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Innovative Design of External Airbag System for Improved Automotive Safety

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ABSTRACT Pedestrians are exceptionally vulnerable in road accidents, and despite the advancements in airbag technology for vehicle occupants, fatal injuries still occur due to contact between pedestrians and vehicle components. To address this issue, an innovative solution is introduced in this research: an external airbag system designed to safeguard pedestrians in cases of brake failure. The proposed system includes four airbag modules strategically positioned within the front bumper of the vehicle. These modules are specifically designed to deploy during a collision, providing protection for the pedestrian's head, legs, and body. Equipped with a highly sensitive sensor, the system triggers the airbag electronic controller unit (ECU) upon collision detection. The external airbag curtains deploy, shielding the pedestrian's head from striking the bonnet, while an additional airbag safeguards the pedestrian's legs from impact with the front bumper. With the introduction of this innovative external airbag system, the main goal is to significantly improve road safety for all individuals and prevent numerous fatalities. The introduction of the innovative external airbag system marks a significant advancement in pedestrian safety within the realm of road accidents. By strategically positioning four airbag modules within the vehicle's front bumper and equipping them with a highly sensitive sensor, this system effectively deploys during collisions to protect pedestrians' heads, legs, and bodies. The deployment of external airbag curtains shields pedestrians' heads from striking the bonnet, while an additional airbag safeguards their legs from impact with the front bumper. Through this research and implementation, the primary objective is to enhance road safety for all individuals and mitigate the occurrence of numerous fatalities resulting from pedestrian-vehicle collisions.

INDEX TERMS Cad, MATLAB, external airbag, pedestrian safety.

I. INTRODUCTION

External airbags represent an innovative advancement in automotive safety technology, revolutionizing the traditional concept of vehicle protection. Unlike conventional airbags that deploy inside the vehicle cabin, external airbags are strategically positioned on the exterior of the vehicle, serving as an additional layer of defence in the event of a collision. These airbags are designed to deploy milliseconds before impact, effectively cushioning and shielding both the vehicle and pedestrians from the force of the crash. By dispersing energy and reducing the severity of impact, external airbags have the potential to mitigate injuries and minimize damage to both the vehicle and its surroundings. Furthermore, their integration into modern vehicle designs underscores a commitment to enhancing road safety and addressing evolving challenges in urban environments where pedestrian accidents are a concern. As automotive manufacturers continue to prioritize safety innovation, external airbags represent a significant step forward in protecting all road users and reshaping the landscape of automotive safety standards. The conclusions drawn from the discussion on external airbags for pedestrian safety suggest several pertinent research objectives. Firstly, there is a need to optimize the deployment timing of external airbags, ensuring swift and accurate responses to potential collisions to maximize their effectiveness in mitigating pedestrian injuries. Additionally, efforts should focus on reducing the cost of materials used in external airbag systems without compromising safety standards, thereby enhancing their economic viability for widespread adoption in vehicles. Real-world validation studies are essential to confirm the performance and effectiveness of external airbag systems under diverse environmental and driving conditions. Integration of advanced sensor technologies, such as LiDAR (Light Detection and Ranging) and radar (radio Detection and Ranging) systems, holds promise for improving collision detection and prediction, leading to more precise deployment and enhanced pedestrian safety outcomes. Furthermore, refinement of deployment algorithms based on insights from field studies and simulation models is crucial to optimize the functionality and performance of external airbag systems across various collision scenarios. Addressing these research objectives will contribute to advancing the development and refinement of external airbag systems, ultimately enhancing pedestrian safety in vehicular environments.

In their study, various analytical, numerical, and hardware testing methods were introduced by Barbat et al. to aid in the development of initial design parameters for the concept of external airbags [1]. Initially, spring-mass models were established to define the desired stiffness targets for the bumper and grille airbags. Simulations, validated through physical testing, were then utilized to devise a structural design for the inflatable system, ensuring both integrity and performance. Furthermore, hardware tests were conducted at subsystem and sled levels, supported by finite element analyses [2]. These tests encompassed the selection of fabric material, determination of construction technique (sewn vs. bonded bags), seam type, and integration of energy management features such as burst-type vent ports. In Phase I, the initial airbag shape and design parameters were established and subsequently refined in Phase II for further enhancements.

Conducting a study to investigate the impact of mass, geometry, and stiffness on occupant responses in front-to-side collisions using computer simulations, Mohan et al. employed a Design of Experiment (DOE) methodology based on Finite Element (FE) models to analyse the effects of select design variables on dummy responses during front-to-side crashes [3].

In another study, Moxey et al. conducted FE analysis to examine the effectiveness of external airbags in pedestrian impact scenarios [4]. Their research involved a model that incorporated a pedestrian being struck by a C-class vehicle equipped with a staged airbag system positioned on top of the bonnet. However, it is important to note that their investigation was still in its preliminary stages, lacking hardware testing or validations. The focus of their paper primarily revolved around the development of pre-crash sensing, and it was concluded that significant additional work was necessary for the advancement of external airbags.

In passive methods, attempts have been made by designers to modify the frontal structure of vehicles to absorb impact energy [5], [6]. However, this approach has a clear limitation as it requires direct contact between the pedestrian and a steel structure. Numerous studies have focused on altering the material characteristics of the bonnet [7], [8]. It has been noted that there are evident constraints in modifying the design of the frontal structure [9], [9]. As a result, protective devices have been increasingly implemented.

In the realm of automotive safety, the integration of passive and active safety systems in modern vehicles has significantly advanced occupant protection and accident prevention. Passive safety systems, such as seatbelts, airbags, and crumple zones, serve as critical safeguards by mitigating the impact forces during collisions, thereby reducing the likelihood and severity of injuries. Conversely, active safety systems, including anti-lock braking systems (ABS), electronic stability control (ESC), and adaptive cruise control, operate proactively to prevent accidents by intervening in the driving process. These technologies actively monitor vehicle dynamics, detect potential hazards, and assist drivers in maintaining control and avoiding collisions. The synergy between passive and active safety systems epitomizes the multifaceted approach toward enhancing automotive safety, ultimately fostering a safer driving environment for all road users. [10]

External airbags represent a novel advancement in automotive safety technology, aiming to mitigate the severity of vehicle collisions by extending protection beyond the confines of the vehicle's interior. These airbags deploy from various locations on the vehicle's exterior upon detection of an imminent collision, forming a cushioning barrier between the vehicle and potential impact objects. Unlike traditional internal airbags, external airbags have the potential to reduce occupant injury by absorbing and dispersing the kinetic energy of the collision before it reaches the pedestrian. The deployment of external airbags heralds a promising frontier in passive safety systems, offering additional layers of protection to enhance overall vehicle safety.

Several automotive manufacturers have begun integrating external airbag systems into their vehicle designs as part of ongoing efforts to enhance safety. For instance, German automaker Mercedes-Benz introduced the PRE-SAFE Impulse Side system, which features external side airbags that deploy from the vehicle's body to provide additional protection in the event of a side collision (Mercedes-Benz, 2019) [11]. Similarly, Swedish automaker Volvo has developed an external airbag system designed to protect pedestrians in the event of a frontal collision. This system deploys a bonnet-mounted airbag that covers the windshield and A-pillars, reducing the risk of head injuries for pedestrians (Volvo Cars, 2020) [12]. These case studies demonstrate the diverse applications of external airbags in mitigating the impact of collisions and enhancing overall vehicle safety.

Preliminary evaluations of external airbag systems have shown promising results in terms of their effectiveness in reducing injury severity and enhancing crashworthiness. A study conducted by the Insurance Institute for Highway Safety (IIHS) found that vehicles equipped with external side airbags experienced significantly reduced injury risk in side-impact crashes compared to those without such systems (Insurance Institute for Highway Safety, 2021). Furthermore, the potential benefit of external airbags is to include enhanced pedestrian safety. By providing an additional layer of cushioning during collisions, external airbags have the potential to mitigate injury severity for both vehicle occupants and vulnerable road users.

Despite their potential benefits, the widespread adoption of external airbag systems faces several challenges, including cost considerations, integration with existing vehicle designs, and regulatory approval processes. Additionally, further research is needed to evaluate the long-term effectiveness and reliability of these systems under real-world driving conditions. As automotive manufacturers continue to innovate in the realm of vehicle safety, ongoing advancements in external airbag technology hold promise for reducing the overall impact of collisions and saving lives on the road. Continued collaboration between industry stakeholders, regulatory agencies, and research institutions will be crucial in overcoming challenges and realizing the full potential of external airbag systems in enhancing automotive safety. [13].

This study introduces a novel strategy aimed at enhancing pedestrian safety during unavoidable collisions by proposing a fresh design concept of external airbags integrated into the front bumper. These airbags extend coverage over both the front bumper and the bonnet, providing an additional protective layer. Accompanying this design is an algorithm detailing its operational steps and distinctive features. The aim of this study is to protect the lower and upper parts of the human body, including the head, in the event of a crash.

The focal achievement of this paper centres on the design concept and CAD modelling of the proposed external airbag system, along with the application of an analytical model and its results. The analytical model results were compared with those obtained by a numerical model developed in MATLAB. Comparison results indicated a good agreement between the two models, underscoring the reliability and accuracy of the analytical model in assessing the performance of the external airbag system. This insight enhances understanding of the system's effectiveness and aids in the refinement of design parameters to optimize pedestrian safety.

Researchers investigated the mechanisms of pedestrian head injury resulting from ground impact in pedestrian–vehicle accidents, an area characterized by limited understanding despite its significance in secondary impact scenarios. Employing multi-body modelling and computational simulations that varied vehicle front-end shapes (bonnet leading-edge height, length, angle, and windshield angle), the study highlighted bonnet leading-edge height as the primary factor influencing head injury severity. Secondary considerations included bonnet angle, length, and windshield angle, offering crucial insights for advancing pedestrian safety through vehicle design. [14]

II. EXTERNAL AIRBAG TECHNOLOGY

External airbags are a relatively new safety feature that are being developed to help protect pedestrians in the event of a collision with a vehicle. These airbags are designed to deploy from the front of the vehicle when sensors detect an impending collision with a pedestrian. The airbag provides a cushion between the pedestrian and the hard surfaces of the vehicle, reducing the impact force and potentially preventing serious injury or death.

During a vehicle collision, the human body undergoes stress and strain. Stress refers to the force exerted on an object, while strain pertains to the resulting deformation caused by that force. In the context of a vehicle impact crash, the body endures significant levels of stress and strain due to the abrupt and intense forces at play. These forces can be mitigated by implementing the following measures to minimize their impact:

Absorbing impact forces: External airbags can absorb some of the impact forces that would otherwise be transferred to the vehicle's occupants. By reducing the force of the impact, external airbags can potentially decrease the risk of serious injuries such as broken bones, traumatic brain injury, and spinal cord damage.

Distributing impact forces: By spreading the force of the impact over a larger area, external airbags can help distribute the impact forces more evenly across the body, reducing the likelihood of localized injuries.

Reducing whiplash: External airbags can potentially reduce the severity of whiplash injuries by providing support to the head and neck during a crash.

Active bonnet lift system has been developed to get more spaces for decreasing the head injury during pedestrian impact. This system is composed of detecting sensor, ECU where the algorithm is embedded and the pyro-type actuators which raise the bonnet. By this system, the rear part of the bonnet is raised up to approximately 120 mm. [15]

A. MATERIALS AND COMPONENTS OF AIRBAG SYSTEMS

Airbags are typically made from a woven nylon fabric that is designed to be strong, flexible, and tear resistant. The fabric used for airbags is usually coated with a heat-resistant material to help protect it from the high temperatures that can occur when the airbag is deployed.

The specific type of nylon fabric used for airbags is called "ballistic nylon", which is a type of synthetic material that is known for its high strength-to-weight ratio. Ballistic nylon is also used in other applications that require high levels of durability and resistance to abrasion, such as military gear, luggage, and sports equipment. [16]

In addition to the nylon fabric, airbags also contain a gas generator, which is a small explosive device that rapidly inflates the airbag when a crash is detected. The gas generator typically contains a mixture of chemicals such as sodium aside and potassium nitrate, which react to produce a large volume of nitrogen gas.

Together, the nylon fabric and gas generator work together to create a protective cushion that can help reduce the risk of injury during a vehicle impact crash. When the airbag is deployed, it inflates rapidly and creates a barrier between the pedestrian and hard surfaces such as the front bumper, bonnet, and the windshield.

By reducing the acceleration experienced by the body and expanding the surface area where the force is distributed, it is

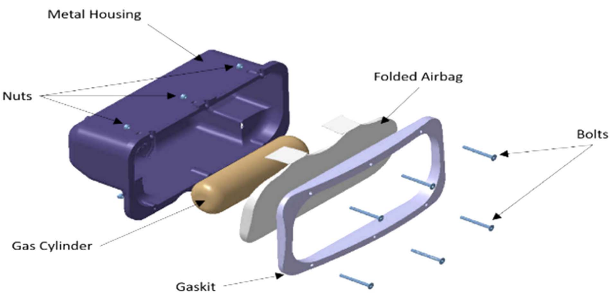


FIGURE 1. Exploded view of front bumper's airbag enclosure design.

TABLE 1. Properties of Nylon 66 and Polyester

Parameters	Nylon 66
Density (Kg/m3)	1140
Specific heat capacity (kJ/kg/K)	1.67
Melting point (○ C)	260
Softening point (○ C)	220
Young's modulus(MPa)	1850
Tensile strength (MPa)	38.6 - 93.1
Energy to melt (kJ/kg)	589

possible to decrease the amount of force applied to the body. This fundamental principle is employed by airbags to mitigate injuries. Airbags extend the duration of time during which the head's velocity undergoes changes, leading to a reduction in acceleration and, consequently, force.

Airbags are typically composed of various materials chosen to offer a balance of strength and flexibility as shown in Fig. 1. A key component in airbag construction is a woven nylon fabric, engineered to be lightweight, tear-resistant, and sufficiently elastic for rapid inflation upon collision impact. To safeguard the nylon fabric from the intense heat generated during deployment, it is coated with a heat-resistant substance like silicone or neoprene. This protective layer not only shields the fabric from melting or burning due to contact with the hot gases produced by the airbag inflator but also enhances its durability. Furthermore, robust stitching reinforces the seams of airbags to ensure structural integrity during deployment. Some airbags may also feature a thin layer of silicone gel or powder to lubricate the fabric, preventing it from sticking together when folded. Additionally, an extra layer of security is provided by fitting a gasket between the airbag housing and the bumper. The meticulous selection and integration of these materials aim to optimise airbag performance in terms of strength, flexibility, and heat resistance, ultimately enhancing occupant safety in the event of a collision.

Tables 2 and 3 illustrate the dimensions and specifications of the airbag housing and middle bumper airbag, respectively. The dimensions are presented for both deflated and inflated states, providing comprehensive information about the size and weight of each mechanism.

TABLE 2. Airbag Housing Dimensions

Dimensions of the airbag fitted at the edges of the bumper	Deflated	Inflated
Length	28.5 cm	43.5 cm
Width	15 cm	100 cm
Width "Depth"	8 cm	8 cm
Weight of the mechanism	2.5 kgs	2.5 kgs

TABLE 3. Middle Bumper Airbag Product Specifications

Dimensions of the middle airbag	Deflated	Inflated
Length	57 cm	180 cm
Height	15 cm	100 cm
Width "Depth"	8 cm	8 cm
Weight of the mechanism	5 kgs	5 kgs

B. SAFETY PROTOCOL AND RELEVANT ENVIRONMENTAL CONDITIONS

Airbags represent a crucial safety feature in modern vehicles, designed to safeguard occupants in the event of a collision. Nonetheless, it's imperative to grasp that airbags can be influenced by diverse environmental factors, and comprehending these variables is essential to guarantee their proper functionality. Below are some of the critical environmental factors that can have an impact on airbags:

Temperature: Extreme temperatures can have repercussions on airbag performance. Elevated temperatures can lead to the degradation of the propellant within the airbag module, while excessively low temperatures can hamper inflation speed and efficiency. Most airbag systems are engineered to operate within specified temperature ranges.

Humidity: Elevated humidity levels can result in moisture infiltration into the airbag system, potentially causing corrosion and electrical malfunctions. Effective sealing and moisture-resistant components are imperative to address this issue.

Altitude: Air pressure and altitude can exert influence on the deployment of airbags. Airbag systems are tailored to function effectively at varying altitudes, necessitating consideration during the design and testing phases.

Dust and Debris: Accumulation of dust, dirt, and debris in and around the airbag system can potentially impede its performance. Regular maintenance and inspections can help prevent these issues.

Vibrations: Vibrations stemming from rough road conditions or off-road driving can impact the sensors and electrical connections within airbag systems. Ensuring a robust design and secure mounting is vital for the proper functioning of these safety mechanisms.

UV Exposure: Prolonged exposure to ultraviolet (UV) radiation from the sun can cause the deterioration of materials,

TABLE 4. Specifications of the Selected Vehicle

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

TABLE 5. Specifications of the Front Bumper and Bonnet

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

including the airbag cover, which may affect both the performance and appearance of the airbag.

Chemical Exposure: Exposure to specific chemicals, such as oils, solvents, or cleaning agents, can inflict damage on airbag components. Prudent storage and handling practices are crucial to prevent chemical exposure.

Age: Airbag systems possess a finite lifespan, and their efficacy can diminish over time. Manufacturers typically advise replacing airbags after a designated number of years, even if they haven't been deployed.

Electrical Interference: Robust electromagnetic fields or electrical interference from nearby devices can disrupt the sensors and electronics within an airbag system. Employing shielding and conducting electromagnetic compatibility testing is essential to mitigate these risks.

Manufacturers take these environmental conditions into careful consideration during the design and testing phases of airbag systems to ensure their reliable performance across a wide range of scenarios. Consistent vehicle maintenance, encompassing inspections and servicing of the airbag system, plays a pivotal role in preserving their reliability and safety. Adhering to the manufacturer's recommendations for maintenance and replacement is critical to ensure that airbags function as intended in the event of a collision. [17]

ISO 14513:2016 outlines a testing procedure designed to replicate the impact of an adult pedestrian's head on the top of the bonnet of passenger vehicles or light trucks weighing up to 3.5 tonnes (GVM), as defined in ISO 3833. [18]

III. VEHICLE SPECIFICATIONS

In the proposed research, Tesla 2016 Model X was used. The specifications of the vehicle, including the front bumper and bonnet, are presented in Tables 4 and 5 respectively.

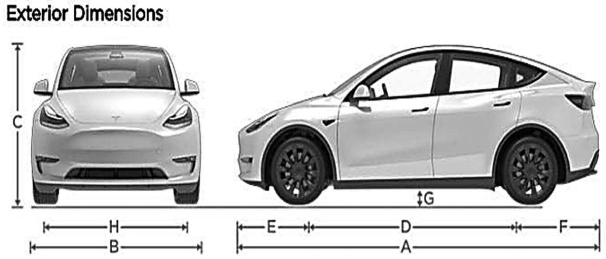


FIGURE 2. Vehicle used in the study.

The Model X's front bumper is constructed using thermoplastic polyurethane (TPU) with an approximate thickness ranging from 4 to 6 mm. The front car bonnet is composed of aluminium and typically has a thickness of around 1.2 to 1.5 mm.

Fig. 2 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 4 and 5, 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.

IV. CAD DESIGN

The following flowchart, depicted in Fig. 3, illustrates the operational procedure of a novel system. This system begins by acquiring data from a 3D camera and various 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, depending on the individual's height, the system may also deploy the bonnet's airbag to provide supplementary safety measures.

Time to collision (TTC) and time to stop (TTS) are critical metrics in the domain of traffic safety and collision avoidance systems. Time to collision refers to the duration remaining until a potential collision occurs between two objects or vehicles, calculated based on their relative positions, velocities, and accelerations. It serves as a fundamental indicator of imminent collision risk, enabling proactive measures to mitigate accidents. Time to stop, on the other hand, quantifies the duration required for a moving vehicle to come to a complete halt from its current speed, considering factors such as braking distance and deceleration capabilities. Both metrics play pivotal roles in the design and evaluation of advanced driver assistance systems (ADAS) and autonomous vehicles, aiding in the development of collision avoidance algorithms, adaptive cruise control systems, and emergency braking mechanisms. Accurate estimation and prediction of TTC and TTS are essential for enhancing road

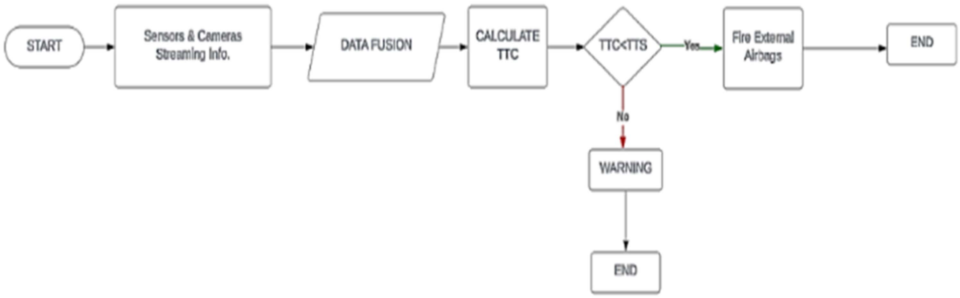


FIGURE 3. **Flowchart of algorithm used in the proposed design.**

safety, optimizing traffic flow, and fostering the realization of safer and more efficient transportation systems. Thus, ongoing research efforts continue to refine methodologies and technologies for robust and reliable estimation of TTC and TTS, ultimately advancing the forefront of automotive safety and intelligent transportation systems. Contemporary collision detection systems have witnessed a surge in sophistication, with the integration of radar sensors and camera-based systems emerging as pivotal components. Radar sensors facilitate the detection of objects in the vehicle's trajectory, precisely measuring the relative speed and distance, thereby enabling the identification of imminent collisions and triggering airbag deployment accordingly. Complementing this technology, camera-based systems harness computer vision algorithms to meticulously analyse the vehicle's surroundings, identifying potential obstacles or hazardous situations, and initiating the deployment sequence upon detecting an impending collision event. These multifaceted sensor modalities operate in concert with the vehicle's airbag control unit (ACU), a highly sophisticated processing unit that evaluates the amalgamated sensor data through predetermined algorithms and thresholds. The ACU's decision-making process is further augmented by the consideration of additional factors, such as the vehicle's velocity, seat belt engagement status, and occupant classification, thereby determining the optimal deployment strategy to maximise occupant protection. It is imperative to acknowledge that different vehicle models and manufacturers may employ diverse combinations of these sensors, with their specific arrangements and algorithms tailored to the vehicle's design and safety requirements, reflecting the ever-evolving landscape of collision detection and mitigation technologies.

The fusion data system will detect and classify obstacles, calculating their distance from the vehicle along with TTC and TTS. The ECU will monitor these distances, comparing them against predetermined thresholds. When the criteria stored in the ECU are met, and if the TTC is less than the TTS, the ECU will activate the front external airbags.

A. BONNET AIRBAG COMPONENTS MECHANISM

Fig. 4 illustrates the bonnet airbag installed within the front bumper, crafted from the same material discussed in Section III. 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.

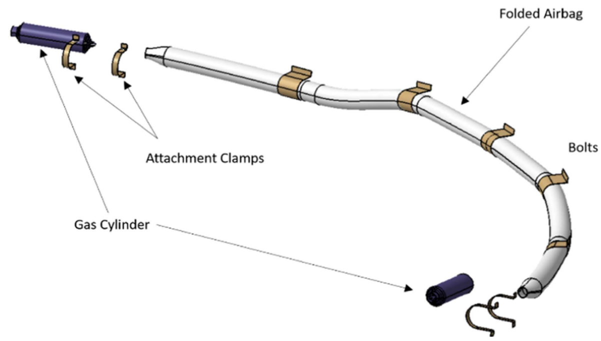


FIGURE 4. **Bonnet folded airbag.**

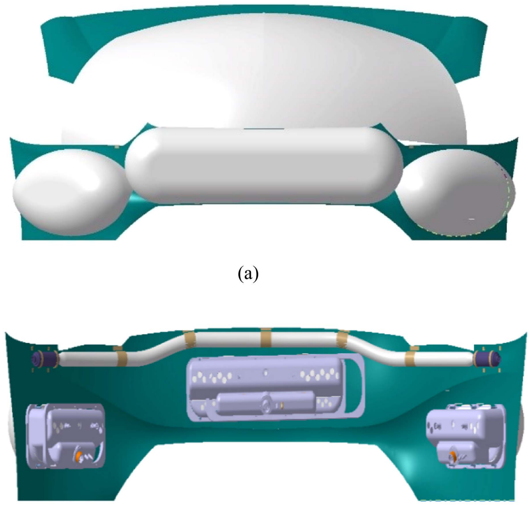
The airbag cylinder is constructed from durable materials such as steel or aluminium, engineered to withstand the high pressures generated during gas release. These cylinders are meticulously designed to meet stringent safety standards and accommodate the specific volume requirements of the gas needed 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 for vehicle occupants in the event of a collision. The utilization of nitrogen gas in external airbags necessitates a rigorous consideration of safety aspects to mitigate potential hazards. Asphyxiation risks arise from the inert nature of nitrogen, which can displace oxygen and compromise atmospheric oxygen concentrations, necessitating proper ventilation and monitoring protocols. Furthermore, the high-pressure storage of nitrogen gas introduces the risk of explosive decompression, posing physical injury threats that mandate meticulous handling and containment measures. Rapid decompression phenomena can induce significant cooling, giving rise to frostbite or cold burn hazards upon contact with exposed skin or cooled surfaces. Odourless and colourless properties of nitrogen gas pose challenges in leak detection, underscoring the criticality of implementing appropriate sensing systems or procedures. Comprehensive training programs, coupled with the mandatory use of personal protective equipment (PPE), are imperative to ensure personnel competency and safeguard their well-being. Moreover, robust emergency response plans must be devised to address contingencies such as leaks, fires, or injuries, encompassing first aid measures and evacuation protocols. Regulatory compliance with local, state, and federal guidelines governing the use, storage, and transportation of nitrogen gas is an essential prerequisite. Ultimately, a holistic risk assessment approach, aligned with the implementation of stringent safety measures and personnel training, is pivotal in mitigating the inherent risks associated with the deployment of nitrogen gas in external airbag systems.

The material composition of external airbags is meticulously engineered to withstand prolonged exposure to the rigours of the external environment, necessitating a judicious selection of fabrics and coatings that exhibit superior durability, weathering resistance, and resilience against ultraviolet radiation, moisture ingress, and temperature extremes. Prevalent materials employed in the construction of external airbag fabrics encompass coated nylons, polyesters, or specialised high-performance fibres such as Vectran or Kevlar. These fabrics are often fortified with robust coatings or reinforcements comprising polyurethane, silicone, or thermoplastic elastomers, thereby augmenting their resistance to abrasion, and enhancing their longevity under adverse environmental conditions. The inflation mechanisms for external airbags prioritise controlled and sustained inflation profiles, frequently harnessing compressed gas inflators that rely on the storage and regulated release of inert gases such as nitrogen or argon. In contrast to the pyrotechnic mixtures employed in interior airbags, these compressed gas inflators facilitate a more measured and controlled inflation process, better suited to the operational requirements of external airbags. Furthermore, external airbags necessitate robust mounting and deployment mechanisms, including specialised brackets, hinges, or pyrotechnic devices, to ensure proper positioning and rapid inflation upon impact, thereby safeguarding the intended protective function in the external environment.

The integration of LiDAR and radar sensors in external airbag systems represents a significant advancement in vehicular safety technology. LiDAR offers precise distance measurements and high-resolution environmental mapping, which are essential for detecting small or distant objects, while radar provides robust performance in various weather and lighting conditions and can penetrate obstructions such as dust or smoke. The complementary strengths of these sensors are leveraged through data fusion, enabling a comprehensive understanding of the vehicle's surroundings and accurate assessment of collision risks based on the size, speed, and trajectory of potential threats. This integrated sensor system processes data in real-time to ensure rapid and optimal airbag deployment, enhancing protection and reducing collision forces. The combined use of LiDAR and radar thus ensures a highly reliable detection system, adaptable to diverse driving scenarios.

TABLE 6. **Bonnet Airbag Product Specifications**

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



(a)

(b)

FIGURE 5. **(a) Front bumper's inflated airbags. (b) Front bumper's housing.**

The disposal of airbag components from interior airbags requires careful handling due to their hazardous nature. These components include inflators, propellants, and pyrotechnic devices that can pose risks if not disposed of properly. The inflators, which contain solid propellants or compressed gases, must be safely deflagrated, or depressurized in controlled environments to prevent accidental ignition or explosions. Specialized facilities with blast-resistant enclosures and trained personnel are necessary to render these components inert before disposal. Additionally, the propellant materials often contain energetic compounds and heavy metals that can be harmful to the environment and human health, so they need to be separated and treated appropriately. Strict local, national, and international regulations regarding the transport, storage, and disposal of hazardous materials must be followed throughout the disposal process.

Table VI 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.

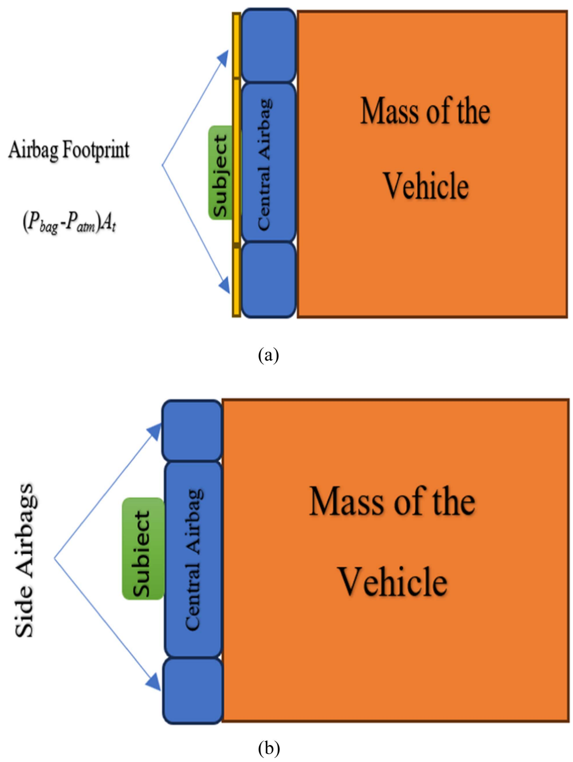


FIGURE 6. **(a) Stroked airbags. (b) Unstroked airbags.**

V. PROTOTYPE OF THE INFLATED AIRBAG

The compression and venting process of airbag are analysed from four subprocesses: system dynamic process, airbag deformation process, gas thermodynamic process and orifice flow process. Then the mathematical model of the whole cushioning process is established by taking the relationship between each subprocess into account.

In this research, a comprehensive analysis of the compression and venting processes of airbags have been introduced, dissecting them into four distinct subprocesses: the system dynamic process, airbag deformation process, gas thermodynamic process, and orifice flow process. Each subprocess is meticulously scrutinized to understand its individual contribution to the overall cushioning mechanism. Through this analytical approach, we establish a mathematical model that encapsulates the intricate interplay between these subprocesses. By intricately considering the relationships between each subprocess, our model provides a holistic representation of the entire cushioning process, offering valuable insights into the dynamic behaviour of airbags during deployment. 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 customisation 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 harmonising the airbag deployment mechanisms with the unique dimensional characteristics of each vehicle model, automakers can maximise the efficacy of these life-saving 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 endeavours to meticulously design the system and perform extensive testing to validate its functionality and safety under diverse operational conditions. Paramount to this endeavour is ensuring stringent compliance with all pertinent automotive safety standards and regulations set forth by governing bodies such as the European New Car Assessment Programme (Euro NCAP) and adhering to international standards promulgated by organisations 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. Subsequent to 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, must 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 standardised 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 organisations 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.

A. AIRBAG KINEMATICS

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

$$M_a + \left(P_{bag} - P_{atm}\right) A_t = 0 \tag{1}$$

Where "Ma" represents the payload mass, "Pbag" 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 (1) is rearranged, it provides the acceleration of the payload

$$-a = \frac{\left(P_{bag} - -P_{atm}\right) A_t}{M} \tag{2}$$

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

$$\Delta V = a{*}\Delta t \tag{3}$$

And the velocity of the payload can be determined from

$$V_t = V_{(t-1)} + \Delta V \tag{4}$$

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

The displacement of the payload is obtained from:

$$u_{t=u_{t-1}} + v_{t-1}\Delta t + \frac{1}{2}a\Delta t^2 \tag{5}$$

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

TABLE 7. 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
Internal pressure	P_{bag}	101325	kg/m3
Gravity	g	9.8	m/s2

B. AIRBAG DEFORMATION PROCESS

The effectiveness of the energy transfer from the payload to the airbags depends on how the geometry changes during the compression process. To gain a more precise prediction of this deformation, researchers often employ a finite element method to study the interaction between the airbag material and the gas in use. Nonetheless, this method is time-consuming, so in practical design phases, the airbag's shape function equations are frequently approximated.

In their investigation of cylindrical airbags, Xuan and Shiming [19] made the assumption that the cylindrical airbag's axial length and the circumference of its cross-section remain constant as it undergoes compression. This assumption is consistent with prior research findings on airbag systems, as demonstrated by X Zhou et al. (2019) [20]. This study provides valuable insights into optimizing airbag design to mitigate rebound effects, offering pertinent considerations for the development of effective airbag landing systems.

$$\pi D_o = \pi D_t + 2L_t \tag{6}$$

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.

$$D_t = D_o - h_t \tag{7}$$

$$h_t = h_{t-1} + u_{t-1}\Delta t + \frac{1}{2}a\Delta t^2 \tag{8}$$

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

When (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:

$$L_t = \frac{\pi}{2}\left(D_o - D_t\right) = \frac{\pi}{2} h_t \tag{9}$$

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

$$S_t = \frac{\pi}{4}Dt^2 + D_t L_t = \frac{\pi}{4(D_o - h_t)^2} + (D_o - h_t) L_t \quad (10)$$

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 (9) and (10) by this constant length. This can be expressed as follows:

$$A_t = \frac{\pi}{2} L_o h_t \quad (11)$$

And

$$V_t = L_o (D_o - h_t) \left[\frac{\pi}{4 (D_o - h_t)} + L_t \right] \quad (12)$$

Where, L0 is the fixed cylindrical airbag axial length.

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

$$F = \frac{1}{2} ((m)(u_t)) / h_t \quad (13)$$

Where m is the mass of the vehicle.

C. MODEL CALCULATION

The model parameters are shown in Table 7, 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 1.50 meters, ensuring comprehensive coverage upon deployment. With a fabric thickness of 0.002 meters, the airbags exhibit robustness while maintaining flexibility. Employing an initial pressure of 101325 kg/m3 and a specific gas constant of 286.9 J/kg/K, our design prioritizes the safety of pedestrians by effectively absorbing impact forces.

VI. RESULTS

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

Despite some variances observed in the graphs, which is a common occurrence in comparative studies, the findings presented in Fig. 7 suggest a strong overall alignment between the model proposed in this paper and analytical analysis models concerning airbag inflation scenarios. The comprehensive analysis covers five pivotal parameters crucial for understanding airbag dynamics:

Airbag Deformation: The model effectively captures the degree of airbag deformation during inflation, providing valuable insights into its structural behaviour under various conditions. Although slight deviations may exist, the general trend indicates a consistent depiction of airbag deformation dynamics.

Impact Force: The model's estimation of impact force exerted by the airbag exhibits notable agreement with analytical predictions. Despite potential discrepancies attributable to real-world complexities, the model reliably characterizes the magnitude and temporal evolution of impact forces, crucial for evaluating occupant safety.

Airbag Volume: By quantifying airbag volume over time, the model provides valuable insights into its expansion dynamics during deployment. Although some variations may be observed due to inherent complexities, the model effectively captures the overarching trends in airbag volume evolution.

Airbag Effective Area: The model's assessment of the effective coverage area of the airbag offers valuable insights into its protective capabilities. While minor deviations from theoretical expectations may occur, the model's depiction of the airbag's spatial coverage remains consistent, facilitating informed design decisions.

Deceleration Dynamics: The presented analysis offers a comprehensive examination of the vehicle's deceleration behaviour during airbag deployment. Despite minor deviations, the model effectively captures the temporal evolution of deceleration, providing valuable insights into the vehicle's braking performance. This nuanced understanding aids in assessing occupant safety and optimizing airbag deployment strategies to mitigate collision forces effectively.

Acknowledging the presence of minor differences in the graphs, it is important to note that such variations are expected in real-world applications and do not diminish the overall validity and utility of the proposed model. These findings underscore the model's robustness and its potential to inform the design and optimization of airbag systems, thereby enhancing occupant safety in automotive contexts.

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. 8 provides a compelling visual representation of the stark contrast in impact forces exerted upon the human body in the event of a non-avoidance vehicular collision scenario. The results vividly illustrate a substantial discrepancy between the two scenarios, underscoring the profound implications for life-saving potential. In the absence of external airbag deployment, the impact forces experienced by the pedestrian or vulnerable road user are significantly elevated, heightening the risk of severe or fatal injuries. Conversely, the mitigation of these forces through the strategic deployment of external airbags yields a remarkable reduction in the magnitude of impact, thereby substantially enhancing the prospects of survival and minimizing the severity of potential injuries sustained during such collisions. This striking dichotomy in impact force profiles accentuates the critical role that external airbag systems can play in augmenting road safety and fostering a paradigm shift towards more effective pedestrian protection measures.

VII. CONCLUSION

External airbags are a promising safety feature for reducing pedestrian injuries in vehicle collisions. They deploy from the front of the vehicle when sensors detect a potential collision,

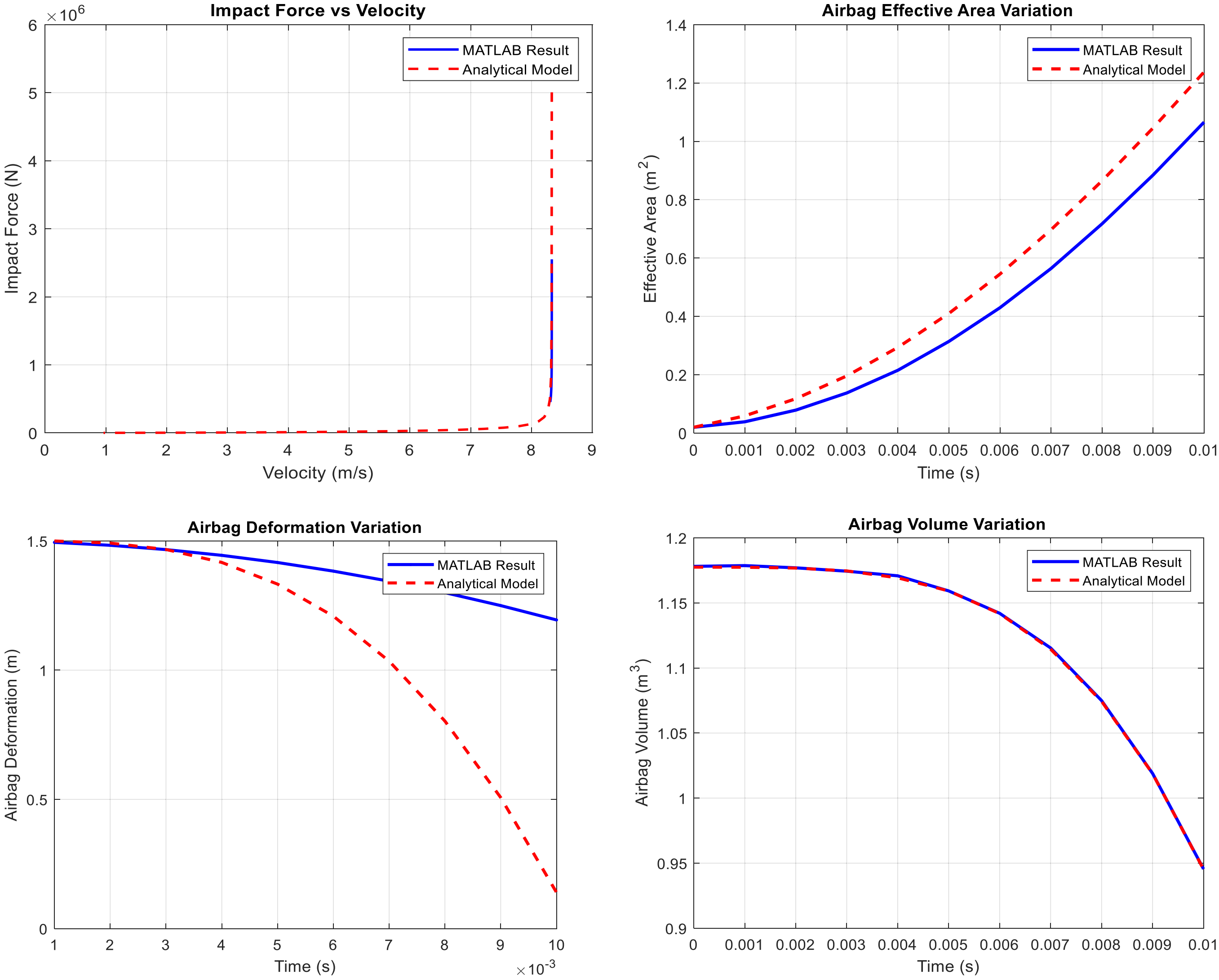


FIGURE 7. **Comparison of results between the numerical model and analytical model.**

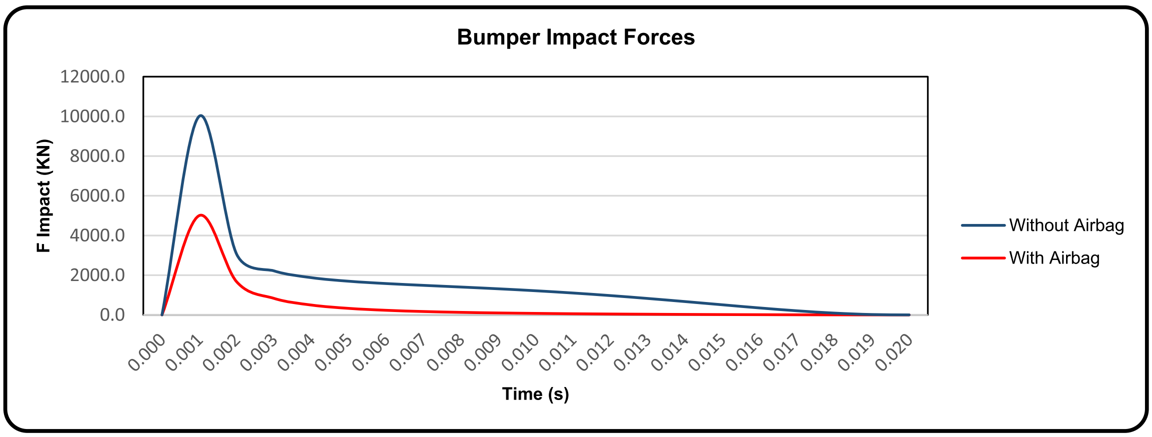


FIGURE 8. **Illustrates the stark contrast in impact forces sustained by the lower body regions of a pedestrian struck by a vehicle traveling at 30 km/h.**

providing a cushion between the pedestrian and hard surfaces. Despite ongoing research and development by automotive companies and research organizations, challenges remain, such as ensuring proper deployment timing. The proposed external airbag system represents a significant advancement in vehicle safety technology, particularly for protecting pedestrians.

Through computer simulations and accident analysis, it has been observed that minivans, among other vehicle types, carry a higher risk of head injuries but a lower risk of leg injuries for pedestrians. In response, the proposed system has been specifically developed to mitigate the severity and mechanics of injuries sustained by pedestrians in vehicle-related accidents. The main goal is to enhance road safety and prevent numerous fatalities. Although challenges persist in refining the technology and ensuring accurate deployment, the advanced external airbag system exhibits tremendous potential as an innovative solution for pedestrian safety.

VIII. FURTHER WORK

Further work in the development of external airbag systems for pedestrian safety in vehicle collisions could focus on several areas to enhance the technology and address remaining challenges. Firstly, there is a need for continued research and development to optimize the deployment timing and effectiveness of external airbags, particularly in real-world scenarios. This may involve further refinement of sensor technology and deployment algorithms to ensure rapid and accurate response to potential collisions. Additionally, ongoing efforts are required to reduce the cost of materials and manufacturing processes associated with external airbag systems, making them more accessible for widespread adoption in vehicles. Bench testing and simulation studies can provide valuable insights into the performance and efficacy of external airbags under various conditions, guiding further improvements in design and functionality. Furthermore, comprehensive field studies and real-world evaluations are essential to validate the effectiveness of external airbag systems in reducing pedestrian injuries in diverse environments and driving conditions. Advancements in sensor technology, materials science, and vehicle design may offer opportunities to enhance the capabilities of external airbag systems, ultimately contributing to the continued improvement of road safety and the prevention of pedestrian fatalities.

This study demonstrates the significant effectiveness of external airbags in enhancing pedestrian safety during unavoidable car crashes. The innovative design and strategic placement of these airbags on the front bumper and bonnet provide critical protection for pedestrians, particularly for the lower and upper body, including the head. The results indicate that the implementation of such airbags can substantially reduce the severity of injuries, thereby saving lives and minimizing the impact of collisions. The findings underscore the potential of external airbags as a vital safety feature in automotive design, paving the way for future advancements in pedestrian protection technology.

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