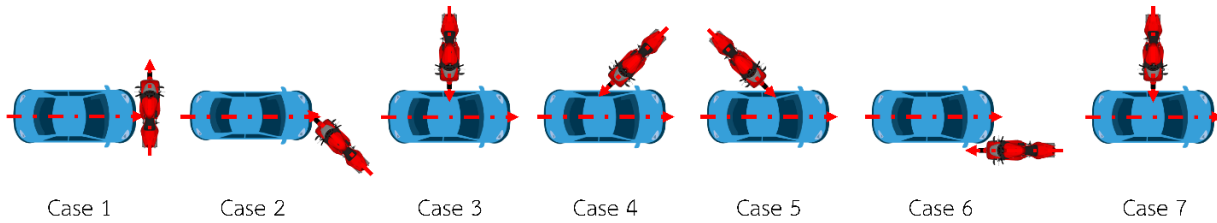


Fig. 1 Full-scale crash test configurations in ISO 13232-8:2005 standard. Source: [32]

Each scenario is designed to analyze specific collision dynamics, allowing for a detailed examination of rider kinematics and potential injury patterns under controlled conditions.

Table 1 Simulation set-up based on ISO 13232 standards. Source: [32]

Case	Colliding vehicle velocity (km/h)	MC velocity (km/h)	MC collision angles (degree)
1	35	0	90
2	24	48	135
3	24	48	270
4	24	48	225
5	24	48	315
6	0	48	180
7	0	48	270

2.2 Simulation Tool and General Setup

The collision and injury response analysis was performed using PC-Crash, which is widely used for accident reconstruction and biomechanical analysis [29-31]. The simulation environment utilized the standard right-hand coordinate system. The collision space was defined on a smooth, dry asphalt surface; static and kinetic friction coefficients (μ) were set to 0.8 and 0.7, respectively. The general restitution coefficient (ε) for primary contact surfaces was set to 0.4, reflecting inelastic energy absorption. All positional and velocity data were anchored to the Center of Gravity (CG) of each vehicle. At the moment of impact ($t = 0$ s), velocity was initialized by applying a linear speed magnitude (km/h, see Table 1) and a heading angle (degrees) to the CG, with zero angular velocity. Simulations utilized a 4th-order Runge-Kutta integration scheme with a constant time step, running until both vehicles and the rider reached a state of rest.

2.3 Human Surrogate Model

The human surrogate for the scooter rider was modeled using multi-body system in PC-Crash. This model represents an average Thai adult male anthropometric data defined by a height of 1.71 m and a total mass of 72.2 kg [33].

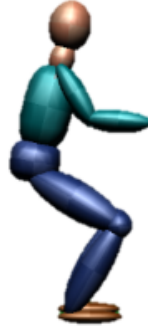


Fig. 2 Multi-body model of human in PC-Crash. Source: authors

The model is composed of 18 connected segments as shown in Figure 2, each defined by specific mass, inertia, and joint properties to accurately simulate dynamic movement during impact. The detailed segmental masses and moments of inertia for the rider are provided in Table 2. The rider was modeled in a standard, hands-on-grips seated posture typical of a 110cc automatic scooter, with a torso angle of approximately 15° forward lean, elbow flexion of 150°, and knee flexion of 105°.

Table 2 Segmental anthropometry and inertia properties of the PC-Crash rider surrogate.

Source: authors

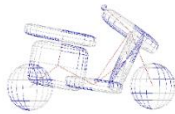
Segment	Mass (kg)	Percentage of total body mass (%)	Moment of inertia (I_{zz}) (kg.m ²)
Head	5.05	7.0	0.040
Neck	0.94	1.3	0.005
Thorax	17.30	24.0	0.250
Pelvis	10.80	15.0	0.200
Upper Arm (each)	2.17	3.0	0.015
Forearm (each)	1.16	1.6	0.008
Hand (each)	0.43	0.6	0.001
Thigh (each)	7.02	9.7	0.120
Leg (each)	3.47	4.8	0.045
Foot (each)	1.01	1.4	0.003

Note: Segmental percentages do not sum exactly to 100% due to rounding of individual segment masses. I_{zz} represents the moment of inertia around the local Z-axis of the segment's coordinate system.

2.4 Vehicle Model

The vehicle models comprise a 110cc automatic scooter and a 1200cc compact passenger car (properties detailed in Table 3).

Table 3 Parametrization of vehicle models. Source: authors

Parameter	Scooter	Passenger Car
PC-Crash model		
Model Type	Dynamic multi-body	Rigid body
Total mass (kg)	104	1076
Dimensions (L / W / H) (m)	1.85 / 0.70 / 1.10	4.40 / 1.70 / 1.45
CG Location (X, Y, Z) (m)	(1.10, 0.00, 0.48)	(2.20, 0.00, 0.56)
Moment of Inertia (I_{xx}) (kg.m ²)	10	600
Moment of Inertia (I_{yy}) (kg.m ²)	12	2500
Moment of Inertia (I_{zz}) (kg.m ²)	3	2800

To establish a conservative, worst-case scenario for rider injury assessment, the passenger car body was modeled as a rigid body. By neglecting the car's energy absorption through plastic deformation, the simulation maximizes the momentum and energy transfer to the lighter scooter and rider system. This approach yields the most critical predictions for the Head Injury Criterion (HIC) and chest deceleration. Despite the rigid body assumption for the shell, the car's dynamic response during impact remained governed by its specific suspension parameters, as detailed in Table 4.

Table 4 Suspension stiffness and damping properties of passenger car model. Source: authors

Parameter	Front Left	Front Right	Rear Left	Rear Right
Stiffness (N/m)	21842.0	21842.0	13,964.5	13,964.5
Damping (N.s/m)	2457.2	2457.2	1571.0	1571.0
Max Suspension Travel (m)	0.1	0.1	0.1	0.1
Roll Stiffness (Front) (N/m)		10,921.0		
Roll Stiffness (Rear) (N/m)		6,982.3		

2.5 Model Validation and Empirical Correlation

To ensure the reliability of the PC-Crash multi-body model in predicting injury outcomes, a validation study was conducted prior to executing the full simulation matrix. The simulated injury criteria were benchmarked against a series of reconstructed real-world accident cases to establish a baseline for computational accuracy.

The validation dataset was derived from forensic accident reconstruction reports provided by the Central Institute of Forensic Science (CIFS) and supplemented by detailed injury data from public health records spanning 2016 to 2022 [34]. This dataset focused exclusively on motorcycle-to-passenger car collisions within the specific regional context of Thailand. From a pool of 22 available reconstructions, four cases were selected as a validation cohort to represent the most prevalent impact configurations. The specific parameters and injury outcomes for these validation cases are summarized in Table 5.

Table 5 Selected reconstructed accident cases for PC-Crash model validation. Source: [34]

Case	Scenario	MC Speed (km/h)	OV Speed (km/h)	Impact Angle (degrees)	Reconstructed HIC	Reconstructed Chest G (g)
1	Head-on	53.6	42.1	-161.1	2223	71.92
2	Head-on	38	44	178.6	670.2	12.79
3	OV U-turn from same direction	44	15	83.9	227.5	36.5
4	OV impacting rear MC	75	80	1.15	2018	75.74

2.6 Injury Assessment Criteria

Two primary injury criteria were utilized in this study: HIC and peak chest deceleration. A threshold value of 700 for HIC₁₅ was established to evaluate the risk of skull fracture [35]. This threshold aligns with international safety standards (such as FMVSS 208 and Euro NCAP) and indicates a significant probability of severe neurological trauma. The HIC₁₅ value is calculated using the Eq. (1):

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

where: $a(t)$ is the resultant acceleration of the head's center of gravity [g]; t_1 and t_2 denote the two time points that define the maximum allowable duration of the impact of 15 ms (0.015 s).

To assess the risk of severe thoracic trauma, a threshold of 60 g was applied for peak chest deceleration [35]. Exceeding this limit signifies an increased probability of an Abbreviated Injury Scale (AIS) score of 3 or higher, which includes life-threatening injuries such as multiple rib fractures or hemopneumothorax.

3. Results

This section presents the results from the multi-body simulations of scooter-passenger car collisions, evaluating head and chest injury outcomes across the seven defined crash scenarios.

3.1 Validation of the Computational Multi-Body Model

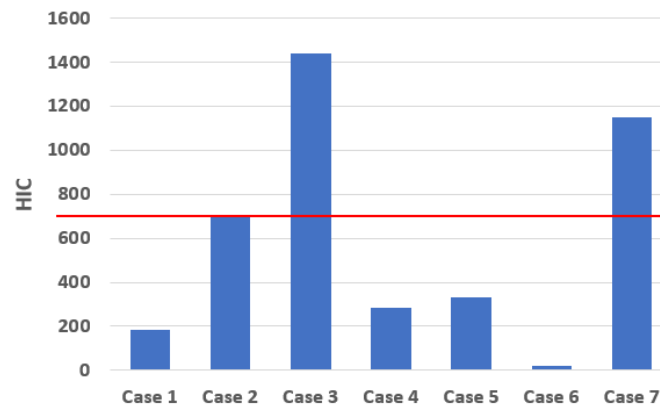
The validation process involved benchmarking the simulated values for the two primary injury metrics HIC and peak chest deceleration against reconstructed values derived from real-world forensic crash analyses. As shown in Table 6, the comparison demonstrates strong agreement between the model's predictions and the reconstructed data. The observed mean deviation was only 6% for both metrics, which is well within the acceptable margin for multi-body kinematic simulations. This high degree of correlation confirms that the parametrized PC-Crash system, utilizing the input parameters detailed in Sections 2.2 to 2.4, is a reliable tool for the injury-risk assessments presented in this study.

Table 6 Comparison of reconstructed vs. simulated injury criteria. Source: authors

Case	Reconstructed HIC	Simulated HIC	Relative error (%)	Reconstructed Chest G (g)	Simulated Chest G (g)	Relative error (%)
1	2223.0	2100.0	-5.5	71.92	70.0	-2.67
2	670.2	650.0	-3.0	12.79	13.5	5.6
3	227.5	253.0	11.2	36.5	37.0	1.4
4	2018.0	2100.0	4.1	75.74	78.0	3.0
Mean absolute error			6.0			3.2

3.2 Analysis of HIC Results

Multi-body simulations quantified HIC across seven scenarios against the skull fracture threshold of 700 (Figure 3). Cases 3 (1442.6) and 7 (1149.7) significantly exceeded this limit, driven by perpendicular impacts against the car's rigid side structure. This configuration caused rapid deceleration and concentrated force transfer. Similarly, Case 2 (698.4) presented a critical risk, nearly reaching the threshold due to a sustained 12 ms head contact duration.

**Fig. 3** Comparison of maximum HIC15 for all seven collision scenarios. Source: authors

Conversely, Cases 1, 4, 5, and 6 remained well below the threshold. Case 1 (186.3) and Case 5 (331.0) benefited from oblique angles or energy distribution through the upper body. Most notably, Case 6 yielded an exceptionally low HIC (18.3); this glancing blow allowed the torso to absorb the primary impact energy, facilitating gradual head deceleration and protecting the brain from high inertial forces.

The results demonstrate that impact orientation is the primary determinant of injury severity. Direct, perpendicular strikes (Cases 3, 7) maximize HIC, while scenarios where energy is distributed or absorbed by the torso (Case 6) significantly mitigate trauma. Furthermore, shorter, intense impact durations (12–13 ms) consistently produced higher injury risks than extended contacts where forces were more widely distributed.

3.3 Analysis of Chest Deceleration Results

Simulation-derived peak chest deceleration values were evaluated against the 60 g threshold, which correlates to a significant risk of severe thoracic injury (AIS $\geq$ 3), such as rib fractures or

hemopneumothorax (Figure 4). The analysis revealed that deceleration remained below this limit in the majority of scenarios, suggesting a lower risk of critical thoracic trauma under most tested conditions.

However, Case 7 (perpendicular side impact at 48 km/h) and Case 5 (oblique front door impact) exceeded the threshold, recording 68.7 g and 61.2 g, respectively. These results highlight that high-energy direct impacts and specific oblique configurations can generate critical thoracic loads. Conversely, Cases 1, 2, 4, and 6 remained well below 60 g. Notably, the side-swipe scenario (Case 6) recorded a low 28.5 g, reinforcing that broader energy dissipation and non-compressive loading significantly mitigate injury risk.

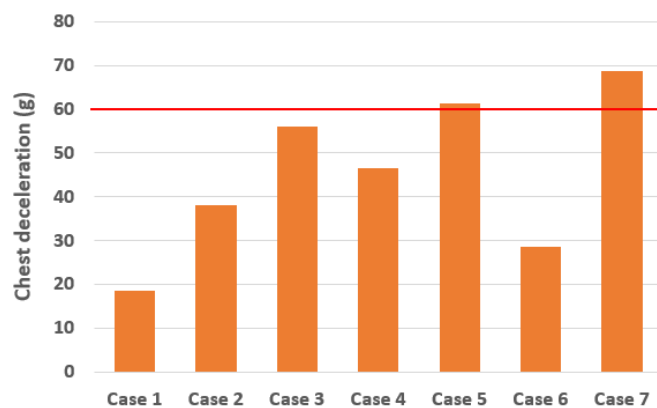


Fig. 4 Comparison of maximum chest deceleration for all seven collision scenarios. Source: authors

Collectively, these findings emphasize that impact direction and intensity are the primary determinants of thoracic dynamic response. While the head is highly susceptible to localized rigid structures, the chest’s injury risk is most acute during high-momentum transfers, particularly in perpendicular orientations.

4. Discussion

4.1 Injury Mechanism

ISO 13232-8:2005-compliant simulations quantified trauma risks across seven configurations, revealing that impact angle and location are the primary determinants of injury severity. Perpendicular impacts (Cases 3 and 7) represent a critical failure threshold; HIC values reached 1442.6 and 1149.7, respectively, nearly doubling the 700-skull fracture limit. This is attributed to abrupt rider deceleration and high-energy contact with the car’s rigid structures, which bypasses the helmet’s energy-dissipating capabilities.

While head injury is the dominant risk, thoracic trauma ($\text{AIS} \geq 3$) is a concurrent threat. Case 7 recorded the highest chest deceleration (68.7 g), followed by Case 5 (61.2 g). These results stem from severe lateral compression of the thorax against the vehicle or scooter handlebars during high-

momentum transfers. Conversely, the glancing blow mechanism in Case 6 (oblique rear impact) yielded the most favorable outcomes (HIC = 18.3; Chest = 28.5 g).

These findings confirm that shifting the rider's trajectory laterally rather than stopping it abruptly distributes impact energy over a longer duration. This kinetic dissipation acts as a passive protective sequence, preventing the concentrated, high-magnitude loading characteristic of lethal perpendicular collisions.

4.2 Comparison to other Studies

The injury risks identified specifically severe head trauma in perpendicular impacts and high thoracic loading in lateral collisions are strongly corroborated by global research [36-38]. Studies by Carmai et al. [36] using Finite Element Analysis (FEA) confirm that direct, concentrated impact mechanisms against rigid vehicle sides significantly elevate HIC (>700) and thoracic compression risk, regardless of vehicle type. This suggests that the physical mechanisms governing trauma in the Thai context are universally applicable.

While this study focused on the head and torso, Li et al. [37] utilized FEA to demonstrate that lower limb fractures are also a prevalent outcome in frontal and lateral collisions. This reinforces the necessity for future Thai safety protocols to expand protective criteria to the lower extremities. Furthermore, the kinematic sensitivities observed in our model align with MADYMO research by Ibitoye et al. [38], which confirms that collision angles dictate post-impact trajectories and ejection velocities.

The consistency between our multi-body dynamics, FEA frameworks [36,37], and kinematic analyses [38] validates these findings for establishing national safety standards. These comparisons prove that the ISO 13232-8:2005 scenarios used here yield universally relevant insights into high-risk injury mechanisms, providing a robust baseline for regional policy.

4.3 Methodological Limitations and Future Work

The primary limitation of this study is the use of a rigid-body car model. While compliant with ISO 13232-8:2005, this approach omits energy absorption from vehicle deformation, potentially overestimating injury metrics like HIC and chest deceleration [39]. However, this assumption is standard in early protocol development as it provides conservative, worst-case estimates necessary for establishing robust initial safety thresholds across all seven cases.

Future research should employ Finite Element Analysis (FEA) to model vehicle crush and refine prediction accuracy. Additionally, incorporating lower extremity criteria, such as the Tibia Index, is recommended to address the prevalent risk of leg and ankle trauma [37]. This expansion will provide a more comprehensive assessment of rider safety for Thai national standards.

5. Conclusion

This study utilized ISO 13232-8:2005-compliant multi-body dynamics to quantify severe head and chest trauma risks across seven scooter-passenger car collision scenarios. The findings provide a data-driven foundation for enhancing national safety protocols in regions with high motorcycle density, such as Thailand. Results unequivocally demonstrate that collision kinematics are the primary determinant of injury severity. Perpendicular impacts (Cases 3 and 7) posed the greatest threat, with HIC and chest deceleration significantly exceeding the 700 and 60 g thresholds, respectively. Conversely, the glancing blow (Case 6) exhibited the lowest metrics, confirming that tangential momentum transfer acts as a passive protective mechanism.

These results emphasize the need for national test protocols to explicitly address lateral vehicle protection and high-magnitude, short-duration impact forces. The data is of direct interest to governmental bodies, manufacturers, and researchers focused on refining passive safety features and national standards. While the rigid-body car model provided the conservative, worst-case estimates necessary for initial thresholds, future research should utilize FEA frameworks to model vehicle crush and incorporate lower extremity injury criteria. Ultimately, quantifying these risks provides a robust baseline for engineering countermeasures aimed at reducing critical rider trauma.

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