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Integrated Reconstruction of Motorcycle Crashes Involving Pulmonary Trauma

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ABSTRACT

Motorcycle road crashes are a specific subject of technical and forensic-medical reconstruction. Unlike occupants of enclosed vehicles, the rider and pillion passenger may become separated from the motorcycle and acquire independent translational and rotational motion. Their subsequent trajectories can involve primary and secondary contacts with another vehicle, the road surface, roadside safety equipment, or fixed objects. Consequently, the injury mechanism is determined not only by the initial collision configuration but by the complete sequence of body motion and contacts.

This study examines pulmonary trauma as a potential linking element between technical reconstruction and forensic-medical assessment. Published clinical, forensic, biomechanical, and transport-safety evidence is structured for pulmonary contusion, pulmonary laceration, pneumothorax, haemothorax, haemopneumothorax, associated rib fractures, and their morphological characteristics. Rider and passenger kinematics are considered separately because their positions on the motorcycle produce different separation times, contact opportunities, and loading pathways.

A bidirectional integrated reconstruction model is proposed. In the forward analytical direction, the sequence is traced from crash mechanism through rider or passenger kinematics, contacts, mechanical loading of the thorax, and pulmonary injury. In the reverse direction, the medical findings are used as an independent consistency criterion for testing the mechanical compatibility of the technically reconstructed mechanism. The model does not treat a single pulmonary lesion as a deterministic marker of one crash mechanism. Across the analysed clinical series, comprising 8,372 injured motorcyclists, the reported frequency of pulmonary contusion or pulmonary injury ranged from 1.47% to 12.5%, pleural complications from 1.61% to 23.6%, and rib fractures from 11.29% to

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19.4%. Owing to differences in sample selection and diagnostic grouping, the results are interpreted comparatively and no pooled overall frequency is calculated.
The proposed approach increases the traceability of complex road-accident reconstructions by requiring agreement among technical traces, body kinematics, contact chronology, thoracic loading, and the distribution of injuries. It can also identify injurious contact configurations relevant to motorcycle protection systems and transport safety.

Keywords: *Motorcycle crash, Reconstruction, Rider kinematics, Pillion passenger, Pulmonary trauma, Injury biomechanics, Forensic medicine*

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INTRODUCTION

Motorcycle crashes differ fundamentally from collisions involving only passenger cars. A motorcycle is a dynamically unstable single-track vehicle, and neither the rider nor the passenger is enclosed by a protective compartment. When stability is lost or an impact occurs, the human body may separate from the motorcycle and continue along a trajectory that no longer coincides with that of the vehicle. Rotation, free flight, impact with another vehicle, contact with the pavement, and collision with roadside objects may follow the initiating event.

Thoracic and pulmonary injuries often arise during secondary contact of the separated body with the road surface or a roadside object. They may also occur during the primary impact with another vehicle, through contact with structural parts of the motorcycle, by crushing, or by run-over. Their reconstructive value therefore depends on morphology, laterality, anatomical distribution, and consistency with the complete contact sequence rather than on the mere presence of a diagnosis.

The presence of a pillion passenger adds another layer of complexity. Rider and passenger occupy different positions, interact with different structural elements, and may separate at different moments. Direct contact between their bodies may alter the trajectory of one or both persons. Computational and biomechanical research has demonstrated different rider and passenger kinematics when impact speed, angle, and collision configuration change (Carmai et al., 2019). In some configurations, appreciable thoracic loading occurs in both positions.

The traumatic outcome cannot be described solely as a function of speed or impact energy. The spatial posture of the body, the direction of displacement, angular motion, the order of contacts, the effective contact area, and the anatomical location of loading are all relevant. Two crashes with comparable vehicle speeds may therefore produce substantially different injury patterns.

Thoracic and pulmonary injuries are among the most clinically important consequences of high-energy motorcycle trauma. They may result from direct impact, rapid deformation of the chest wall, sudden deceleration or acceleration, penetration, and combined loading. The medical spectrum includes pulmonary contusion and laceration, pneumothorax, haemothorax, haemopneumothorax, tracheobronchial injury, vascular disruption, and associated rib or sternal fractures.

Pulmonary trauma has a dual relevance. Clinically, it is a major component of severe chest injury. Reconstructively, some findings are spatially characterisable by side, region, depth, and association with injuries of the chest wall. These characteristics can be compared with the reconstructed direction of loading and contact chronology. Nevertheless, similar pulmonary findings can arise from different mechanical events; they must never be interpreted in isolation.

The aim of this study is to develop a bidirectional integrated model for motorcycle-crash reconstruction based on the relationship between crash mechanism, rider and passenger kinematics, contact sequence, mechanical loading of the thorax, and pulmonary findings. The study also systematises published quantitative data and defines a consistency framework for complex technical and forensic-medical assessment.

LITERATURE REVIEW

2.1. Motorcycle Crash Mechanism and Rider and Passenger Kinematics

The mechanism of a motorcycle crash is a sequence of interrelated dynamic and contact processes. Depending on the configuration, the event may begin with loss of stability, impact with another road user, collision with a fixed object, or a combination of these processes. The reconstruction must therefore extend beyond a broad crash-type label and identify the phases that generate the final traces and injuries.

In loss-of-control events, lowside and highside mechanisms produce substantially different separation conditions. During a lowside event, loss of tyre adhesion generally causes the motorcycle and rider to fall toward the slipping side and to slide with relatively small vertical separation. During a highside event, recovery of tyre grip after lateral slip can generate rapid roll and catapult the rider above the motorcycle. The direction and magnitude of initial body velocity, angular velocity, and height above the pavement differ between these mechanisms.

In a motorcycle-to-car collision, the decisive parameters include the contact point, relative angle, closing speed, orientation of the motorcycle, stiffness and geometry of the struck vehicle, and subsequent interaction of the rider and passenger with that vehicle. A frontal configuration may project the upper body toward the handlebar, fuel tank, windscreen, bonnet, roof edge, or road surface. A lateral configuration can generate localised thoracic loading combined with substantial body rotation.

A complete reconstruction should follow the sequence: pre-crash motion → hazardous situation → rider response → loss of stability or collision → separation → first body contact → secondary contacts → motion over the terrain → final rest position. Each transition must be supported by physical traces, vehicle deformation, road geometry, video data where available, or medically compatible injury evidence.

Position on the motorcycle is not a purely descriptive variable. Carmai et al. (2019) demonstrated different kinematic sequences for rider and child pillion passenger and identified configurations in which the passenger was compressed against the rider's back, producing appreciable thoracic loading. A multicentre series of 7,594 injured persons included 6,636 riders and 958 passengers and found broad similarities in overall injury patterns and hospital outcome, while crash circumstances and some treatment requirements differed (Ramezani et al., 2025). Thus, group-level clinical similarity does not imply identical injury mechanisms.

2.2. Biomechanics and Morphology of Thoracic and Pulmonary Trauma

Unlike the driver of a passenger car, whose exposure is modified by the occupant compartment, seat belt, energy-absorbing structures, and airbags, the motorcyclist can receive mechanical energy directly through the body. Kinetic energy $\frac{mv^2}{2}$) increases with the square of velocity. Severe

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parenchymal injury is therefore mechanically possible even at travel speeds of approximately 40–50 km/h when the contact configuration concentrates energy on the thorax.

Four principal mechanisms, frequently acting in combination, are considered: direct impact and compression; rapid acceleration or deceleration; pressure-wave effects in air-containing structures; and penetration.

2.2.1. Direct Impact and Compression

Direct blunt chest trauma is common in frontal and oblique impacts, when the upper body moves forward and upward relative to the motorcycle. The chest may strike the handlebar, fuel tank, windscreen, another vehicle, or a fixed roadside object. The mechanically relevant variables are impact velocity, effective mass, contact area, stiffness, contact duration, and the direction of force relative to the chest wall.

Rapid inward deformation of the thoracic cage compresses the pleural cavities and the porous, air- and blood-containing pulmonary parenchyma. A pressure wave propagates through the lung, and the delicate alveolar-capillary membranes may fail. Local contusions, band-like subpleural haemorrhages corresponding to the ribs, and rib fractures may result. Displaced sharp rib fragments can additionally perforate the visceral pleura and lacerate the lung.

The absence of rib fractures does not exclude severe pulmonary injury. In young persons, an elastic chest wall may deform substantially and then recover without fracturing, while the internal pressure transient and shear deformation damage the lung. Conversely, rib fractures may indicate localised chest-wall loading but do not by themselves identify the exact phase in which the pulmonary lesion occurred.

2.2.2. Inertial Mechanism During Rapid Deceleration or Acceleration

Deceleration occurs when the body, whether still associated with the motorcycle or already separated, strikes a relatively immovable surface such as the pavement, a barrier, or a tree. Acceleration occurs when a relatively slow rider-motorcycle system is struck by another vehicle, or when the separated body is intercepted by a moving vehicle. Although the initial conditions differ, both situations create relative motion between the external thoracic frame and the internal organs.

When the chest wall changes velocity or direction abruptly, the heart, aorta, lungs, and mediastinal structures tend to preserve their previous state of motion. Tensile and shear stresses develop at anatomical fixation sites, particularly the pulmonary hila and ligaments. Lower loading may cause hilar or ligamentous haemorrhage. Greater loading may disrupt the main bronchus or pulmonary vessels, cause partial or complete avulsion, and lead to massive haemorrhage, haemopneumothorax, or air embolism.

For reconstruction, inertial injury requires evidence of a sufficiently abrupt velocity change. The conclusion cannot be based solely on the final position of the body. It should be supported by a compatible impact surface, trajectory, deformation, trace pattern, and the distribution of internal and external injuries.

2.2.3. Air Trapping and Pressure-Wave Effects

Immediately before an anticipated impact, a rider may inhale, close the glottis, and tense the thoracoabdominal musculature. The lungs then behave as partly closed, air-containing structures. A rapidly applied pressure wave can produce marked local pressure gradients at interfaces between tissue, blood, and air.

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Spallation refers to tensile failure at an interface between media of different acoustic impedance. A compressive wave travelling through denser tissue is reflected at the air-containing boundary as a tensile wave. Biological tissues tolerate compression better than tension; alveolar septa and capillary walls may therefore rupture, producing intra-alveolar haemorrhage.

Implosion and rebound effects describe rapid compression and re-expansion of microscopic gas spaces. Alveoli compressed during the pressure peak may expand abruptly as external pressure falls. The resulting local shear and tensile stresses can damage surrounding cells and capillaries. These effects help explain severe internal injury without a proportionate external lesion, although their role in an individual road crash must be assessed cautiously and together with the complete mechanical evidence.

2.2.4. Penetrating Injury

Penetration occurs when an external object or an internally displaced bone fragment crosses the chest wall or visceral pleura and enters the pulmonary parenchyma. In motorcycle crashes, penetrating lesions frequently accompany high-energy blunt trauma rather than occurring as isolated sharp-force injuries.

Internal penetration is commonly produced by fractured ribs displaced inward. The sharp ends may perforate the visceral pleura and create superficial or deep wound channels. External penetration may be caused by broken motorcycle parts, glass or plastic fragments, barrier elements, posts, or branches encountered during fall, ejection, or sliding. Once the pleural cavity is opened, air and/or blood enter the pleural space and pneumothorax, haemothorax, or haemopneumothorax may develop.

2.2.5. Macroscopic Morphology

Pulmonary Contusion

Pulmonary contusions are commonly peripheral and subpleural, often involving the posterior and basal regions. A contrecoup lesion may occur in the opposite lung after transmission of the pressure wave across the mediastinum. Band-like haemorrhages reproducing the rib pattern may be visible on the pleural surface. The affected tissue is raised, firm, poorly aerated, and red to dark blue or purple. Small subpleural gas bubbles represent acute traumatic emphysema. On sectioning, dark non-frothy blood and oedematous fluid drain from an ill-defined region that merges gradually with the surrounding parenchyma.

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Figure 1. Pulmonary contusion with traumatic emphysema.

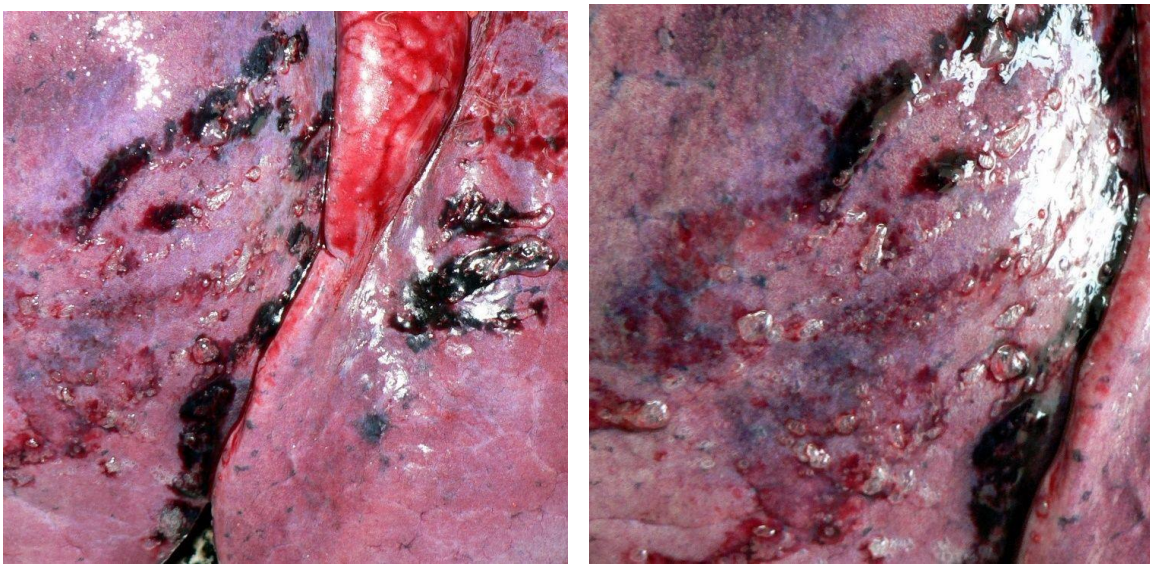


Figure 2. Rib-pattern subpleural haemorrhages and traumatic emphysema.

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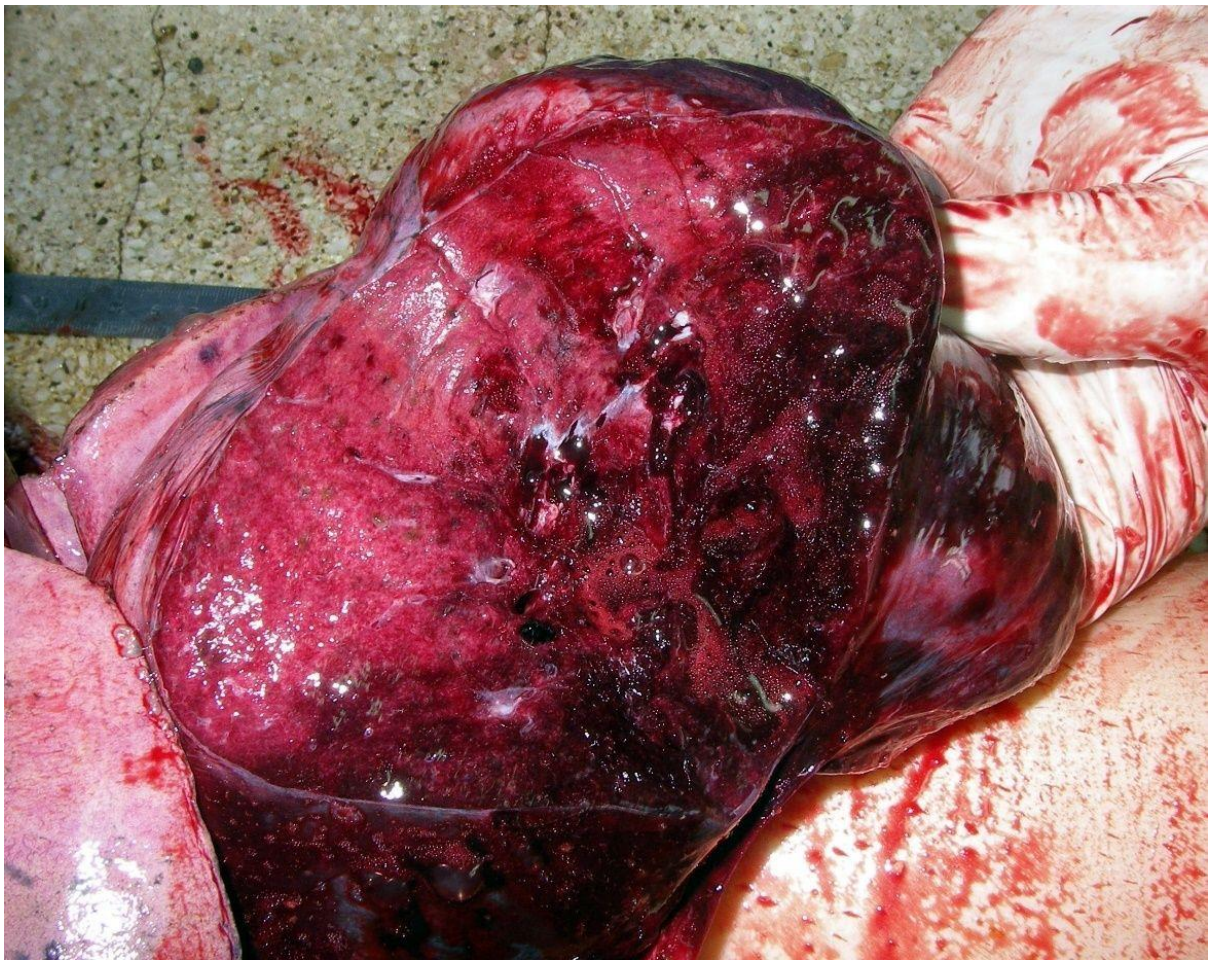


Figure 3. Pulmonary contusion on the cut surface.

Pulmonary Laceration

Pulmonary lacerations may be linear, slit-like, stellate, or irregular, with uneven margins and walls. In young riders with an elastic chest and no rib fracture, deeper central tears can arise through shear deformation.

When fractured ribs are present, local perforations of the visceral pleura and superficial wound tracks are more typical. Severe chest deformation or high-energy inertial loading may disrupt a lobe or produce partial or complete hilar avulsion. Deep tears can retract and form traumatic pseudocysts: a pneumatocele when filled mainly with air, or a haematocele when filled with liquid blood and clot.

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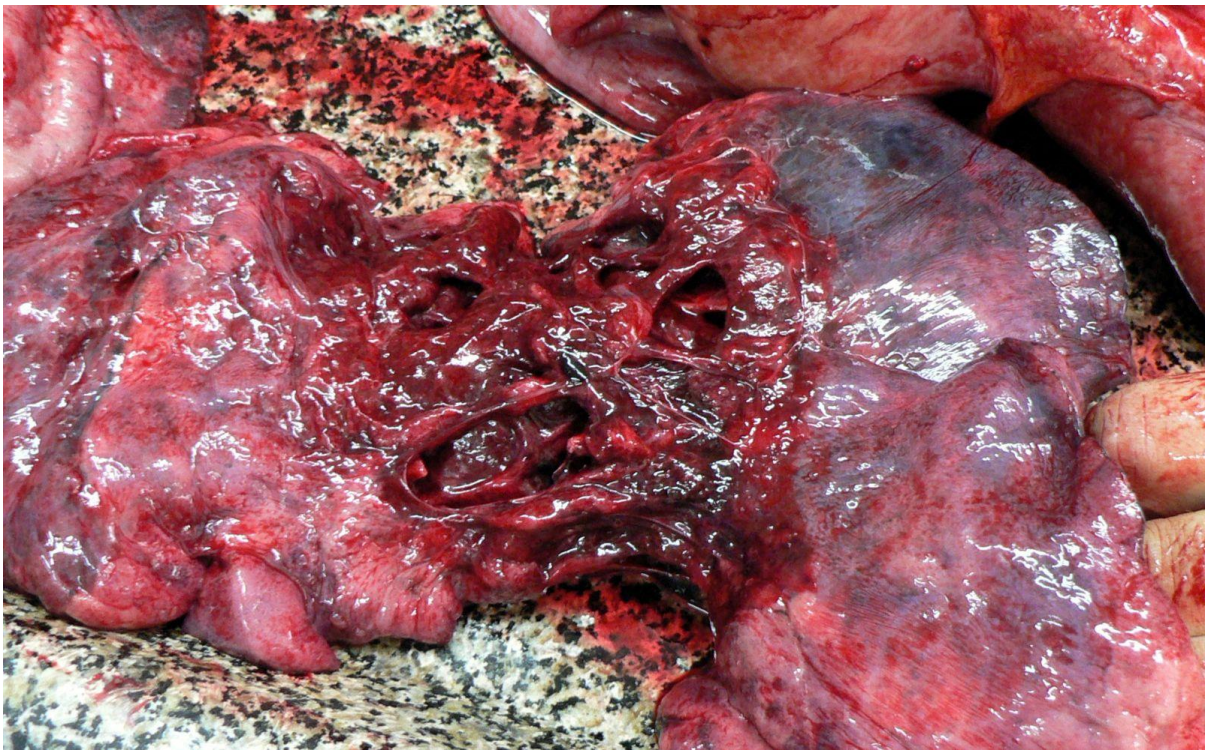


Figure 4. Pulmonary laceration.

Tracheobronchial and Great-Vessel Injury

Tracheobronchial rupture commonly occurs near anatomical fixation zones, often within approximately 2–2.5 cm of the carina. Tears can involve the membranous or cartilaginous bronchial wall. Hilar-vessel avulsion produces anatomical discontinuity, massive mediastinal haemorrhage, and collapse of the corresponding lung. Such injuries indicate severe loading but still require reconstruction of the specific acceleration, compression, and contact sequence.

2.2.6. Microscopic and Histopathological Characteristics

The microscopic appearance changes with the interval between trauma and death. During the first two hours, alveolar septa may be disrupted and alveolar spaces filled with erythrocytes. Interstitial, perivascular, and peribronchial oedema and erythrocyte extravasation are observed, while capillaries may be markedly dilated and congested.

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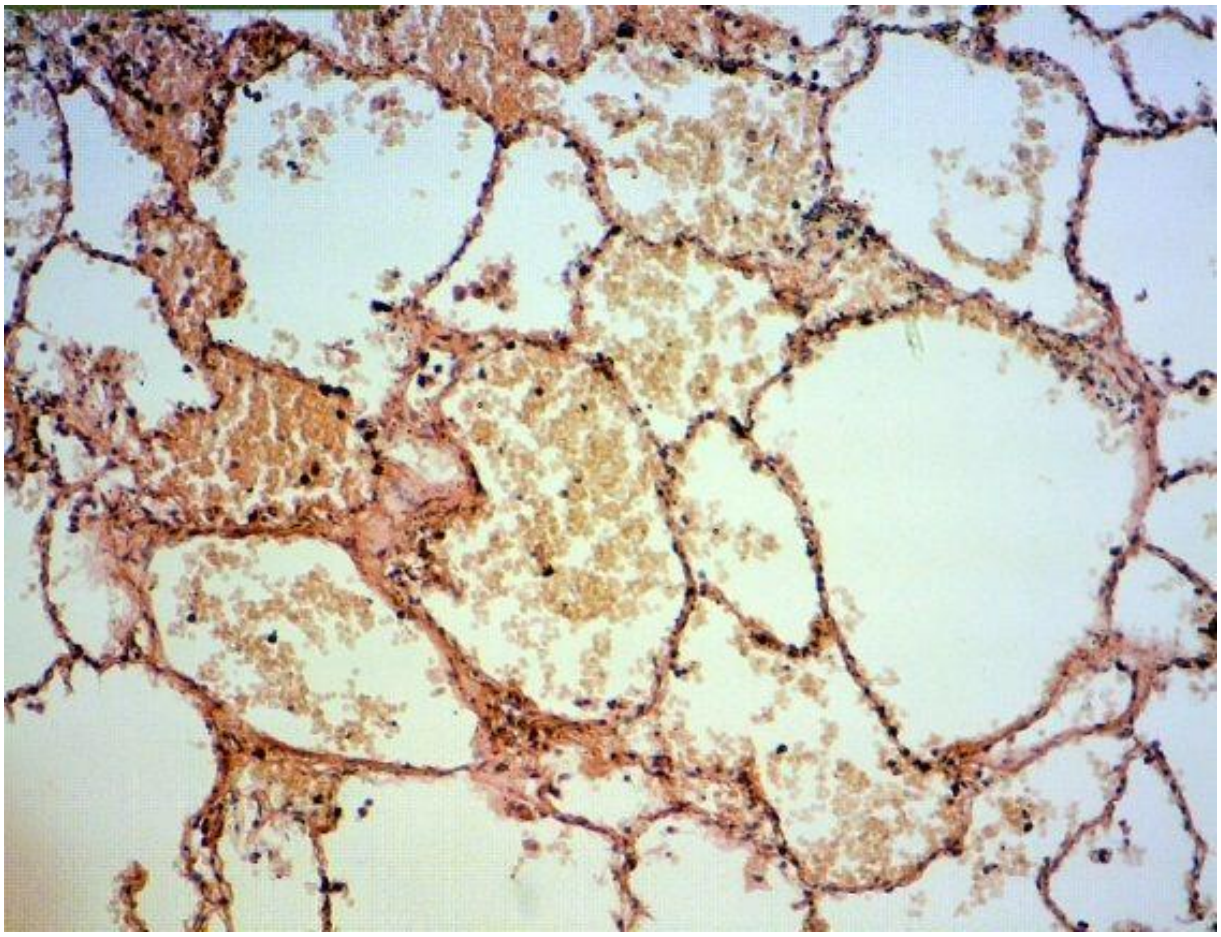


Figure 5. Recent pulmonary contusion with intra-alveolar haemorrhage; H&E, original magnification 10×20.

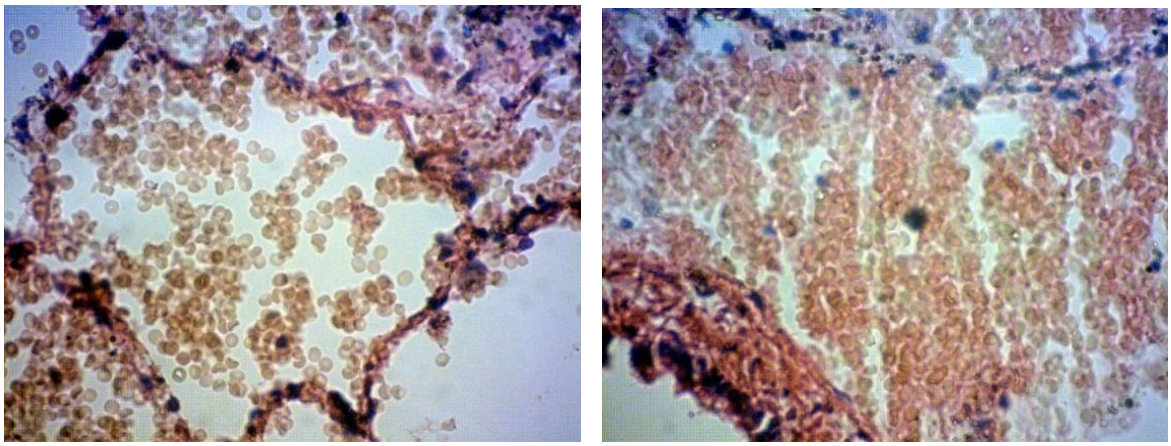


Figure 6. Recent pulmonary contusion with intra-alveolar haemorrhage; H&E, original magnification 10×40.

Between approximately two and twenty-four hours, polymorphonuclear leukocytes begin to marginate and migrate. By twelve to twenty-four hours, neutrophils and fibrin strands may be present within septa and alveolar spaces, accompanied by desquamation of type I and type II pneumocytes. During the next two to three days, hyaline membranes can develop as part of diffuse alveolar damage, and macrophages progressively replace neutrophils and phagocytose erythrocyte debris.

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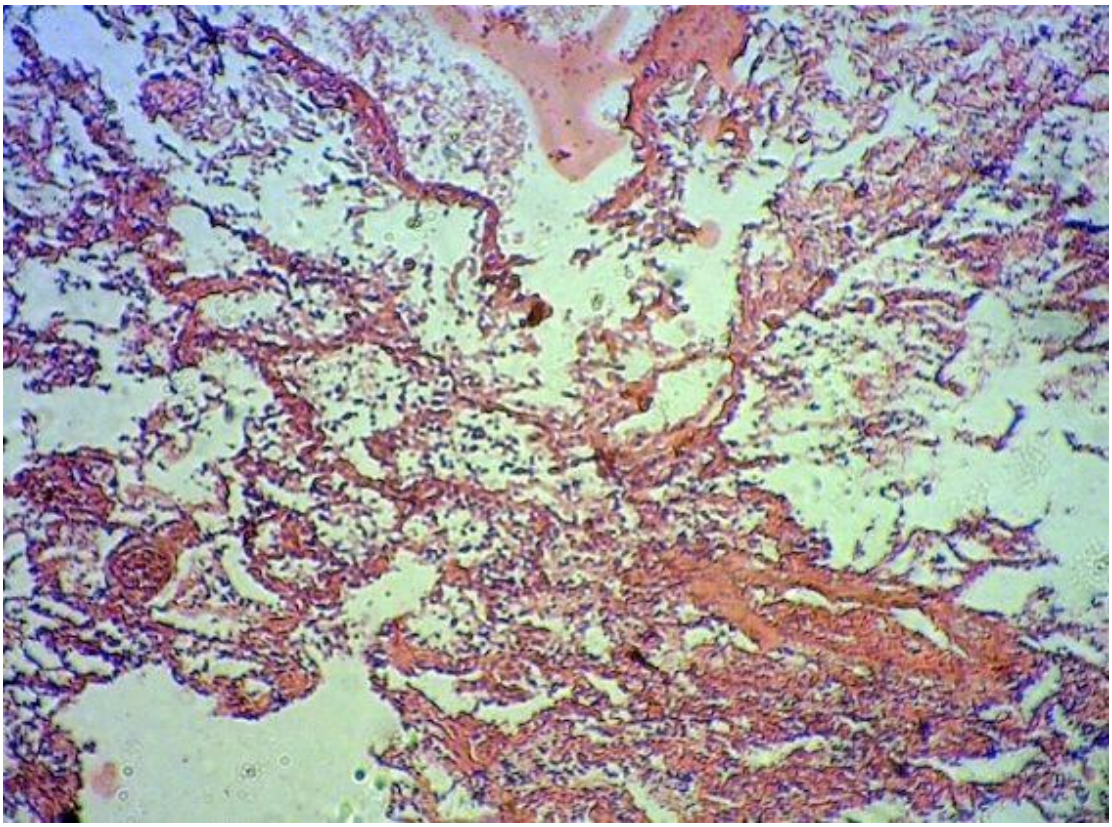


Figure 7. Recent pulmonary contusion with haemorrhage and traumatic emphysema; H&E, original magnification 10×10.

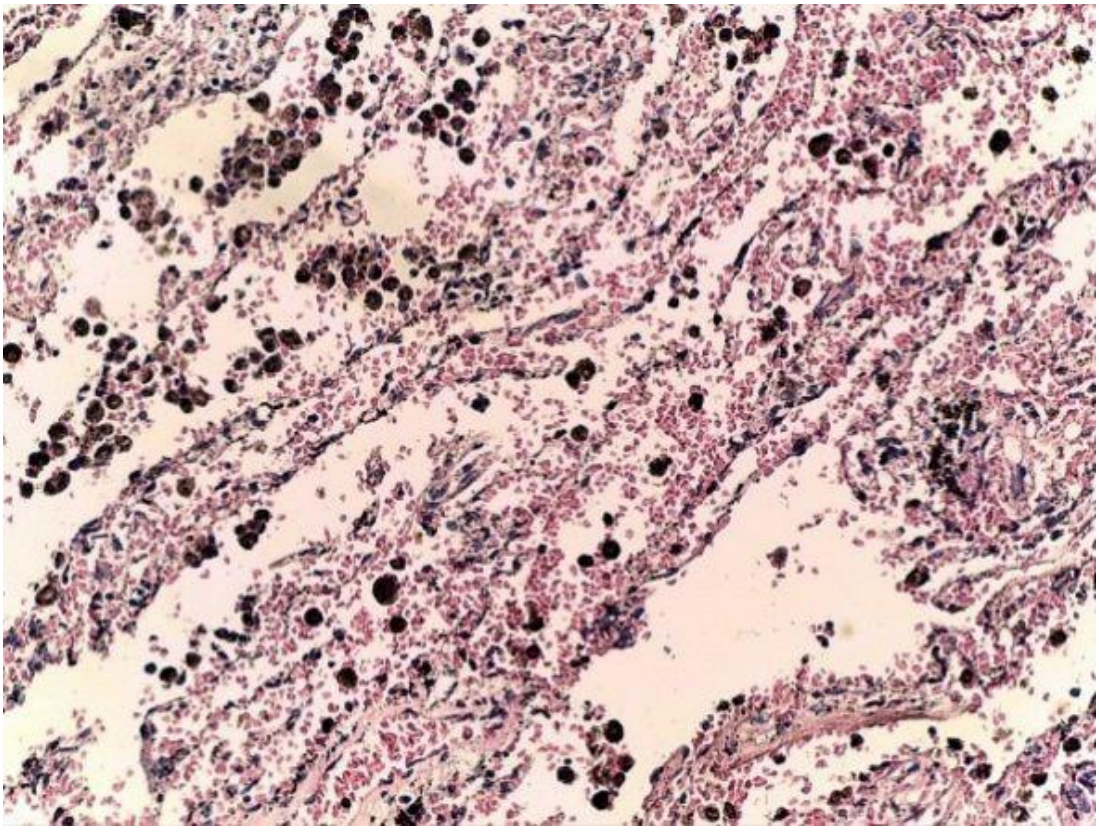


Figure 8. Evolving pulmonary contusion with siderophages in the alveoli; iron stain, original magnification 10×20.

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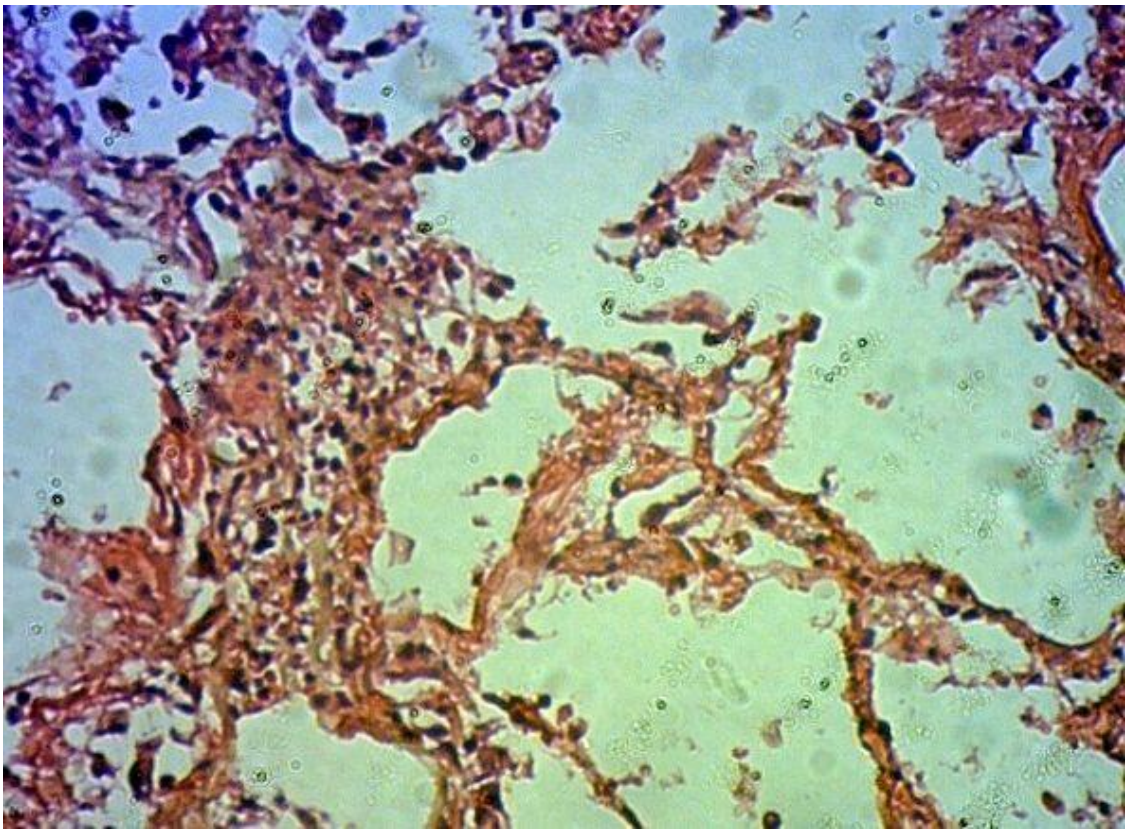


Figure 9. Evolving pulmonary contusion with thickened fibrotic alveolar walls and granulation tissue; H&E, original magnification 10×20.

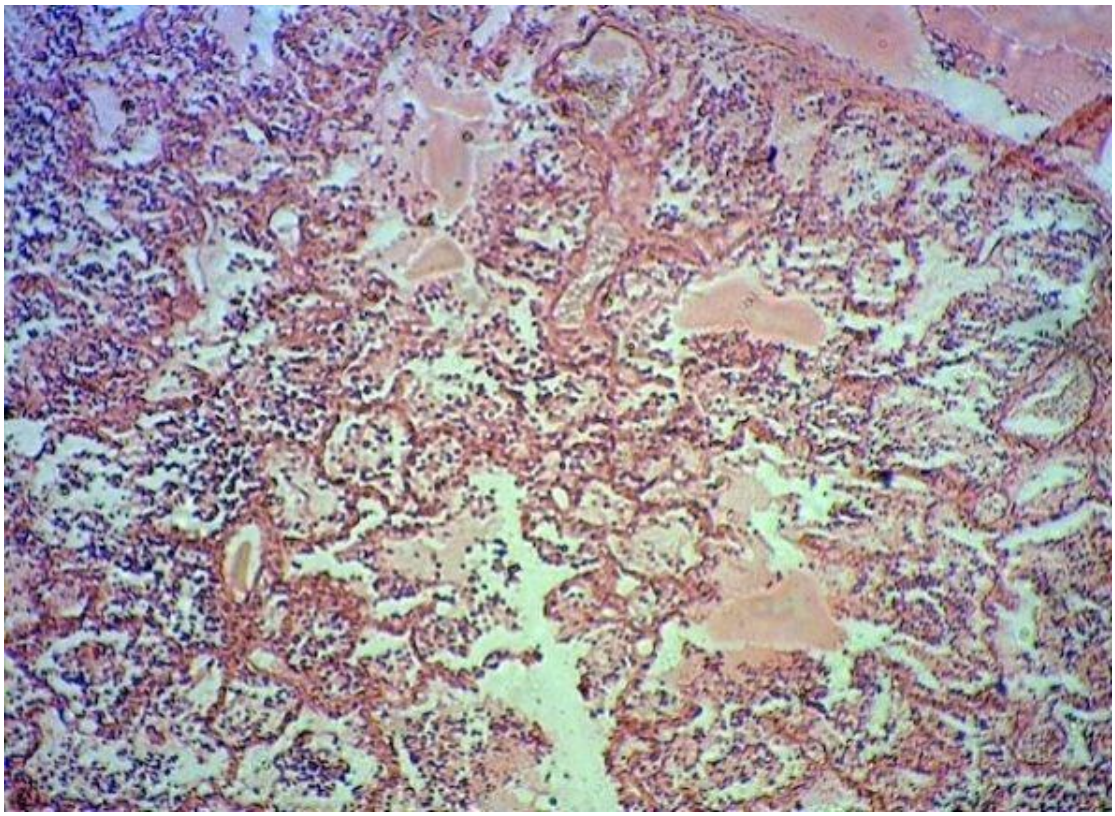


Figure 10. Post-traumatic contusion pneumonia; H&E, original magnification 10×10.

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When death occurs rapidly, pulmonary contusion may not be the principal pathogenetic factor. With survival, however, the contused area can become the substrate for post-contusion pneumonia, diffuse alveolar damage, acute respiratory distress syndrome, abscess formation, or fibrosis.

2.2.7. Criteria of Vital Reaction

Demonstrating that pulmonary injury occurred during life is a central forensic question. Active haemorrhage extends under circulatory pressure into alveolar spaces, and inflammatory cells may be identified at the periphery when survival time permits. Passive post-mortem congestion or artefactual haemorrhage is more limited and lacks a vital cellular response.

Aspiration of blood into distal bronchioles and alveoli remote from the direct lesion supports preserved respiratory activity. Blood in these regions may be mixed with air and appear frothy. Immunohistochemical markers such as P-selectin, E-selectin, ICAM-1, interleukins, and tumour necrosis factor may support vitality and approximate timing, but their interpretation requires validated methods, appropriate controls, and consideration of resuscitation and disease.

Fat droplets or bone-marrow emboli in pulmonary arterioles, demonstrated with suitable staining of frozen tissue, support functioning circulation after skeletal injury. No single marker should be used alone; macroscopic, microscopic, histochemical, and circumstantial evidence must be integrated.

2.2.8. Approximate Dating of Pulmonary Injury

The chronology of a contusion focus is estimated from combined macroscopic, microscopic, and histochemical criteria. The intervals below are approximate and must be interpreted together with clinical treatment, resuscitation, hypoxia, infection, age, and comorbidity.

Table 1. Morphological and histochemical criteria for approximate dating of pulmonary injury

Interval	Macroscopic changes	Microscopic changes	Histochemical / IHC indicators
0–30 min	Bright-red suffusions; superficial rib pattern	Intra-alveolar erythrocyte extravasation; interstitial oedema	Increased fibronectin immunoreactivity in the lesion
1–4 h	Parenchymal consolidation; dark-red cut surface	Initial leukocyte margination around vessels	Emerging IL-1β and TNF-α expression
4–12 h	Purple-black region; non-frothy blood on section	Marked neutrophilic infiltration and epithelial desquamation	Peak ICAM-1 and E-selectin expression
12–24 h	Loss of aeration and firm consistency	Leukocyte breakdown; early fibrin networks	Loss of cellular enzymes in the necrotic centre

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24–48 h	Grey-red colour	Hyaline membranes and macrophage infiltration	Positive fibrin reaction
3–5 days	Yellow-brown or greenish focus	Erythrophagocytosis, siderophages, and fibroblast proliferation	Positive iron reaction

2.2.9. Complications and Causes of Death

Immediate complications include massive blood loss from pulmonary or hilar vessels, tension pneumothorax, and reflex cardiorespiratory arrest. A valvular pleural lesion permits air to enter during inspiration but prevents its escape, leading to progressive mediastinal shift, diaphragmatic depression, impaired venous return, and collapse of the affected lung.

Early complications during the first twenty-four to forty-eight hours include traumatic asphyxia after severe thoracic compression, acute respiratory distress syndrome as the clinical expression of diffuse alveolar damage, and pulmonary fat embolism after fractures of long bones or the pelvis. Both direct parenchymal damage and systemic inflammatory responses contribute to respiratory deterioration.

Later complications include post-traumatic or aspiration pneumonia, pulmonary abscess, pleural empyema, organisation of intrapulmonary haematomas or pseudocysts, and pulmonary fibrosis. These complications may become the proximate cause of death after an interval of survival even when the initial contusion alone would not have been immediately fatal.

2.3. Published Quantitative Evidence

Statistical studies of motorcycle injury are more common than detailed reconstructions, but pulmonary outcomes are not coded consistently. Giovannini et al. (2024) reviewed 142 publications and reported substantial heterogeneity in injury patterns and reconstruction data. They emphasised the need to combine forensic, situational, and engineering evidence.

Ramezani et al. (2025) found that head-and-thorax injury was a frequent combination among polytraumatised riders and passengers, but their study was clinical and did not provide detailed kinematic reconstruction. Yakubu et al. (2024) identified a statistical relationship between rider and passenger injury severity, with a model correlation of 0.63, while several risk factors affected the two seating positions differently.

The four studies used for quantitative comparison include 8,372 injured persons. The samples are not homogeneous. Hsieh et al. (2017) and Burns et al. (2015) examined broad motorcycle-injury populations, whereas Hsieh et al. (2016) selected patients with severe hepatic and/or splenic injury and Hsieh et al. (2022) selected surgically treated bowel and/or mesenteric injury. In the latter studies, thoracic injuries were associated findings rather than the principal inclusion criterion.

2.4. Scientific Gap and Novelty

Two well-developed but insufficiently integrated scientific directions can be distinguished. Engineering and biomechanical research focuses on collision configuration, motorcycle stability, rider

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and passenger motion, body contacts, and mechanical loading. Clinical and forensic research focuses on injury type and severity, pulmonary diagnosis, prognosis, treatment, and mortality.

Far fewer studies trace the complete chain from crash mechanism through kinematics, contact, thoracic loading, and pulmonary injury. The reverse analytical step is even less developed: medical findings are seldom used as an independent test of a technically reconstructed sequence without being treated as deterministic proof of that sequence.

The novelty of the present study lies in a bidirectional model in which independently established kinematics and contact chronology are systematically compared with pulmonary findings. The medical evidence functions as a consistency criterion rather than as a stand-alone identifier of the crash mechanism.

METHODOLOGY

3.1. Research Design

The study comprises three components: a structured review of research on motorcycle kinematics and thoracic injury; comparative statistical systematisation of published clinical data when outcome definitions are sufficiently clear; and development of a bidirectional consistency model for potential application to anonymised expert cases. The design uses published medical evidence and does not create a new identifiable patient database.

The present study is primarily conceptual and methodological in nature. Its main objective is to develop an integrated analytical framework based on the synthesis of existing scientific evidence, rather than to conduct new empirical investigations or validate the proposed model through a series of individual accident cases. The quantitative analysis of previously published clinical data serves a supporting role, providing context for the proposed framework. Empirical validation through independently reconstructed cases remains a direction for future research.

3.2. Literature Selection

The literature search covered Scopus, Web of Science, and PubMed. Preference was given to peer-reviewed English-language papers indexed in Scopus or Web of Science. Eligible studies contained at least one of the following: motorcycle crash configuration, rider or passenger kinematics, thoracic or pulmonary trauma, forensic reconstruction, or quantitative injury data. Publications were assessed for sample definition, diagnostic grouping, mechanism description, and availability of absolute or relative frequencies.

3.3. Technical Reconstruction

For each expert case, the technical analysis should identify the pre-crash situation, motorcycle motion, loss of stability or collision, separation of rider and passenger, body trajectory, primary contact, secondary contacts, motion over the terrain, and final position. The reconstruction relies on road traces, motorcycle damage, deformation of other vehicles, final positions, photographs, road geometry, contact marks, video recordings, and other technical evidence contained in the case file.

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3.4. Bidirectional Reconstruction Model

A Forward analytical direction	B Reverse analytical direction
Crash mechanism	**Pulmonary injury finding**
↓	↓
Rider / passenger motion	**Type and region of injury**
↓	↓
Contact sequence	**Mechanically compatible loading**
↓	↓
Thoracic loading	**Possible contact phase**
↓	↓
Pulmonary injury	**Kinematic compatibility**
↓	↓
Comparison with medical findings	**Comparison with technical reconstruction**

Figure 11. Bidirectional model for integrated reconstruction of a motorcycle crash

In the forward direction, the sequence is crash mechanism → rider or passenger kinematics → contact sequence → thoracic loading → pulmonary injury. In the reverse direction, the sequence is pulmonary findings → mechanically compatible loading → possible contact phase → comparison with the independently reconstructed technical mechanism.

3.5. Consistency Classification

After independent technical and forensic-medical assessment, a case may be classified as consistent, partially consistent, discordant, or indeterminate. The classification measures internal mechanical consistency between two groups of evidence; it does not determine legal correctness or substitute for the court's evaluation.

Table 2. Matrix for testing reconstruction consistency

Technical indicator	Forensic-medical indicator	Relationship assessed
Direction of contact	Laterality of injury	Spatial compatibility
Thoracic contact	Pulmonary and rib injury	Mechanical compatibility
Body trajectory	Distribution of injuries	Kinematic compatibility
Secondary contact	Secondary injury complex	Sequence compatibility
Contact with terrain or object	Blunt or contact injury	Post-impact compatibility

3.6. Statistical Analysis

Published clinical series were analysed using absolute and relative frequencies. The relative frequency of a given injury was calculated as follows:

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$$p = \frac{x}{n} \times 100 \qquad (1)$$

where n_i is the number of persons with the injury and n is the sample size. A 95% confidence interval was estimated using the Wilson method without continuity correction:

$$CI_{95\%} = \frac{\hat{p} + \frac{z^2}{2n} \pm z\sqrt{\frac{\hat{p}(1-\hat{p})}{n} + \frac{z^2}{4n^2}}}{1 + \frac{z^2}{n}} \qquad (2)$$

When only a rounded percentage was available in the original paper, the interval was calculated from the published proportion and sample size and marked as approximate. Because study design, inclusion criteria, and diagnostic categories differed, no meta-analytic pooling was performed.

For expert-case verification, the percentage of complete reconstruction consistency is calculated as:

$$C_{full} = \frac{N_{full}}{N_{eval}} \times 100 \qquad (3)$$

where N_C is the number of consistent cases and N_E is the number of evaluable cases. The combined indicator for complete and partial consistency is:

$$C_{combined} = \frac{N_{full} + N_{partial}}{N_{eval}} \times 100 \qquad (4)$$

where N_PC is the number of partially consistent cases. These indicators are applicable after a sufficiently documented series of independently reconstructed cases has been evaluated.

3.7. Ethical Considerations

The quantitative medical data were obtained from published scientific sources. Expert cases should be presented only in anonymised form and only to the extent required for analysis of technical and injury sequences. If unpublished identifiable medical material is included in a later version, the applicable ethics approval, waiver, and data-protection requirements must be satisfied before submission.

RESULTS AND DISCUSSION

4.1. Statistical Profile of Pulmonary and Thoracic Injury

Pulmonary and other thoracic injuries are recurring components of motorcycle polytrauma. Reported frequencies depend on the composition of the sample, injury severity, diagnostic method, and coding practice. Some studies report pulmonary contusion, pneumothorax, haemothorax, and

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haemopneumothorax separately; others combine them under broader categories such as pulmonary injury or haemo-/pneumothorax.

Table 3. Pulmonary and thoracic injuries in broad motorcycle-injury samples

Study	Sample	Pulmonary contusion / injury	Pneumothorax	Haemothorax	Haemo-/pneumothorax	Rib fractures
Hsieh et al., 2017	6,947	102 (1.47%)	146 (2.10%)	133 (1.91%)	112 (1.61%)	784 (11.29%)
Burns et al., 2015	1,252	9.07%	8.79% combined haemo-/pneumothorax	—	—	16.93% ribs/sternum

In the broad samples, rib and/or sternal fractures had the highest reported proportions: 11.29% in Hsieh et al. (2017) and 16.93% in Burns et al. (2015). Direct comparison of the other outcomes is limited because one study separated pulmonary and pleural diagnoses while the other used combined categories.

Table 4. Associated thoracic injuries in selected severe abdominal-trauma samples

Study	Sample	Pulmonary contusion / injury	Pleural injury	Rib fractures
Hsieh et al., 2016	101 motorcyclists with severe hepatic and/or splenic injury	5.0%	9.9% haemo-/pneumothorax	15.8%
Hsieh et al., 2022	72 motorcyclists with surgically treated bowel and/or mesenteric injury	12.5%	23.6% haemopneumothorax	19.4%

The selected abdominal-trauma samples showed higher proportions of associated thoracic injury. These values cannot be extrapolated to the overall motorcycle-injury population, but they demonstrate that chest and abdominal injuries can form part of one high-energy polytrauma complex.

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Table 5. Precision of published pulmonary and thoracic injury frequencies

Study and sample	Outcome	Frequency, %	95% CI
Hsieh 2017, broad	Pulmonary contusion	1.47	1.21–1.78
	Pneumothorax	2.10	1.79–2.47
	Haemothorax	1.91	1.62–2.26
	Haemopneumothorax	1.61	1.34–1.94
	Rib fractures	11.29	10.56–12.05
Burns 2015, broad	Pulmonary injury	9.07	7.60–10.79*
	Haemo-/pneumothorax	8.79	7.34–10.48*
	Rib/sternal fractures	16.93	14.96–19.11*
Hsieh 2016, selected	Pulmonary injury	5.0	2.13–11.07*
	Haemo-/pneumothorax	9.9	5.47–17.27*
	Rib fractures	15.8	9.99–24.19*
Hsieh 2022, selected	Pulmonary injury	12.5	6.72–22.08*
	Haemopneumothorax	23.6	15.30–34.60*
	Rib fractures	19.4	11.95–30.03*

The Wilson intervals are narrow for the large sample of Hsieh et al. (2017) and substantially wider for the selected samples of 101 and 72 patients. The high frequencies in those selected groups should therefore be interpreted cautiously.

A lack of interval overlap is not used as independent proof of a statistically significant difference because the samples and outcome definitions are not equivalent. The asterisk identifies approximate intervals derived from rounded published percentages.

In 2,499 reconstructed motorcycle-to-car collisions from the GIDAS database, pulmonary injuries represented 42% of serious thoracic injuries of AIS 3+ severity and rib fractures represented 48%. This finding supports analysis of pulmonary trauma in relation to collision configuration, rider or passenger kinematics, and contact chronology rather than as a purely clinical endpoint.

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4.2. Rider and Passenger

Rider or passenger position should be treated as an independent reconstruction variable. Ramezani et al. (2025) reported broadly similar overall injury patterns and in-hospital outcomes after adjustment for covariates, but this clinical similarity does not establish identical mechanical pathways. Yakubu et al. (2024) found a relationship between rider and passenger injury severity while also identifying different effects of demographic, road, and situational factors. Each person's motion and contacts must therefore be reconstructed separately.

4.3. Reconstructive Value of Pulmonary Trauma

Pulmonary trauma should not be interpreted as a unique imprint of a particular collision type. Its evidential value increases when laterality and regional distribution are considered together with rib fractures, external chest injury, an identified contact surface, and a reconstructed body trajectory.

The strongest inference is not generated by one diagnosis but by convergence among independently established signs. A unilateral contusion may be compatible with a lateral impact, but it becomes reconstructively persuasive only when the side and height of loading, vehicle deformation, clothing traces, chest-wall injury, and subsequent motion are concordant. Bilateral or diffuse findings may reflect multiple contacts, compression, pressure transmission, resuscitation, or complications and therefore require particular caution.

A complex motorcycle case published in 2025 combined post-mortem CT, the injury pattern, and kinematic analysis to reject an initial run-over hypothesis and support a different mechanism. This illustrates the value of interdisciplinary reasoning while also demonstrating that medical and technical evidence retain distinct domains of expertise.

4.4. Complex Technical and Forensic-Medical Expertise

The proposed model does not erase professional boundaries. The road-accident reconstruction expert determines vehicle motion, trajectories, contacts, and mechanical parameters. The forensic physician determines injury type, location, vitality, severity, and mechanically possible causation. Their shared question is whether the documented injuries are compatible with the independently reconstructed mechanical events. This question can be answered jointly without the engineer making medical diagnoses or the physician reconstructing vehicle dynamics.

4.5. Relevance to Transport Safety

Identification of crash configurations that produce harmful thoracic loading can contribute to the design of chest protectors, wearable airbag systems, motorcycle structures, roadside barriers, and injury-classification systems. It can also reveal secondary contacts that are underrepresented in conventional crash coding. Reconstruction thus has preventive value beyond its evidential role in litigation. More specifically, the proposed framework may contribute to:

- development and evaluation of thoracic protectors and motorcycle airbag systems;
- improvement of motorcycle and vehicle contact geometry;
- assessment of roadside protection systems for powered two-wheelers;
- more accurate coding of primary and secondary motorcycle-crash contacts;
- identification of injurious configurations suitable for simulation and controlled testing.

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4.6. Limitations

The approach has several limitations. Published medical series are heterogeneous in diagnostic definitions and crash description. Detailed technical reconstruction is available for only a limited number of cases. Similar pulmonary findings may arise from different mechanical processes, and multiple contacts can obscure the distinction between primary and secondary injury mechanisms. Treatment, resuscitation, survival interval, and pre-existing disease may modify the observed morphology. The consistency model therefore requires further testing in a larger independently reconstructed series.

CONCLUSION

A motorcycle crash is a dynamic system in which the initiating collision is only one phase of the injury-producing sequence. After separation from the motorcycle, rider and passenger may follow different trajectories and experience different primary and secondary contacts.

Pulmonary trauma is suitable for integrated analysis because of its clinical importance and the possibility of spatially characterising some lesions. It is not sufficiently specific to determine the crash mechanism independently. Reliable interpretation requires correspondence among technical traces, body kinematics, contact chronology, thoracic loading, and associated injuries.

The proposed bidirectional model uses two analytical pathways: technically reconstructed mechanism → expected mechanical loading → comparison with medical findings; and medical findings → mechanically compatible loading → comparison with technical reconstruction. Its scientific contribution is a structured procedure for mutual testing of independently established technical and forensic-medical evidence rather than a new deterministic injury marker.

The approach provides a reproducible framework for complex expertise and may also support the identification of harmful contact configurations relevant to motorcycle protection and road safety.

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