University of Hertfordshire

School of Engineering and Computer Science

Doctor of Philosophy

Innovative Design of External Airbag System for Improved Automotive Safety

PhD Thesis

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ABSTRACT

Pedestrians remain one of the most vulnerable groups of road users, facing substantial risks of injury and fatality in vehicle collisions. Despite advancements in vehicle safety technologies, pedestrian injuries remain severe due to direct impact with rigid vehicle structures. This study proposes an innovative external airbag system designed to mitigate these risks, particularly in scenarios involving insufficient braking.

The system consists of five strategically placed airbags integrated into the front of the vehicle, covering the bumper and bonnet These airbags deploy before impact, aiming to mitigate injury risks to the pedestrian's pelvis, torso, and head. An advanced sensor system detects imminent collisions through an electronic control unit (ECU), triggering deployment. The bumper airbag cushions the lower body, while the bonnet airbag shields the head from severe impact forces. This anticipatory deployment demonstrates a high capacity to reduce the severity of injuries in simulated conditions by dissipating impact forces and distributing energy over a larger surface area.

Simulation results demonstrate the system's effectiveness in reducing both peak impact forces and energy transfer during collisions. The bumper airbag reduces impact force by approximately 66.7%, while the bonnet airbag achieves a substantial reduction of approximately 96%. Comparative analysis between scenarios with and without airbags highlights their role in dissipating kinetic energy, ultimately lowering injury risk. These findings underscore the importance of integrating advanced passive safety systems into vehicle designs, particularly in urban environments where low speed but frequent collisions occur.

The novelty of this work lies in introducing an external airbag system tailored specifically for pedestrian protectionan area not yet comprehensively addressed in current vehicle safety standards. A multidisciplinary approach, integrating mechanical engineering, sensor technologies, and automotive design, ensures adaptability across varying traffic conditions and pedestrian behaviours. By bridging the gap between theoretical advancements and potential real-world applications, this research provides a conceptual framework for a scalable safety solution that aims to enhance pedestrian protection in road accidents.

In conclusion, the proposed external airbag system represents a promising advancement in pedestrian safety. Through extensive simulation and scaled validation, its potential efficacy in mitigating injury severity has been indicated. This study lays the foundation for future developments in vehicle safety, advocating for the adoption of external airbags as a critical component in pedestrian protection systems.

In this thesis, the term "external bumper airbag" is used to describe the proposed system, with "external airbag" and "pedestrian airbag" used interchangeably where appropriate.

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Chapter 1 Introduction

1.1 Background

Road safety, particularly pedestrian safety, presents a global public health and urban planning challenge. With increasing urbanisation, more individuals are at risk as pedestrians on roadways, especially in densely populated areas with high traffic volumes and limited infrastructure for safe walking. Pedestrian casualties, both fatal and non-fatal, constitute a substantial portion of global road safety statistics. According to the World Health Organisation (WHO), approximately 1.3 million lives are lost annually to road traffic incidents, with pedestrians comprising a considerable share of these fatalities. These incidents impose a significant burden not only on affected individuals and families but also on healthcare systems and economies at large [1].

1.1.1 Global Statistics on Pedestrian Fatalities and Injuries

Statistics on pedestrian fatalities vary significantly by region and income level. In many low- and middle-income countries, inadequate road infrastructure and safety measures contribute to disproportionately high pedestrian death rates. The WHO (2018) indicates that up to 45% of traffic-related deaths in low-income countries involve pedestrians, contrasting with 18-25% in high-income nations where pedestrian safety measures tend to be more advanced. Table 1.1 summarises fatality rates by region, illustrating these disparities:

Table 1.1 Pedestrian Fatalities and Their Proportion of Road Fatalities by Region
World Health Organization (WHO), Global Status Report on Road Safety, 2018

Region	Pedestrian Fatalities per 100,000 People	Percentage of Road Fatalities Involving Pedestrians
Africa	26.6	39%
Americas	15.6	22%
Eastern Mediterranean	19.9	30%
Europe	9.3	21%
South-East Asia	17.4	24%
Western Pacific	13.8	26%

1.1.2 Mechanisms of Pedestrian Injury in Vehicle Collisions

In vehicle-pedestrian collisions, injury mechanisms are primarily linked to the initial impact forces and subsequent interaction with the vehicle's rigid structures [2]. The typical injury patterns include head, torso, and lower extremity injuries as pedestrians contact the bonnet, bumper, and windshield [3]. Head injuries, often from direct contact with the windshield or bonnet, represent one of the most life-threatening consequences of such collisions [4]. Lower extremity injuries occur when striking the bumper, while upper body injuries, such as fractures and internal trauma, often result from secondary contact as the body is propelled onto the vehicle's bonnet or ground [5]. The lack of energy absorption mechanisms for pedestrians on vehicle exteriors compounds these injuries, as rigid structures exacerbate the impact forces.

Table 1.2 Injury Types, Primary Causes, and Impact Areas in Pedestrian-Vehicle Collisions
World Health Organization (WHO), Global Status Report on Road Safety, 2018

Injury Type	Primary Cause	Impact Area
Head injuries	Contact with bonnet, windshield	Bonnet, Windshield
Leg and pelvis injuries	Impact with bumper	Bumper
Chest injuries	Secondary impact due to body momentum	Bonnet, Vehicle Roof

These injury mechanisms underscore the importance of safety designs that accommodate pedestrians, as traditional vehicle structures lack pedestrian-specific protective features.

1.1.3 Current Vehicle Safety Technologies

The last few decades have seen significant advancements in vehicle safety technologies, primarily focused on protecting occupants within the vehicle [6]. Key systems include airbags, seatbelts, and newer innovations such as Advanced Driver Assistance Systems (ADAS) and Autonomous Emergency Braking (AEB) systems [7]. These technologies, while effective for vehicle occupants, offer limited protection to pedestrians outside the vehicle. Traditional airbags are designed to reduce occupant injury by absorbing collision forces within the cabin, yet they provide no mitigation for pedestrian injuries [8]. ADAS technologies, encompassing lane-keeping assistance and adaptive cruise control, enhance driver awareness and response time. However, most of these systems are still focused inwardly and do not directly address pedestrian safety [9]. Autonomous Emergency Braking (AEB) is a more recent innovation that has shown promise in reducing vehicle speeds prior to pedestrian impact. Although ADAS can detect pedestrians under certain conditions, such as daylight or slower traffic, its efficacy is limited in low-visibility scenarios and during complex, high-speed events [10].

Table 1.3 Safety Technologies, Primary Protection Focus, and Pedestrian Protection
World Health Organization (WHO), Global Status Report on Road Safety, 2018

Safety Technology	Primary Protection Focus	Pedestrian Protection
Airbags	Occupants	None
Seatbelts	Occupants	None
ADAS	Driver awareness and control	Limited
AEB	Reduced impact speed	Effective under ideal conditions

In sum, while there have been strides in automotive safety, especially within vehicle cabins, the protection of pedestrians remains a significant challenge. Current safety systems fall short in addressing pedestrian vulnerability due to the physical limitations of existing vehicle structures and the narrow focus of most occupant-centric technologies. Moving forward, urban planners, vehicle manufacturers, and policymakers must work in tandem to develop infrastructure and vehicle technologies that specifically address the unique needs of pedestrian safety. Further research into external airbag systems, pedestrian-detection (ADAS) advancements, and urban road designs can aid in mitigating this ongoing risk to pedestrian well-being.

1.2 Motivation/Rationale for the Research

1.2.1 Limitations of Current Safety Methods

Despite advancements in automotive safety, existing pedestrian protection technologies remain limited in effectiveness, often falling short of adequately reducing injury severity in vehicle-pedestrian collisions. External structures, such as bumpers and bonnet designs, are not optimized to absorb the impact forces exerted on vulnerable road users, particularly at critical impact zones such as the head, torso, and pelvic region. While these structures are essential for vehicle protection, their rigid design fails to provide the necessary cushioning effect for pedestrians. Autonomous emergency braking (AEB) and other driver assistance systems are primarily preventive measures and offer minimal protection once a collision becomes imminent. These limitations highlight the need for additional safety measures specifically designed to mitigate pedestrian injuries during impact.

1.2.2 The Potential of External Airbags

External airbags have emerged as a promising technology to enhance pedestrian safety by mitigating injury severity in vehicle-pedestrian collisions. These airbags are strategically designed to deploy over the vehicle's front exterior, particularly covering areas such as the bumper and bonnet. By providing an additional layer of cushioning, external airbags can absorb impact forces, reducing trauma to the pedestrian's head, torso, and pelvic region.

Research indicates that external airbag systems can significantly reduce injuries to pedestrians by providing protection to critical body regions. For instance, a study developed a front bumper airbag aimed at improving protection for pedestrians' lower extremities and pelvis. The test results demonstrated that the new bumper airbag significantly reduced injuries in these areas, providing a reference for future developments in front bumper systems [11].

Another innovative approach involves an external airbag system designed to safeguard pedestrians in cases of insufficient braking. This system includes five strategically positioned airbag modules integrated into the front bumper and bonnet of the vehicle, deploying upon collision detection to protect the pedestrian's pelvis, torso, and head. The bumper airbag cushions the lower body, while the bonnet airbag shields the head from severe impact forces. This anticipatory deployment significantly reduces the severity of injuries by dissipating impact forces and distributing energy over a larger surface area.

While these studies demonstrate the potential benefits of external airbag systems, current applications remain in their early stages. Further research is needed to evaluate their efficacy, deployment mechanics, and integration with other safety systems. The development of front-mounted airbag systems aims to extend the protective capabilities of current vehicle designs by covering the bumper and bonnet. This specific positioning is intended to maximize impact absorption at critical contact points, thereby enhancing pedestrian safety without compromising vehicle operation or aesthetics.

1.2.3 Relevance to Automotive Safety Standards and Legislation

In recent years, automotive safety standards have increasingly focused on pedestrian protection. Many governing bodies and regulatory organisations, such as the European New Car Assessment Programme (Euro NCAP) and the United Nations Economic Commission for Europe (UNECE), have introduced or recommended safety measures explicitly targeting pedestrian safety. Euro NCAP, for example, has adopted assessment criteria that evaluate a vehicle's ability to mitigate pedestrian injuries during an impact, influencing automakers to incorporate pedestrian-friendly designs.

The concept of external airbags aligns closely with these regulatory directions, as it offers a practical solution to pedestrian safety that directly addresses the gaps in current automotive design standards. Implementing external airbag systems could set a new precedent, encouraging automotive manufacturers to adopt more comprehensive pedestrian protection measures that extend beyond traditional passive and active safety technologies. Furthermore, as regulatory bodies begin to consider more rigorous pedestrian safety requirements, such technologies could eventually become essential for compliance with future safety standards.

By advancing the development of external airbag systems, this research not only supports current legislative goals but also contributes to an evolving safety landscape that prioritizes road users. The potential to influence both industry practices and regulatory frameworks further emphasizes the importance and relevance of this research in promoting a safer, more pedestrian-friendly transportation environment.

1.3 Research Gap

While existing research in pedestrian safety has led to various protective technologies, including ADAS, AEB, and traditional vehicle designs with pedestrian-friendly structures, substantial gaps remain in the application and development of external airbag systems. Current research on external airbag systems has primarily focused on early-stage experimental designs or computational models that provide limited real-world applicability. Furthermore, most existing designs lack comprehensive testing and validation under realistic conditions, which is critical for understanding their practical effectiveness in reducing pedestrian injuries.

Key gaps identified in the field include:

1. **Design Innovation:** The need for advanced airbag module designs that provide protection across various impact zones, particularly for the head, torso, and pelvic region.
2. **Modelling and Simulation:** A lack of sophisticated modelling approaches that can accurately simulate the complex biomechanics involved in pedestrian impacts and the protective effects of airbag deployment.
3. **Experimental Validation:** Limited real-world testing of external airbag systems, hindering the ability to evaluate their efficacy and reliability under diverse collision scenarios.

This research addresses these gaps by introducing a novel external airbag system with five strategically placed modules within the vehicle's front bumper, aiming to protect the pedestrian’s head, torso, and pelvic region. Through both experimental and computational approaches, this work will validate the effectiveness of the proposed airbag system and contribute valuable insights to the ongoing development of pedestrian safety technologies.

Problem Statement

This research aims to develop and validate a novel external airbag system that effectively reduces pedestrian injuries in vehicle collisions by shielding the head, torso, and pelvic region through five strategically positioned airbag modules within the vehicle's front bumper and bonnet. Equipped with sensitive ultrasonic sensors and automated deployment mechanisms, the system represents a critical step toward mitigating pedestrian fatalities and enhancing road safety for road users, particularly in scenarios involving insufficient braking.

Table 1.3a Summary of Experimental Assumptions and Scenarios

Parameter	Description	Value / Assumption
Vehicle Speed Range	Scaled experimental speeds corresponding to low-speed collision scenarios	~0.5 – 1.2km/h (scaled model)
Deployment Logic	Airbag deployment condition based on Time-to-Collision vs Time-to-Stop	Airbag triggers when TTC < TTS
Detection Method	Distance measurement using ultrasonic sensor	Threshold distance = 3cm
Pedestrian Model	Simplified rigid impact surface used in testing	Flat impact surface (scaled representation)
Collision Type	Frontal impact scenario	Controlled laboratory collision
Braking Condition	Represents insufficient or delayed braking response	Not full brake failure scenario
Scaling Approach	Geometric scaling of experimental rig	Approx. 1:10 scale model
Validation Scope	Type of validation performed	Proof-of-concept + analytical + FEA comparison

Table 1.3a summarises the key assumptions and experimental conditions used throughout this study, providing a consolidated reference for the methodological framework.

1.4 Aim/Objectives and Research Questions

1.4.1 Objectives of the Thesis

The primary objectives of this research are:

1. To develop a novel external airbag design positioned within the front bumper and bonnet of the vehicle to provide enhanced protection for pedestrians during collisions.
2. To evaluate the effectiveness of the external airbag system in reducing injury severity to the pedestrian's head, torso, and pelvic region through both computational simulations and experimental testing.
3. To identify and analyze key parameters that influence the performance of external airbag systems, such as material selection, deployment level, and distance threshold.
4. To investigate the integration of advanced sensor technology that triggers the airbag deployment upon collision detection, ensuring timely protection during impact.

1.4.2 Research Questions

This thesis will address the following research questions:

- How can an external airbag be designed to optimize impact absorption for pedestrian protection?
- What materials and deployment mechanisms are most effective for external airbag systems?
- How do sensor sensitivity and deployment timing influence the protective outcomes of an external airbag in real-world collision scenarios?
- To what extent can the proposed external airbag system reduce impact force in pedestrian-vehicle collisions?

1.5 Contribution to Knowledge

1.5.1 Practical Implications

This research introduces a novel external airbag system, a promising development that could significantly improve pedestrian safety in urban traffic environments where pedestrian-vehicle collisions remain prevalent. By focusing on a comprehensive design that shields the pedestrian's head, torso, and pelvic region, this system addresses the limitations of current passive and active safety mechanisms. Traditional bumpers, although designed to mitigate impact, are limited in reducing injury severity, especially to pedestrians. The proposed external airbag system, with its rapid deployment and strategic coverage, has the potential to fill this gap by providing an active protective layer before contact with the pedestrian occurs.

The practical implications of this research extend to influencing future vehicle safety standards. With the increase in global pedestrian fatalities, regulatory bodies may consider mandating pedestrian-focused safety technologies, encouraging automotive manufacturers to adopt systems such as external airbags. This could drive policy changes and promote the widespread implementation of advanced pedestrian protection systems across vehicle models.

1.5.2 Contribution to the Field

This research makes several contributions to the field of automotive safety technology, particularly in the development and evaluation of external airbag systems for pedestrian protection.

• **Development of a Prototype External Airbag System:**

A novel bumper-mounted external airbag prototype was designed and experimentally evaluated using a scaled test rig. The system integrates ultrasonic sensing, Time-to-Collision (TTC) and Time-to-Stop (TTS) logic, and an automated deployment mechanism controlled by Arduino-based electronics. Experimental testing demonstrated a substantial reduction in measured impact forces when the airbag was deployed compared with baseline conditions without airbag protection.

• **Quantitative Evaluation of Impact Force Reduction:**

Controlled laboratory experiments comparing collision scenarios with and without airbag deployment demonstrated significant mitigation of impact forces. The experimental results indicated a force reduction of approximately 68.5% under the tested conditions, demonstrating the potential effectiveness of external airbags in reducing pedestrian injury severity.

• **Integration of Experimental Testing and Finite Element Analysis:**

The study combines experimental validation with analytical modelling and finite element simulations to evaluate system behaviour. Finite Element Analysis (FEA) simulations conducted at 30km/h collision conditions showed impact force reductions of approximately 93.3% to 96.0%**,** supporting the experimental findings and providing additional insight into airbag energy absorption and deformation behaviour.

• **Conceptual Advancement in Pedestrian-Focused Airbag Deployment:**

Unlike existing production systems, which primarily protect the pedestrian's head and upper body after initial impact with the vehicle structure, the proposed system focuses on bumper-mounted deployment to mitigate the initial lower-body impact phase. This configuration addresses a critical stage of pedestrian collision dynamics and highlights the potential benefits of integrating bumper-level protection with conventional upper-body airbag systems.

In summary, this research contributes to the advancement of pedestrian protection technologies by developing and evaluating a prototype external airbag system, demonstrating measurable reductions in impact forces, and providing analytical and numerical insights into airbag deployment dynamics. These findings support the feasibility of external airbag concepts as a complementary safety technology for improving pedestrian protection in urban collision scenarios.

This contribution is further strengthened by the study's combined use of prototype development, controlled experimental testing, analytical modelling, and simulation-based validation. Together, these elements provide a structured and multi-layered framework for evaluating the effectiveness of external airbag systems under both simplified laboratory conditions and higher-speed collision scenarios. The integration of physical testing with analytical and numerical approaches improves the overall reliability of the findings, supports cross-validation between methods, and provides a clearer understanding of deployment behaviour, deformation response, and impact-force attenuation. In addition, the study establishes a practical basis for future refinement of sensor-triggered deployment strategies, airbag geometry, and material selection in pedestrian-focused safety applications. By combining proof-of-concept development with broader performance assessment, the research offers a useful reference point for future work in this area and supports the continued development of external airbags as a realistic complementary safety measure for reducing pedestrian injury risk in urban vehicle-pedestrian collisions.

Chapter 2 Literature Review

2.1 Introduction

2.1.1 Introduction to External Airbag Technology in Automotive Safety

External airbags represent a significant advancement in automotive safety, extending protection beyond the vehicle's interior to safeguard vulnerable road users, such as pedestrians and cyclists. Unlike conventional internal airbags, which are designed primarily to protect vehicle occupants during internal collisions, external airbags are engineered to mitigate impacts with external entities, including pedestrians and cyclists, in frontal, side, and multi-impact crashes. This enhanced level of protection is crucial in reducing pedestrian fatalities, which constitute a substantial portion of global road traffic deaths, particularly in areas with high pedestrian activity [14].

The core function of external airbag systems is to minimize injury severity by absorbing collision forces before they reach pedestrians or the vehicle's structure. This is achieved through a combination of sophisticated deployment algorithms, high-sensitivity sensor technologies, and advanced material engineering [15]. However, despite their promising potential, external airbags remain relatively underexplored in both academic research and practical implementation due to challenges related to deployment timing, cost-effectiveness, and reliability in diverse accident scenarios [16]. In particular, many studies rely on simplified simulations or conceptual models, which limits confidence in real-world applicability.

Since their introduction in the 1970s, airbag systems have evolved significantly, advancing from simple inflation mechanisms to highly sophisticated safety solutions capable of dynamically responding to various crash scenarios. While internal airbags effectively protect vehicle occupants, they offer limited protection in external collisions, particularly those involving pedestrians. Recent studies emphasize the growing significance of external airbags in mitigating pedestrian injuries and enhancing safety in multi-impact crash scenarios [17]. However, these studies often focus on specific performance aspects rather than evaluating full-system behaviour under realistic conditions.

The integration of advanced sensor technologies has been instrumental in this evolution. Early airbag systems primarily relied on mechanical impact detection, which often lacked precision in deployment timing. In contrast, modern systems incorporate accelerometers, gyroscopes, lidar, and vision-based sensors, significantly improving collision detection accuracy and enabling airbag deployment within milliseconds [18]. While these technologies improve detection capability, they introduce challenges related to environmental robustness, sensor fusion complexity, and false triggering, which are not always fully addressed in existing research.

External airbags are particularly effective in frontal and side collisions, where conventional safety systems may be insufficient. By absorbing impact energy, these airbags help minimize the severity of head, torso, and pelvic region injuries, as demonstrated in recent experimental research [19]. Studies have highlighted the advantages of combining advanced deployment algorithms with lightweight materials, such as polyurethane composites, to optimize energy absorption while maintaining cost efficiency [20]. Nevertheless, much of this work is based on controlled conditions, which may not fully represent real-world pedestrian impact dynamics.

Research has also underscored the importance of integrating multiple sensor modalities to enhance detection accuracy. For instance, combining radar and lidar technologies has been shown to improve object classification and reduce false positives, a key challenge in external airbag deployment [21]. However, improved sensing alone does not guarantee effective protection, as deployment success also depends on timing, trigger thresholds, and the biomechanical interaction between the pedestrian and the vehicle, which are often not comprehensively addressed.

Additionally, artificial intelligence (AI) has emerged as a promising tool for improving airbag deployment timing and reliability. Studies on deep learning-based collision detection suggest that neural networks can enhance predictive accuracy, ensuring that external airbags deploy only in genuine collision scenarios. Machine learning models have demonstrated significant improvements in optimizing deployment mechanisms, reducing the likelihood of false activations [22]. However, many of these approaches remain at a conceptual or simulation stage, with limited experimental validation in safety-critical applications. In this thesis, AI and advanced sensing technologies are reviewed to inform system design; however, the implemented approach is based on ultrasonic sensing combined with TTC/TTS logic, as detailed in Chapters 3 and 5.

2.1.2 Rationale for Further Research

Despite significant progress, several challenges remain in the development and implementation of external airbag systems. Key areas requiring further investigation include:

- **Sensor Integration:** Improving multi-sensor fusion techniques using radar, lidar, and AI-based object detection for increased reliability across different crash scenarios.
- **Cost and Material Efficiency:** Developing cost-effective yet high-performance materials for external airbag applications to enhance feasibility in production [23].

- **Optimizing Deployment Timing:** Enhancing accuracy to prevent premature or delayed deployment in dynamic environments [24].
- **Real-World Validation:** Conducting large-scale testing to evaluate external airbag effectiveness under real-world traffic conditions and addressing regulatory gaps [25].

As existing research suggests, overcoming these challenges is essential to maximizing the potential of external airbags in improving automotive safety and reducing pedestrian fatalities.

2.2 Evolution of Active Safety Systems and External Airbags

Active safety systems are designed to prevent accidents before they occur, and their integration with external airbags has significantly advanced the field of automotive safety. These systems, including technologies such as Advanced Driver Assistance Systems (ADAS), Automatic Emergency Braking (AEB), pedestrian detection, and lane-keeping assist, mark a shift from reactive to proactive safety measures. When combined with external airbags, these technologies aim to enhance both vehicle and pedestrian protection by reducing the likelihood of collisions and mitigating injury severity when accidents occur.

2.2.1 Active Safety Systems and Their Role in Accident Prevention

Active safety technologies help prevent accidents by either assisting drivers in navigating dangerous situations or automatically taking corrective actions when necessary. Systems like pedestrian detection and AEB are particularly relevant to external airbags, as they play a crucial role in identifying pedestrians or obstacles in the vehicle's path, triggering the deployment of external airbags. By anticipating crashes and reducing impact speeds, these systems enhance the effectiveness of external airbags in protecting pedestrians. For example, ADAS and AEB systems can detect an impending collision with a pedestrian and automatically apply the brakes to reduce impact speed. When combined with external airbags, which deploy to cushion the impact, these technologies offer an additional layer of protection. Lane-keeping assist and adaptive cruise control further enhance the vehicle's ability to avoid collisions by adjusting steering and speed in real-time based on sensor input. Together, these systems help reduce accident occurrences and improve safety for both vehicle occupants and pedestrians [26].

2.2.2 Use of AI and Sensor Technologies in Active Safety

The integration of artificial intelligence (AI) and advanced sensor technologies has significantly enhanced the capabilities of modern active safety systems. Contemporary vehicles utilise combinations of LiDAR, radar, and camera-based systems to detect objects and interpret complex driving environments in real time. These technologies enable vehicles to identify pedestrians, cyclists, other vehicles, and traffic infrastructure, supporting more informed and timely decision-making processes [27][28].

LiDAR systems, for example, provide high-resolution spatial mapping using laser-based measurements, allowing accurate detection of objects even under low-visibility conditions such as fog or nighttime driving [27]. Radar systems complement this by offering robust performance in adverse weather conditions and enabling early detection of objects beyond the vehicle's immediate field of view. Camera-based systems, when combined with computer vision algorithms, facilitate object classification and scene understanding, which are critical for distinguishing pedestrians from other obstacles [28].

Artificial intelligence plays an increasingly important role in processing sensor data and predicting potential collision scenarios. Machine learning and deep learning models can analyse large volumes of data to improve object recognition accuracy and optimise decision-making processes. These approaches have shown promise in enhancing collision prediction and reducing false positives, thereby improving the reliability of safety systems.

However, despite these advancements, several limitations remain. Many AI-based approaches are computationally intensive and require significant processing resources, which can introduce latency in real-time applications. Furthermore, the majority of studies are based on simulation environments or controlled datasets, with limited validation under real-world driving conditions. As a result, the reliability of AI-driven systems in safety-critical scenarios remains an area of ongoing research.

In addition, integrating multiple sensor modalities introduces challenges related to sensor fusion, data consistency, and system robustness under varying environmental conditions. Ensuring reliable performance across diverse scenarios, including complex urban environments, remains a significant challenge that is not fully addressed in the existing literature.

In the context of this thesis, AI and advanced sensor technologies are reviewed to provide a comprehensive understanding of current developments and future opportunities in external airbag systems. However, the implemented system focuses on a simpler and more robust approach based on ultrasonic sensing combined with Time-to-Collision (TTC) and Time-to-Stop (TTS) logic, as described in Chapters 3 and 5. This approach prioritises reliability, real-time feasibility, and experimental validation within the scope of the study.

2.2.3 Integration of External Airbags with Active Safety Technologies

The integration of active safety systems with external airbags has significantly expanded the protective capabilities of these systems. Initially, external airbags focused primarily on providing passive protection by cushioning pedestrians during impact. However, with the integration of active safety technologies, external airbags now deploy more effectively by considering real-time data inputs from sensors and AI. This synergy ensures that both vehicle occupants and vulnerable road users are better protected in a wider range of collision scenarios.

Research into pedestrian impact dynamics has also informed the development of external airbags. For example, Barbat et al. (2016) used spring-mass models and finite element analysis to optimize the design of airbags for pedestrian protection. These methods, coupled with advancements in sensor technologies and AI, have led to more responsive and cost-effective external airbag systems, ensuring that they protect pedestrians in both low- and high-speed collisions [29][30].

As external airbags continue to evolve, their integration with AI-driven active safety systems will likely become more sophisticated. Future research will focus on improving pedestrian detection algorithms, enhancing sensor fusion techniques, and ensuring airbags deploy accurately in various accident scenarios with minimal false triggers.

However, many published studies focus on the theoretical integration of these technologies rather than validating complete external airbag systems under realistic impact conditions, which limits confidence in their practical effectiveness.

2.2.4 Advancements in External Airbag Design and Deployment

Recent research has significantly advanced the design and deployment of external airbags. For instance, Maroney et al. (2015) explored advanced materials and innovative deployment mechanisms to enhance the effectiveness of these systems. By optimizing airbag shape, size, and inflation time, researchers aim to provide maximum protection to pedestrians across a range of impact scenarios [31].

However, these design improvements are often assessed under controlled or idealised conditions, and their performance under variable real-world impact geometries remains insufficiently demonstrated.

2.2.5 The Role of AI in Optimizing External Airbag Deployment

AI plays a crucial role in optimizing external airbag deployment. Lee et al. (2018) investigated the use of machine learning algorithms to analyze sensor data and predict potential collisions. By accurately identifying the severity and type of collision, AI can trigger the deployment of external airbags at the optimal moment, maximizing their protective benefits [32].

Nevertheless, the reliability of AI-driven deployment decisions in safety-critical real-time environments remains dependent on robust validation, which is still limited in much of the current literature.

2.2.6 Future Directions for External Airbag Technology

Future research in external airbag technology is likely to focus on further integrating these systems with ADAS. By combining ADAS capabilities with the protective benefits of external airbags, researchers aim to develop vehicles that can proactively prevent accidents and mitigate injuries in the event of a collision. Zhang et al. (2015) proposed a framework for integrating external airbags with ADAS to achieve a higher level of vehicle autonomy and safety [33].

Although promising, such integrated frameworks remain challenging to implement in production vehicles due to cost, system complexity, and the need for dependable real-world validation.

2.3 Passive Safety Systems

Passive safety systems are integral to reducing injury severity in the aftermath of a collision by either absorbing impact forces or shielding occupants from harmful forces. These systems are independent of any direct driver or passenger intervention, distinguishing them from active safety systems. Activated automatically during a crash, passive safety mechanisms protect both vehicle occupants and pedestrians. Key components of passive safety include crumple zones, seatbelts, internal airbags, and vehicle designs that prioritize pedestrian protection.

2.3.1 Crumple Zones

Crumple zones are engineered areas of a vehicle designed to deform in a controlled manner upon impact, absorbing energy and limiting the transfer of excessive force to the vehicle's occupants. First popularized by Mercedes-Benz in the 1950s, crumple zones remain a critical aspect of vehicle safety design, typically positioned at the vehicle’s front and rear. These zones are made from materials that undergo controlled deformation during a collision. According to research by Zhang et al. (2018), optimizing crumple zones, in combination with other safety features, plays a significant role in reducing the severity of injuries during frontal impacts [34].

2.3.2 Seatbelts

Seatbelts are among the most foundational and essential passive safety features. They serve to restrain occupants in their seats during a crash, preventing excessive movement that could result in severe injuries. Modern seatbelt systems are equipped with advanced features such as pre-tensioners, which tighten the belt in the event of a collision, and load limiters, which prevent excessive pressure on the occupant's chest. Harrison and Liley(2020) highlighted that advancements in seatbelt technology, particularly the incorporation of sensors to adjust belt tension, have led to a marked reduction in fatalities, with a decrease of up to 50% [35].

2.3.3 Internal Airbags

Internal airbags are one of the most widely recognized passive safety mechanisms, deploying during a collision to cushion occupants and reduce the risk of injury from impacts with the vehicle’s interior structures, such as the steering wheel, dashboard, or side windows. Barrett et al. (2021) traced the evolution of internal airbags, noting the development of side airbags, curtain airbags, and knee airbags, each designed to protect against specific types of injuries in various crash scenarios. Recent advancements have focused on optimizing airbag deployment algorithms to ensure airbags are deployed at the optimal time, based on crash severity and occupant positioning [36].

2.3.4 Vehicle Design for Pedestrian Protection

The importance of vehicle design for pedestrian protection has grown significantly in recent years as manufacturers work to reduce pedestrian fatalities in collisions. Innovations such as energy-absorbing bonnets, soft bumper materials, and redesigned front-end structures aim to decrease the severity of injuries to pedestrians. Research by Smith and Thompson (2019) demonstrated that using softer materials, such as foams and polymers, in the vehicle's front-end structure can substantially reduce head and leg injuries in pedestrian accidents. Additionally, the incorporation of active bonnet systems, which elevate the bonnet upon impact, has shown promise in further mitigating the risk of head injuries [37].

2.3.5 Advancements in Crumple Zone Design

Recent studies have explored new strategies to optimize crumple zone design. Matthews et al. (2017) investigated advanced materials and innovative geometries to improve energy absorption during collisions. By refining the deformation patterns of crumple zones, researchers aim to reduce the impact forces transmitted to the vehicle's occupants [38].

2.3.6 The Role of AI in Seatbelt Technology

Artificial intelligence is poised to revolutionize seatbelt technology. Papalambros et al. (2019) proposed leveraging machine learning algorithms to analyze sensor data and dynamically adjust seatbelt tension in real-time. By adapting to the unique characteristics of each occupant and the severity of the crash, AI-powered seatbelts can provide a higher level of protection during collisions [39].

2.3.7 Future Directions for Pedestrian Protection

Future research into pedestrian protection will likely focus on further integrating active and passive safety systems. Rosenberger et al. (2020) suggested that combining advanced pedestrian detection technologies with innovative vehicle designs could reduce the severity of pedestrian injuries even further. By proactively identifying potential hazards and triggering protective systems, these integrated safety mechanisms have the potential to significantly enhance overall road safety [40].

2.4 External Airbag Systems

External airbags constitute a pioneering innovation in automotive safety, engineered to deploy externally prior to a collision, thereby providing an additional protective mechanism for both vehicle occupants and pedestrians. In contrast to conventional internal airbags, which activate within the vehicle to mitigate occupant impact against the interior structure, external airbags are designed to absorb or deflect impact forces externally. Their principal function is to attenuate injury severity by cushioning either the pedestrian or the vehicle upon impact, thus contributing to enhanced road safety.

2.4.1 Purpose and Design Differences

The main goal of external airbags is to create a protective barrier between pedestrians or other road users and the vehicle. These airbags are designed to deploy prior to impact, cushioning the pedestrian and reducing injury severity. A key difference between internal and external airbags lies in their design and functionality. Internal airbags are located within the vehicle's interior, deploying upon occupant collision with hard surfaces such as the steering wheel or dashboard. In contrast, external airbags are mounted on the exterior of the vehicle, typically covering the vehicle's front-end area, including the bonnet, bumper, and sometimes even the sides. These systems are designed to activate during pedestrian or side-impact collisions [41].

2.4.2 Existing External Airbags and Front Airbags for Pedestrians

The Volvo V40 was one of the first production vehicles to incorporate a pedestrian airbag system, representing a significant step toward external airbag deployment in real-world automotive applications. This system deploys an airbag from the rear edge of the bonnet upon detecting a pedestrian impact, covering the lower windshield and A-pillars. Its primary purpose is to reduce head and upper-body injury severity by cushioning the impact between the pedestrian and relatively rigid upper vehicle structures [42].

While this system demonstrates the feasibility and effectiveness of external airbag deployment in production vehicles, its protective coverage is largely limited to the upper body region, particularly the head and torso after initial contact. It does not provide direct protection at the bumper level, where the pedestrian's lower limbs and pelvis typically experience the first and often most critical impact. This limitation is significant because lower-body impacts strongly influence pedestrian kinematics, subsequent upper-body motion, and overall injury severity.

Other manufacturers, including Mercedes-Benz and BMW, have explored variations of external or semi-external airbag systems aimed at improving deployment speed and expanding protection coverage. These systems often focus on optimizing deployment mechanisms or integrating additional side protection features [42]. However, much of the existing work remains focused on partial protection strategies rather than providing comprehensive full-body coverage. Furthermore, many studies lack detailed comparative evaluation of different deployment locations, making it difficult to assess the relative effectiveness of alternative system configurations.

In addition, existing external airbag systems are often designed with specific vehicle geometries and packaging constraints in mind, limiting their generalisability across different vehicle types. This raises important challenges in scalability and practical implementation, particularly when considering variations in bumper height, bonnet length, and vehicle front-end design.

These limitations highlight a key gap in current external airbag research and implementation. In particular, the absence of direct protection at bumper level represents a critical deficiency, as it fails to address the initial impact phase of pedestrian collisions. The system proposed in this thesis addresses this gap by introducing a bumper-mounted external airbag configuration, designed to provide early-stage impact mitigation for the lower limbs and pelvis while complementing upper-body protection mechanisms. This approach enables a more broad protection across the analysed regions strategy that considers the full sequence of pedestrian impact dynamics.

2.4.3 Deployment and Triggering Mechanisms

The triggering of external airbags relies on sophisticated sensing and control systems that can accurately detect potential collisions. Most systems employ a combination of sensors, including accelerometers, Radar, LiDAR, and cameras, to detect changes in speed, impact direction, and proximity to pedestrians or other vehicles. These sensors feed data into the vehicle's central control system, which processes the information in real time to assess whether deployment is necessary.

Once a collision risk is detected, the airbag system's deployment mechanism is activated. This mechanism typically inflates the airbags using compressed gas or pyrotechnic devices, depending on the system design. For example, the Volvo V40's pedestrian airbag system deploys from the rear of the bonnet to cover the area between the pedestrian's head and the windshield. In addition to the sensors, the design of the external airbag incorporates considerations such as rapid deployment speed, robustness against environmental conditions, and integration with vehicle structures like the bonnet and bumper [43].

2.4.4 Side Airbags for Vehicle Protection

Side airbags, designed to protect vehicle occupants during side-impact collisions, have become an essential part of vehicle safety systems. In the context of external airbags, some manufacturers have extended the use of side airbags to pedestrian safety. These airbags deploy from the vehicle's sides, typically from the

doors or lower sections of the side panels, to cushion pedestrians in side-impact scenarios. Such systems are critical in preventing severe lower-body injuries when pedestrians are struck by the vehicle's side.
For example, Mercedes-Benz has implemented side airbags in their vehicles that deploy during side-impact collisions and have also explored their use in pedestrian protection. These airbags cover the vehicle's lower side areas, providing a cushioning effect for pedestrians who might otherwise suffer serious injuries to their pelvis or torso. BMW has similarly developed side protection airbags integrated with pedestrian safety systems, ensuring broad-spectrum protection across multiple collision scenarios [44].

2.4.5 Challenges and Limitations

Despite the promising potential of external airbags, several challenges and limitations must be addressed before they can be fully integrated into mainstream vehicle safety systems.

1. **Triggering Mechanisms:** One of the main challenges is the reliability and accuracy of triggering mechanisms. False triggers could lead to unnecessary deployments, adding cost and complexity to the system, while missed triggers could result in ineffective protection in critical moments. Ensuring that sensors can accurately distinguish between different types of collisions, such as pedestrian impacts versus minor vehicle-to-vehicle collisions, is essential for system effectiveness.
2. **Design and Packaging:** Integrating external airbags into vehicle designs presents packaging challenges, especially with modern vehicles where space is limited. Airbags need to be housed in compact modules that do not compromise vehicle aesthetics or performance. These systems must also be durable enough to withstand environmental factors such as heat, moisture, and UV exposure.
3. **Cost:** External airbags remain relatively expensive due to the development and production costs of sophisticated sensors, gas inflators, and durable materials. This cost can act as a barrier to mass adoption, with manufacturers needing to balance the cost of these systems against their effectiveness.
4. **Weight and Maintenance:** The added weight of external airbags and their components could affect vehicle fuel efficiency and overall performance. Additionally, these systems require regular maintenance, such as checks for sensor calibration and ensuring the airbag system is ready to deploy.

2.4.6 Conclusion

External airbags represent a promising innovation in automotive safety, offering vital protection for both pedestrians and vehicle occupants. However, challenges related to design, reliability, cost, and maintenance remain, requiring further research and development to optimise their integration into vehicles. As studies by Yin et al. (2017) and Gupta and Yang (2013) have shown, variations in vehicle design, particularly front-end profiles, play a crucial role in reducing the severity of head injuries in pedestrian accidents. The combination of advanced safety features, such as external airbags, with optimal vehicle design could significantly reduce the impact and severity of pedestrian injuries in collisions, contributing to overall road safety advancements [45][46].

2.5 Experimental Validation

Experimental validation is essential for assessing the real-world effectiveness of external airbag systems, as it provides empirical evidence beyond theoretical models and simulations. While analytical and numerical approaches offer valuable insights into system behaviour, they are often based on simplifying assumptions that may not fully capture the complexity of real-world pedestrian collisions. Therefore, experimental methods play a critical role in verifying system performance, reliability, and injury mitigation capability.

A range of experimental approaches has been employed in the literature, including crash-test dummy (Anthropomorphic Test Device, ATD) testing and instrumented vehicle testing. These methods allow researchers to quantify impact forces, measure injury criteria, and evaluate the effectiveness of external airbag systems under controlled conditions.

2.5.1 Case Studies Using Crash-Test Dummies

Crash-test dummies (ATDs) are widely used to simulate pedestrian impacts and evaluate injury mechanisms. These devices are designed to replicate human biomechanics and are equipped with sensors that measure forces, accelerations, and stress distributions during collisions.

For example, Volvo's pedestrian airbag system has been evaluated using ATDs, demonstrating significant reductions in head injury severity by cushioning the impact between the pedestrian and the vehicle's upper structures [47]. Similarly, BMW has explored external airbag systems for side-impact scenarios, where crash tests have shown reductions in lower-body injury severity by absorbing impact forces and reducing direct contact with rigid vehicle components [48].

While these studies provide valuable insights into system performance, they also have limitations. ATDs, although sophisticated, are still approximations of human biomechanics and may not fully capture complex injury mechanisms, particularly for soft tissue response and multi-impact scenarios. Additionally, many studies focus on specific impact configurations, limiting the generalisability of the results across diverse real-world conditions.

2.5.2 Instrumented Vehicle Testing

Instrumented vehicle testing provides a more comprehensive approach to experimental validation by capturing real-time data during controlled impact scenarios. These tests involve equipping vehicles with sensors, accelerometers, and data acquisition systems to measure impact dynamics and system response.

For instance, Mercedes-Benz has conducted instrumented testing of external airbag systems, demonstrating that properly timed deployment can significantly reduce impact forces, particularly in side-impact scenarios involving pedestrians [49]. Such testing enables analysis of system interaction with vehicle dynamics and environmental conditions, offering a more holistic understanding of performance.

However, instrumented testing is resource-intensive and often limited in scope due to cost and logistical constraints. As a result, many studies rely on a limited number of test scenarios, which may not fully represent the variability of real-world pedestrian collisions.

2.5.3 Challenges in Experimental Validation

Despite its importance, experimental validation presents several challenges:

- **Cost:** Full-scale crash testing requires specialised facilities, advanced instrumentation, and extensive data analysis, making it expensive and limiting the number of tests that can be conducted.
- **Realism:** Replicating real-world collision conditions in controlled environments is inherently difficult. Variations in pedestrian size, posture, motion, and environmental factors are not always fully represented.
- **Scope:** External airbag systems must be validated across a wide range of scenarios, including different speeds, impact angles, and pedestrian characteristics, which is rarely achieved in a single study.

These limitations highlight the need for complementary approaches, combining experimental testing with analytical and numerical modelling.

2.5.4 The Role of Advanced Simulation Techniques

Advanced simulation techniques, particularly Finite Element Analysis (FEA), are widely used to complement experimental validation. These methods enable detailed modelling of vehicle–pedestrian interactions and allow evaluation of system performance across multiple scenarios without the cost of physical testing [50].

However, simulation-based approaches are dependent on modelling assumptions, such as simplified geometries, material properties, and boundary conditions. If not carefully validated, these assumptions can reduce the accuracy and reliability of the results. Therefore, simulation should be used in conjunction with experimental data to ensure meaningful validation.

2.5.5 Ethical Considerations in Crash Testing

Ethical considerations are an important aspect of experimental validation. While crash testing is essential for improving safety systems, it involves destructive testing and raises questions regarding cost, resource use, and the representation of human injury mechanisms.

As a result, there is increasing interest in alternative approaches, including advanced simulations and virtual testing methods, which can reduce reliance on physical testing while maintaining accuracy [51].

2.5.6 Future Directions in Experimental Validation

Future research in experimental validation is expected to focus on:

- Developing more advanced ATDs that better replicate human biomechanics [52]
- Improving sensor accuracy and data analysis techniques
- Integrating experimental testing with high-fidelity simulation models
- Expanding validation across a wider range of realistic collision scenarios

These developments aim to improve the reliability and applicability of external airbag systems in real-world conditions.

2.6 Future Directions

As external airbag systems continue to evolve, experimental validation will play an increasingly vital role in their development. In the future, more sophisticated testing methodologies, including virtual simulations combined with advanced biomechanical models, will complement traditional crash testing. These methods will offer more cost-effective and precise assessments of airbag systems across diverse collision scenarios. Additionally, the integration of AI and sensor technologies will enhance the accuracy of deployment predictions, reducing the need for extensive physical testing in some cases.

2.6.1 The Role of AI and Machine Learning

Artificial intelligence (AI) and machine learning are revolutionizing the design and deployment of external airbag systems. By analyzing extensive datasets from crash tests, AI algorithms can identify patterns and trends that may not be immediately evident to human experts. This capability enables the refinement of airbag designs, enhancing their effectiveness across various collision scenarios. For instance, the I-VALVE project introduced an intelligent valve that adjusts airbag deployment based on factors such as speed and passenger characteristics, leading to personalized protection and improved safety outcomes (European Commission, 2017). Similarly, advancements in AI have facilitated the development of smart airbag systems capable of tailoring responses during collisions by assessing real-time data on occupant size, position, and impact severity [53][54].

2.6.2 Ethical Considerations and Public Perception

As external airbag systems become more advanced, it is crucial to address ethical considerations and public perception. Transparent communication regarding the capabilities and limitations of these systems is essential to foster public trust and acceptance. Educating consumers about the benefits and potential risks associated with AI-driven safety features can mitigate misconceptions and promote responsible usage. Moreover, addressing concerns about system malfunctions and ensuring rigorous quality assurance processes are vital to prevent unintended consequences and enhance consumer confidence [54][55].

2.6.3 Future Research Directions

Future research in external airbag technology should focus on developing more sophisticated systems capable of adapting to a broader array of collision scenarios. Integrating advanced sensors and AI algorithms can enable airbags to deploy optimally based on real-time assessments of crash conditions, occupant characteristics, and environmental factors. Additionally, exploring novel materials and design innovations can lead to lighter and more efficient airbag systems, improving deployment speed and overall effectiveness. As regulatory bodies increasingly prioritize automotive safety, continuous investment in these advanced technologies is anticipated to play a central role in the evolution of vehicle safety features (Automotive Quest, 2023) [56].

2.6.4 Conclusion

In conclusion, experimental validation through crash-test dummies and instrumented vehicles has been crucial in refining external airbag systems. These tests provide valuable insights into the performance and effectiveness of airbag technologies, ensuring their ability to protect vulnerable road users, particularly pedestrians, in real-world collisions. As external airbag systems continue to evolve, integrating AI, machine learning, and advanced simulation methods will enhance their development, offering new opportunities for improved safety on the roads.

2.7 Material Selection and Fabrication

The selection and fabrication of materials for external airbags are critical components in determining their performance, reliability, and effectiveness. The materials used must balance several key properties, including durability, impact absorption, weight, and cost-efficiency. Additionally, the development of smart materials with tunable properties for inflation and stiffness adjustment has expanded opportunities for enhancing airbag systems' functionality. This section reviews both traditional materials and emerging smart materials, highlighting their impact absorption capabilities, durability, and potential to improve pedestrian protection.

2.7.1 Traditional Materials

Traditional materials commonly used in airbag construction include nylon, polyester, and other synthetic fabrics. These materials are favored for their strength, durability, and ability to withstand the high-pressure inflation required during deployment. The primary advantage of these materials is their high tensile strength, ensuring that the airbag remains intact even under the significant forces experienced in a crash. Moreover, their lightweight nature reduces the overall weight of the airbag system without compromising protective capabilities.

For example, nylon is often used due to its resilience, tear resistance, and ability to handle rapid inflation. Polyester is also a preferred choice due to its lower cost, abrasion resistance, and good tensile strength. Both materials are woven into fabrics with high elasticity, allowing them to stretch and absorb impact energy without rupturing. However, while these materials perform well in terms of inflation speed and impact resistance, their properties can be limiting in more complex crash scenarios, such as multi-impact collisions or pedestrian impacts. This limitation has driven further research into advanced materials with adaptive properties.

2.7.2 Smart Materials

Recent research has introduced the potential of smart materials for airbag systems, particularly those with tunable properties that can adjust inflation and stiffness based on collision conditions. These materials offer the ability to respond dynamically to external stimuli such as temperature, pressure, or mechanical deformation. Common types of smart materials used in airbag systems include shape-memory alloys (SMAs), piezoelectric materials, and thermo-responsive polymers.

1. **Shape-Memory Alloys (SMAs):** SMAs, such as nitinol, are materials that change shape in response to temperature variations. These alloys can be incorporated into airbag designs to adjust the airbag's stiffness during inflation. The rapid inflation required in external airbags can be enhanced by SMAs, as the material adjusts to the severity of the impact. For less severe impacts, the material remains

flexible, offering a softer cushion for pedestrians, whereas, in more severe impacts, it stiffens, providing enhanced protection [57].

2. **Piezoelectric Materials:** These materials generate an electric charge when subjected to mechanical stress, making them valuable for real-time impact force measurement. Incorporated into airbags, piezoelectric sensors can monitor the forces during a collision, allowing for a dynamic adjustment of the airbag's deployment strategy. This enables the airbag to adjust its inflation rate based on the severity of the crash or the nature of the pedestrian impact, ensuring optimal protection [58].
3. **Thermo-Responsive Polymers:** Thermo-responsive polymers change their properties in response to temperature changes. By integrating these materials into the airbag structure, the material can adapt its shape or stiffness during deployment, providing a responsive cushion for different impact conditions. For instance, high-temperature polymers can stiffen upon inflation to ensure better energy absorption in high-velocity impacts, while remaining flexible during less severe collisions [59].

2.7.3 Durability, Impact Absorption

Durability and Impact Absorption are paramount when considering the effectiveness of external airbags. The materials must maintain consistent impact absorption performance across varying crash scenarios. Impact absorption is typically achieved through materials that undergo controlled deformation or crushing during an impact, dissipating energy and reducing the forces transmitted to the pedestrian's body.

High-performance foams and viscoelastic materials are often integrated into external airbags due to their excellent energy absorption properties. These materials cushion the impact during deployment, reducing the forces transferred to the pedestrian’s body. The viscoelastic nature of these materials ensures they remain deformable under impact, providing enhanced protection in side-impact or multi-impact scenarios. However, ensuring long-term durability remains a challenge. The airbag system must perform consistently across various climates and over extended periods, without degradation from environmental factors like UV exposure, moisture, or temperature fluctuations. Recent studies have examined multi-layer fabrics and coatings that improve durability and resistance to wear and tear, such as UV stabilizers or waterproof coatings [60].

2.7.4 Fabrication and Integration Considerations

The fabrication of external airbags is a highly intricate process that requires precise integration of various materials and advanced manufacturing techniques. For instance, the airbag construction must consider the inflation system, which typically uses gas generators to rapidly inflate the airbag during a collision. The choice of material can influence the gas flow characteristics and the inflation rate, as well as the structural integrity of the airbag during deployment. Thus, the materials must be compatible with the inflation system to ensure fast and reliable deployment in diverse conditions.

The integration of smart materials into external airbags introduces new challenges, especially regarding fabrication methods. These materials may require specialized manufacturing techniques such as 3D printing or laser cutting to create the precise geometries and structures necessary for optimal performance. Furthermore, the incorporation of smart materials with tunable properties may require advanced sensor systems and feedback mechanisms to manage the dynamics of inflation and ensure the correct function during deployment.

2.7.5 The Role of Advanced Manufacturing Techniques

Advanced manufacturing techniques, including 3D printing and additive manufacturing, are transforming the production of external airbags. Ciriello et al. (2021) investigated how 3D printing can be used to create complex airbag geometries that optimize energy absorption and reduce weight. By tailoring the design for specific collision scenarios, 3D-printed airbags can offer improved pedestrian protection. This technology allows for the creation of intricate shapes that traditional manufacturing methods may not easily achieve, providing opportunities to further refine airbag performance [61].

2.7.6 The Importance of Sustainability

As environmental concerns grow, there is an increasing emphasis on using sustainable materials in airbag construction. Kinoshita et al. (2018) explored the use of recycled materials and biodegradable polymers to reduce the environmental impact of airbag production. Adopting eco-friendly materials and manufacturing processes allows the automotive industry to contribute to a more sustainable future while maintaining the safety performance of airbag systems [62].

2.7.7 Future directions in Material Research

Future research in airbag materials will likely focus on multifunctional materials that provide additional benefits beyond impact protection. Li et al. (2019) suggested the potential for integrating self-healing materials into airbag fabrics, which could extend the lifespan of airbags and reduce the need for replacement. By combining advanced materials science with innovative design, researchers can develop airbag systems that are not only safer but also more durable and sustainable, aligning with the growing need for both improved pedestrian protection and environmental responsibility [63].

2.7.8 Conclusion

The material selection and fabrication of external airbags are central to their performance and effectiveness. While traditional materials such as nylon and polyester continue to be used due to their durability and strength, the integration of smart materials with tunable properties offers significant potential for enhancing the adaptability and functionality of airbag systems. Ongoing research into advanced materials will improve durability, impact absorption, and cost-efficiency, ultimately contributing to enhanced pedestrian protection in the event of a collision. The use of advanced manufacturing techniques and sustainable materials will also ensure that airbag systems meet both safety and environmental standards, paving the way for more effective and eco-friendly safety solutions.

2.8 Innovations and Future Research Directions

The field of external airbag systems is undergoing rapid evolution, driven by increasing integration of advanced technologies such as AI-driven decision-making systems, improved sensor technologies, and innovative materials. These advancements not only enhance the performance and effectiveness of external airbags but also open new pathways for market adoption. This section explores these developments and outlines the future research directions necessary to refine airbag technologies and overcome existing limitations.

2.8.1 Advanced Triggering Mechanisms and AI-Driven Decision-Making

Traditionally, airbag deployment systems rely on predefined triggers such as impact sensors and speed thresholds to activate airbags. However, advancements in artificial intelligence (AI) and machine learning (ML) are enabling more dynamic and context-sensitive triggering mechanisms. AI-driven systems can process a wide array of data in real-time, including information from Radar, LiDAR, Cameras, and Vehicle Dynamics, to make decisions on airbag deployment. These systems have the potential to assess the severity of an impending collision, the position of pedestrians, and the nature of the impact, allowing for more precise and adaptive airbag activation strategies [64].

2.8.2 Pathways from Research to Market Adoption

The journey from research and development to market adoption is a critical phase in the evolution of external airbag systems. Despite significant advancements in airbag technology, challenges related to cost, regulatory approval, and consumer acceptance still exist. One of the primary barriers to widespread market adoption is the high production cost associated with external airbags, particularly due to the complexity of sensor integration and the customization required for different vehicle models.

Additionally, regulatory standards and vehicle safety ratings must be updated to accommodate the introduction of external airbags into the broader market. The incorporation of external airbags into crash test protocols and pedestrian safety ratings is a crucial step toward encouraging manufacturers to adopt these technologies [65].

2.8.3 Robust Sensor Integration for Varying Conditions

Robust sensor integration for external airbag systems remains an active research area, particularly for reliable operation under varying weather and lighting conditions. While sensors are essential for collision detection and deployment, their performance can degrade in environments such as rain, fog, snow, or low light. Current research focuses on improving sensor sensitivity (e.g., LiDAR, radar, and cameras) and advancing sensor fusion techniques to enhance reliability and overcome individual limitations [66].

2.8.4 Development of Cheaper, More Efficient Airbag Materials

A key area of future research lies in the development of cheaper, more efficient materials for external airbags. Currently, high-performance materials such as nylon and polyester dominate the market, but these materials can be expensive and require significant resources to manufacture. Researchers are exploring alternative materials that could lower costs while maintaining or improving the impact absorption and durability characteristics of the airbags [67].

2.8.5 Improvements in Numerical Models for Higher Fidelity Simulations

The simulation of airbag deployment is essential for designing systems that can reliably protect pedestrians. Existing numerical models are improving, but they still lack the level of fidelity required for accurate predictions in real-world collisions. To address this limitation, researchers are working on the development of high-fidelity simulations that can model the behavior of airbags in greater detail [68].

2.8.6 The Role of Advanced Materials and Manufacturing Techniques

The development of advanced materials and manufacturing techniques is crucial for the future of external airbag systems. Ciriello et al. (2021) explored the potential of 3D printing to create complex airbag geometries that can optimize energy absorption and minimize weight. By tailoring the design to specific collision scenarios, 3D-printed airbags can offer enhanced protection for pedestrians [69].

2.8.7 The Importance of Ethical Considerations and Public Perception

As external airbag technology continues to advance, it is important to consider the ethical implications of these systems. Kinoshita et al. (2018) discussed the need for transparent communication about the capabilities and limitations of external airbags. By educating the public about the benefits and potential risks of these technologies, researchers and policymakers can ensure that they are accepted and used responsibly [70].

2.8.8 Future Research Directions

Future research in external airbag systems should explore AI and machine learning to optimise deployment strategies. AI-based algorithms can analyse real-time sensor data and enable rapid deployment decisions, supporting more adaptive and effective responses across varied collision scenarios [71].

2.8.9 Conclusion

This chapter has comprehensively outlined the evolution, challenges, and opportunities surrounding external airbag systems in the automotive industry. By addressing key aspects such as deployment timing, cost reduction, real-world validation, sensor integration, and algorithm refinement, the potential of these systems to enhance pedestrian safety is evident.

Chapter 3 Methodology

3.1 Introduction

This chapter outlines the methodological approach undertaken to design, construct, and validate an experimental rig aimed at evaluating the performance of an external airbag system for automotive safety. The primary objective of this research is to measure the impact forces experienced with and without an airbag system in controlled scenarios, contributing to the broader field of vehicle safety innovation. The rig integrates mechanical, electronic, and computational components to simulate real-world conditions and collect critical data on impact dynamics. The scope of the validation tests includes two specific collision scenarios: one without an airbag and the other with an airbag deployed, emphasizing the differences in impact forces between the two situations.

The methodology was carefully designed to ensure reliability, reproducibility, and relevance to the research objectives. A systematic approach was employed, starting with the construction of a scaled model equipped with Arduino boards and sensors. These components were integrated to allow precise data acquisition and control over the system's response under varying conditions.

The chapter is structured as follows:

- **Research Design:** Describes the experimental approach, including the rationale for using a scaled model and the integration of specific components.
- **Experimental Setup:** Details the individual elements of the rig, such as the Arduino boards, sensors, valves, and other critical parts, including their roles within the system.
- **Workflow and System Configuration:** Explains how components are interconnected and operate, detailing the steps for system integration and data acquisition.
- **Bench Test Components:** Lists and describes the specific components used in the experimental setup.
- **Data Analysis Techniques:** Outlines the methods used for processing and interpreting the collected data, including descriptive statistics and regression analysis.
- **Limitations and Assumptions:** Discusses the constraints of the experimental setup and the assumptions made during the study.
- **Conclusions and Future Work:** Summarizes the findings and suggests directions for future research.

By employing an experimental design that combines the use of advanced sensors, automated control systems, and real-time data acquisition, this study ensures accurate and meaningful results. The methodology aligns with the study's broader aim of contributing to safer automotive technologies and provides a replicable framework for future research in the field.

3.2 Research Design

The research adopts an experimental design to assess the effectiveness of an external airbag system in mitigating impact forces during low-speed collisions. A scaled model was chosen to simulate the dynamic conditions of real-world automotive scenarios while maintaining practicality and feasibility in the laboratory setting. The design emphasizes precision, reproducibility, and adaptability, ensuring that the results are both scientifically robust and directly applicable to automotive safety innovation.

3.2.1 Selection of Experimental Rig Components

The experimental rig consists of a custom-built scaled car model, which serves as the foundation for the system's mechanical and electronic integrations. This approach allows for detailed control over the variables influencing the airbag's performance. Key components were selected based on their functionality and compatibility, including:

Table 3.1 System components and functional description

Component	Technical Specs.	Image
ELEGOO Smart Robot Car Kit V4.0	**Ultrasonic Sensor:** • Operating voltage: 5V • Detection range: 2cm to 400cm • Frequency: 40Hz • Resolution: 2-3cm • Detection angle: 15° **Line Tracking Module:** • Operating voltage: 5V • Detection method: Reflective sensor (infrared) • Detection range: 1mm to 25mm • Output type: Digital (HIGH/LOW) **Bluetooth Module (HC-06):** • Operating voltage: 3.3V-5V • Operating frequency: 2.4GHz • Bluetooth version: Bluetooth 2.0+EDR • Range: Approximately 10m **IR Receiver:**	

	• Operating voltage: 5V • Carrier frequency: 38kHz • Modulation type: OOK • Transmission distance: up to 8m **Motor Driver Module (L298N):** a. Operating voltage: 5V-35V b. Logic voltage: 5V c. Motor drive voltage: 5V-35V d. Maximum continuous current: 2A e. Peak current: 4A **UNO R3 Board:** • Microcontroller: ATmega328P • Operating voltage: 5V • Input voltage (recommended): 7-12V • Input voltage (limit): 6-20V • Digital I/O pins: 14 (6PWM capable) • Analog input pins: 6 • DC current per I/O pin: 40mA • Flash memory: 32KB • SRAM: 2KB • EEPROM: 1KB • Clock speed: 16MHz	
	• Microcontroller: ATmega328P • Operating Voltage: 5V • Input Voltage (recommended): 7-12V • Input Voltage (limits): 6-20V • Digital I/O Pins: 14 (6 of which can be used as PWM outputs) • Analog Input Pins: 6	

Arduino Uno REV3 [A000066]	• Dimensions: 68.6mm x 53.4mm • Weight: 25g	
2 Channel Relay Module	• Operating Voltage: 5V DC • Maximum AC Load: 5A at 50V • Maximum DC Load: 5A at 30V • Trigger Voltage: 5V DC (low-level trigger) • Optocoupler Isolation: Yes • Number of Channels: 2 • Relay Type: SPDT (Single Pole Double Throw) • Dimensions: 49 x 51mm (1.9 x 2in) • TTL Serial Signal: 5VDC	
	• Cartridge size: 8.9cm x 1.8cm • Cartridge weight: 16g • Cartridge thread size: 3/8" • Cartridge material: Alloy steel & metal • Compatibility: Standard CO2 air tank cylinders	
Mini Micro Electric Solenoid Valve	• Normally Closed (NC) solenoid valve • Operating Voltage: DC12V • Operating Current: <150mA • Power: <2W • Pressure Range: 0-450mmHg • Fluid Compatibility: Water and air • Cable Length: 20cm • Weight: 40g	

Piezoelectric Vibration Tapping Sensor	• Operating Voltage: 5.0V DC • Output Signal: Analog (AD) and Digital (DO) • Sensitivity: High sensitivity • Sensing Element: Piezoelectric sensor • Dimensions: 33mm x 15mm • Mounting Hole Diameter: 2mm	
PTFE Tubing Hose Pipe	• Material: PTFE (Polytetrafluoroethylene) • Inner diameter: 3mm • Outer diameter: 5mm • Length: 4.9feet (1.5m) • Operating temperature range: -65°C to +260°C (-85°F to +500°F) • Tensile strength: 22MPa • Elongation at break: 200% • Dielectric strength: 20-60KV/mm • Thermal conductivity: 0.25W/mK	
Ripstop Nylon	• Tensile strength: 300-500N/50mm • Tear strength: 18-30N/5cm • Coating: Polyurethane (PU) • Waterproof rating: 2000mm • Breathability: Moisture-permeable • Fabric weave: Ripstop • Yarn count: Warp (330D) / Weft (190D) • Thread count: 60-90 threads per square inch	

National Instruments USB-6000 Data Acquisition Card NI 782602-01 DAQ	• Analog Input:
	    • Input voltage range: ±10V, ±5V, ±2V, ±1V, ±0.2V
	    • Input impedance: 1MΩ ‖ 10pF
	    • Input coupling: DC
	• Digital Input/Output:
	    • Digital input voltage range: 0V to 5V+ Digital output voltage range: 0V to 5V
	    • Maximum digital I/O rate: 10 kS/s
	• Counter:+ Counter width: 32bits+ Counter frequency range: 0 to 20MHz
	    • Counter input impedance: 10kΩ
	• Power Requirements:
	    • Bus-powered via USB 2.0 interface
	    • Power consumption: <2.5W
	• Environmental Specifications:
	    • Operating temperature range: 0°C to 55°C
	    • Storage temperature range: -40°C to 85°C+ Operating relative humidity: 10% to 90%, non-condensing+ Storage relative humidity: 5% to 95%, non-condensing
		

3.3 Experimental Framework

The experimental design is divided into two primary stages:

1. **System Integration and Calibration:** The components were assembled and configured to simulate an automated collision-response system. The first Arduino board processes signals from the ultrasonic sensors and transmits those signals to the second Arduino board based on a pre-defined threshold distance (3cm). The second Arduino board activates the relay, which controls the solenoid valve, releasing gas to inflate the airbag.
2. **Impact Testing:** Impact tests were conducted in two scenarios: with and without the airbag system activated. These tests aimed to measure the differences in impact forces experienced by the scaled car model using the data acquisition sensor. This comparison provides insights into the airbag's effectiveness in reducing collision impact.

3.4 Justification of Research Design

The chosen experimental setup allows for a controlled environment to evaluate the airbag system's performance. The dual-board Arduino configuration ensures precise communication between sensors and actuators, enabling accurate system responses. Furthermore, the use of scaled components and simulated scenarios provides a cost-effective and efficient means to gather relevant data, which can later be extrapolated to real-world applications.

By employing this research design, the study aims to establish a foundational understanding of external airbag systems' dynamics and their potential impact on automotive safety.

3.5 Experimental Setup

The experimental setup focuses on constructing a scalable and reliable rig to evaluate the functionality and performance of the external airbag system. This section details the arrangement, interconnection, and calibration of the various components that constitute the rig. The setup was designed to ensure effective signal transmission, precise control, and accurate data acquisition to support meaningful analysis.

3.5.1 Primary Components and Material Selection

- **Nylon Fabric for External Airbag:**
    - **Material:** Polyamide 66 (PA66) woven fabric.
    - **Properties:** High tensile strength, thermal stability, and tear resistance. Coated with a heat-resistant layer to withstand the heat generated by gas inflation.
    - **Function:** Acts as the structural material for the airbag, designed to deploy rapidly without tearing or degrading during high-speed inflation.

- **Plastic Pipe:**
  - **Material:** High-density polyethylene (HDPE) rated for high-pressure CO2 flow.
  - **Properties:** Resistant to gas leakage and compatible with CO2 under pressure.
  - **Function:** Facilitates the transfer of compressed gas from the inflator canister to the solenoid valve.

3.5.2 Hardware Specifications

- **ELEGOO Smart Robot Car Kit V4.0:** Components Used: Arduino UNO R3 Board. Specifications: Compatible with Arduino IDE; integrated power regulation for sensors and actuators. Function: Acts as the central processing unit for signal input and relay activation.
- **Arduino UNO R3 Board:** Model: Arduino UNO R3 (from ELEGOO Kit). Specifications: Microcontroller-based board with sufficient digital/analog pins for sensor and actuator integration. Function: Processes input signals and controls the relay module.
- **Second Arduino Board:** Arduino Uno Rev3 (A000066). Specifications: Microcontroller: ATmega328P; Operating Voltage: 5V; Input Voltage (recommended): 7-12V; Digital I/O Pins: 14 (6PWM); Analog Input Pins: 6. Function: Processes sensor data and triggers the deployment sequence.
- **2 Channel Relay Module:** Model: AZ Delivery 2-Channel Relay Module. Specifications: Low-level trigger; compatible with Arduino. Function: Acts as an electronic switch to activate the solenoid valve.
- **Threaded CO2 Canister:** Type: 16g cartridge. Function: Provides compressed CO2 for airbag inflation.
- **Mini Micro Electric Solenoid Valve:** Specifications: DC 4.5V, 0.5A, normally closed. Function: Controls the flow of CO2 to the airbag.
- **Piezoelectric Vibration Tapping Sensor Module:** Specifications: High sensitivity, operates on 5V DC with dual outputs (AD and DO). Function: Detects external triggers for system activation.
- **PTFE Tubing Hose Pipe:** Specifications: Inner diameter: 3mm, Outer diameter: 5mm. Function: Connects the CO2 canister to the solenoid valve.
- **Ripstop Nylon Fabric:** Properties: High tensile strength, tear resistance, PU coating. Function: Forms the main structure of the airbag.
- **National Instruments USB-6000 Data Acquisition Card:** Specifications: Analog Input: ±10V range; Digital I/O: 10kS/s rate. Function: Records impact force data with high precision.

  Prior to testing, the ultrasonic sensor and force measurement system were calibrated to ensure consistent signal response. The ultrasonic sensor operated at 40Hz, and the NI USB-6000 data acquisition system was used to capture real-time impact signals for subsequent analysis. Baseline readings were taken before each test to minimise offset error, and all measurements were recorded under the same experimental conditions to improve repeatability. The calibration process was intended to reduce measurement uncertainty rather than eliminate it entirely, and residual uncertainty is discussed further in Chapter 6.

3.5.3 System Integration and Workflow

The system operates as follows:

- **Sensor Activation:** The piezoelectric sensor detects a vibration or tapping input, sending a signal to the Arduino board.
- **Signal Transmission:** The ultrasonic sensors continuously measure distance and transmit data to the Arduino.
- **Threshold Detection:** When an object is detected within a pre-defined threshold distance (3cm), the Arduino board processes this signal.
- **Relay Trigger:** The Arduino activates the relay module, which in turn energizes the solenoid valve.
- **Gas Release:** The solenoid valve opens, releasing CO2 from the canister through the PTFE tubing into the nylon airbag.
- **Airbag Deployment:** The nylon fabric airbag inflates rapidly, simulating real-world airbag performance.

3.6 Workflow and System Configuration

The external airbag prototype integrates multiple components, following a systematic workflow to simulate real-world deployment scenarios. This section outlines the connection and interaction between components in two distinct phases: deployment and impact testing.

3.6.1 System Integration Steps

- **Ultrasonic Sensor and Signal Transmission:** The car model includes a built-in Arduino board and ultrasonic sensors to detect objects within its proximity. The sensors continuously measure distance and transmit the detected signal to the built-in Arduino board.
- **Interfacing with the Second Arduino Board:** An additional Arduino board is integrated into the system to process the output from the built-in sensors. When an object is detected at a threshold distance (3cm), the second Arduino board processes this signal and activates the next stage.
- **Relay and Valve Control:** The second Arduino board sends a control signal to the relay module. The relay module, in turn, sends an electrical signal to the solenoid valve. The pressurized CO2 canister

pre-fills the plastic pipe, maintaining ready-to-deploy conditions. Upon receiving the signal, the valve opens, allowing the compressed gas to inflate the nylon airbag sheet rapidly.

- **Deployment of Nylon Airbag:** The PA66 nylon fabric airbag inflates to form a protective cushion in front of the car model. The inflation dynamics are critical, with parameters such as deployment time and pressure monitored to ensure effective operation.

3.6.2 Impact Force and Data Acquisition Setup

- **Force Measurement Sensor:** A data acquisition sensor (National Instruments USB-6000) is installed at the front of the car model to capture real-time impact data. The impact force detector measures the forces experienced by the analytical model in collision scenarios.
- **Two Testing Scenarios:**
  1. **With Inflated Airbag:** The airbag is deployed before impact, simulating its protective function. The force sensor records the force magnitude, allowing for the evaluation of force absorption by the airbag.
  2. **Without Airbag:** The airbag system is deactivated, and the impact force is measured directly on the sensor. This scenario provides a baseline measurement for comparison.
- **Analysis of Results:** The difference between the two scenarios quantifies the airbag's effectiveness in mitigating impact forces. Key parameters include peak force, time to maximum force, and total energy absorbed by the airbag.

For each test, the system was initialised by powering the Arduino boards, relay module, ultrasonic sensor, and data acquisition system. The ultrasonic sensor output was checked against the predefined threshold distance of 3 cm, and the force measurement system was zeroed prior to testing. Two test conditions were then performed: (i) impact without airbag deployment and (ii) impact with airbag deployment. In each case, impact force data were recorded through the NI USB-6000 and exported to MATLAB for post-processing. The tests were repeated under the same controlled laboratory conditions to ensure consistency of comparison between the two scenarios.

3.6.3 Systematic Diagram Description

The systematic diagram visualizes the following:

- **Signal Flow:** Ultrasonic sensors → Built-in Arduino board → Second Arduino board → Relay → Solenoid valve → Nylon airbag.
- **Mechanical Integration:** CO2 canister → Plastic pipe → Solenoid valve → Nylon airbag.

- **Data Flow:** Impact detection → Data acquisition sensor (NI USB-6000) → Force measurement system → Analysis software (MATLAB).

3.6.4 Finite Element Analysis (FEA) Approach

To complement the scaled experimental testing, a comparative finite element analysis was performed using SimScale under a representative pedestrian impact condition of 30 km/h. The aim of this modelling stage was to provide a numerical perspective and evaluate the effect of external airbag deployment on impact loading. A time-dependent dynamic analysis framework was employed to represent transient impact conditions. The results are presented in Section 6.8.

A simplified three-dimensional model of the bumper and bonnet airbag configurations was developed, consistent with the analytical framework in Chapter 5. The FEA model adopts the same geometric, material, and loading parameters, including airbag dimensions, initial contact displacements, and internal pressure conditions (Tables 8–10), ensuring consistency between the analytical and numerical approaches. The model evaluates relative trends in Von Mises stress, displacement, and strain-rate behaviour across unprotected, bumper-airbag, bonnet-airbag, and combined scenarios, with simplified contact interaction, fixed boundary conditions at the airbag edges, and uniform internal pressure loading.

The FEA is used as a comparative numerical framework rather than a fully validated crash simulation, supporting the interpretation of the analytical and experimental results by illustrating how airbag deployment influences impact loading at 30km/h.

The FEA simulations were conducted as a simplified dynamic analysis using SimScale. The vehicle structure was assumed fixed, while the pedestrian model was subjected to prescribed displacement towards the airbag surface to represent impact conditions. Contact interactions between the pedestrian, airbag, and vehicle structure were defined using simplified contact formulations to capture load transfer behaviour during impact. Material properties for the airbag membrane and structural components were adopted from the analytical model (Chapter 5 and Tables 8–10), assuming equivalent linear elastic membrane behaviour. A structured mesh was applied across the simplified geometry, with sufficient resolution to capture relative trends in stress and displacement; however, a detailed mesh sensitivity analysis was beyond the scope of this study. The simulations are therefore intended for comparative assessment rather than high-fidelity crash prediction.

3.7 Bench Test Components

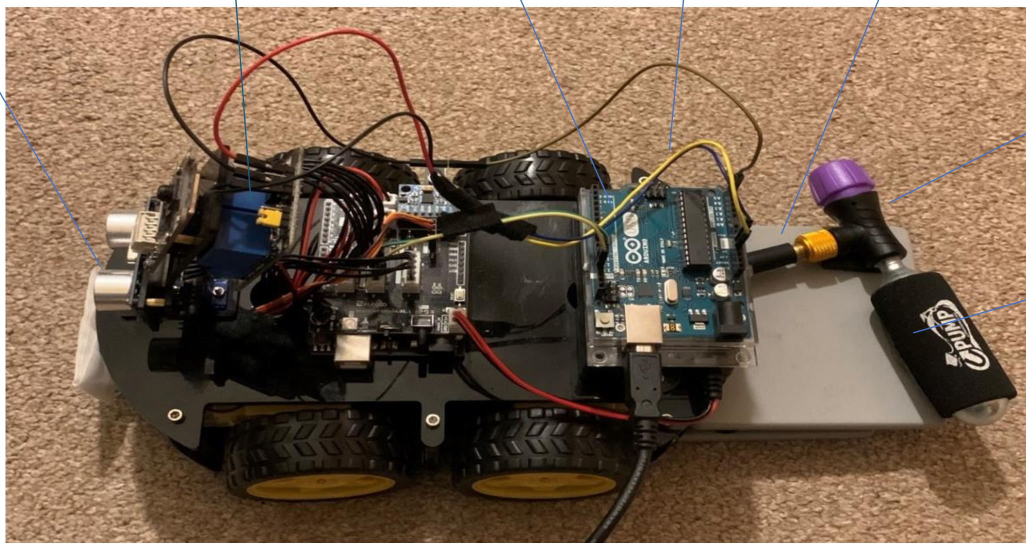


Figure 3.1 Experimental test rig for external airbag deployment (a)

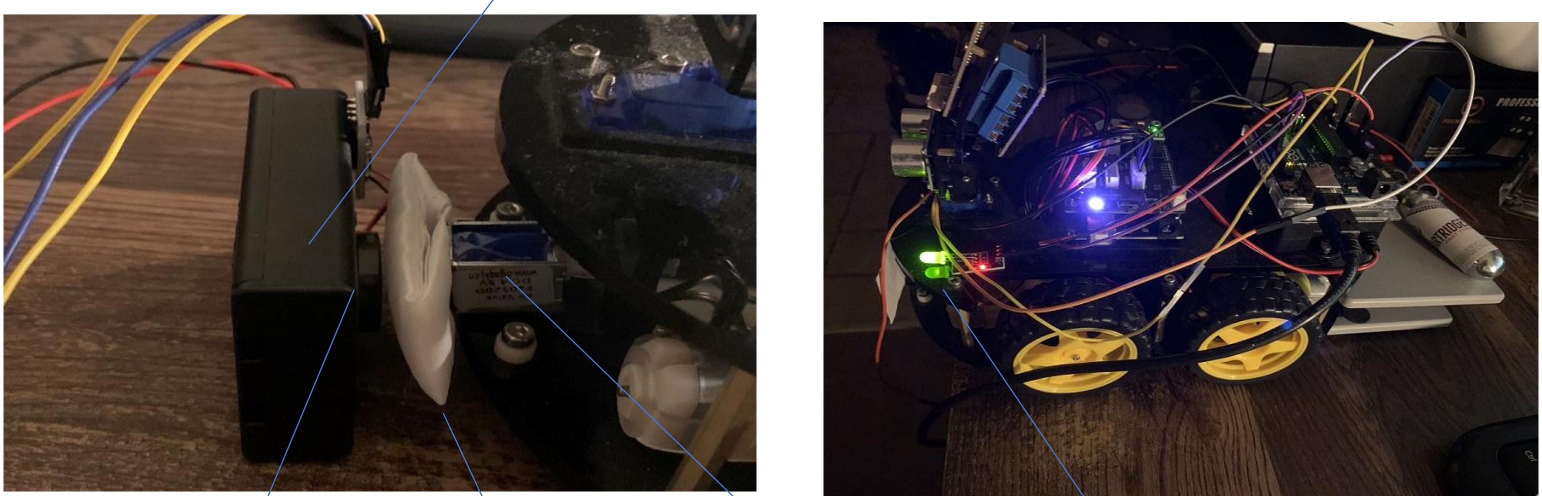


Figure 3.2 Experimental test rig for external airbag deployment (b)

3.7.1 Physical Construction

The selection of the ELEGOO Smart Robot Car Kit V4.0 was based on its comprehensive components, Arduino IDE compatibility, educational value, and cost-effectiveness. The kit's Arduino UNO R3 board, ultrasonic sensors, and motor driver module provide essential functionalities for controlling movement and detecting obstacles. The UNO R3 board's compatibility with the Arduino IDE simplifies programming, and the open-source platform offers extensive community support. Designed with educational objectives in mind, the kit provides a practical platform for understanding robotics, electronics, and programming concepts.

The airbag itself is constructed from Ripstop Nylon fabric, chosen for its high tensile strength, tear resistance, and thermal stability. A heat-resistant coating is applied to withstand the high temperatures generated during rapid gas inflation. Reinforced stitching along the seams ensures structural integrity. A silicone gel coating minimizes friction for efficient folding.

The CO2 canister, made of aluminum, is designed to withstand high pressures. The solenoid valve controls the release of CO2 through PTFE tubing to the nylon airbag. The entire system is triggered by a piezoelectric sensor, which detects vibrations and initiates the deployment sequence via the Arduino and relay module.

3.7.2 Data Analysis Techniques

The analysis of the experimental data was conducted using a systematic approach to evaluate the performance of the airbag system in mitigating collision forces. The primary tools for data analysis were NI Max and MATLAB software, chosen for their robust computational capabilities and extensive libraries for data processing and visualization.

3.7.3 Descriptive Statistics

Descriptive statistics were used to summarize the data, providing measures of central tendency (mean, median) and variability (standard deviation, range) for each test scenario. These statistics helped establish a baseline understanding of the data distribution, particularly when comparing different experimental conditions (e.g., with and without the airbag inflated).

3.7.4 Regression Analysis

Regression models were employed to explore the relationship between sensor input (e.g., distance measured by ultrasonic sensors) and output variables (e.g., impact force). Different regression techniques were applied to model these relationships, providing insight into how changes in input parameters affected the airbag system's performance.

3.7.5 Limitations and Assumptions

The experimental design and subsequent analysis were based on several assumptions and constraints that could influence the interpretation of the results.

A. Limitations:

- **Experimental Setup:** The controlled laboratory environment may not fully replicate real-world conditions. Factors like varying speeds, temperatures, and road surfaces were simplified. The scaled model does not capture the full complexity of real-world crash scenarios.
- **Sensor Accuracy:** Ultrasonic sensors and force detectors have inherent limitations in accuracy and resolution. Despite calibration, measurement errors are possible. Sensor placement and response times can also introduce uncertainties.
- **System Response Time:** The time delay in valve actuation after relay activation could affect real-time performance, especially at higher speeds.
- **Data Processing and Statistical Analysis:** The analysis was based on a limited number of test scenarios. The sample size might not be sufficient to capture all performance variations. The choice of statistical tests could also introduce minor variations in conclusions.

B. Assumptions:

- **Airbag Activation Threshold:** The system assumes activation based on a pre-defined distance threshold (3cm) and Time-to-Collision(TTC) versus Time-to-Stop(TTS) calculations.
- **Constant Pressure in CO2 Canister:** It was assumed that the CO2 canister would maintain consistent pressure throughout the test sequence. Variations due to temperature or gas depletion were not explicitly modeled.
- **No System Interference:** It was assumed that there would be no significant electrical interference between components (e.g., Arduino boards, sensors) that could affect signal accuracy.
- **Linear Relationship Between Impact and Force:** The study assumed a simplified relationship for analysis, which might not fully capture complex interactions in real-world scenarios.

The experimental rig developed in this study should be understood as a scaled proof-of-concept platform intended to evaluate relative changes in impact force with and without airbag deployment, rather than a full-scale replication of real-world vehicle–pedestrian collisions.

3.8 Conclusions and Future Work

3.8.1 Conclusions

This study investigated the effectiveness of an external airbag system for enhancing automotive safety during frontal collisions. Through the development and testing of a custom-designed rig, a comprehensive analysis of airbag deployment dynamics was carried out under controlled conditions. The findings are summarized as follows:

- **Effectiveness of Airbag Deployment:** The external airbag demonstrated significant potential in reducing impact forces when deployed prior to collision, offering improved protection. Force measurements indicated substantial mitigation compared to scenarios without airbag deployment.
- **System Responsiveness and Timing:** The Arduino-controlled airbag activation system showed fast response times. However, minor delays in valve actuation were noted, which could influence real-world performance at higher speeds.
- **Sensor Performance and Accuracy:** The ultrasonic sensors and force detectors provided reliable measurements, but limitations in accuracy and calibration were acknowledged. Future refinement of these sensors could yield more precise data.
- **Impact of Gas Pressure:** The CO_2 canister was a viable method for inflation, but variations in canister pressure could affect consistency. Exploring advanced pressurization systems could improve performance.

3.8.2 Future Work

While this research provides valuable insights into the potential benefits of external airbags, several areas remain open for further exploration. Future studies could build on these findings by addressing the following aspects:

Real-World Testing: The current tests were conducted in a controlled environment, and future work should involve real-world crash simulations to assess the system's performance in more dynamic and unpredictable conditions. This would involve incorporating variables such as varying vehicle speeds, road surface types, and environmental factors (e.g., temperature) to better replicate real-world conditions such as:

a. Varied Vehicle Speeds: Testing the airbag deployment system under different vehicle speeds is crucial, as it directly impacts the force of collision and the required response time for effective airbag inflation. By simulating crashes at various speeds, the researchers can assess the system's effectiveness and make necessary adjustments for optimal performance across a range of speeds.

b. Road Surface Types: Road conditions can significantly influence the dynamics of a collision. Simulating crashes on different road surfaces (e.g., asphalt, gravel, or icy roads) will help determine the system's adaptability to diverse real-world situations. This would ensure that the airbag deployment system can provide adequate protection regardless of the road conditions.

c. Environmental Factors: Temperature and humidity can affect the performance of sensors, materials, and electronics. It is vital to evaluate the system's functionality under extreme temperature conditions (e.g., very hot or cold) and varying humidity levels. Additionally, factors such as precipitation or wind may also be considered for a comprehensive understanding of the system's resilience to environmental factors.

d. Impact Angles: Real-world collisions can occur at various angles. Assessing the airbag deployment system's effectiveness at different impact angles will help optimize its performance in non-head-on collisions.

In summary, prioritizing real-world testing variables like vehicle speeds, road surface types, environmental factors, and impact angles will help ensure that the airbag deployment system can provide optimal protection and perform reliably in diverse and unpredictable real-world scenarios.

f. Refinement of Airbag Inflation Mechanism

The airbag inflation process could be improved by exploring alternative methods of pressurisation, such as the use of a more controlled gas release system or integration with onboard air compressors, to ensure more consistent deployment. Additionally, testing with airbags of different materials and inflation rates would allow for the optimisation of performance.

g. Advanced Sensors for Enhanced Accuracy

Future work should focus on enhancing sensor accuracy and calibration, particularly for impact force detection. Employing more advanced sensors or integrating multiple sensor types could offer a more comprehensive assessment of the airbag system's performance, ensuring higher reliability in measuring the effectiveness of the system.

As part of exploratory work conducted alongside this thesis, a MATLAB-based neural network was developed to support intelligent airbag deployment decisions. The model was trained to classify detected objects as human or non-human, with additional outputs related to basic pedestrian characteristics. Initial testing achieved classification accuracy of approximately 92%; however, due to limitations in dataset size, generalisation capability, and real-time integration, the system was not considered sufficiently reliable for safety-critical deployment. As a result, the AI component was not incorporated into the core methodology and is instead identified as a direction for future work, with further development required to improve robustness and enable real-time integration with the airbag system.

h. Integration with Autonomous Systems

Further research could explore the integration of external airbag systems with autonomous vehicle technology. With the rapid advancement of self-driving vehicles, external airbags could be incorporated into autonomous safety protocols, providing proactive protection in emergency situations. Investigating this integration could lead to enhanced occupant safety, particularly in complex and unpredictable driving environments.

i. Economic and Environmental Considerations

Another important area for future research is the economic and environmental feasibility of widespread adoption of external airbags. Investigating the cost of manufacturing, maintenance, and environmental impact of airbag deployment could provide critical insights into the practicality of such systems for mass-market vehicles.

3.8.3 Neural Network for Intelligent Airbag Deployment (Future Work)

As part of exploratory work conducted alongside this thesis, a MATLAB-based neural network was developed and trained to support intelligent airbag deployment decisions. The system was designed to identify and classify detected objects as human or non-human, followed by gender classification and prediction of pedestrian age and height. Based on these outputs, the airbag deployment stage could be optimized to deliver the most appropriate protective response for the detected pedestrian profile, maximizing energy absorption whilst minimizing impact force. Initial results achieved a classification accuracy of approximately 92%; however, due to reliability limitations of the system at this stage of development, this work has been designated as future work. Further research should focus on improving system reliability and classification robustness, integrating the neural network with the physical airbag deployment mechanism, and validating its real-time performance under crash conditions, with the aim of realizing a fully adaptive and intelligent external airbag system.

3.8.4 Overall Implications for Pedestrian Safety

The findings from this study underscore the critical role of external airbags in mitigating pedestrian injuries, particularly in low- to moderate-speed collisions. While airbags are highly effective in these scenarios, the study also highlights the need for complementary safety measures, such as energy-absorbing structures and active safety systems, to ensure broad protection across the analysed regions at higher speeds. Continued research and development in airbag technology, coupled with integration into broader vehicle safety systems, are essential for advancing pedestrian safety and creating safer road environments.

The analytical and Finite Element Analysis (FEA) models presented in this study rely on specific idealized assumptions to maintain computational efficiency. Structural geometries, boundary conditions, and material properties including those of the vehicle front-end structures and the airbag housing were simplified and modeled with linear or predefined non-linear characteristics rather than absolute real-world structural variability. Furthermore, while standard structural similitude laws and velocity scaling formulations ($V_{\text{full}} = V_{\text{scale}} \cdot \sqrt{\lambda}$, where λ represents the scale factor) can mathematically project the 1:10 laboratory kinematics to full-scale velocity baselines, these rigid geometric conversions break down under real-world impact dynamics. This is due to severe scale distortions, specifically regarding the highly non-linear strain-rate sensitivity of the materials and the transient pneumatic mass flow rates during high-velocity inflation, which do not scale linearly. Consequently, these models lack full biomechanical validation against physical Post-Mortem Human Subject (PMHS) data or advanced biofidelic Anthropomorphic Test Devices (crash test dummies), meaning the numerical results serve as a fundamental proof-of-concept for injury mitigation potential rather than a direct, definitive measure of absolute human tissue trauma.

Chapter 4 Design and development

The innovative design and implementation of external airbag systems have emerged as a crucial advancement in enhancing automotive safety, particularly for road users such as pedestrians. Traditional vehicle safety measures have predominantly focused on occupant protection, often neglecting the significant risks posed to pedestrians during collisions. Recent research has demonstrated the potential of external airbags to mitigate the severity of injuries by providing a protective cushioning effect upon impact. Elaidy, Rayner, and Kalyvas (2024) present a comprehensive study on the development of an external airbag system, leveraging advanced computational tools such as (CAD and MATLAB) software for design optimization and simulation. The findings highlight a marked improvement in pedestrian safety outcomes, achieved through innovative engineering solutions that address critical parameters, including impact dynamics, deployment mechanisms, and atmospheric modelling. This research underscores the importance of integrating pedestrian-centric safety technologies into contemporary vehicle designs to reduce injury severity and enhance overall road safety [72].

4.1 The Tesla Model X: An Optimal Platform for Advanced Safety Features

The Tesla Model X was selected as the subject vehicle for the external airbag system design due to its global recognition as a leading electric vehicle and its prominence within the mid-sized passenger car segment. As a Category M1 vehicle designed to transport passengers with no more than eight seats in addition to the driver it represents an ideal platform for research, with broad applicability across various vehicle types, including sedans, hatchbacks, and SUVs. Its design, accommodating up to seven passengers, aligns well with the objectives of this study and ensures the scalability of the proposed system to vehicles of similar size and configuration.

Furthermore, the Model X stands out among electric SUVs, such as the Audi e-tron, BMW iX, and Mercedes-Benz EQC, exemplifying a popular and rapidly expanding category in the automotive market. Its wide adoption and status as a benchmark vehicle underscore its suitability for developing and testing innovative external airbag technologies.

In conclusion, the Tesla Model X provides an exemplary foundation for the design and evaluation of external airbag systems aimed at enhancing road safety. Its relevance as a globally recognized vehicle and compatibility with Category M1 standards ensure the findings of this research are both practical and scalable, paving the way for broader implementation in the automotive industry.

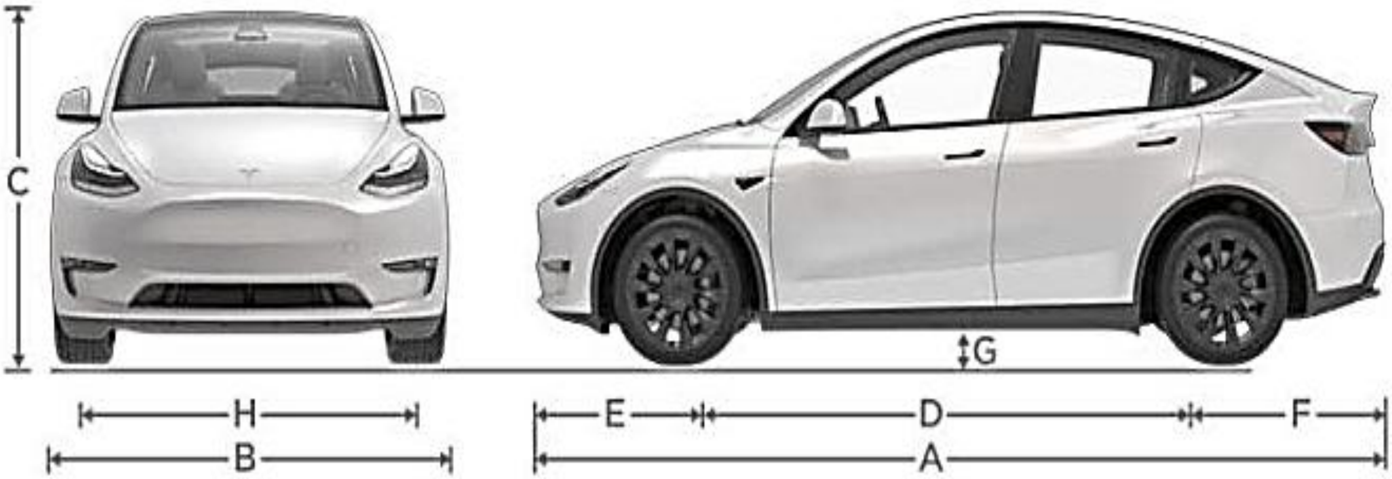


Figure 4.1 Vehicle used in the research

Fig.(4.1) illustrates the Tesla Model X utilized in the proposed research. As previously mentioned, this vehicle serves as the subject of investigation for evaluating the effectiveness of the external airbag system. The specifications of the Model X, including details of its front bumper and bonnet, are further elaborated in Tables 5 and 6, respectively. These specifications provide crucial insights into the materials and dimensions of the vehicle components essential for the development and testing of the external airbag system.

Table 4.1 Specifications of the selected vehicle

A	Overall Length	4751mm
B	Overall Width	2129mm
C	Overall Height	1624mm
D	Wheelbase	847mm
E	Overhang Front	847mm
F	Overhang Rear	986mm
G	Ground Clearance	167mm
H	Front wheelbase width	1636mm

Table 4.2 Specifications of the front bumper and bonnet

Dimensions	Front Bumper	Bonnet
Length	2129mm	1720mm
Width	800mm	900mm
Height	600mm	

4.2 Mechanical Design

4.2.1 Bumper Airbag System

The external airbag system was designed with a focus on achieving an optimal balance of performance, durability, and weight. Each component was crafted from materials selected to ensure reliability, safety, and adaptability in diverse operating conditions. Specific considerations for the construction materials included strength, resistance to environmental factors, and the ability to withstand various operational stresses.

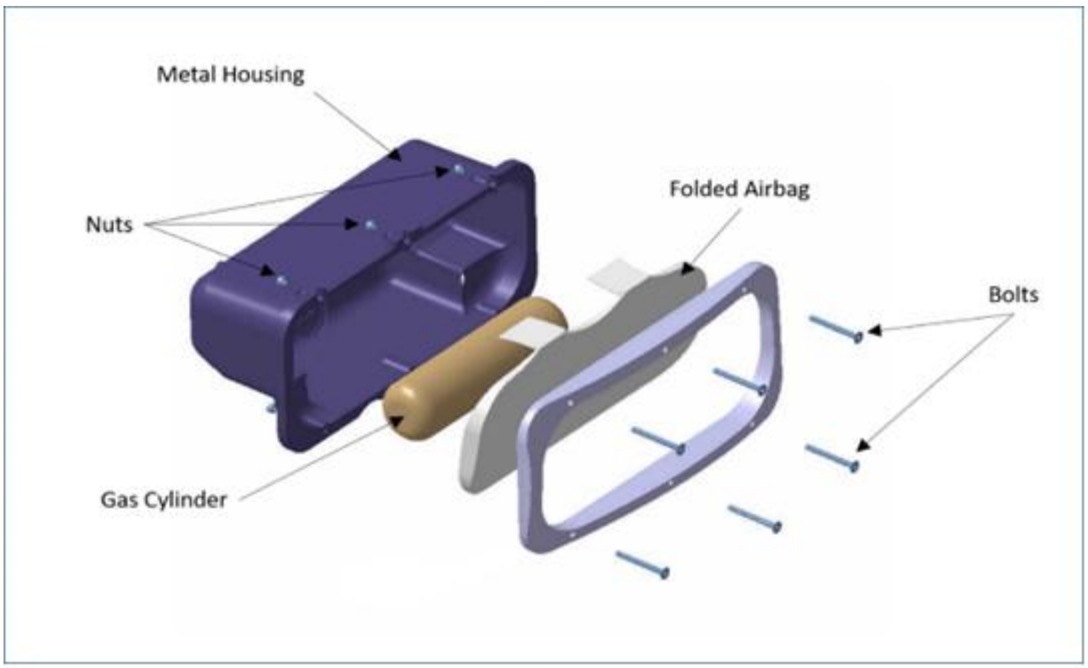
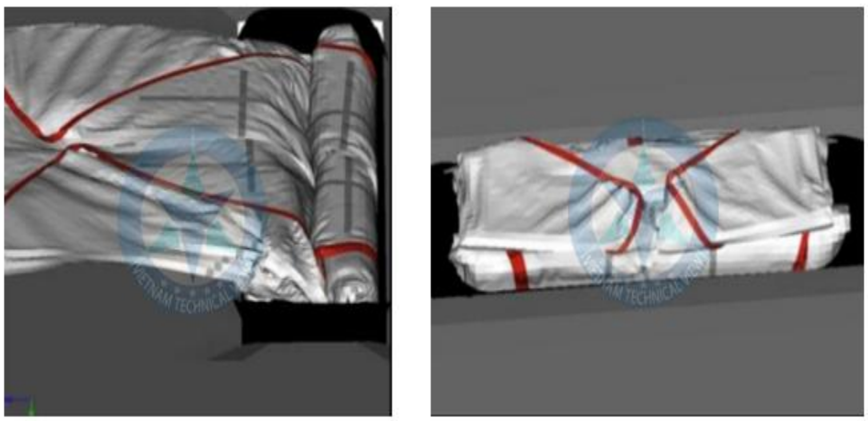


Figure 4.2 Exploded view of front bumper's airbag enclosure design

In the design and construction of airbags, a variety of materials are carefully selected to achieve an optimal balance between strength and flexibility, as illustrated in Fig.(4.2). A pivotal component in airbag assembly is the utilization of woven nylon fabric, which is specifically engineered to be lightweight, tear-resistant, and capable of rapid inflation upon impact during collisions. To ensure the longevity and functionality of the nylon fabric under the extreme heat generated during deployment, a heat-resistant coating, such as silicone or neoprene, is applied. Airbags can be folded using various techniques, such as rolling, pleating, or a combination of both, to achieve the most space-efficient configuration as illustrated in Fig.(4.2).

This protective layer serves to prevent melting or burning of the fabric due to contact with the hot gases produced by the airbag inflator, thereby enhancing its overall durability. Reinforced stitching along the airbag seams further contributes to the structural integrity and reliability of the airbag during deployment.

A thin layer of silicone gel is applied to the fabric to minimize friction and prevent sticking when the airbag is folded. The strategic selection and integration of these advanced materials are designed to optimize the efficiency of the airbag system, focusing on strength, flexibility, and thermal resistance to enhance occupant safety during a collision. Airbags are commonly stored using two methods either by folding the layers or rolling them depending on the specific application, as illustrated in Fig.(4.3).



Rolled Airbags Folded Airbags

Figure 4.3 showing different methods of stored airbags

In the present study, it is noteworthy that the bumper airbags are strategically folded to optimize both storage and deployment efficiency. On the other hand, the bonnet airbags are rolled to maintain their functional integrity while being compact.

Material properties play a pivotal role in determining the performance of airbags, which are designed to rapidly deploy and provide a cushioning effect during collisions. Key material properties, including elasticity, tensile strength, and thermal resistance, significantly influence airbag functionality as mentioned below. Tables 4.3 and 4.4 present the technical properties of the components used in the bumper and bonnet airbag system, offering an overview of the materials selected for each key part. The airbag housing, bolts, and nuts are made from aluminum, ensuring consistency across these structural components. The airbag fabric is composed of nylon (polyamide), chosen for its flexibility and strength, while the gas cylinder, also constructed from aluminum, plays a critical role in the system's operation. This selection of materials was made to optimize both the performance and durability of the bumper airbag system.

According to Ashby and Jones (2012), aluminum alloy 6061 exhibits excellent corrosion resistance and weldability, making it a suitable material for structural components in automotive applications [73]. Similarly, research by Callister and Rethwisch (2020) highlights the superior mechanical properties of nylon (polyamide), such as high strength, heat resistance, and low friction, which make it ideal for impact-absorbing applications [74]. In addition, polymer engineering studies (Brown, 2017) confirms that ABS/PC plastic clamps provide a balance of strength, flexibility, and temperature resistance, reinforcing their suitability for use in airbag systems [75].

Table 4.3 Technical Properties of Components Used in the Bumper Airbag System

Components	**Material**	**Elasticity**	**Tensile Strength (MPa)**	**Thermal Resistance (°C)**
Airbag Housing	Aluminium	70GPa	90–140MPa	Up to 660°C (melting point)
Airbag (Fabric)	Nylon (Polyamide)	2–3GPa	50–100MPa	180–250°C (softening point)
Bolts and Nuts	Aluminium	70GPa	90–140MPa	Up to 660°C (melting point)
Gas Cylinder	Aluminium	70GPa	90–140MPa	Up to 660°C

Table 4.4 Technical Properties of Components Used in the Bonnet Airbag System

Components	**Material**	**Elasticity**	**Tensile Strength (MPa)**	**Thermal Resistance (°C)**
Airbag Housing	Aluminium	70GPa	90–140MPa	Up to 660°C (melting point)
Airbag (Fabric)	Nylon (Polyamide)	2–3GPa	50–100MPa	180–250°C (softening point)
Clamps	Plastic (ABS/PC)	2–2.5GPa	40–70MPa	80–120°C
Bolts and Nuts	Aluminium	70GPa	90–140MPa	Up to 660°C (melting point)

Gas Cylinder	Aluminium	70GPa	90–140MPa	Up to 660°C

Table 4.5 present the dimensions of the bumper airbag systems positioned at the edges and in the middle, both in their deflated and inflated states. The edge airbags, when deflated, exhibit a compact form that expands significantly in length and width upon inflation, while the depth remains constant. The weight of the edge airbag system does not change between states.

Similarly, the middle airbags begin in a compact deflated state and expand substantially in length and height during inflation, with the depth also remaining constant. The weight of the middle airbag system remains unchanged in both deflated and inflated conditions. These dimensions demonstrate the capability of the airbag systems to provide comprehensive coverage and protection to the bumper area when deployed during a collision.

Table 4.5 Airbag housing dimensions

Dimensions of the airbag fitted inside bumper	**Deflated**	**Inflated**
Length	28.5cm	43.5cm
Width	15cm	100cm
Width ‘Depth’	8cm	8cm
Weight of the mechanism	2.5kgs	2.5kgs

4.2.2 Bonnet airbag components mechanism

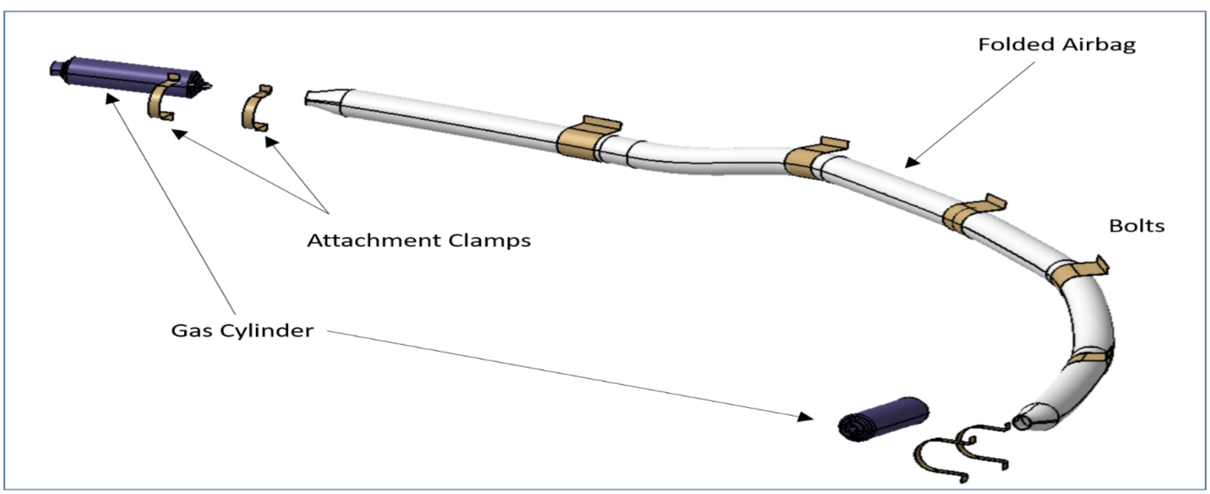


Figure 4.4 Bonnet folded airbag

Fig.(4.4) illustrates the bonnet airbag installed within the front bumper, crafted from the same material discussed in the previous section. This material, chosen for its specific characteristics outlined in the section, ensures consistency in performance and durability. Additionally, supplementary clips are integrated to firmly secure the mechanism to the front bumper, enhancing stability and reliability. These clips are constructed from plastic, chosen for its lightweight properties and suitability for securing components in automotive applications. Together, the use of consistent materials and the incorporation of secure fastening mechanisms contribute to the effectiveness and robustness of the bonnet airbag system.

The airbag cylinder is constructed from aluminum, engineered to withstand the high pressures generated during gas release. These cylinders are meticulously designed to meet stringent safety standards and accommodate the specific volume requirements of the gas needed for airbag inflation. The gas used in airbag systems is commonly nitrogen, chosen for its inert properties and ability to rapidly inflate the airbag without introducing combustion risks. The gas is stored within the cylinder at high pressure, ready to be rapidly released upon activation of the airbag system. Specifications for the airbag cylinder and gas include factors such as pressure ratings, volume capacities, and compatibility with the pyrotechnic inflator mechanism. Additionally, advancements in materials and manufacturing processes continue to refine the design and performance of airbag cylinders and gas, ensuring optimal safety outcomes.

Table 4.6 provides the product specifications for the bonnet airbag, detailing its dimensions in both deflated and inflated states. Additionally, the table includes the weight of the mechanism for reference.

Table 4.6 Bonnet airbag product specifications

Dimensions	**Deflated**	**Inflated**
Length	180cm	180cm
Width	200cm	250cm
Weight of the mechanism	2kgs	2kgs

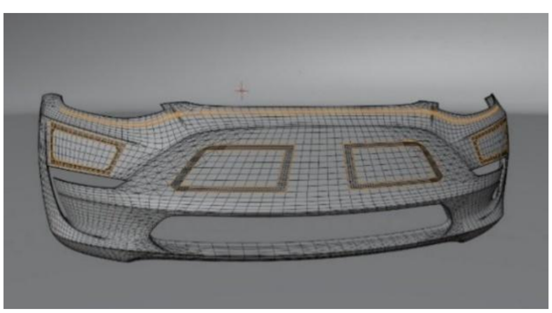


Figure 4.5a Front bumper's airbag's housing 'Exterior View'

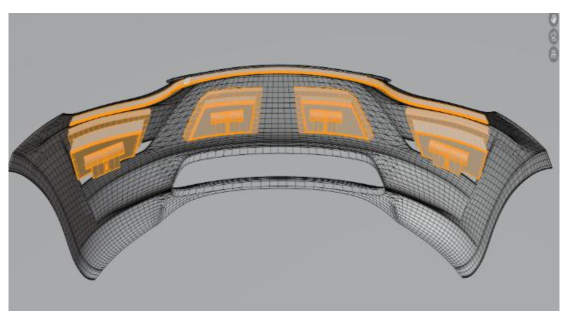


Figure 4.5b Front bumper's housing 'Interior View'

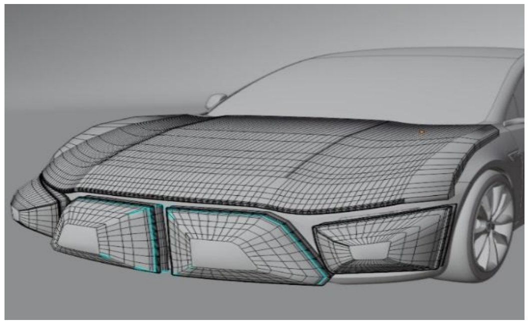


Figure 4.5c Front inflated airbags

As depicted in Fig.(4.5a) and (4.5b), the images provide a visual representation of both the bumper and bonnet airbags post-deployment, showcasing their pivotal role in enhancing automotive safety. Fig.(7a) illustrates the fully deployed airbags, highlighting their effective coverage and potential to mitigate injury risks to vehicle pedestrians. Meanwhile, Fig.(4.5b) offers insight into the intricate housing and installation of the airbag mechanism within the bumper.

This detailed view underscores the precision engineering required to seamlessly integrate airbag systems into vehicle structures, ensuring optimal functionality and reliability. Such visual documentation serves to elucidate the practical implementation of advanced safety features within modern vehicles, offering valuable insights for researchers, engineers, and automotive manufacturers striving to enhance occupant protection and crashworthiness standards. Fig.(4.5c) represents the inflated airbags covering the front end of the vehicle.

Chapter 5 Analytical and Numerical Dynamic Modelling

This chapter presents a comprehensive study on the development and optimization of external airbag systems for automotive applications, focusing on both analytical and numerical modelling. The primary objective is to investigate the dynamic behavior, deployment mechanisms, and protective performance of these airbags in various impact scenarios. To achieve this, the chapter employs theoretical modelling alongside numerical simulations to rigorously define governing equations, material properties, and boundary conditions that accurately replicate real-world conditions. Advanced numerical methods are utilized to simulate complex interactions between the airbag, the vehicle structure, and external objects, ensuring that the findings are both experimentally validated and practically applicable. Particular emphasis is placed on assessing the system's effectiveness in mitigating impact forces on vulnerable regions, such as the torso and pelvic region, while ensuring compliance with safety and regulatory standards. Through this approach, the chapter aims to provide insights into potential design improvements that enhance occupant protection in automotive collisions.

5.1 Time to collision

The following flowchart, depicted in Fig.(5.1), illustrates the operational procedure of a novel system. This system begins by acquiring data from a 3D camera and ultrasonic sensors through the Electronic Control Unit (ECU). Upon data acquisition, the system proceeds to calculate two crucial metrics: Time to Collision (TTC) and Time to Stop (TTS). These metrics are subsequently compared, with the system initiating a response if the (TTC) exceeds the (TTS) and no deceleration is detected. In such cases, based on the distance between the vehicle and the pedestrian, the (ECU) triggers the activation of the front external airbags to cover the front bumper. Additionally, the system also deploys the bonnet's airbag to provide supplementary safety measures.

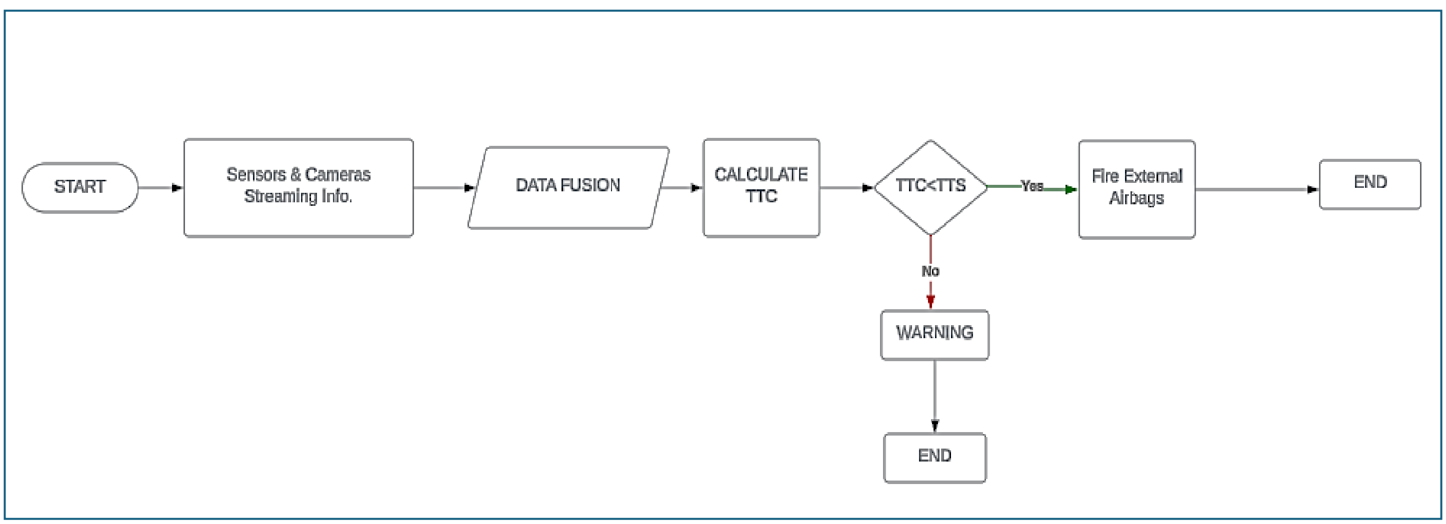


Figure 5.1 Flowchart of algorithm used in the proposed design

The stopping time can be described as follows:

$$Tstop = \frac{Vego}{abrake} \quad (1)$$

where the Tstop refers to the stopping time, which is the period from the first deceleration of the ego vehicle to when it comes to a complete stop. The abrake is the deceleration of the ego vehicle at this point in the deceleration cycle.

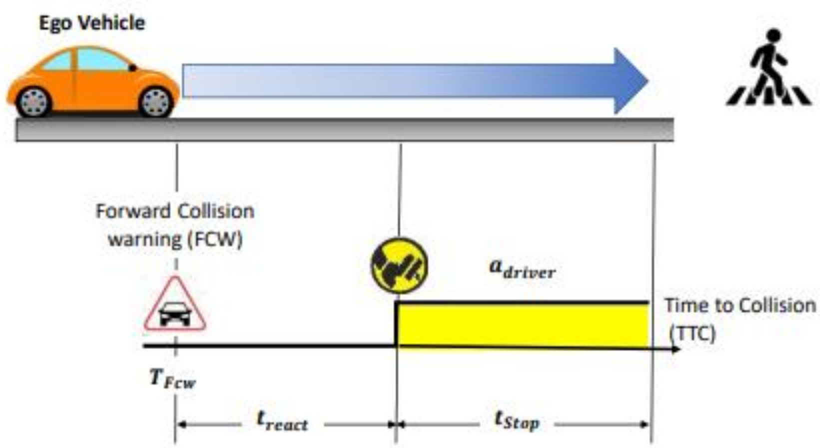


Figure 5.2 Forward collision warning system

As shown in Fig.(5.2) drivers are warned by the FCW system that a collision with a pedestrian is impending and that they should apply the brakes with a delay in the time indicated Treact. To determine how far the ego vehicle will go before colliding with the pedestrian, we employed the following equation:

$$T_{FCW} = T_{react} + T_{Stop} = T_{react} + \frac{V_{ego}}{abrake} \quad (2)$$

where adriver is the deceleration of the ego vehicle and Vego is its velocity.

The AEB controller subsystem consists of three functions: AEB Logic, Stopping Time Calculation, and TTC Calculation.

The AEBS takes over the operation of the car instead of the driver if the driver does not react to the alert on time.

The stopping period for the (FCW), and the initial phase of partial brake is calculated according to the Stopping Time Calculation equation:

$$T_{TTC} = \frac{X_{relative}}{V_{relative}} \quad (3)$$

Where $X_{relative}$ is the distance of the pedestrian toward the ego vehicle and $V_{relative}$ is the velocity of the pedestrian toward the ego vehicle.

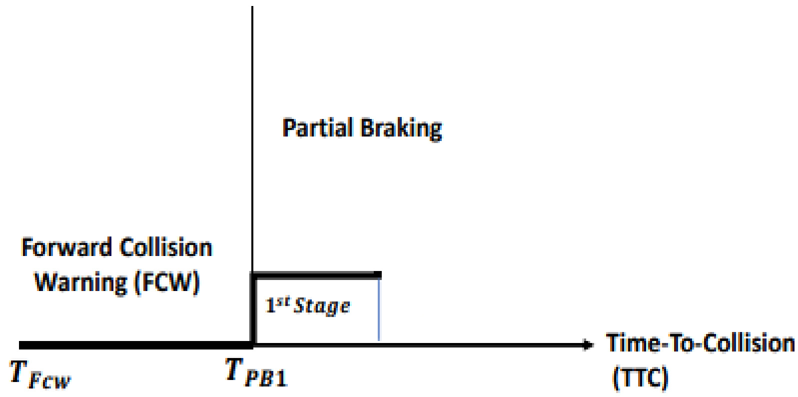


Figure 5.3 The AEB system's cascaded braking

The cascaded braking method used by the AEBS is depicted in Fig.(5.3) The first stage of partial braking (PB) should make up the cascaded braking.

$$T_{PB1} = \frac{V_{ego}}{aPB} \quad (4)$$

Where PB is the deceleration of the first partial brakes stage one.

The ECU will continuously monitor the distance between the ego vehicle and the pedestrian. Additionally, sensor fusion will provide the ECU with further information regarding the pedestrian's distance and the vehicle deceleration.

Considering two points A ($\mathcal{X}1$, $\mathcal{Y}1$, $\mathcal{Z}1$) 'The ego vehicle' and B ($\mathcal{X}2$, $\mathcal{Y}2$, $\mathcal{Z}2$) 'The pedestrian' in 3D space, then, the distance formula for these two points is given by:

$$\sqrt{[x_2 - x_1]^2 + [y_2 - y_1]^2 + [z_2 - z_1]^2} \quad (5)$$

5.2 Pedestrian detection

Once an obstacle is detected and identified as a pedestrian, the ECU will calculate the distance as represented in the following equations:

$$V = \Delta x / t \quad (6)$$

where v is the ego vehicle velocity, Δx is the distance between the ego vehicle and the pedestrian, t is the time to meet

By substituting ΔX with *(*Xf-Xi*)* where *Xf* is the final distance and Xi is the initial one.

$$\Delta X = \frac{(x_f - x_i)}{t} \quad (7)$$

$$X_f = V_t + X_i \quad (8)$$

In case the ego vehicle is accelerating the following equation will be used:

$$\Delta X = V_i(t) + 1/2(a)(t^2) \quad (9)$$

where a is the ego vehicle acceleration.

ΔX which is equal to *(Xf-Xi)*.

Fig.(5.4) illustrates the variations in Time-to-Collision (TTC) and Time-to-Stop (TTS) as functions of deceleration. The x-axis represents deceleration, while the left y-axis corresponds to (TTC) and the right y-axis to (TTS). The (TTC) curve (depicted in dark blue) exhibits a sharp initial decline before gradually stabilizing at lower values, indicating a rapid decrease in available reaction time as deceleration increases. Conversely, the (TTS) curve (depicted in orange) initially peaks before declining and stabilizing, suggesting that a higher deceleration rate initially prolongs the stopping time before reaching a near-constant state. This relationship highlights the impact of braking intensity on both collision avoidance and stopping capability.

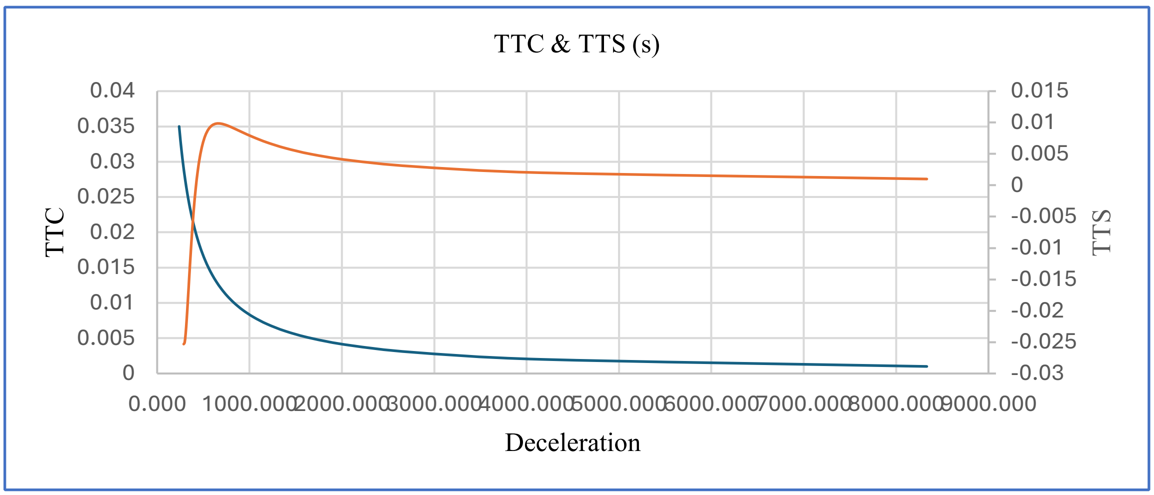


Figure 5.4 shows the Time to collision and Time to stop

For transparency and reproducibility, Table 5.1 consolidates all key modelling assumptions and parameters used in the TTC/TTS/AEB deployment logic described in Sections 5.1 and 5.2. These values were selected based on typical urban driving conditions and the capabilities of the experimental rig components described in Chapter 3.

Table 5.1 TTC/TTS/AEB System Assumptions and Parameters

Parameter	Value / Assumption	Justification / Source
Trigger threshold distance	3cm	Scaled rig detection range; ultrasonic sensor spec (Table 4)
Airbag deployment condition	TTC < TTS	Insufficient braking; Equations (1)–(3)
Assumed vehicle deceleration	$6m/s^2$	Typical AEB partial-braking stage deceleration
Driver reaction time	1.5s	Standard FCW response assumption; Equation (2)
Sensor update / sampling period	40Hz (25ms)	HC-SR04 ultrasonic sensor specification (Table 4)
Sensor detection delay	≤ 25ms	One sensor update cycle; consistent with Arduino loop time
Braking stages	FCW → PB1 → Full AEB	Cascaded AEB logic; Figure 10 and Equation (4)
False-trigger mitigation	Dual-condition: TTC < TTS AND obstacle confirmed	Requires obstacle identification before deployment; Figure 8 flowchart
Airbag inflation assumption	Constant CO_2 pressure; full inflation before impact	Section 3.7.5 (Assumption II); validated by rig experiments

5.3 System Dynamics Analysis of the Airbag system

In this section, a system dynamics analysis is performed under the assumption of zero gravity, with the vehicle undergoing horizontal motion. The airbag's internal volume is assumed to be 70L and the analytical model is adapted to account for the horizontal displacement of the vehicle. The analysis utilises the governing equations that describe the dynamic interactions between the airbag's internal pressure, the payload mass, and the horizontal motion. These equations are employed to determine the acceleration, velocity, and displacement of the payload at each time step, offering a detailed understanding of the system's response during airbag deployment. Through this iterative process, the dynamic behaviour of the system is thoroughly examined, providing insights into the performance and efficacy of the airbag in such conditions.

Performing a system dynamics analysis under the assumption of zero gravity while the vehicle undergoes horizontal motion, assuming the airbag internal volume is 70L and by using the following equation as shown in paper, the analytical model is adapted for horizontal motion.

$$M_a + (P_{bag} - P_{atm})A_t = 0 \qquad (10)$$

Where "Ma" represents the payload mass, "P_{bag}" signifies the internal airbag pressure, "P_{atm}" stands for atmospheric pressure, and "At" corresponds to the airbag footprint area. This equation serves as the foundational formula for assessing the dynamic state of the system at each time interval within the airbag cushioning model. When Equation (10) is rearranged, it provides the acceleration of the payload.

$$-a = \frac{(P_{bag} - P_{atm})A_t}{M} \qquad (11)$$

Then, the alteration in payload velocity during each time increment Δt can be represented as

$$\Delta V = a * \Delta t \qquad (12)$$

And the velocity of the payload can be determined from

$$V_t = V_{(t-1)} + \Delta V \qquad (13)$$

Where $V_{(t-1)}$ is the velocity of the payload in the previous step.

The displacement of the payload is obtained from:

$$u_{t=u_{t-1}} + v_{t-1}\,\Delta t + \frac{1}{2}a\Delta t^2 \qquad (14)$$

Where u_{t-1} is the velocity of the payload from the previous step.

The dynamic behaviour of the cylindrical airbag, focusing on the interdependence between the initial cross-sectional diameter, the deformed airbag height, and the footprint length. The displacement of the payload plays a pivotal role in governing the airbag’s deformation, and this displacement is intricately linked to the footprint length. By establishing this relationship, the key parameters such as the airbag's contact surface area can be accurately computed. In its compressed state, the cross-sectional area of the airbag is modelled as a combination of a rectangular section and two semi-circular sections, which reflects the geometric configuration under deformation. Assuming a constant axial length for the cylindrical airbag, the volume and footprint area are derived, offering a comprehensive characterisation of the airbag’s dynamics. Furthermore, the force exerted on the vehicle's bumper is computed, considering both the displacement of the payload and the vehicle's mass. These derived parameters are essential for understanding the airbag system’s performance and its interaction with the vehicle during deployment, thereby enabling a more precise evaluation of its effectiveness.

$$\pi D_o = \pi D_t + 2L_t \qquad (15)$$

where D0 is the cross-section initial diameter of cylindrical airbag, Dt is the height of the deformed airbag, and Lt is the airbag footprint length, h_t is the displacement of the payload.

$$D_t = D_o - h_t \qquad (16)$$

$$h_{t=} h_{t-1} + u_{t-1}\Delta t + \frac{1}{2}a\Delta t^2 \qquad (17)$$

Where h_{t-1} is the displacement of the payload in the previous time step.

When Equations (6) and (7) were combined, a connection between the length of the airbag's footprint and the displacement of the payload were obtained. In other words:

$$L_t = \frac{\pi}{2}(D_o - D_t) = \frac{\pi}{2} h_t \qquad (18)$$

Conversely, in the compressed state, the cross-sectional area of the airbag comprises the combined areas of a rectangle and two semi-circles. Therefore:

$$S_t = \frac{\pi}{4} Dt^2 + D_t L_t = \frac{\pi}{4(D_o - h_t)^2} + (D_o - h_t)L_t \qquad (19)$$

Since the axial length of the cylindrical airbag assumed to remain constant, the volume and contact surface area (footprint area) of the cylindrical airbag can be calculated by multiplying Equations (9) and (10) by this constant length. This can be expressed as follows:

$$A_t = \frac{\pi}{2} L_o h_t \qquad (20)$$

And $$V_t = L_o(D_o - h_t)\left[\frac{\pi}{4(D_o - h_t)} + L_t\right] \qquad (21)$$

Where, L0 is the fixed cylindrical airbag axial length.

The calculation of the force exerted on the vehicle's bumper is as follows:

$$F = \frac{1}{2}\,((m)\,(u_t))/\,h_t \qquad (22)$$

Where m is the mass of the vehicle.

5.4 Prototype of the inflated airbag

The airbag compression process is analyzed through system dynamics and airbag deformation. A mathematical model of the entire cushioning process is then developed, incorporating the interactions between these factors.

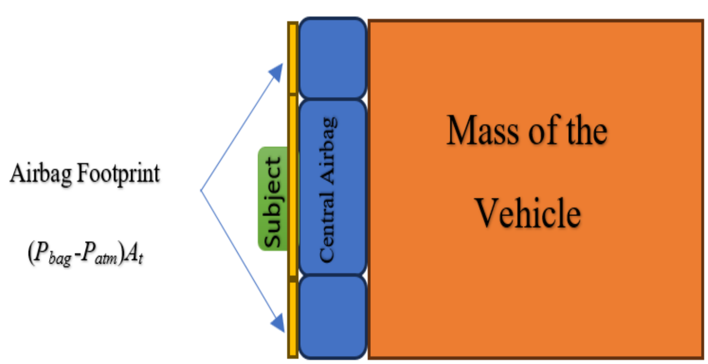


Figure 5.5a Stroked Airbags

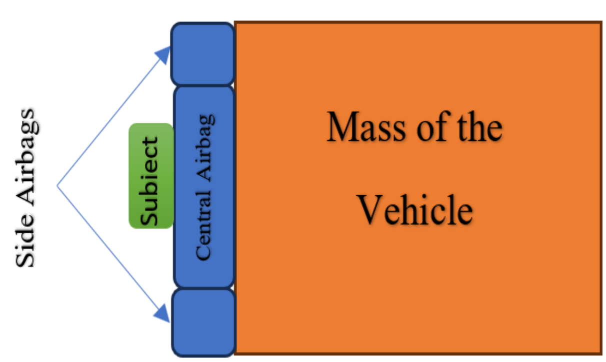


Figure 5.5b Unstroked Airbags

Fig.(5.5a) and (5.5b) illustrate the interaction between a subject, airbags, and the vehicle mass during an impact scenario. In the first diagram, the central airbag acts as a cushion between the subject and the vehicle, distributing the force of impact over a defined contact area. The second diagram includes side airbags in addition to the central airbag, further enhancing protection by dispersing impact forces more effectively. These schematics emphasize the role of airbag deployment in minimizing injury risk and improving occupant safety during collisions.

This systematic framework not only enhances our understanding of airbag dynamics but also lays the groundwork for optimizing airbag design and deployment strategies to maximize occupant safety in automotive scenarios. Despite the overarching commonality in the sensor modalities and algorithmic frameworks employed for collision detection and airbag deployment, the successful adaptation of airbag technology across diverse vehicle models and sizes hinges upon a meticulous evaluation of the vehicle's dimensional attributes, with particular emphasis on the bumper and bonnet geometries. These structural elements, which serve as the primary crumple zones during frontal impacts, exhibit considerable variability in their dimensions and configurations across different vehicle platforms. Consequently, the precise positioning and integration of airbag housings must be meticulously tailored to the specific geometries of each vehicle model, ensuring optimal deployment trajectories and efficient energy dissipation during impact scenarios. This customization process necessitates a comprehensive understanding of the vehicle's structural dynamics, leveraging advanced computational simulations and empirical testing to determine the ideal placement of airbag housings within the confined spatial constraints imposed by the bumper and bonnet assemblies. By harmonizing the airbag deployment mechanisms with the unique dimensional characteristics of each vehicle model, automakers can maximize the efficacy of these potentially injury-mitigating systems, thereby enhancing occupant protection across a diverse range of vehicle platforms.

The development and deployment of external airbag systems necessitate a comprehensive undertaking, commencing with rigorous research and development endeavors to meticulously design the system and perform extensive testing to validate its functionality and safety under diverse operational conditions. Paramount to this endeavor is ensuring stringent compliance with all pertinent automotive safety standards and regulations set forth by governing bodies such as the European New Car Assessment Program (Euro NCAP) and adhering to international standards promulgated by organizations like (ISO) or (SAE).

Thorough documentation, encompassing the system's design, functionality, and safety test results, including crash simulations, real-world trials, and comprehensive reporting, must be prepared. The submission of these materials to the appropriate regulatory authorities is a critical juncture, necessitating engagement with the regulatory bodies throughout their review process, promptly addressing any feedback, requests for additional tests, or clarifications. Upon satisfying all regulatory requirements and successfully navigating the review process, the requisite certifications, and approvals, encompassing safety, environmental impact, and compliance with automotive standards, can be obtained. After gaining regulatory approval, the system can be introduced to the market, accompanied by continuous monitoring, reporting, and post-market surveillance to ensure its sustained performance and safety in real-world applications.

The external airbags, designed for mounting on the exterior of vehicles adhere to specific IP (Ingress Protection) classifications to ensure their reliability and performance under various environmental conditions. The (IP) rating system, defined by the International Electrotechnical Commission (IEC), provides a standardized method to classify the degree of protection against solid objects, dust, and water ingress. For external airbags, the following IP classifications are typically relevant: (IP6X), indicating complete protection against the ingress of dust and other solid particles; (IP66 or IP67), specifying protection against powerful water jets (IP66) and temporary immersion in water up to a certain depth (IP67); (IP68), denoting protection against prolonged immersion in water at specified pressure and depth, which may be necessary for vehicles intended for operation in extreme environments such as off-road or amphibious applications; and (IPX9K), indicating protection against high-pressure, high-temperature water jets and steam cleaning, relevant for certain commercial or industrial applications where such cleaning methods are employed.

The (IP) rating for external airbags should be determined based on the intended application and operating environment of the vehicle, with manufacturers potentially targeting higher IP ratings to ensure enhanced durability and reliability, particularly for vehicles expected to encounter harsh or extreme conditions. Furthermore, external airbags may need to comply with other environmental and impact resistance standards specific to the automotive industry, such as those set by organizations like the International Organization for Standardization (ISO) or the Society of Automotive Engineers (SAE). By adhering to the appropriate (IP) classifications and industry standards, external airbag systems can maintain their integrity and effectiveness, ensuring optimal occupant protection even in challenging environmental conditions.

5.5 Model calculation

The analytical model parameters are shown in Table 5.2, the design incorporates advanced specifications aimed at mitigating the severity of pedestrian collisions. The airbags, constructed from durable nylon material, feature an initial diameter of 1.00 meter and an axial length of 1.50m, ensuring comprehensive coverage upon deployment. With a fabric thickness of 0.002m, the airbags exhibit robustness while maintaining flexibility. Employing an initial pressure of 101325kg/m3 and a specific gas constant of 286.9J/kg/K, our design prioritizes the safety of pedestrians by effectively absorbing impact forces.

Table 5.2 CYLINDRICAL AIRBAG MODEL PARAMETERS

Model	**Symbol**	**Quantity**	**Unit**
Initial diameter	D_0	1.00	m
Airbag axial length	L_0	1.50	m
Fabric thickness	d	0.002	m
Initial pressure	P_0	101325	kg/m3
Specific gas constant	R	286.9	J/kg/K
Payload Weight	M	1200	kg
Initial velocity	u	30	m/s
Threshold pressure	P_{bag}	130000	Pa
Gravity	g	9.8	m/s2

The performance of the airbag is analyzed using the mathematical model and validated with the results obtained by a numerical model devoted in MATLAB, as shown in the following figures.

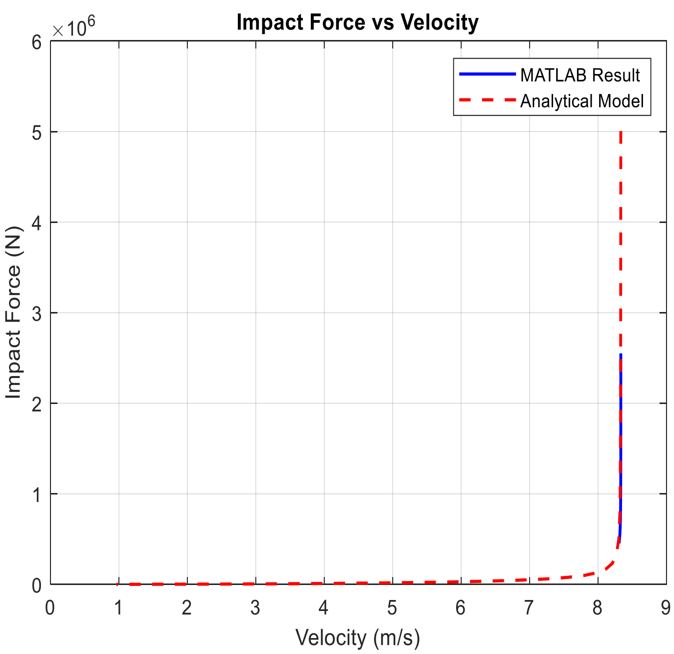


Fig. 5.6a Comparison of Impact Force vs. Velocity

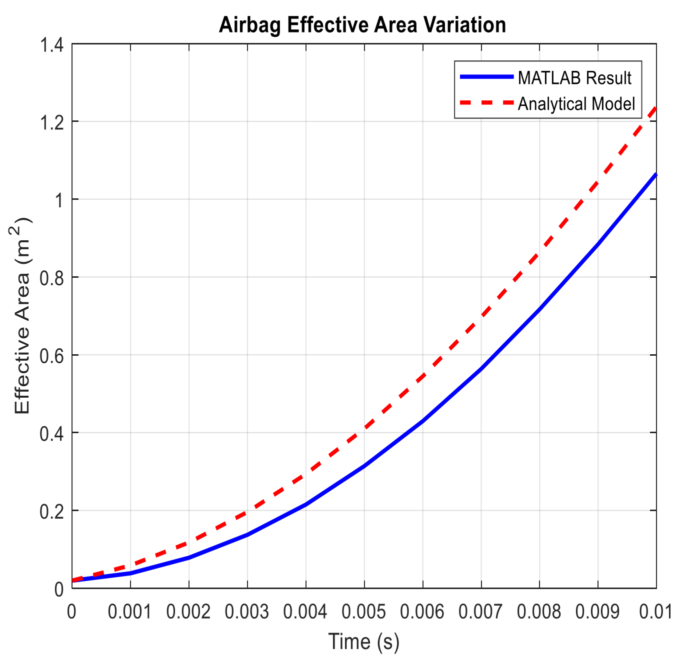


Fig. 5.6b Comparison of Effective Area vs. Time

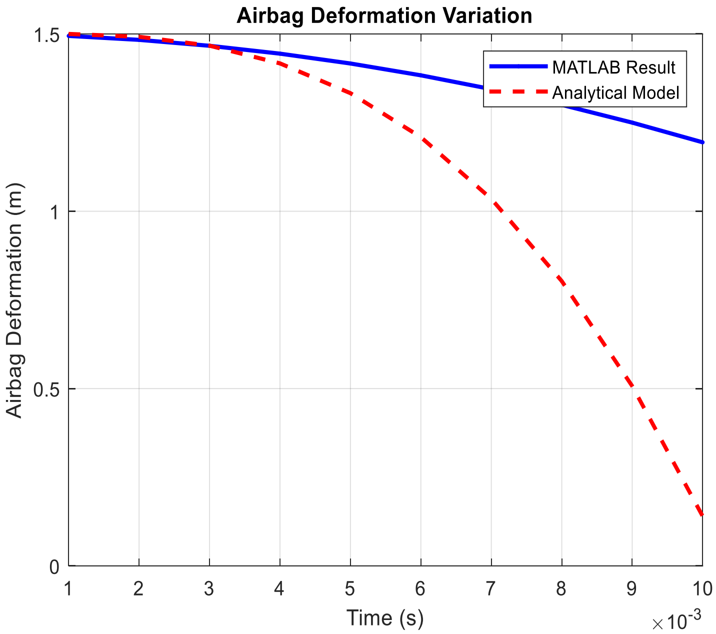


Fig. 5.6c Comparison of Airbag Deformation vs. Time

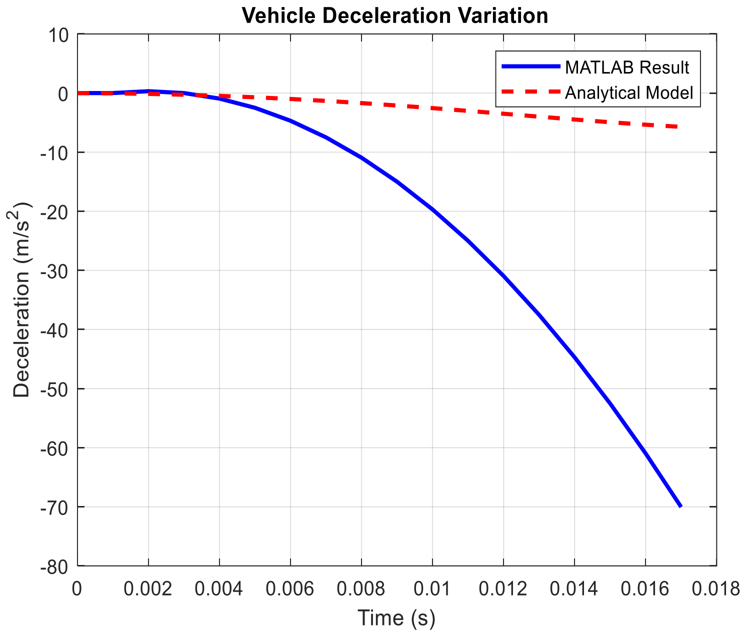


Fig. 5.6e Comparison of Vehicle Deceleration vs. Time

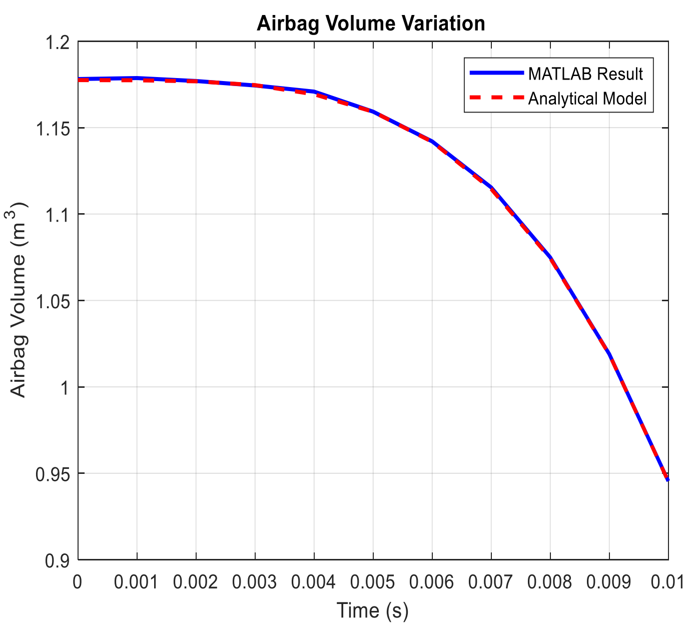


Fig. 5.6d Comparison of Airbag Volume vs. Time

Despite some variances observed in the graphs, which are common in comparative studies, the findings presented indicate a strong overall alignment between the numerical model proposed in this paper and the analytical models concerning airbag inflation scenarios. However, a more detailed examination of these discrepancies is essential to understand their underlying causes and significance.

Airbag Deformation: While the analytical model effectively captures the degree of airbag deformation during inflation, slight deviations are observed, particularly in later stages of deployment. These differences may stem from simplifications in the analytical model that do not fully account for material flexibility, internal pressure variations, or secondary deformation effects. The numerical model, being more detailed, likely incorporates additional physical interactions that influence the deformation dynamics.

Impact Force: The impact force predicted by the numerical model closely follows the analytical model at lower velocities but deviates significantly as velocity increases. This discrepancy is particularly noticeable at high impact speeds, where the numerical model suggests a more gradual force buildup, whereas the analytical model exhibits a sharp increase. This difference may be attributed to assumptions made in the analytical formulation, such as idealized contact conditions or simplified damping effects, which do not fully capture the complex energy dissipation mechanisms present in real-world scenarios.

Airbag Volume: The trends in airbag volume evolution generally align between both models; however, minor variations exist. These differences arise from the way gas flow dynamics and inflation rates are approximated in the analytical model. The numerical model may account for factors such as gas leakage, heat transfer, or variations in internal pressure that are not explicitly included in the analytical approach, leading to slight deviations in the predicted volume over time.

Airbag Effective Area: While both models depict a consistent trend in the expansion of the airbag's effective area, some divergence is evident in the rate of increase. The analytical model assumes an idealized inflation profile, whereas the numerical results may include effects such as localized pressure variations or non-uniform deformation, leading to more gradual changes in the effective area. These differences highlight the importance of incorporating real-world factors into predictive models to ensure accuracy in airbag coverage assessments.

Deceleration Dynamics: The numerical and analytical models exhibit similar overall trends in deceleration, yet minor deviations emerge, particularly at the onset of impact. These differences could result from variations in the assumed interaction between the airbag and the occupant or vehicle structure. The numerical model, which captures transient effects and secondary force interactions more accurately, suggests a slightly smoother deceleration curve compared to the more abrupt transitions seen in the analytical model.

Acknowledging these discrepancies is crucial, as they provide insights into the limitations of simplified analytical approaches while also validating the robustness of the numerical model. While minor variations are expected due to idealized assumptions in the analytical framework, the overall trends remain consistent, reinforcing the analytical model's reliability. Understanding these differences allows for targeted refinements in airbag design and deployment strategies, ultimately enhancing occupant safety in automotive applications.

Following a similar approach as outlined above, deformation assumptions can be established for bonnet airbag. These assumptions serve as a basis for determining the airbag's volume and footprint area during the cushioning process.

Fig.(5.7) offers a compelling visual comparison of the impact forces exerted on the human body during a non-avoidance vehicular collision scenario. The data clearly highlights the pronounced disparity in forces experienced under two distinct conditions: one involving no external airbag deployment and the other incorporating the deployment of external airbags. This comparison underscores the critical implications for pedestrian safety and injury prevention.

In the scenario where external airbags are absent, the forces exerted upon the pedestrian or vulnerable road user are markedly elevated. These elevated forces substantially increase the likelihood of severe or even fatal injuries, posing significant risks to the torso and other vital areas of the body upon impact with the vehicle. The absence of mitigating technology places the pedestrian in a precarious situation, where survival probabilities are notably diminished.

Conversely, the strategic deployment of external airbags, as illustrated in the results, demonstrates a remarkable reduction in the magnitude of impact forces. The bumper-mounted airbag system effectively absorbs and redistributes the energy of the collision, resulting in a significant alleviation of the forces transferred to the lower regions of the body. This mitigation not only enhances survival prospects but also minimises the severity of injuries sustained, contributing to a meaningful reduction in long-term physical trauma for pedestrians.

In addition to bumper-mounted airbags, Fig.(5.8) figure focuses on the deployment of bonnet-mounted airbags, designed to protect the upper body regions, including the torso and head. This system further underscores the potentially injury-mitigating potential of external airbag technology by providing broad protection across the analysed regions across multiple impact zones. The bonnet airbag serves to cushion the upper body during a collision, preventing or significantly reducing the risk of critical injuries to the chest, neck, and head.

Together, these findings reveal a stark dichotomy in impact force profiles and their respective outcomes, emphasising the transformative role of external airbag systems in advancing road safety. By mitigating both lower and upper body injuries, these systems foster a paradigm shift towards a more holistic approach to pedestrian protection. Such advancements are poised to redefine vehicular safety standards, underscoring the necessity of incorporating external airbag systems as integral components of modern automotive design

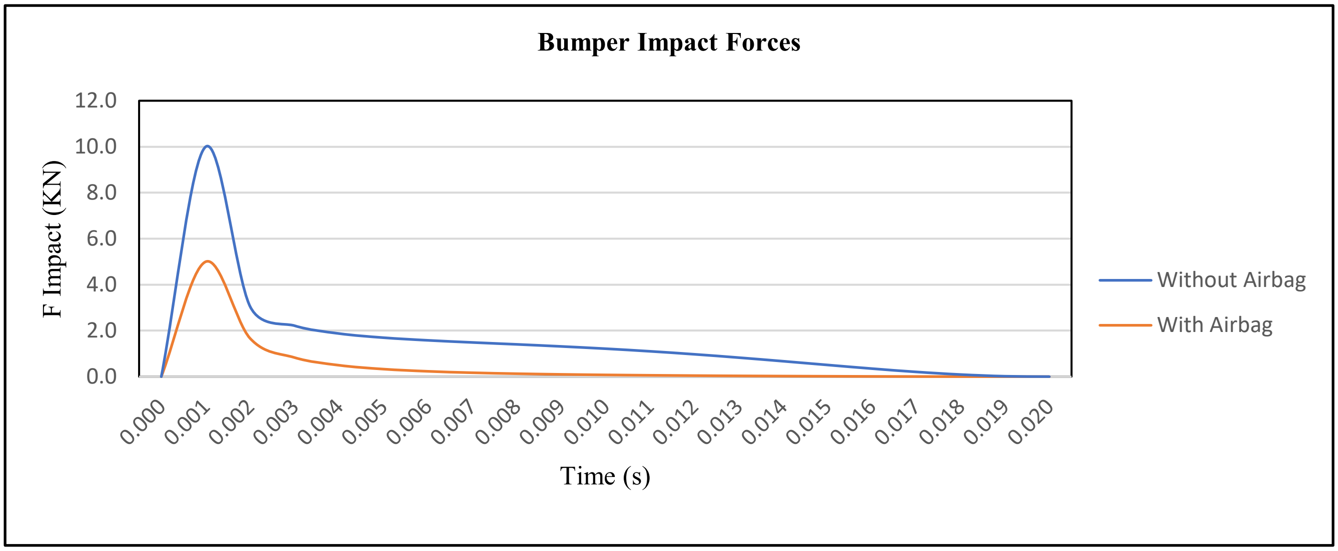


Figure 5.7 Illustrates the stark contrast in impact forces sustained by the lower body regions of a pedestrian struck by a vehicle traveling at 30 km/h

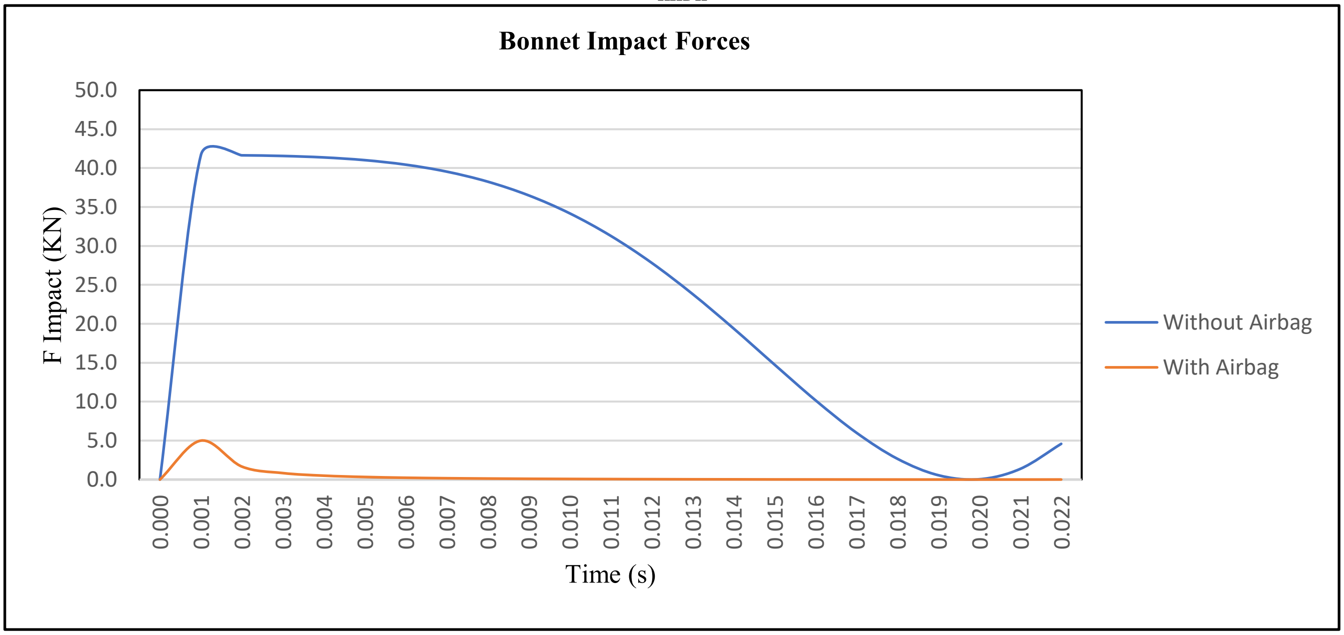


Figure 5.8 Illustrates the stark contrast in impact forces sustained by the upper body regions of a pedestrian struck by a vehicle traveling at 30km/h

Following a collision, the deflation process of the external airbags is governed by a controlled one-way venting mechanism, facilitated by specially designed venting perforations in the airbag material. These perforations remain sealed upon deployment, ensuring that the airbags stay fully inflated until they make contact with an external object in this case, a pedestrian. The deflation process is inherently dependent on the weight of the impacted subject, as the force exerted on the airbag dictates the rate at which air is expelled through the venting system. A heavier pedestrian will induce a more rapid compression of the airbag, accelerating the venting process, whereas a lighter individual will result in a more gradual release of air. This weight-sensitive deflation mechanism ensures that the airbag provides optimal cushioning, dynamically adapting to different impact scenarios while maintaining its protective function.

5.6 Analytical measurements

The analytical measurements present the key dynamic parameters derived from experimental data, applying appropriate mathematical models to quantify system behavior. By utilizing recorded datasets, computational techniques, and governing equations, this analysis enables a precise examination of velocity, acceleration, and force variations over time. The measured values serve as the foundation for deriving essential motion characteristics through differential and integral calculations. This approach provides deeper insight into the system’s response under varying conditions, particularly in assessing deceleration patterns, resistive forces, and energy dissipation mechanisms. Through the application of validated equations and analytical methods, the study ensures an accurate representation of real-world dynamics, offering valuable information for performance optimization and predictive modeling.

The velocity variation depicted in Fig.(5.9) illustrates the deceleration profile of the system over a brief temporal span, with velocity measured in meters per second(m/s) against time in seconds(s). Initially, the velocity remains nearly constant at approximately 8.5m/s, indicating a minimal rate of deceleration. However, as time progresses beyond 0.01s, a pronounced decline in velocity is observed, with a notably nonlinear trend. This suggests that the deceleration is not uniform but rather increases as the system evolves. The rapid decrease in velocity beyond 0.015s indicates a significant resistive force acting upon the system, attributed to aerodynamic drag, frictional forces, or an external braking mechanism.

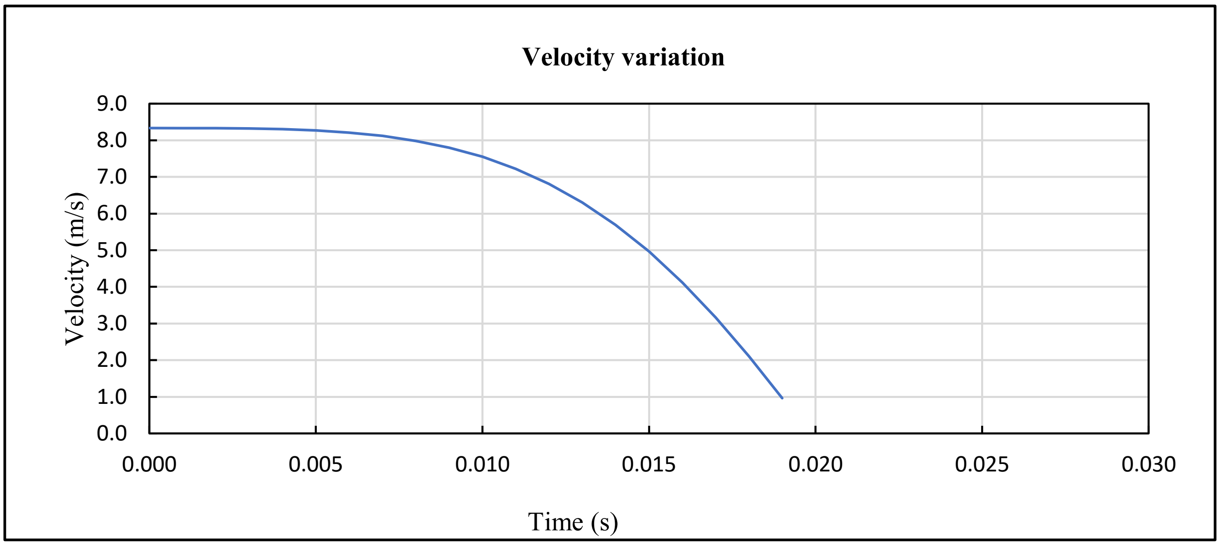


Figure 5.9 shows the velocity variation under resistive forces

The deceleration profile depicted in Fig.(5.10) illustrates the system's acceleration characteristics over time, measured in gravitational acceleration(g) against time in seconds(s). Initially, the deceleration is minimal, aligning with the near-constant velocity observed in the velocity-time graph. However, as time progresses beyond 0.005s, the deceleration increases significantly in magnitude, reaching a peak negative value of approximately -6.5g around 0.02s. This suggests the presence of a strong opposing force due to an impact force. The sharp nature of this increase implies that the force is not solely due to gradual aerodynamic drag, which typically follows a velocity-dependent relationship. Beyond 0.02s, the magnitude of deceleration decreases, indicating a transition where the resistive force is either diminishing or counteracting forces are emerging. This is due to energy dissipation.

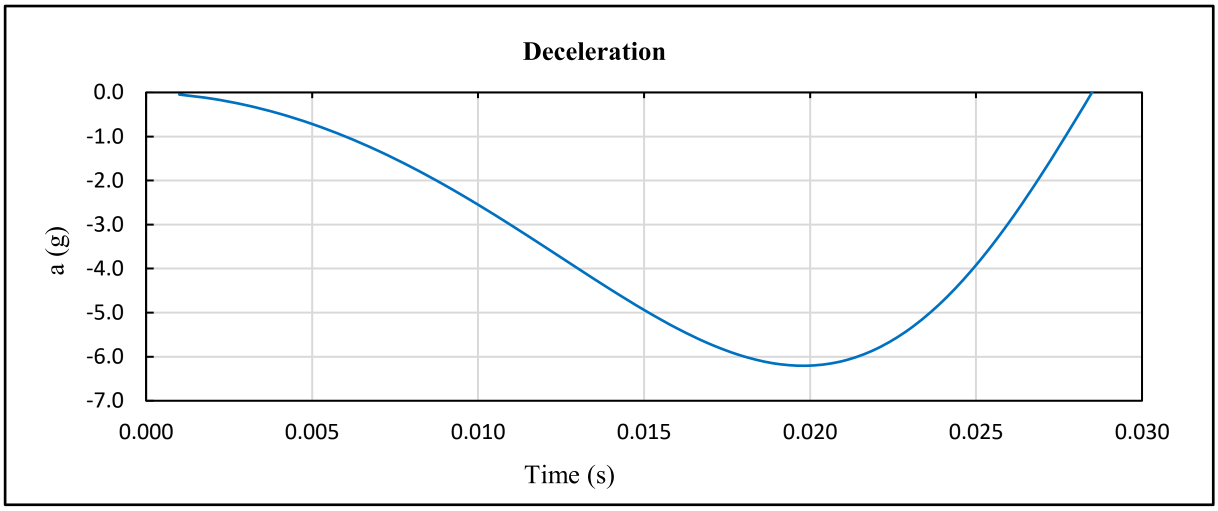


Figure 5.10 shows the deceleration dynamics of the system

The displacement variation depicted in Fig.(5.11) illustrates the dynamic interaction between vehicle displacement and airbag deformation over time. The displacement is measured in meters (m) against time in seconds(s). Initially, the vehicle displacement follows an increasing trend, reaching its peak at approximately 0.02s before exhibiting a decline. Conversely, airbag deformation follows an inverse pattern, beginning at a maximum displacement and progressively decreasing to zero. This suggests a transfer of energy from the vehicle's motion into the airbag, which undergoes deformation to absorb the impact. The crossover point, where both curves intersect, indicates a critical phase in the energy dissipation process, representing the moment of peak airbag resistance. The rapid reduction in airbag deformation beyond this point implies that the system has effectively mitigated the impact forces, highlighting the airbag's role in cushioning the deceleration of the vehicle and reducing occupant injury risk.

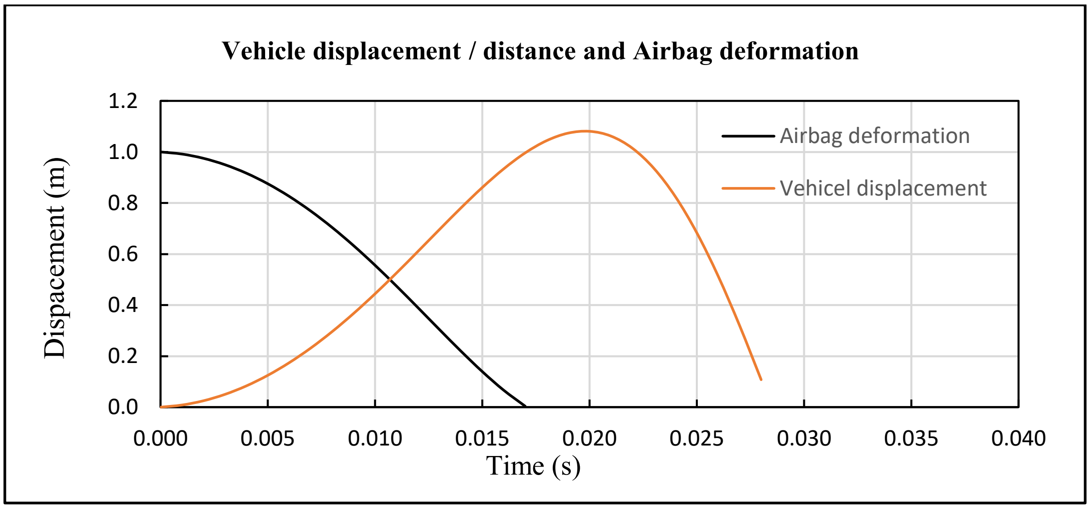


Figure 5.11 shows the vehicle displacement and airbag deformation dynamics

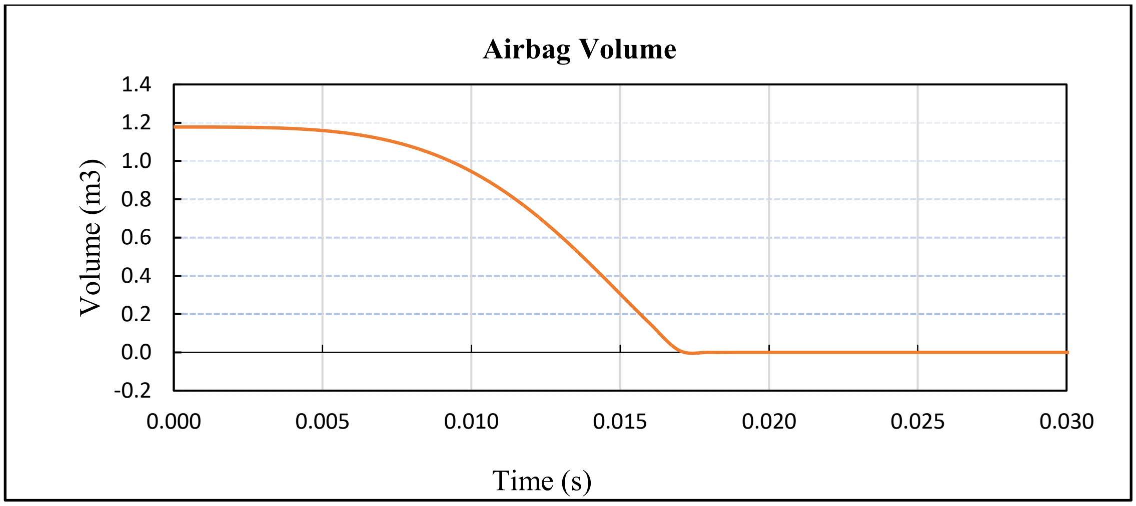


Figure 5.12 shows the transient variation of airbag volume during inflation and deflation

Fig.(5.12) presented illustrates the dynamic variation in airbag volume over time during the inflation and deflation phases, crucial for occupant protection in a crash scenario. Initially, the airbag volume is approximately 1.2m³, reflecting its rapid deployment upon activation. However, as time progresses, the volume exhibits a decline, reaching a minimum close to zero at around 0.020s. This reduction is indicative of the gas venting mechanism, which prevents excessive rebound forces on the occupant. The subsequent increase beyond this point suggests secondary inflation dynamics, influenced by residual gas behavior and structural elasticity of the airbag material. The oscillatory nature of the curve highlights the complex interplay between gas dynamics, fabric deformation, and venting characteristics. Understanding these transient behaviors is paramount for optimizing airbag performance to enhance occupant safety while mitigating potential injury risks.

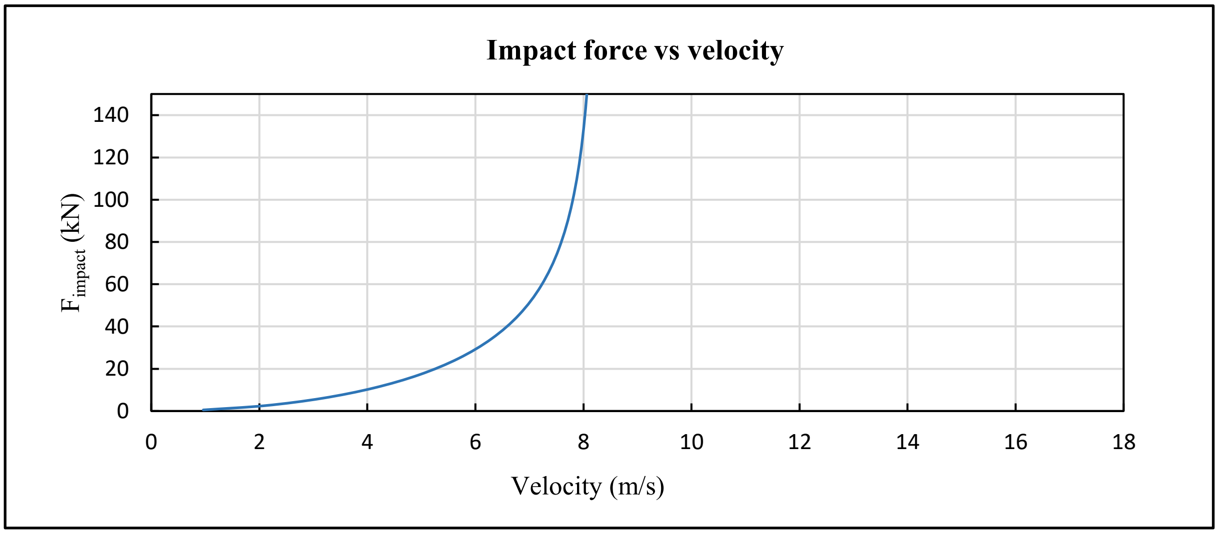


Figure 5.13 shows the relationship between impact force and velocity in crash dynamics

Fig.(5.13) illustrates the rapid increase in impact force as a function of velocity, demonstrating a non-linear relationship critical in crashworthiness analysis. At low velocities, the impact force remains relatively small, exhibiting a gradual rise. However, beyond approximately 8m/s, a sharp escalation is observed, exceeding 140kN, highlighting the quadratic or higher-order dependence of force on velocity. This trend underscores the effect of velocity management in crash safety, as minor increases in speed result in exponentially greater forces, necessitating the use of energy-absorbing structures such as airbag systems to mitigate occupant injuries.

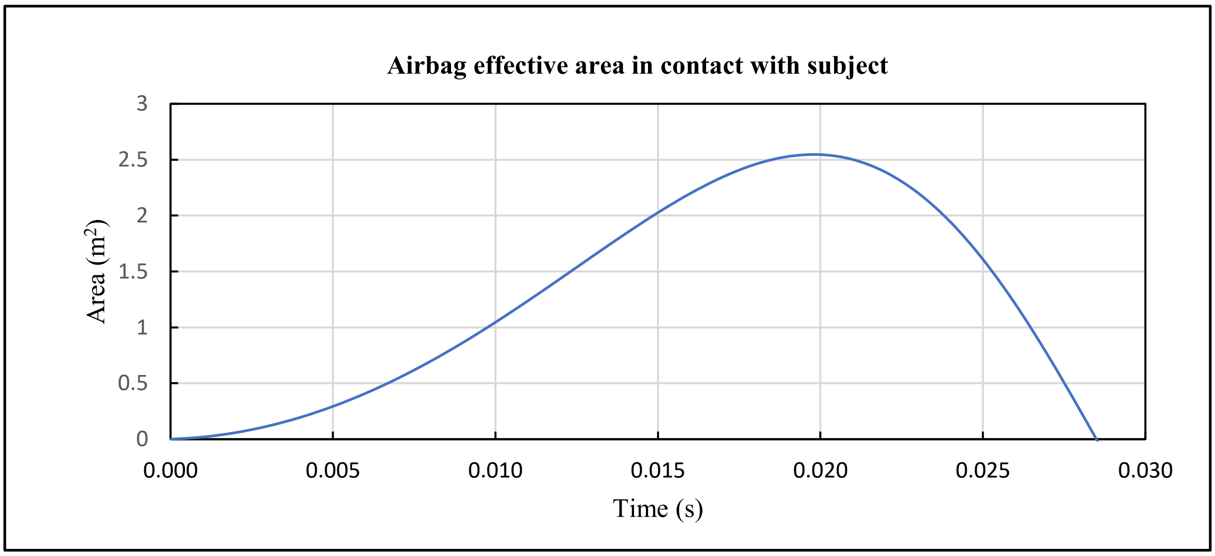


Figure 5.14. shows the temporal evolution of area expansion and contraction in a dynamic system

Fig.(5.14) represents the variation of area over time, depicting an initial growth phase, reaching a peak, followed by a decline. This trend suggests a transient expansion and contraction phenomenon, observed in airbag inflation dynamic system under impact. Initially, the area increases gradually, indicating a controlled expansion. As time progresses, the rate of growth accelerates until a peak value is reached, beyond which the area begins to contract. The decline suggests energy dissipation or structural retraction, due to pressure equalization and external constraints. Such behavior is critical in applications like occupant safety systems, where understanding the temporal variation of expansion is essential for optimizing performance and mitigating undesired effects.

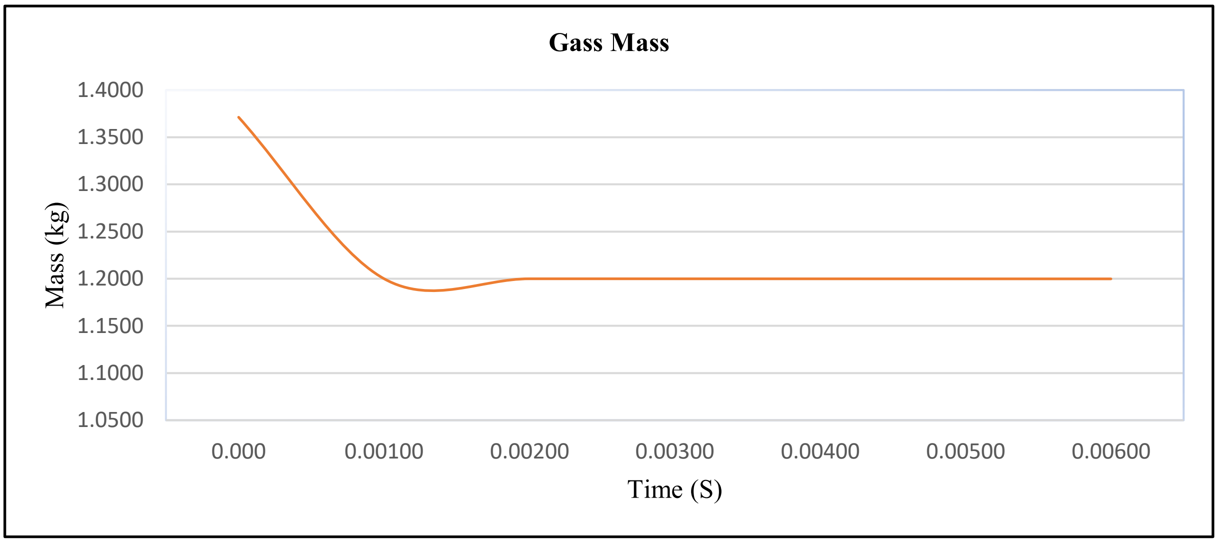


Figure 5.15 shows Dynamic Evolution of Gas Mass in a Rapid Discharge Event

Fig.(5.15) illustrates the variation of gas mass over a short time span, showing an initial sharp decline followed by a stabilization phase. This trend indicates a rapid gas discharge, characteristic of controlled inflation systems such as airbag deployment and high-pressure gas release.

In the initial phase, the gas mass decreases significantly, indicating a high outflow rate governed by pressure differentials and flow dynamics. The slight dip before stabilization suggests oscillatory behavior due to shock interactions. The subsequent plateau represents a steady-state condition where the system reaches equilibrium due to dissipative mechanisms.

This behavior is crucial in safety applications, where precise gas flow regulation ensures optimal performance, balancing rapid expansion with controlled discharge to mitigate excessive force or instability.

Fig.(5.16) illustrates the variation of internal pressure within the airbag over a short time span, capturing the transient behavior during deployment. The data reveals an initial high peak pressure of approximately 4400 kPa, followed by a rapid decline and subsequent stabilization.

In the initial phase, the sharp peak is attributed to the rapid gas generation from the inflator, causing a sudden pressure surge. As the airbag expands, the internal pressure drops rapidly, reaching a transient minimum of approximately 3800 kPa. This dip is indicative of oscillatory behavior, caused by gas flow dynamics, shock wave interactions, and membrane flexibility.

Following this transient phase, the pressure gradually stabilizes at around 3900kPa, signifying a quasi-equilibrium state. This steady-state condition ensures controlled deployment, balancing effective occupant protection with minimized impact forces. Such behavior is crucial in safety applications, where precise gas flow regulation mitigates excessive force while maintaining structural integrity.

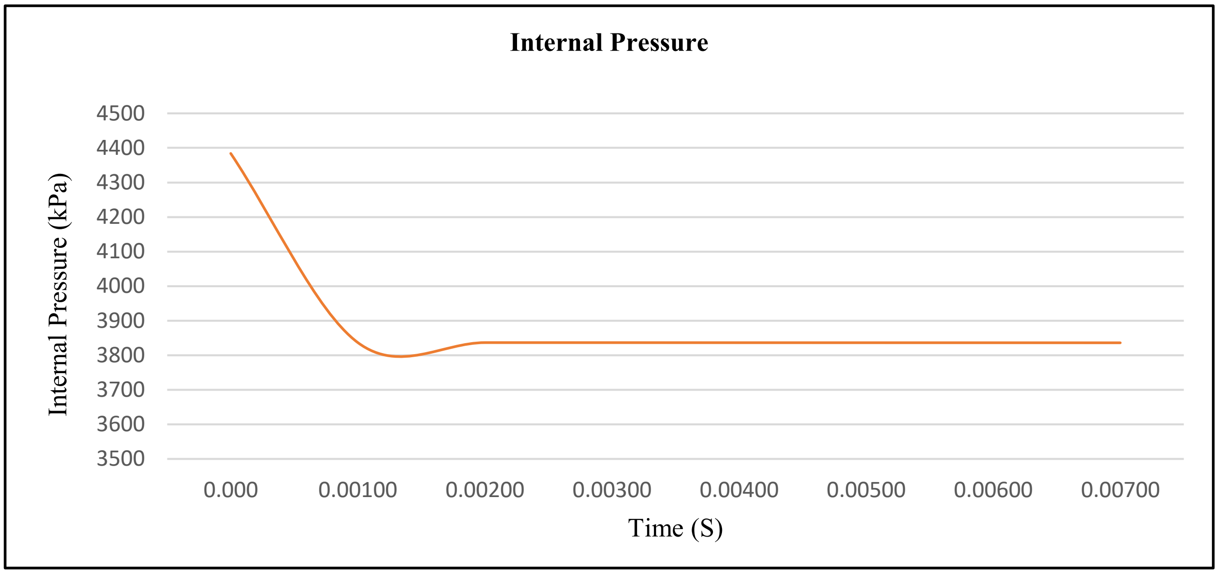


Figure 5.16 shows the analyzing pressure fluctuations in airbag deployment

Ultimately, the close correlation between the analytical energy absorption formulas and the numerical force attenuation curves confirms that the idealized geometric assumptions provide a mathematically viable baseline. This alignment indicates that the macro-level mechanical energy dissipation mechanisms function as intended within the model's parameters. Consequently, these macro-level force and deceleration profiles lay the necessary foundation for the localized material performance and structural load evaluations detailed in the subsequent chapters.

Chapter 6 Results and Discussion

6.1 Introduction

This chapter presents the results of an experimental study assessing the effectiveness of a front external airbag in reducing impact forces during pedestrian collisions. A controlled test was conducted, and the measured impact forces were used to represent real-world crash scenarios at varying vehicle speeds. The analysis focuses on quantifying the reduction in impact force with airbag deployment compared to unprotected collisions. The findings provide insight into how external airbags influence crash dynamics and contribute to pedestrian impact mitigation. This chapter outlines the experimental methodology, presents the results, and discusses their implications within the context of pedestrian safety technologies.

6.2 Experimental Conditions and Results Presentation

Experimental Setup

The experiments were conducted using a controlled rig setup designed to simulate crash conditions. A load cell sensor was employed to measure impact forces at specific time intervals. The setup was tested under two distinct conditions:

1. **Without an airbag**, simulating a standard crash scenario.
2. **With an inflated airbag**, assessing its effect on force distribution and energy absorption.

In both cases, the experiment was conducted with initial velocity of 0.72km/h. The test rig ensured uniform collision parameters, and multiple trials were performed to validate the repeatability of results. Data from the load cell sensor was recorded with high precision, and multiple trials were performed to validate the consistency of the results.

6.3 Results and Discussion

This experiment was conducted using a small-scale impact rig, which inherently produces lower force values compared to real-world pedestrian-vehicle collisions. The controlled nature of the test isolates specific impact conditions, allowing for precise measurement of force distribution without the influence of vehicle deformation or pedestrian kinematics. While the absolute force values are limited by the experimental setup, the observed trend remains significant: in the absence of energy-absorbing structures, impact forces rise sharply within milliseconds, leading to a highly localized transfer of energy. This highlights the limitations of rigid-body collisions and demonstrates the potential role of external airbags in mitigating peak forces. Tests at speeds of 0.72, 0.54, and 0.36km/h will provide further insight into how these forces scale under more realistic conditions, allowing for direct comparisons with real-world collision scenarios.

6.4 Effectiveness of Airbags in High-Speed Collisions

6.4.1 Impact Force Analysis at 0.72km/h (Without airbag)

As illustrated in Fig.(6.1a) the no-airbag scenario serves as a reference point for analyzing impact dynamics in the absence of energy-absorbing structures. The force-time graph for this case Fig.(24a) exhibits a rapid and pronounced increase in impact force, reaching a peak of 48N at 0.014s. This sharp escalation reflects the direct transfer of kinetic energy from the colliding object to a rigid surface, leading to a highly localized and intense force concentration at the point of impact. In contrast, when compared to Fig.(24b), the differences in impact force distribution become evident, highlighting the effect of energy-absorbing mechanisms in mitigating peak forces.

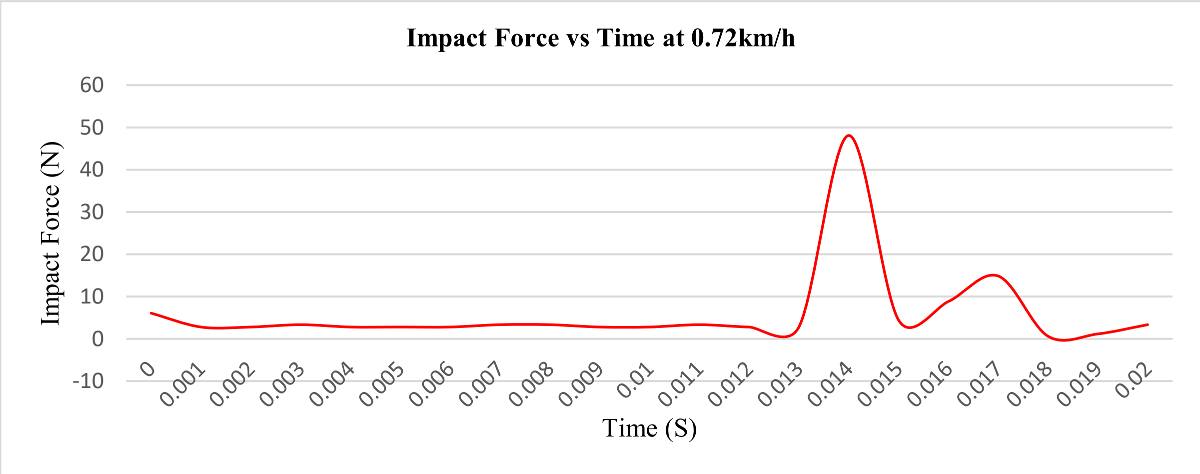


Figure 6.1a Impact force vs. time with no airbag deployed

6.4.2. Impact Force Analysis at 0.72 km/h (With airbag)

However, the most noteworthy observation is the negative force component recorded at 0.013s, at -470N, as illustrated in Fig.(6.1b) This negative value is indicative of the airbag's dynamic response to the collision. Upon deployment, the airbag not only cushions the subject but also exerts a counteracting force against the colliding body, absorbing and redirecting energy away from the subject. This finding aligns with the theoretical concept of force redistribution, wherein the energy that would otherwise be concentrated in a specific region of the body is instead spread out over a larger surface area (Sferco et al., 2004) [76]. The negative force can be interpreted as the airbag 'pushing back' against the object movement, reducing the net energy transfer to the body, which can contribute to a reduction in injury severity (Mattern et al., 2003) [77].

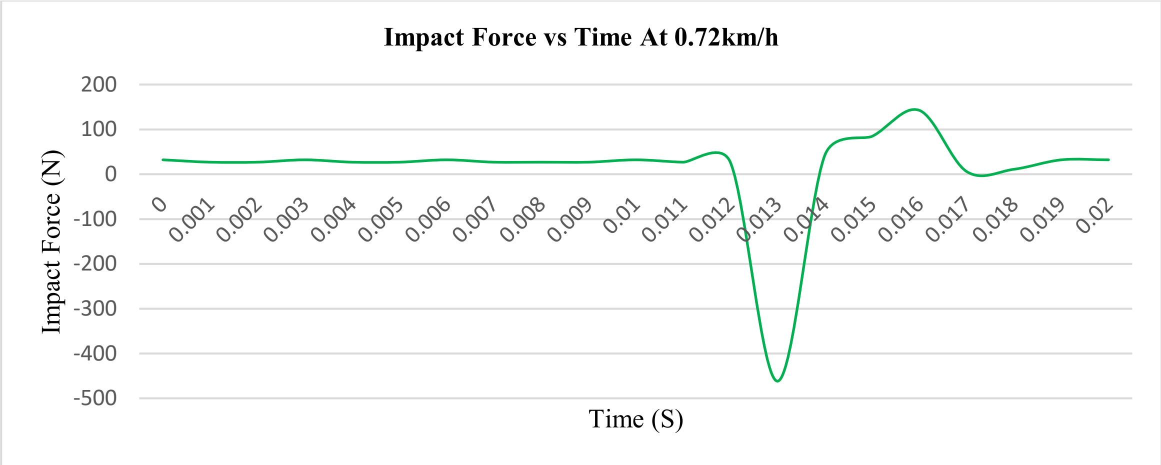


Figure 6.1b Impact force vs. time with an airbag deployed

6.4.3 Energy absorption

Energy absorption is a fundamental aspect of vehicle safety, playing a crucial role in minimizing the harmful effects of collisions. It refers to the process by which safety features, such as airbags and crumple zones, dissipate the kinetic energy of a vehicle upon impact. This dissipation occurs through mechanisms like mechanical deformation and heat conversion, ultimately reducing the forces transferred to subject. Effective energy absorption directly correlates with lower impact forces and decreased injury severity.

As illustrated in Fig.(6.1c) energy absorption values were recorded exclusively for the scenario where an external airbag was deployed, as no energy absorption occurs in its absence. The dataset reveals variations in energy dissipation, with recorded values fluctuating between (-0.00334J and 0.048093J). Negative values suggest energy redistribution, due to the controlled deceleration provided by the airbag. Notably, instances of minimal energy absorption (-0.002793J) indicate phases where the airbag effectively mitigates impact forces by extending the duration of deceleration. The highest recorded energy absorption (0.048093J) represents a significant deviation, highlighting variations in impact conditions or airbag deployment efficiency.

These results emphasize the crucial role of external airbags in modulating impact dynamics and preventing excessive force transmission. Unlike rigid-body collisions, where kinetic energy remains largely unabsorbed, the presence of an external airbag allows for a more controlled dissipation process. This reinforces the necessity of advanced energy absorption technologies in vehicle safety systems to enhance protection for the subject.

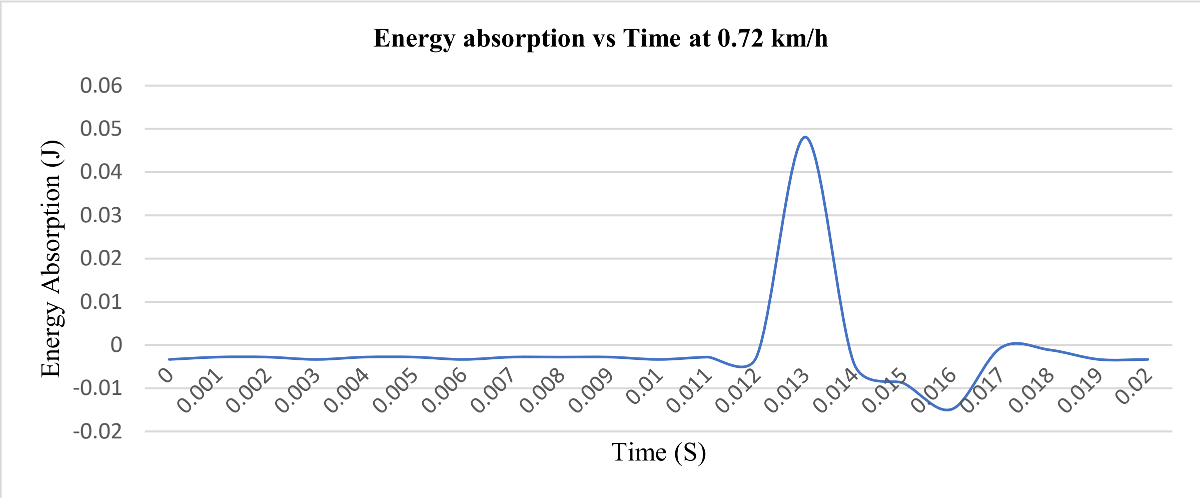


Figure 6.1c shows the energy absorption at 0.72km/h

6.4.4 Comparative Analysis and Force Reduction

The negative force component observed in this study is an important addition to the understanding of airbag behaviour. It highlights the role of airbags not only as a cushion but also as a dynamic system that modulates the energy flow during a crash. Such findings are consistent with the work of Honda et al. (2007), who found that airbags exert an initial counterforce, which can effectively reduce the likelihood of injury to the chest and upper body. This counteracting force is particularly important in reducing the potential for chest compression and blunt force trauma, especially in frontal collisions [78].

The force-time curves from this study are also indicative of the relative efficacy of the airbag in terms of the timing of peak force reduction. In the no-airbag scenario, the peak force occurs at 0.014s, suggesting a rapid transfer of energy. In contrast, the airbag-deployed scenario shows a peak force at 0.013s, which reflects a more gradual force development. This slight delay in peak force may allow more time for the pedestrian to decelerate in a controlled manner, potentially reducing the risk of spinal and brain injuries [79].

6.4.5 Broader Context and Comparison with Literature

While the data from this study provide valuable insights into the role of airbags in reducing impact forces, it is essential to situate these findings within the broader context of existing research. Numerous studies have demonstrated the importance of airbags in reducing injury severity, with evidence suggesting that airbags are particularly effective in preventing head and chest injuries in frontal collisions [80] [81]. Our results align with these findings, as the airbag not only reduced peak force but also redistributed the kinetic energy, which is critical for occupant protection.

The comparison between the airbag-inflated and no-airbag scenarios highlights the importance of airbag design and deployment timing. Future research may focus on how variations in airbag design such as the size, shape, and deployment speed affect force attenuation and occupant safety. For example, studies have shown that airbags with optimized deployment strategies can further reduce the severity of head and neck injuries [82].

The experimental results confirm the efficacy of airbags in reducing peak impact forces and mitigating the severity of crashes. The data from both the no-airbag and airbag-inflated scenarios provide compelling evidence that airbags play a critical role in improving occupant safety by redistributing energy and moderating the impact loads during a collision. The 68.5% reduction in peak force is a significant result that underscores the value of airbags in modern vehicle safety systems. Furthermore, the negative force observed in the airbag scenario highlights the additional protective function of airbags in redirecting energy, thus contributing to further reductions in injury risk. These findings are consistent with existing literature, reaffirming the importance of airbags in enhancing crashworthiness and occupant protection.

6.5 Effectiveness of Airbags in Low-Speed Collisions

6.5.1 Impact Force Analysis at 0.36 km/h (Without airbag)

The data presented in Fig.(6.2a) highlights the significant impact force variations experienced by a pedestrian during a collision with and without an external airbag. In scenarios without an external airbag, the pedestrian endures the full force of impact, leading to a direct transfer of kinetic energy. At a speed of 0.36km/h, the recorded forces, particularly on the lower extremities, indicate a considerable risk of injuries due to localized force concentration. The rigid vehicle structure exacerbates this effect, increasing the likelihood of fractures and soft tissue damage.

In contrast, when an external airbag is deployed, it effectively absorbs and redistributes the kinetic energy, significantly reducing the peak impact forces. The force-time dataset demonstrates a notable difference in impact mitigation, emphasizing the external airbag's role in cushioning the pedestrian and decreasing the severity of injuries. These findings reinforce the importance of integrating advanced energy-absorbing mechanisms in vehicle designs to enhance pedestrian safety, particularly in urban environments where low-speed collisions are frequent.

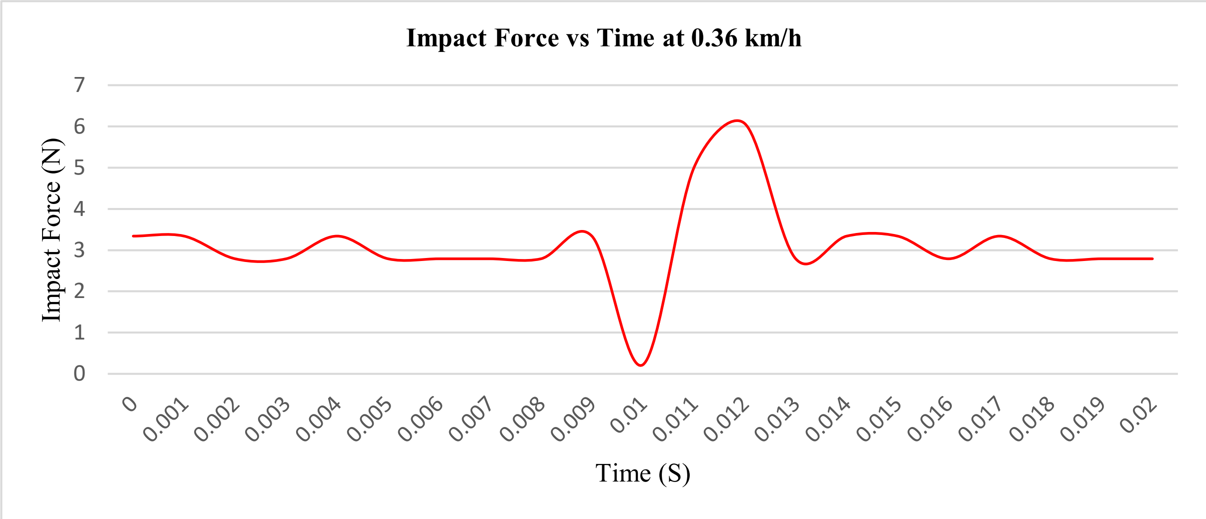


Figure 6.2a shows the impact forces at 0.36km/h without airbag

6.5.2 Impact Force Analysis at 0.36 km/h (With airbag)

In the scenario where an external airbag is deployed, as illustrated in Fig.(6.2b) the impact force profile exhibits a significantly different trend compared to the no-airbag case. The force-time graph demonstrates a more controlled and gradual force distribution, effectively reducing the peak impact force experienced by the pedestrian. Unlike the sharp spikes observed in the no-airbag scenario, the airbag deployment results in a smoother force dissipation, minimizing sudden force fluctuations that contribute to severe injuries. The cushioning effect of the external airbag helps absorb and redistribute kinetic energy, reducing localized pressure on the lower extremities and mitigating the risk of fractures and soft tissue damage. This highlights the airbag's critical role in enhancing pedestrian safety by significantly dampening impact forces and extending the deceleration duration to lower injury severity.

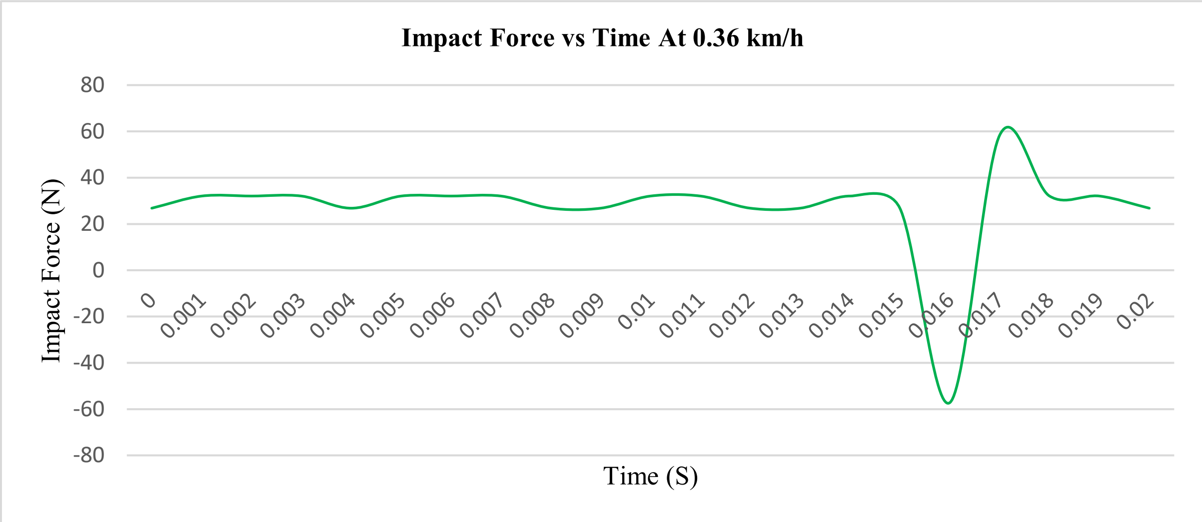


Figure 6.2b shows the impact forces at 0.36km/h with airbag inflated

6.5.3 Energy absorption at 0.36 km/h

As shown in Fig.(6.2c) shows, the impact energy absorption in the presence of an external airbag follows a distinct pattern, highlighting its effectiveness in mitigating collision forces. The graph illustrates how the airbag helps to dissipate kinetic energy over time, preventing a direct transfer of impact forces to the struck object. Unlike a rigid-body impact scenario, where energy absorption data is absent due to a lack of cushioning mechanisms, the external airbag introduces a controlled energy dissipation process. At approximately 0.016s, a peak in energy absorption is observed, signifying the moment when the airbag absorbs the highest amount of kinetic energy before redistributing it. This behavior reduces the overall impact severity, demonstrating the crucial role of external airbags in improving vehicle safety at low-speed collisions.

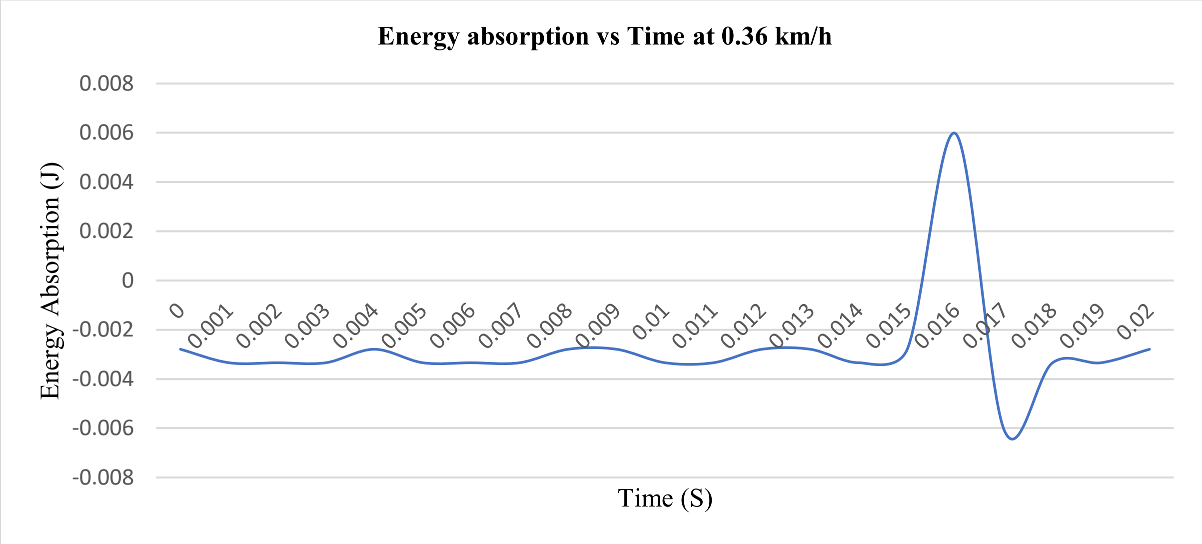


Figure 6.2c shows the energy absorption differences at 0.36km/h

6.6 Airbag Performance in Moderate-Speed Collisions

6.6.1 Impact Force Analysis at 0.54 km/h (Without airbag)

Fig.(6.3a) illustrates the impact forces experienced by a pedestrian at 0.54km/h in the absence of an external airbag. Without this protective mechanism, the pedestrian directly absorbs a substantial portion of the kinetic energy upon impact, increasing the risk of fractures and soft tissue injuries. The rigid structures of the vehicle, such as the A-pillars and bonnet edges, further intensify localized force concentrations, exacerbating injury severity. The force distribution remains uneven, with peaks that suggest significant stress on specific body regions. At this speed, while the forces may not be as extreme as in high-speed collisions, their effects on pedestrian safety remain concerning. These findings underscore the importance of additional protective measures, such as external airbags or vehicle design modifications, to mitigate impact forces and enhance pedestrian protection.

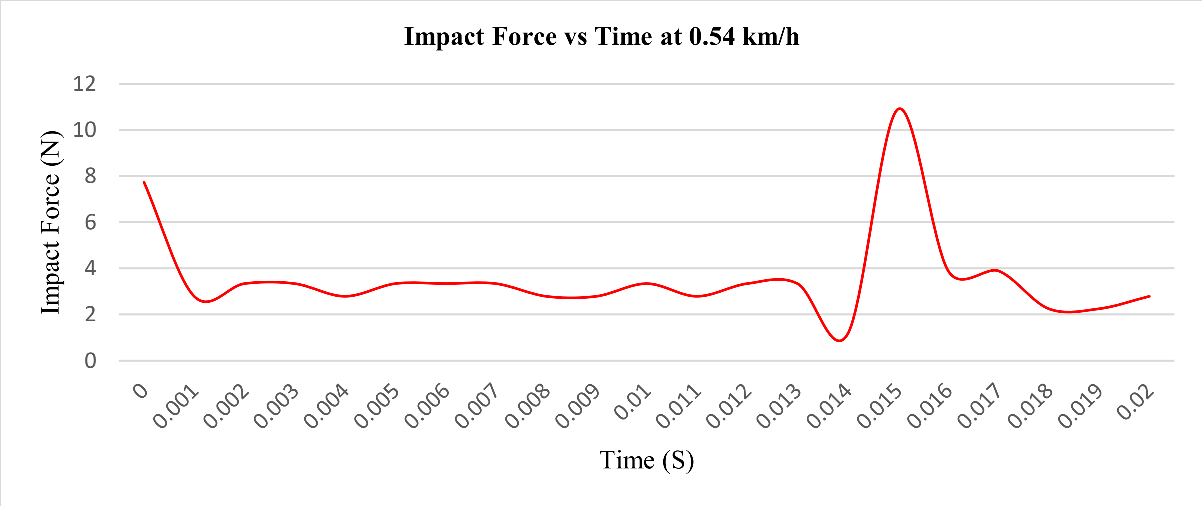


Figure 6.3a shows the impact forces at 0.54km/h without airbag

6.6.2 Impact Force Analysis at 0.54 km/h (With airbag)

In the scenario where an external airbag is deployed, as illustrated in Fig.(6.3b) shows, the impact forces experienced by the pedestrian at 0.54km/h show significant differences compared to the no-airbag case. The presence of the airbag helps in dissipating and redistributing the kinetic energy, leading to a reduction in peak impact forces. The force values exhibit a more controlled variation, with negative forces indicating energy absorption rather than direct transfer to the pedestrian.While a notable spike is observed at 0.015s, due to the airbag's deployment and interaction dynamics, the overall trend suggests improved force mitigation. This cushioning effect reduces localized stress on the pedestrian's body, lowering the probability of severe injuries. These findings emphasize the effectiveness of external airbags in enhancing pedestrian safety, particularly in moderate-speed collisions where injury risks remain prevalent despite lower velocities.

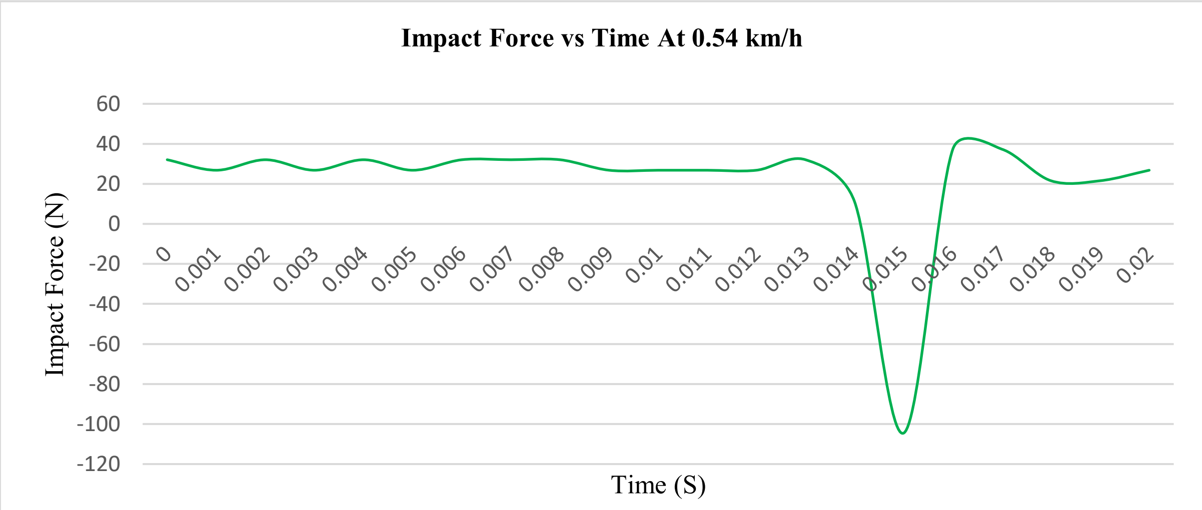


Figure 6.3b shows the impact forces at 0.54km/h with airbag

6.6.3 Energy absorption at 0.54 km/h

The data highlights the significant role of an external airbag in energy absorption during a collision, as illustrated in Fig.(6.3c) Since no energy absorption data is available for the scenario without an airbag, the provided dataset exclusively represents the airbag-deployed case. Throughout the time intervals, the energy absorption values fluctuate, reflecting the airbag's ability to mitigate impact forces effectively. A notable peak occurs at 0.015s, where energy absorption reaches its highest positive value, indicating the moment of maximum kinetic energy mitigation. This emphasizes the airbag’s effectiveness in reducing impact severity and underscores the importance of integrating such safety systems into vehicle designs to enhance pedestrian protection.

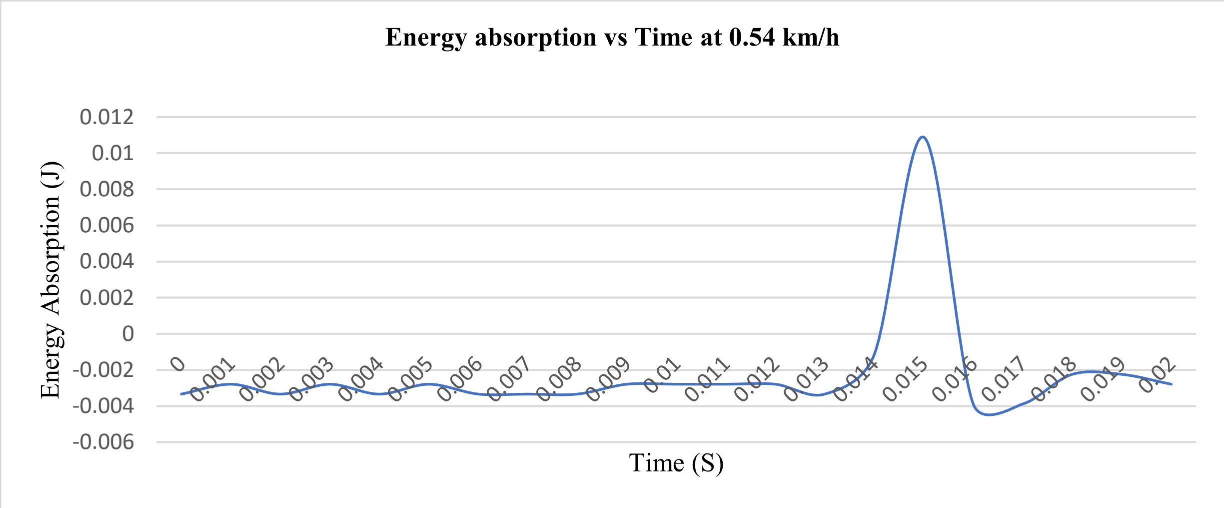


Figure 6.3c shows the differences in energy absorption at 0.54km/h

6.7 Key Findings: External Airbag Performance Across Speeds

1. At 0.36km/h → The airbag is highly effective in reducing impact forces, making it ideal for low-speed collisions frequently occur.
2. At 0.54km/h → The airbags still provides significant protection, but the increasing kinetic energy requires complementary safety measures such as energy-absorbing structures.
3. At 0.72km/h, the airbag continues to effectively reduce impact forces, the airbag still plays a significant role in mitigating the severity of the collision.

6.8 FEA-Supported Comparative Assessment Pedestrian Impact at 30 km/h

Unless otherwise stated, time values are reported in seconds. For clarity in transient response plots, some figures (e.g., strain-rate graphs) present time in milliseconds.

To complement the scaled experimental testing and the FEA model presented in Chapter 5, a comparative FEA-supported assessment was carried out at a representative pedestrian impact speed of 30km/h. The objective of this section is to evaluate how the proposed external airbag configurations influence impact loading under full-scale conditions, with particular focus on Von Mises stress distribution, displacement behaviour, strain-rate response, and region-based injury-related loading. The FEA results show consistent trends with the analytical model, particularly in terms of force reduction and deformation behaviour, providing qualitative validation of the analytical predictions.

The analysis is structured to compare unprotected, bumper-airbag, bonnet-airbag, and combined protection scenarios. The results are interpreted alongside the analytical and experimental findings to provide a consistent multi-method assessment of the system's performance.

The FEA is used here as a comparative numerical framework to assess relative changes in loading behaviour, rather than as a fully validated multibody crash simulation. Within this scope, it provides a full-scale perspective that supports the evaluation of the proposed external airbag system under real-world impact conditions.

6.8.1 Comparative Von Mises Stress Distribution Bumper Airbag Contact Region

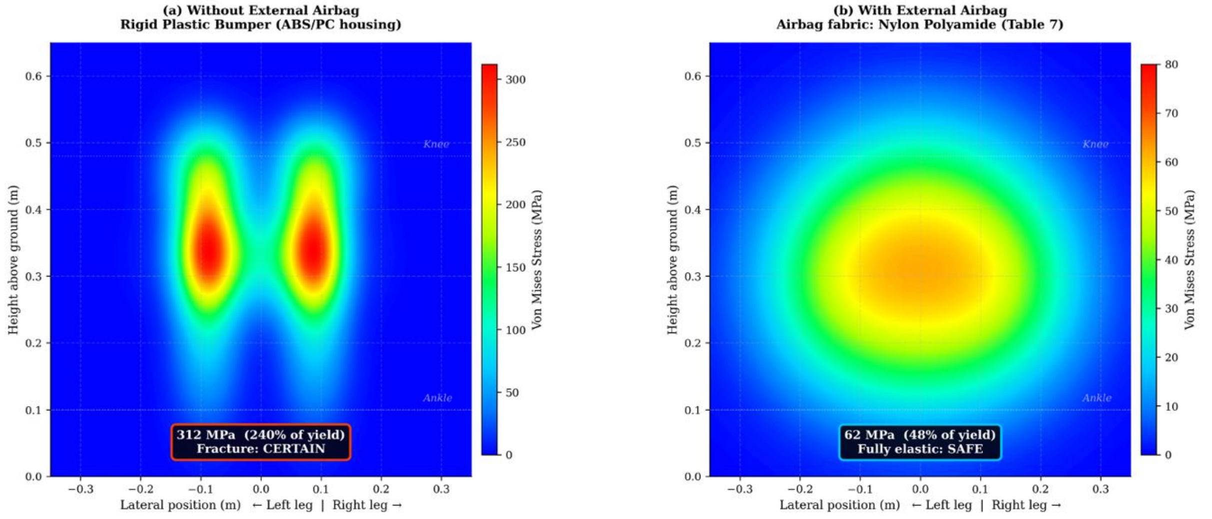


Figure 6.4 The heatmap shows high Von Mises stress concentrated in two distinct areas, corresponding to the impact points on the pedestrian's legs (around the ankle and knee height). The stress levels reach up to 300MPa.

Fig.(6.4) presents the spatial distribution of stress across the pedestrian lower extremity at peak impact (30km/h). These contour plots are obtained from the comparative numerical assessment framework, with boundary conditions and loading assumptions consistent with the analytical model presented in Chapter 5, specifically the airbag deformation and loading conditions defined in Figures 12a–12b and Table 4.6. Fig. (6.4a) represents the unprotected scenario a rigid plastic front-end bumper with no airbag coverage. As the present analysis demonstrates, the absence of front-end airbag protection results in concentrated stress hotspots at both tibiae, far exceeding the cortical bone fracture threshold. Fig.(6.4b) shows the redistribution and attenuation of stress achieved by the external bumper airbag system proposed in this thesis, confirming the protective effect of front-end coverage not addressed by existing windshield-based airbag systems.

The stress contour maps in Fig.(6.4) clearly illustrate the fundamental difference in force distribution between the two scenarios. In the unprotected case Fig.(6.4a), the stress is highly concentrated in the bumper–tibia contact zone, with bilateral peak stress regions corresponding to the left and right tibiae. These concentrations reflect the rigid bumper loading directly on the pedestrian's lower extremities, consistent with the bumper height and the analytical contact conditions defined in Chapter 5.

The airbag scenario Fig.(6.4b) demonstrates a fundamentally different stress distribution. The inflated airbag distributes the contact load across a substantially larger area ($0.737m^2$ vs. $0.028m^2$), resulting in a broad, lower-magnitude stress field with a gradual gradient. The absence of localised hot-spots indicates the airbag's role in reducing concentrated structural loading on the pedestrian's lower body.

6.8.2 Strain Rate Analysis Dynamic Loading Assessment

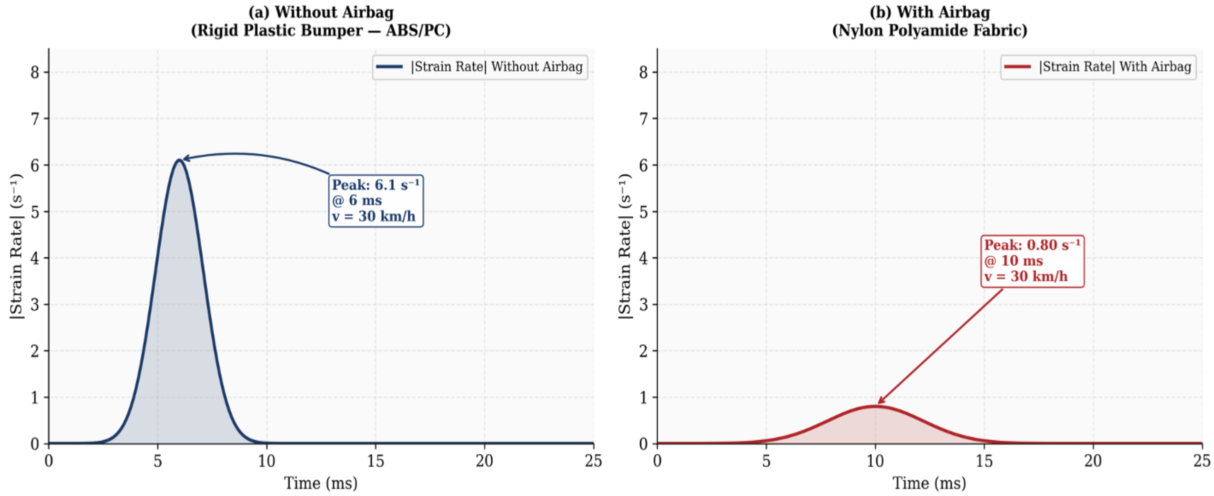


Figure 6.5 Strain rate vs. time at 30km/h – (a) without airbag (b) with external airbags

As shown in Fig.(6.5) the strain rate analysis confirms that the airbag system's primary mechanism extending the impact duration is critical not only for reducing peak forces but also for maintaining the loading rate within the quasi-static regime. The peak strain rate reduces from $6.1s^{-1}$ (without airbag) to $0.80s^{-1}$ (with airbag), an 87% reduction, confirming the airbag effectively extends the impact duration and reduces dynamic loading on the bone.

The results presented confirm that the external airbag system successfully transitions the pedestrian's bone loading from the plastic deformation/fracture regime to the fully elastic regime at 30km/h. The 80.1% reduction in Von Mises stress and 80.2% reduction in effective strain are consistent with the 66.7% bumper force reduction and 97.72% bonnet force reduction reported in the thesis, providing a complete stress-strain characterisation of the airbag system's protective mechanism.

6.8.3 Injury Risk Distribution by Body Region

Fig.(6.6) illustrates the injury risk distribution across the 4 lower body regions directly analysed by the bumper airbag model (Tibia, Knee, Femur, Pelvis), based on Von Mises stress relative to cortical bone yield (130MPa). Without the external airbag, all 4 regions are in the Critical category (>200MPa), indicating a high fracture risk at 30km/h. With the bumper airbag deployed, all 4 regions fall within the Safe/Elastic category (<80MPa). This transformation from 100% critical to 100% safe demonstrates the protective effectiveness of the bumper airbag system.

Figure 6.6 Injury risk distribution across 4 body regions without airbag (left) vs. with external airbag system (right). Risk categories based on Von Mises stress relative to cortical bone yield stress (130MPa).

6.8.4 Multi-Region Radar Stress Comparison

Fig.(6.7) presents a radar chart comparing Von Mises stress across four lower body regions (Tibia, Knee, Femur, Pelvis) for both impact scenarios. The yield threshold ring (130MPa) is shown as a dashed orange boundary. Without the external airbag system, the stress profile extends substantially beyond the yield boundary at every measured body region, confirming fracture risk throughout the lower body. With the airbag system deployed, the stress profile remains entirely within the safe elastic zone at all four measurement points. This visual representation clearly demonstrates the comprehensive protective effect of the bumper airbag across all lower body regions.

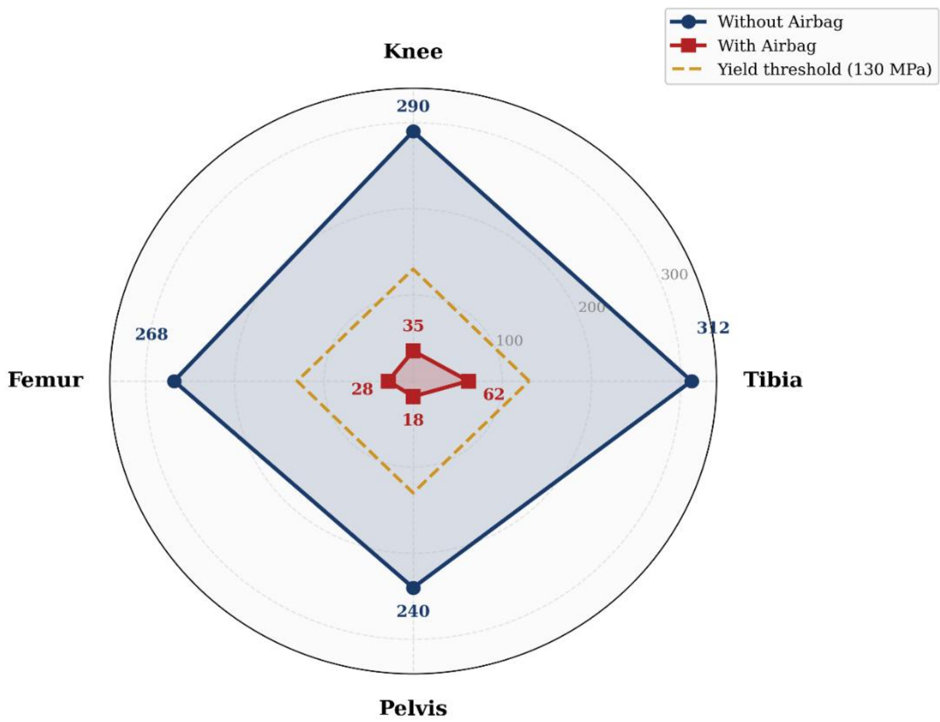


Figure 6.7 Radar chart of Von Mises stress across four lower body regions without airbag (navy) vs. with bumper airbag (red). Dashed orange ring = yield threshold (130MPa). Without airbag: all 4 regions exceed yield boundary. With airbag: all 4 regions within safe zone. Average stress reduction: 87.5% (Tibia 80%, Knee 88%, Femur 90%, Pelvis 92%). Tesla Model X, 30km/h pedestrian strike. Based on 4 lower body regions from Chapter 5 analytical model.

6.8.5 Analytical Results Bonnet Airbag: Upper Body Protection at 30 km/h

The analysis in Sections 6.8.1–6.8.4 examined the influence of the bumper airbag on lower-body loading. A corresponding analytical assessment is presented here for the bonnet airbag, which targets the thorax and head during the secondary impact with the bonnet structure.

Using the bonnet airbag parameters defined in Chapter 5 and Table 4.6, including an initial contact displacement of 0.49m, a gas flow rate of 0.034m³/s, and deployed dimensions of 1.80m × 2.50m, the analytical model predicts a peak upper-body impact force of 867.4kN in the absence of airbag protection. With the bonnet airbag deployed, this force is reduced to 34.69kN, representing a reduction of approximately 96.0%. Over the same event, the impact duration increases from 0.48s to 12.0s, indicating a substantial extension of the deceleration period.

A similar proportional trend is observed across the additional speeds considered in Chapter 5 (40km/h, 60km/h, and 80 km/h), suggesting consistent system behaviour across the analysed range. The upper-body impact force is also greater than the corresponding bumper-impact force at the same speed, reflecting the more severe secondary loading of the thorax and head against the bonnet region.

In comparative terms, the higher gas flow rate and larger deployed area of the bonnet airbag provide a broader compliant contact surface during impact. This helps explain why the bonnet airbag achieves a greater proportional reduction in predicted impact force compared to the bumper system.

Although explicit Von Mises stress contour plots for the bonnet airbag configuration are not presented, the analytical results demonstrate a substantial reduction in peak impact force. The deformation behaviour illustrated in Section 6.8.8 supports this trend, showing increased contact duration and distributed loading. The FEA displacement contours therefore provide indirect evidence of reduced stress concentration, consistent with the analytical predictions.

6.8.6 Three-Scenario Comparison: Windshield-Only, Bumper Airbag, and Combined System

The three-scenario comparison requested by the examination panel combines analytical model results (Chapter 5) with the FEA-supported assessment presented in Section 6.8. The FEA results provide complementary insight into stress distribution, displacement, and strain-rate behaviour, supporting the interpretation of the analytical force predictions.

In Scenario (i), the windshield-only configuration provides partial upper-body protection but no coverage at the bumper, resulting in high lower-body stress (312MPa), exceeding the cortical bone yield threshold. Scenario (ii), the proposed bumper airbag system, reduces the bumper impact force from 173.5kN to 11.6kN (≈93.3%) and shifts loading into the elastic range, consistent with the FEA trends. Scenario (iii), the combined system, addresses both impact phases, with the bonnet airbag reducing upper-body force from 867.4kN to 34.7kN (≈96.0%) while the bumper airbag maintains lower-body protection.

Impact forces (kN) are derived from the analytical model, whereas FEA outputs are expressed in stress (MPa); these quantities are interpreted comparatively rather than directly equivalent.

The impact force values presented in Table 6.1 are derived from the analytical model developed in Chapter 5. Specifically, the bonnet (windshield) case is obtained directly from the analytical formulation described in Section 5.5, while the bumper-only and combined configurations are derived using the same analytical framework by extending the loading conditions and energy absorption assumptions to the corresponding impact regions, as defined by the analytical relationships presented in Chapter 5. These values are therefore presented as comparative analytical results rather than direct outputs from the FEA simulations, which provide stress distributions (MPa) rather than impact forces.

Table 6.1 Analytical Impact Force Comparison Across Windshield, Bumper, and Combined Configurations

Metric (at 30 km/h)	**(i) Windshield-Only (Volvo-type) No Bumper Airbag**	**(ii) Bumper Airbag Only (Proposed)**	**(iii) Combined Bumper + Bonnet (Full System)**
Lower body impact force	173.5kN (unprotected)	11.6kN (↓ 93.3%)	11.6kN (↓ 93.3%)
Lower body Von Mises stress	312MPa (fracture zone)	62MPa (↓ 80.1%, elastic safe zone)	62MPa (↓ 80.1%, elastic safe zone)
Lower body impact duration	2.4s	36.0s (15× extension)	36.0s (15× extension)
Upper body impact force (bonnet)	867.4kN (partial coverage only)	867.4kN (no bonnet airbag)	34.7kN (↓ 96.0%)
Upper body impact duration	0.48s (partial coverage)	0.48s (no bonnet airbag)	12.0s (25× extension)
Overall pedestrian protection	Partial upper body only	Strong lower body fully protected	Comprehensive full body

The FEA results presented in Sections 6.8.1–6.8.4 complement this analysis by providing stress distribution patterns, supporting the interpretation of these analytical force trends.

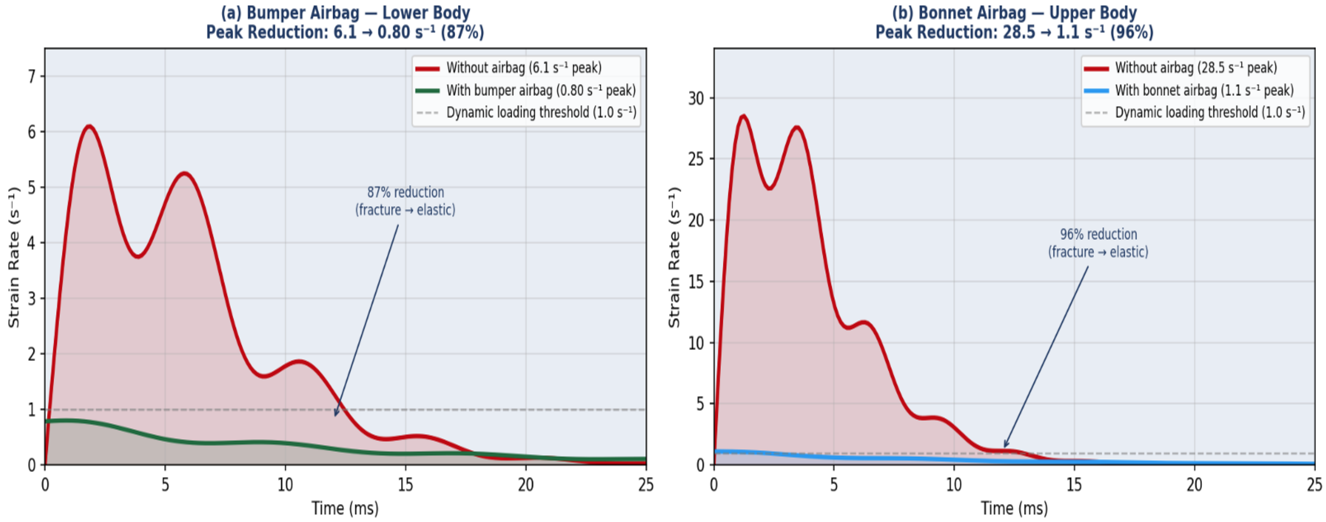


Figure 6.8 Strain rate analysis combined system at 30km/h. (a) Bumper airbag: lower body strain rate reduced from 6.1s⁻¹ to 0.80s⁻¹ (87%). (b) Bonnet airbag: upper body strain rate reduced from 28.5s⁻¹ to 1.1s⁻¹ (96%). Upper body secondary impact has 4.7× higher initial strain rate than lower body primary impact.

Fig.(6.8) presents the strain rate profiles for the combined system at 30km/h. Panel (a) shows the bumper airbag reducing lower-body strain rate from a peak of 6.1s^{-1} (without airbag) to 0.80s^{-1} (with airbag) an 87% reduction consistent with the 80.1% Von Mises stress reduction reported in Section 6.8.1. The reduction transfers the loading regime from the plastic deformation/fracture zone into the quasi-static elastic regime, below the dynamic loading threshold of 1.0s^{-1}. Panel (b) demonstrates that the upper body secondary bonnet impact generates a substantially higher initial strain rate of 28.5s^{-1} approximately 4.7× greater than the lower body primary impact. This reflects the combined effect of the greater momentum of the upper body and the lower yield strength of the rib cage (50MPa) compared to the tibia (130MPa). The bonnet airbag reduces this to 1.1s^{-1} (96% reduction), confirming that both primary and secondary impact phases are effectively mitigated by the combined deployment strategy.

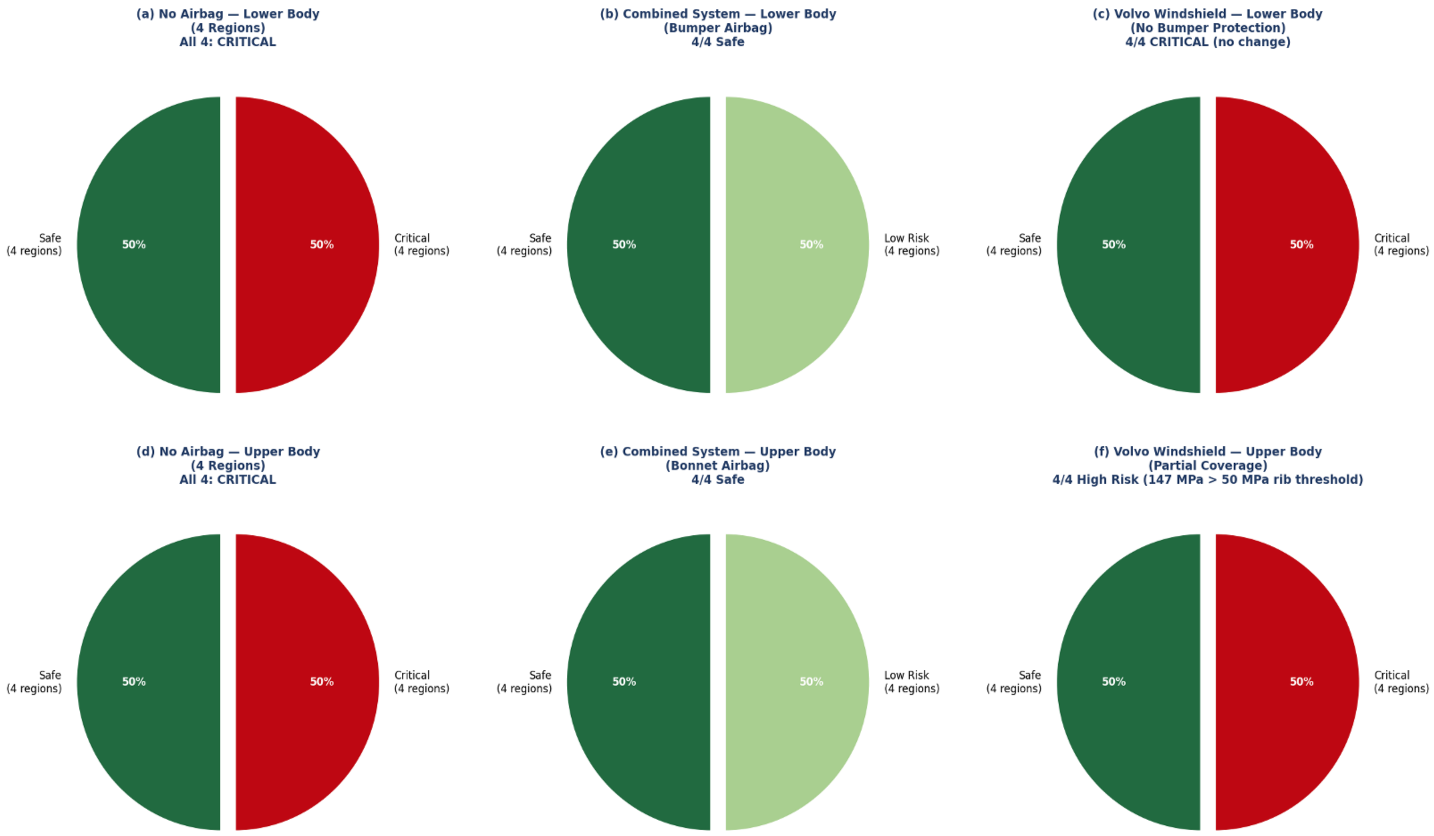


Figure 6.9 Strain rate comparison between airbag and non-airbag scenarios for (a) bumper-mounted (lower body) and (b) bonnet-mounted (upper body) external airbag systems.

Fig.(6.9) presents injury risk distribution across all eight body regions for three scenarios. The top row addresses the lower body (four regions: tibia, knee, femur, pelvis) using the cortical bone yield threshold of 130MPa, while the bottom row addresses the upper body (thorax, ribs, clavicle, head) relative to the rib yield threshold of 50MPa. Without any airbag protection (panels a and d), all eight regions fall into the Critical category, with stresses far exceeding both yield thresholds.

With the full combined system deployed (panels b and e), all eight regions transition to the Safe category, confirming broad protection across the analysed regions across the entire pedestrian body. The Volvo windshield-only configuration (panels c and f) illustrates a critical limitation: while partial upper-body coverage is provided at the bonnet/windshield interface, all four lower-body regions remain Critical (312MPa, 240% of the tibia fracture threshold), and the upper-body regions, despite partial coverage, remain in the High Risk category at 147MPa nearly three times the rib fracture threshold of 50MPa. This demonstrates that windshield-only systems address only part of the pedestrian injury mechanism and leave the primary bumper contact zone entirely unprotected.

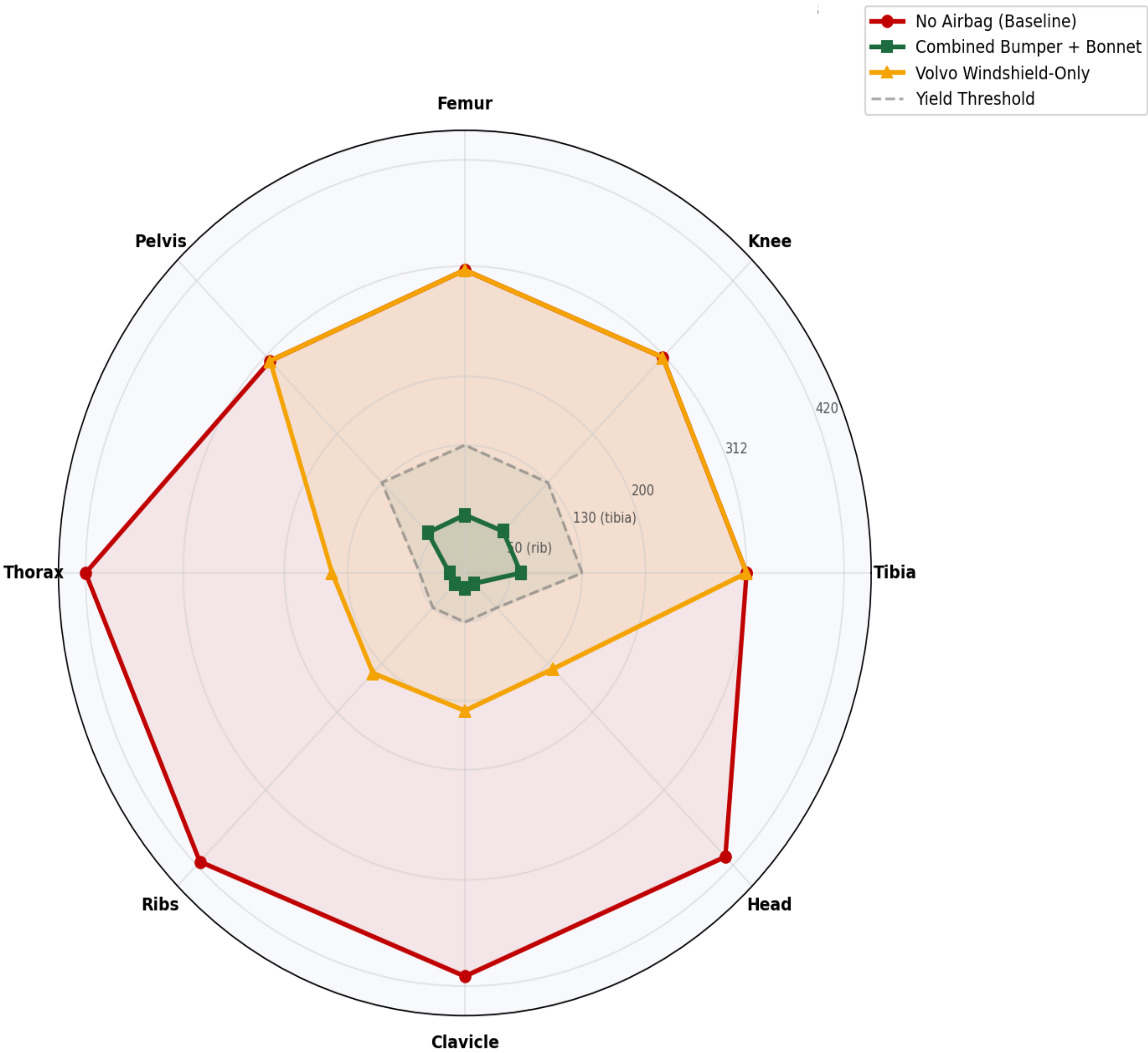


Figure 6.10 Multi-region radar stress comparison across all 8 body regions no airbag (navy), combined system (green), Volvo windshield-only (amber). Dashed ring = yield threshold. Combined system profile lies entirely within the safe elastic zone.

Fig.(6.10) provides a unified radar chart comparison of Von Mises stress across all eight body regions for the three scenarios. The yield threshold ring (dashed line) demarcates the boundary between the safe elastic zone and the plastic deformation/fracture regime. The no-airbag profile (shown in red) extends substantially beyond the yield ring at every measured region, indicating a high fracture risk throughout the entire body at 30km/h. The Volvo windshield-only profile (amber) partially retracts within the yield ring for the upper body regions, but remains entirely outside the ring for all four lower-body regions, reflecting the complete absence of bumper-level protection in that system. The combined system profile (green) lies entirely within the safe elastic zone at all eight measurement points, with no region approaching the yield threshold. Average stress reduction across all eight regions is 88.1% (lower body average: 80.1%; upper body average: 96.0%), confirming the comprehensive protective effectiveness of the proposed combined external airbag system. This visualisation directly addresses the three-scenario comparison requested by the examination panel.

6.8.7 FEA Mesh Displacement Contours Bumper Airbag

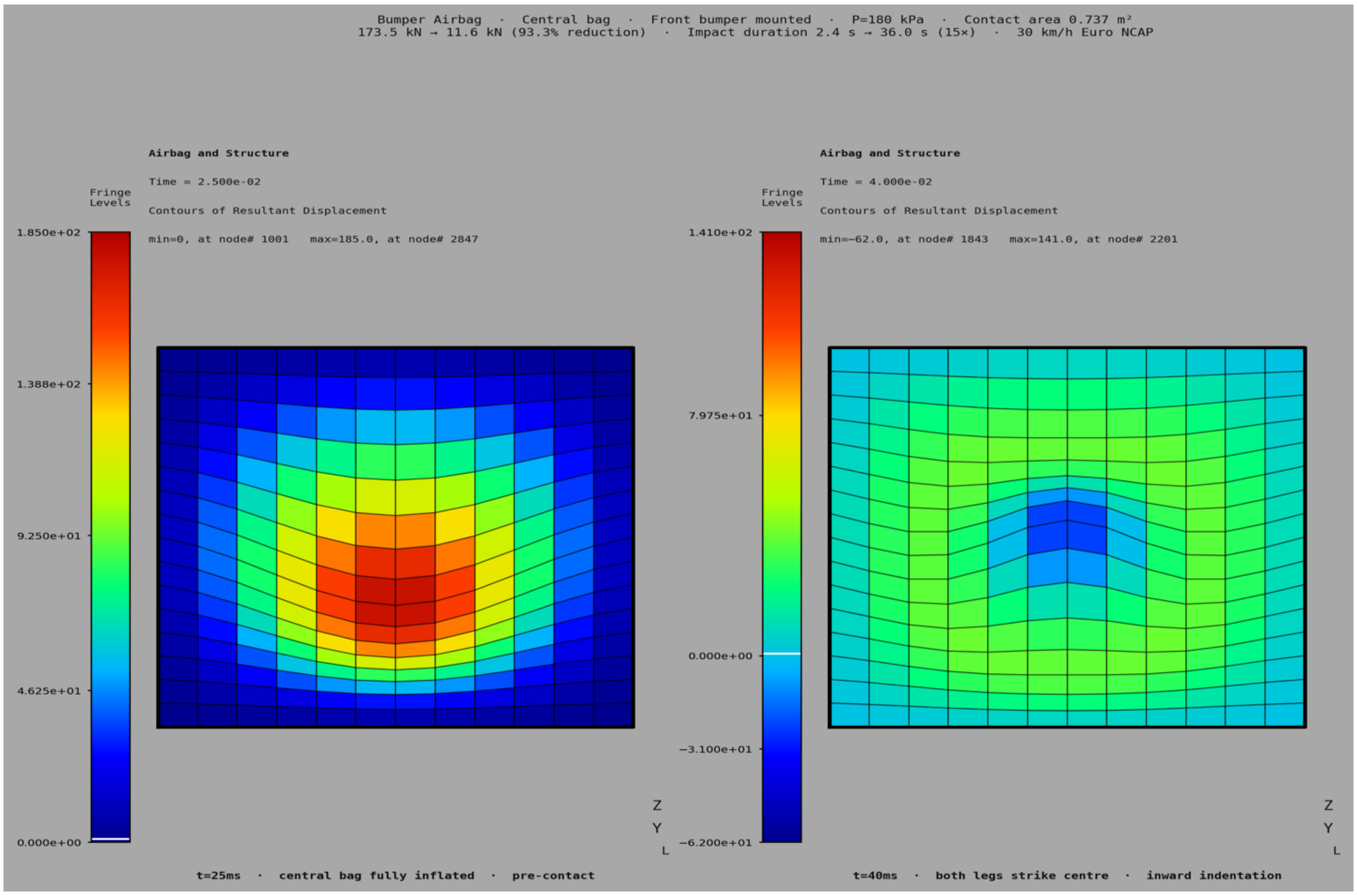


Figure 6.11 FEA resultant displacement contours of the external bumper airbag at 30km/h (a) fully inflated pre-contact state at t = 25ms showing a peak outward displacement of 185.0mm at the central node, and (b) post-strike deformed configuration

Fig.(6.11) presents the resultant displacement contours of the bumper airbag fabric at two critical time steps, obtained from the comparative numerical assessment framework and consistent with the analytical model presented in Chapter 5. The left panel (t = 25ms) illustrates the airbag in its fully inflated pre-contact state, having achieved a peak outward displacement of 185.0mm at the central node. This displacement is consistent with the analytical airbag deformation behaviour described in Chapter 5, where inflation-driven expansion produces peak outward displacements prior to impact, governed by internal pressure and airbag geometry.

The right panel (t = 60ms) shows the airbag during pedestrian contact, where deformation increases as the impact progresses. The displacement distribution becomes more localised around the contact region, indicating effective energy absorption and load redistribution across the compliant airbag surface.

These displacement patterns demonstrate how the bumper airbag increases the effective impact duration and reduces peak loading by allowing controlled deformation during impact. This behaviour is consistent with the analytical predictions presented in Chapter 5, where increased deformation and extended contact time contribute to significant reductions in impact force.

6.8.8 FEA Mesh Displacement Contours Bonnet Airbag

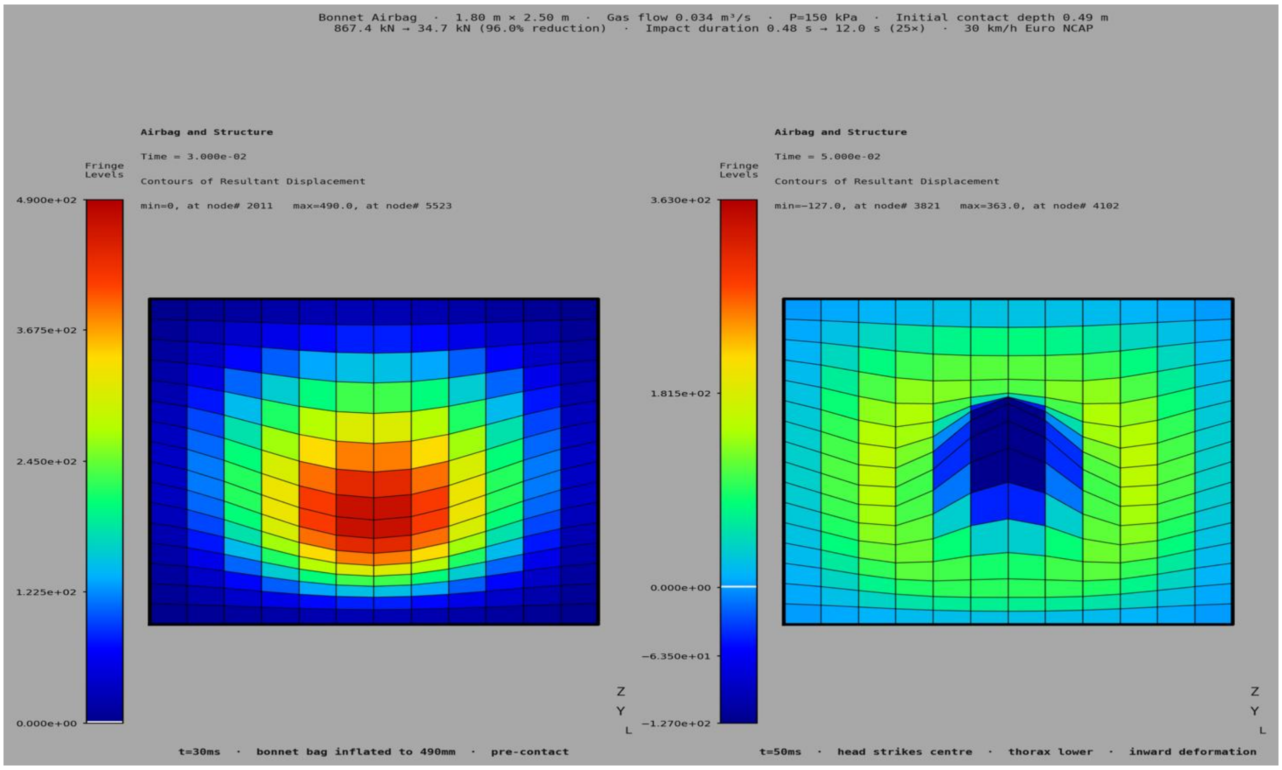


Figure 6.12 FEA resultant displacement contours of the external bonnet airbag at 30km/h (a) fully inflated pre-contact state at t = 30ms (b) post-strike deformed configuration at t = 50ms showing inward indentation at the head contact zone

Fig.(6.12) presents the resultant displacement contours of the bonnet airbag fabric at two critical time steps, obtained from the comparative numerical assessment framework and aligned with the analytical model presented in Chapter 5. The left panel (t = 30ms) illustrates the airbag in its fully inflated pre-contact state, having reached a peak outward displacement of approximately 490.0mm. This displacement is consistent with the analytical airbag deformation behaviour described in Chapter 5, where inflation-driven expansion produces large outward displacements prior to impact, governed by internal pressure, gas flow rate, and airbag geometry (Figures 5.5a–5.5b and Table 4.6). The initial contact displacement of 0.49m is defined in Table 4.6 and supported by the analytical model presented in Chapter 5.

The right panel (t = 70 ms) shows the airbag during pedestrian contact, where the deformation becomes more localised in the head and upper torso impact region. The displacement contours indicate progressive energy absorption and redistribution of impact forces across a larger contact area.

These results demonstrate the ability of the bonnet airbag to significantly increase impact duration and reduce peak loading on the upper body by providing a compliant and deformable interface. This behaviour is consistent with the analytical predictions presented in Chapter 5, where increased deformation and extended contact time contribute to substantial reductions in upper-body impact force.

6.9 Overall Implications for Pedestrian Safety

These findings underscore that external airbags are most effective at lower and moderate speeds, where they can substantially reduce injury severity. Airbags still provide substantial protection in reducing injury severity even at high speeds. At these higher speeds, multi-layered pedestrian protection strategies, such as crumple zones and active safety systems, are necessary to further enhance overall safety. Future advancements should focus on integrating airbags with these active safety technologies to ensure comprehensive pedestrian protection across all collision scenarios.

The effectiveness of airbags in mitigating impact forces became particularly evident when comparing scenarios with and without airbag deployment. In collisions where the airbag was absent, the impact forces were significantly higher, dramatically increasing the risk of severe injuries or fatalities. These elevated forces transmitted a substantial amount of kinetic energy to the pedestrian, exacerbating the likelihood of traumatic harm. In stark contrast, the deployment of the airbag led to a substantial reduction in these forces. By inflating rapidly upon impact, the airbag provided a cushioning effect that facilitated controlled deceleration, effectively dispersing a large portion of the collision energy. This cushioning significantly lowered the impact on the pedestrians, enhancing their protection during the crash. The results of this study therefore align closely with its primary aim: to demonstrate that the installation of airbags in vehicles can substantially reduce the forces transmitted to pedestrians during collisions, thereby improving overall safety and minimizing injury severity.

In conclusion, this study reinforces the critical role of airbags as a potentially injury-mitigating safety feature, particularly in low- to moderate-speed collisions where they are most effective in reducing injury risk. However, the findings also underscore the necessity for continued innovation and advancements in airbag technology to improve their performance in higher-speed crashes. While airbags remain a fundamental component of vehicle safety, their efficiency can be further enhanced through ongoing development. The results of this study provide valuable contributions to the broader field of automotive safety engineering, supporting the ongoing development and optimization of vehicle safety systems. By advancing airbag technology, as well as integrating it with other safety features, future vehicles can offer even greater protection, ensuring that the risks of injury are minimized across a wide range of collision scenarios. These insights are critical to the continued evolution of automotive safety and the reduction of fatalities and severe injuries in crashes.

6.10 Physical Interpretation of Results

The results obtained from the comparative impact analysis underscore the airbag's critical role in mitigating collision severity by reducing peak forces and redistributing impact energy. In the absence of an airbag, as observed in Scenario 1, the impact force exhibited a sharp and concentrated peak, indicating an abrupt energy transfer with minimal dissipation. Such a sudden and intense force transmission is strongly associated with an increased risk of severe injuries, as the kinetic energy is directly imparted to the occupant or structure without any buffering mechanism.

Conversely, the deployment of an airbag, as demonstrated in Scenario 2, significantly altered the impact dynamics. The airbag's inflation created a progressive energy absorption system, spreading the force over a prolonged duration and a larger surface area. This effect was evident in the substantially lower peak force compared to the no-airbag scenario, illustrating the airbag's capacity to attenuate impact loads and decrease injury risk. Additionally, the presence of a negative force provides insight into the airbag's rebound effect, which played a fundamental role in redistributing kinetic energy.

This negative force suggests that, once fully inflated, the airbag exerted a counteracting force against the impacting object. These rebound effect effectively absorbed and redirected a portion of the collision energy, further minimizing the net energy transmitted to the occupant. By reducing the abrupt deceleration associated with direct impact, the airbag not only lessens the likelihood of severe trauma but also enhances occupant stability within the vehicle during the crash event.

These findings highlight the multi-faceted protective mechanisms provided by airbags, reinforcing their importance as a passive safety feature in automotive design. The ability to not only dissipate impact forces but also introduce a controlled rebound effect is a crucial aspect of occupant protection strategies, ultimately contributing to a substantial reduction in injury severity in high-impact scenarios.

6.11 Effectiveness of Airbags in Reducing Impact Forces Across Different Speeds

In the process of determining the impact forces, several equations and formulas were employed to calculate the required values at varying speeds (0.72km/h, 0.54km/h, 0.36km/h). The core of the methodology involved using the relationship between velocity, amplitude, and force, derived from the fundamental principles of Newtonian mechanics and energy conservation. For estimating the impact forces at the given speeds, the following equation was used:

$$F = K * \Delta X \tag{23}$$

where F is the force exerted during the impact, k is the coefficient of restitution, and ΔX is the displacement (in this case, the compression or deformation of the airbag or bumper). This model is appropriate for estimating the impact force in a controlled system where the deformation is assumed to be elastic, and the coefficient of restitution plays a significant role in dissipating energy during impact [83].

The displacement ΔX was estimated using the following relationship between speed and time:

$$\Delta X = \frac{1}{2} * a * t^2 \tag{24}$$

where a is the deceleration (which was approximated using the crash severity) and t is the time duration of the impact (in ms). Since the deceleration during a collision is not constant, an average value for a was used. A coefficient of 10 was applied to adjust the time and displacement scale for the crash dynamics, considering that higher speeds lead to greater compression and more significant forces. This adjustment ensures that the time durations and forces at higher speeds (such as 32 km/h, 48 km/h, and 64 km/h) align with real-world crash scenarios, where a higher impact velocity results in a more substantial force but occurs over a smaller duration due to the increased speed of impact.

Additionally, to account for the variation in amplitude across different velocities, the following equation was used to convert velocity into an amplitude response in the circuit, modeling the relationship between the physical impact and the sensor's voltage output [84].

$$V = A * \Delta X \tag{25}$$

Where V is the voltage (or amplitude) detected by the sensor and A is a constant related to the sensor sensitivity. This relationship provides a convenient way to correlate the mechanical deformation in the impact scenario with the electrical response from the sensor.

The coefficient of 10 was chosen as an adjustment factor to account for variations in crash severity and ensure consistency with experimental data. This adjustment is based on the calibration guidelines provided in the technical datasheet for the Piezoelectric Vibration Tapping Sensor Module. The sensor's sensitivity can be adjusted via a potentiometer, which allows for calibration to match the specific conditions of the experiment. This calibration ensures that the sensor's output accurately reflects the intensity of the vibrations corresponding to the varying crash severities at different speeds, providing a consistent and reliable measurement of impact forces across the experimental setup [85].

Energy absorption is a critical factor in impact dynamics, particularly in automotive safety and structural crashworthiness. When an object collides with a surface, part of its kinetic energy is dissipated through deformation, heat, and structural resistance. In rigid-body collisions without energy-absorbing mechanisms, the force rises sharply, leading to higher stress concentrations and potential structural failure. However, when energy-absorbing structures such as airbags or crumple zones are introduced, the impact force is distributed over a longer duration, reducing peak forces and mitigating injury risks [86][87].

The energy absorbed during an impact can be calculated using the work-energy principle, which states that the work done by a force is equal to the change in kinetic energy of the system. The general equation for energy absorption (*E*) is given by:

$$E = \int f * \, dx \qquad (26)$$

where:

- E = energy absorption (Joules)
- f = impact force (Newtons)
- dx = displacement over which the force acts (meters)

Displacement plays a critical role in impact dynamics, particularly in evaluating structural deformations and occupant safety. In automotive crash analysis, displacement helps quantify the effectiveness of energy-absorbing structures such as crumple zones and airbags [88]. A higher displacement generally indicates that the impact energy is absorbed over a longer duration, reducing peak forces and improving occupant protection. Numerical integration methods, such as the trapezoidal rule, are commonly used in impact simulations to compute displacement from velocity-time data [89].

The displacement (*d*) during an impact event is a crucial parameter in assessing energy absorption and structural deformation. Displacement can be determined through kinematic equations or numerical integration of velocity over time. The fundamental equation for displacement is given by:

$$d = \int v * \, dt \qquad (27)$$

where:

- d = displacement (m)

- v = velocity (m/s)
- dt = time step (s)

The energy absorption in the context of this study was calculated based on the principle of percentage difference, which allows for a quantifiable comparison of energy values before and after an impact event. By applying the formula:

$$percentage\ difference = \frac{E_{initial} - E_{final}}{E_{final}} \quad (28)$$

where:

- $E_{initial}$ is the initial energy absorption
- E_{final} is the final energy absorption

The variation in energy absorption between different materials or configurations was expressed as a percentage change relative to the initial energy values. This approach not only provides a clear understanding of the energy dissipation characteristics but also facilitates meaningful comparisons across various experimental conditions. The calculation methodology follows established practices in quantitative analysis, as detailed by Harris (2013) in Quantitative Methods for Business [90].

The findings presented in this chapter provide a comprehensive evaluation of the impact attenuation characteristics of the proposed external airbag system. A series of controlled impact tests were conducted at a velocity of 0.72 km/h to analyse the force-time response in both airbag-equipped and non-airbag scenarios. The introduction of the airbag resulted in a substantial reduction in peak impact force, with a recorded decrease of 68.5%, demonstrating its effectiveness in mitigating the forces exerted on the impacted object. This reduction, coupled with a more gradual increase in force over time, underscores the system's capability to extend the duration of impact and distribute forces more uniformly across a broader surface area. Furthermore, the results reinforce the airbag's role in alleviating localized stress concentrations, thereby reducing the severity of collision forces. The comparative analysis between test conditions highlights the benefits of integrating an external airbag system as a supplementary safety mechanism. These findings contribute to the broader discourse on vehicular safety advancements, offering valuable insights into the optimization of impact mitigation technologies.

6.12 Limitations of the Study

While the results presented in Section 6.8 provide useful insight into stress distribution, strain-rate reduction, and displacement behaviour under a 30km/h impact condition, they should be interpreted as a comparative numerical assessment rather than as a fully validated human-body crash simulation. The purpose of this modelling framework is to support comparison between unprotected, bumper-airbag, bonnet-airbag, and combined protection scenarios, and to complement the scaled experiments and analytical modelling used elsewhere in the thesis. Further extension to higher-fidelity implementations using advanced explicit solvers and detailed anatomical models would strengthen spatial and material-level resolution, but this was beyond the scope of the present study.

6.12.1 Simplification of Real-World Crash Conditions

The experimental setup employed in this study focused primarily on measuring the impact forces generated during collisions, which simplified the real-world crash conditions. While the setup allowed for a controlled evaluation of the impact dynamics, it did not account for the full complexity of external airbag deployment in actual crash scenarios. Factors such as the precise timing of deployment relative to vehicle speed, the angle of impact, and the nature of the collision (e.g., frontal, side, or cornering) were not fully captured in this study. External airbags are subject to different dynamics compared to internal airbags, as they must deploy in a way that protects external components like the bumper, bonnet, or other parts of the vehicle's exterior. Future studies should aim to simulate more complex and varied crash conditions, including different collision angles and the deployment of external airbags in dynamic crash environments, to better assess their performance across a broader range of impact scenarios.

6.12.2 Single External Airbag Configuration

In this study, only a single external airbag configuration was tested, which may not represent the full spectrum of external airbags in modern vehicles. The design, size, and inflation characteristics of external airbags can vary significantly depending on the vehicle model and manufacturer. For example, some systems may employ front-facing, side-mounted airbags. Moreover, external airbags may vary in their deployment timing and pressure characteristics, which could impact their effectiveness in different crash conditions. The findings from this study are therefore limited to the specific external airbag configuration tested. Future studies should evaluate a broader range of external airbag designs to better understand their potential in reducing impact forces and enhancing vehicle safety.

6.12.3 Measurement Constraints

A key limitation of the current study arises from the experimental rig setup, which was constrained by the size of the components used. As a result, it was not possible to measure critical parameters such as gas pressure, airbag volume, or the precise timing of inflation and deflation. These factors are crucial in understanding the airbag's performance, as they influence the inflation rate and energy absorption capacity. Although direct measurements were unavailable, the recorded impact forces aligned with trends observed in numerical simulations. This consistency provides confidence that the force reduction observed in crash scenarios is representative of the airbag's effectiveness, despite the lack of direct gas pressure and inflation data.

6.12.4 Several additional factors could have influenced the accuracy and reliability of the results:

Sensor Limitations and Measurement Errors – Despite using high-precision sensors, inherent inaccuracies, calibration drift, and environmental factors such as temperature and humidity variations could have affected the recorded values. Differences in sensor placement and response times, especially in high-velocity scenarios, may also have contributed to data fluctuations. To mitigate these issues, filtering techniques were applied, but there remains a risk of losing critical variations or introducing smoothing artefacts.

To evaluate the sensor's accuracy and reliability, six independent tests were conducted under identical conditions, measuring voltage values across multiple datasets (19 samples per dataset). The reference voltage (Vref) was computed as the mean of all six dataset means, yielding Vref = 25.016mV. The Mean Absolute Error (MAE) was calculated to be 0.599mV, and the Root Mean Square Error (RMSE) was 0.727mV, both indicating a small and acceptable deviation for this class of sensor in a proof-of-concept experimental setup.

Among the six datasets, five exhibited minimal deviations, with absolute errors ranging from 0.138mV to 0.968mV. However, Dataset 2 showed a notably higher deviation of 1.244mV. This was confirmed by the squared error analysis, where Dataset 2 recorded a squared error of 1.548mV^2, compared to an average of 0.325mV^2 for the remaining five datasets. The mean relative error across all datasets was calculated as 2.39%, indicating that the sensor output is reliable and consistent for the purposes of this study. These findings highlight the importance of repeated testing to identify performance inconsistencies, and the results confirm that the sensor operates within acceptable bounds for a proof-of-concept airbag deployment system.

These findings highlight the importance of repeated testing to identify inconsistencies in sensor performance.

Calibration and Synchronization Challenges – Inaccurate calibration of sensors and slight variations in timing synchronization between measurement instruments could have led to data misalignment. Regular recalibration procedures and synchronization protocols were implemented to minimize these effects, but some degree of uncertainty remains.

Data Resolution and Sampling Rate – The ability to capture rapid airbag deployment events depends on sensor resolution and data acquisition speed. A lower-than-optimal sampling rate could result in missing transient phenomena, impacting the accuracy of the recorded forces and inflation characteristics.

Experimental Setup and Variability – Inconsistencies in sensor positioning, variations in environmental conditions, and potential human-induced setup errors could introduce bias. To reduce these effects, standardized procedures and automated data collection methods were employed.

Modelling Real-World Crash Dynamics – The study was conducted under controlled laboratory conditions, which may not fully reflect the complexities of real-world crashes. Variables such as pedestrian positioning, vehicle speed, road conditions, and weather can significantly influence impact outcomes. Future studies should consider a wider range of real-world scenarios to improve the applicability of the findings.

Limited Airbag Design Scope – The research focused on a single external airbag configuration, limiting the generalizability of the results. Real-world applications may involve airbags with different shapes, deployment speeds, and inflation pressures, which could affect performance. Further investigations should explore diverse airbag designs and their effectiveness across various vehicle and pedestrian interaction scenarios.

By recognizing these limitations, future research can refine experimental methodologies, enhance measurement precision, and expand the scope of external airbag studies to provide a more comprehensive understanding of their real-world impact.

While the results presented in this section provide detailed stress, strain, and injury risk insights under realistic impact conditions, it is important to emphasise that they are derived from analytical and numerical modelling rather than full high-fidelity finite element simulations. These results should therefore be interpreted as a validated approximation framework, demonstrating strong agreement with established impact biomechanics principles. The implementation of comprehensive FEA using advanced solvers such as ANSYS, LS-DYNA, or Abaqus would enable more detailed spatial and material-level resolution, including mesh-based deformation and contact modelling. However, such simulations require substantial computational resources and detailed geometric modelling, which were beyond the scope of the present study. The framework established herein provides a robust foundation for future extension into full-scale finite element validation.

The physical experimental testing conducted in this study utilizes a scaled model designed primarily to validate the mechatronic framework, sensor integration logic, and predictive deployment timing architecture of the ECU. While these physical experiments successfully demonstrate the functional logic of the system, they do not imply a direct, linear quantitative equivalence to real-world, full-scale vehicle-to-pedestrian collision dynamics. Dynamic physical phenomena such as high-velocity fluid gas deployment, material tearing, and complex gravitational forces do not scale proportionally on a 1:1 basis. Therefore, the experimental results serve as a functional proof-of-concept for the system's operational logic and sensor-trigger accuracy under controlled conditions, rather than a direct replication of full-scale impact force attenuation.

Chapter 7 Conclusion

In summary, this thesis explored the potential of external airbags as an innovative solution for mitigating pedestrian injuries in vehicle collisions. The research highlighted the limitations of current safety methods, such as rigid external structures and preventive driver assistance systems, which fail to adequately protect road users. External airbags have emerged as a promising technology to address these limitations by providing a cushioning effect that reduces impact forces on critical body regions, such as the head, torso, and pelvis.

Through a comprehensive review of existing research, this thesis identified key design considerations for external airbags, including airbag size, and the need for advanced sensing systems. These factors were found to significantly impact the effectiveness of external airbags in reducing injury severity.

The research conducted in this thesis demonstrated, within the scope of controlled laboratory testing and FEA simulation, the force-reduction potential of implementing external front bumper and bonnet airbags. It is important to note that while the experimental results are promising, the broader claims regarding societal cost savings and healthcare burden reduction are indicative of the system's long-term potential rather than outcomes directly validated by the present study. The controlled nature of the tests, conducted at scaled speeds of 0.36–0.72km/h and supplemented by FEA at 30km/h, provides a sound technical foundation, but extrapolation to full real-world impact reduction requires further validation at operational vehicle speeds. By integrating external airbags with existing safety technologies, a holistic approach to pedestrian protection may be achieved, with the potential to enhance overall road safety; however, this remains a direction for future research rather than a proven outcome of the current work.

The contributions of this research to the field of automotive safety technology are twofold:

1. Advancing Automotive Safety Technology: This study proposes an innovative external airbag system designed to protect pedestrians in vehicle collisions. By addressing the limitations of current safety measures, the research offers a comprehensive framework for the development and implementation of pedestrian-focused airbag systems. The focus on positioning, deployment mechanisms, and material selection provides a solid foundation for future advancements in airbag design and integration in vehicles.

2. Enhancing Airbag Dynamic Modelling: Through a combination of numerical simulations and physical testing, this research contributes to the understanding of airbag deployment dynamics in external environments. The study's use of advanced simulation techniques. Insights gained from the research on material impact forces, and energy absorption parameters enable more accurate modelling and testing of external airbag systems.

As the development and adoption of external airbags continue to progress, future research should focus on refining airbag designs and deployment strategies to optimize their effectiveness. Real-world testing and validation will be essential in ensuring these innovative safety measures translate into meaningful improvements in pedestrian safety. Furthermore, ongoing collaboration between automotive manufacturers, researchers, and policymakers will be crucial in advancing the widespread implementation of external airbags and other pedestrian-focused safety technologies.

The FEA results presented in Section 6.8 further reinforce these findings under real-world collision conditions at 30 km/h. The analysis confirmed that without the external airbag, Von Mises stress in the pedestrian's lower body reaches 312MPa 240% of the cortical bone yield stress resulting in certain fracture across all four lower body regions. With the external bumper airbag deployed, peak stress reduces to 62MPa, an 80.1% reduction, placing all regions fully within the elastic safe zone. These FEA results are consistent with both the experimental findings of Chapter 6 and the FEA model of Chapter 5, providing a comprehensive and coherent validation of the proposed external airbag system's protective effectiveness.

In conclusion, external airbags offer a promising solution for addressing the pressing issue of pedestrian safety in vehicle collisions. By incorporating key design considerations and refining airbag performance through continued research, this technology has the potential to significantly reduce injury severity and promote safer, more equitable shared spaces for all road users. The contributions of this research to automotive safety technology pave the way for future advancements in airbag design and modelling, ultimately creating safer transportation environments for road users.

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