Crashworthiness analysis of electric vehicles during frontal collision using FEA

By

Bereket Eshetu Zerihun

A Thesis Submitted to

The Department of Mechanical Engineering, College of Mechanical, Chemical and Materials Engineering

Presented in Partial Fulfillment of the Requirement for Master of Science in Automotive Engineering

Office Of Graduate Studies

Adama Science and Technology University

May, 2025

Adama, Ethiopia

Crashworthiness analysis of electric vehicles during frontal collision using FEA

By

Bereket Eshetu Zerihun

Advisor: Dr. Ramesh Babu Nallamothu

A Thesis Submitted to

The Department of Mechanical Engineering, College of Mechanical, Chemical and Materials Engineering

Presented in Partial Fulfillment of the Requirement for Master of Science in Automotive Engineering

Office Of Graduate Studies

Adama Science and Technology University

May, 2025

Adama, Ethiopia

DECLARATION

I declare that this thesis entitled “Analysis of crashworthiness of electric vehicles during frontal collision Using FEA” is my work and has not been submitted to any university for a similar purpose. The references used in this thesis are duly recognized by proper citations.

Bereket Eshetu Zerihun	____________________	______________
Name of student	Signature	Date

RECOMMENDATION

I, the major advisor of this thesis, hereby certify that I have closely advised/supervised the student while developing this thesis and read the draft thesis entitled "Analysis of crashworthiness of electric vehicles during frontal collision Using FEA" prepared under my guidance by Bereket Eshetu. Therefore, I recommend the submission of the thesis to the department for further review and evaluation.

Dr. Ramesh Babu Nallamothu

Major Advisor	Signature	Date

ORIGINALITY DECLARATION FORM FOR STUDENTS

This form must be completed and signed for all works submitted to the University for Examination.

Name of student	Bereket Eshetu Zerihun
Id. No.	PGE/25014/14
Department	Mechanical Engineering
College	CoMCME
Course Title	M.Sc. Thesis
Title of work / Assignment name	"Analysis of crashworthiness of electric vehicles during frontal collision Using FEA"
Date of submission	May 21, 2025

DECLARATION

1) I understand what plagiarism is and I am aware of the university's policy in this re- grade.
2) I declare that this thesis entitled "Analysis of crashworthiness of electric vehicles during frontal collision Using FEA" is my original work and has not been submitted elsewhere for examination or award of a degree or publication. Wherever others' work or my own work has been utilized, it has been duly acknowledged and referenced in compliance with the university's requirements.
3) I have not sought or used the services of any professional agencies to produce this work.
4) I have not permitted, nor will I permit, anyone to plagiarize my work with the intention of presenting it as their own.
5) I am aware that making any false claims regarding this work will lead to disciplinary action in accordance with the university's Anti-Plagiarism Guidelines.

Signature ______________________________

Date ___________________________________

APPROVAL OF BOARD OF EXAMINERS

The advisors of the thesis entitled “Analysis of crashworthiness of electric vehicles during frontal collision Using FEA” and developed by Bereket Eshetu, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Major Advisor	Signature	Date

We, the undersigned, members of the Board of Examiners of the thesis by Bereket Eshetu have read and evaluated the thesis entitled “Analysis of crashworthiness of electric vehicles during frontal collision Using FEA” and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of Master of Science in Automotive Engineering.

Chairperson	Signature	Date
Internal Examiner	Signature	Date
External examiner	Signature	Date

Finally, approval and acceptance of the thesis is contingent upon submission of its final Copy to the Office of Postgraduate Studies (OPGS) through the Department Graduate Council (DGC) and School Graduate Committee (SGC).

Department Head	Signature	Date
School Dean	Signature	Date
Office of Postgraduate Studies, Dean	Signature	Date

ACKNOWLEDGMENT

First and foremost, I want to sincerely thank and appreciate Dr. Ramesh Babu Nallamothu, my advisor and teacher who helped me conduct extensive research and offered me the wise counsel I needed to complete this amazing endeavor. He is constantly pleased and eager to assist me clear up any uncertainty, patiently answer my queries, and guide me toward the thesis's conclusion. In addition, he is a laid-back and accepting individual who I consider to be a close friend. This project would not have come to fruition and been completed without his support and direction. Last but not least, in addition to my own efforts, the guidance and assistance of others are essential to the accomplishment of any project. I want to take a moment to express my gratitude to everyone who has helped me finish this project. Specifically, I would want to thank my parents and friends for their essential help in completing this thesis.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

CAD	Computer-aided design
CATIA	Computer aided three-dimensional interactive application
EA	Energy Absorption
EV	Electric vehicles
FEA	Finite element method
FMVSS	The federal motor vehicle safety standard
HAZ	Heat affected zone
HIC	Health insurance community
ICE	Internal combustion engine
IGES	Initial graphics exchange specification model
IIHS	Insurance institute for highway safety
LWV	Light-weight vehicles
LS-DYNA	Liver more dynamic simulation
MBD	Movable deformable barrier
NACP	New car assessment program
NHTSA	National highway traffic safety administration
SID	Side impact dummy
SWR	Strength to weight ratio
WHO	World health organization

NOMENCLATURE

A	Acceleration (mm/s^2)
$E_{i,}$	Internal energy (kJ)
E_{11}	Young's modulus (MPa)
E_{22}	Young's modulus (MPa)
E_d	Damping energy (kJ)
E_h	Hourglass energies (kJ)
E_{ke}	Kinetic energy (kJ)
E_s	Interface sliding (dissipated contact energy) (kJ)
F	Force of vehicles (N)
G	Acceleration Due to Gravity (m/s^2)
G_{12}/G_{31}	Shear modulus
G_{23}	Shear modulus
M	Momentum (kg.m/s)
M	Mass (kg)
SL	Shear strength
V	Velocity of vehicles (m/s)
W_{ext}	Work done by the external forces (kJ)
	Mass density(kg/m^3)
	Poisson's ratio (minor)

ABSTRACT

As electric vehicles (EVs) increasingly replace internal combustion engine (ICE) vehicles, understanding their crash characteristics is critical for ensuring safety and promoting adoption. Unlike conventional vehicles, EVs face unique challenges, including fire risks from battery damage, lightweight design constraints, and crashworthiness trade-offs with driving range. This research investigates the frontal crashworthiness of a Tesla Model S3 using finite element analysis (FEA). A 3D model was developed in CATIA, and a frontal impact simulation at 56 km/h was performed using LS-DYNA to evaluate energy absorption, structural deformation, and occupant injury criteria (HIC, CSI). The results demonstrate effective energy dissipation, with the front structure absorbing 153 kJ, controlled cabin intrusion, and injury metrics within safe limits. Simulation accuracy was validated against experimental data from the Center for Collision Safety and Analysis (CCSA). The study identifies optimal design strategies, including a front bumper thickness of 6.76 mm for balanced energy absorption and weight efficiency. Additionally, robust front-end structures and strategic battery placement are emphasized to mitigate post-crash thermal hazards. Recommendations include the use of advanced materials, multi-material designs, and optimized component layouts to enhance safety without compromising efficiency. These findings provide actionable insights for developing safer, high-performance EVs, supporting sustainable mobility.

***Keywords**: Electric vehicle crashworthiness, Frontal impact simulation, Finite element analysis (FEA), Occupant safety, Battery protection, LS-DYNA modeling*

CHAPTER ONE

1. INTRODUCTION

1.1 Back ground of study

Motor vehicle accidents rank among the primary causes of unintentional injuries and fatalities worldwide. Understanding crash characteristics and devising effective preventive measures stands as a crucial responsibility for transportation agencies. While numerous studies have scrutinized motor vehicle crashes from diverse perspectives, the majority have focused on traditional internal combustion engine vehicles (ICEVs), with limited attention directed towards the emerging electric vehicles (EVs) (Liu, etal., 2022)

Internal combustion engine (ICE) vehicles have historically been a major contributor to air pollution, emitting carbon dioxide (CO), nitrogen oxides (NOx), particulate matter, and volatile organic compounds (VOCs) due to their reliance on fossil fuels like petroleum and diesel. These emissions have detrimental effects on human health and the environment, leading to air contamination, haze formation, respiratory illnesses, and global climate change (Liu, etal., 2022). In contrast, electric vehicles (EVs), powered by rechargeable batteries and electric motors, offer a promising solution by eliminating exhaust emissions and reducing dependence on fossil fuels (Scurtu, etal., 2023)

The rapid growth of EVs over the past two decades suggests a gradual shift away from ICE vehicles in the future, making it imperative to investigate the characteristics and trends of EV crashes. By embracing electrification, we can significantly mitigate pollution and work towards a cleaner, more sustainable future. Furthermore, the widespread adoption of battery electric vehicles in public transportation globally serves as an environmentally friendly approach to promoting sustainable mobility, ultimately contributing to reductions in greenhouse gas emissions and improvements in energy efficiency (Jongpradist, etal., 2022)

An increasing influx of electric vehicles (EVs) into our daily lives has garnered significant attention from industry professionals and consumers alike. However, the development of EVs faces numerous challenges, including lightweight design and range limitations (Hao, et., 2017). Presently, a primary concern revolves around EV safety, with the industry recognizing that ensuring intrinsic safety is essential for their widespread adoption. The crash safety of EVs differs from conventional vehicles due to the absence of internal combustion engines and the presence of battery-powered propulsion systems. In the event of a collision, EVs face heightened risks such as electrolyte leakage, short circuits, and fire, posing severe dangers to occupants and responders (Gong, C. (2021).

The surge in global EV sales has been accompanied by numerous reports of fire incidents, often linked to lithium-ion battery ignition. Battery safety is a critical factor, as even advanced EVs have experienced fire-related issues during crashes (Hao, etal., 2017). Over the past decade, EV accidents have resulted in hundreds of fatalities, with specific incidents highlighting the risks associated with high-voltage electric shock and battery pack fires. For instance, in 2016 in Taiyuan, China, a taxi driver tragically succumbed to high-voltage electric shock. Additionally, in May 2018, a fatal EV accident occurred when the battery packs of a Tesla Model S, driven for only one month, caught fire and exploded, claiming the lives of five individuals (Gong, C. 2021). Figure 1.1 shows A case of a battery fire accident due to collision.

Figure 1-1 A case of a battery fire accident due to collision (Setiawan, & Salim, 2017)

Official agencies in various countries have documented statistics related to EV fire accidents. For instance, China, a global leader in EV sales, has recorded an annual average of 31 fire incidents, with a significant portion attributed to sudden ignition and charging. In the United States, specific incidents involving Tesla and BMW i3 vehicles underscore the challenges posed by high-speed impacts and the combustible nature of Li-ion battery components, leading to large fires that are difficult to extinguish (Victor, etal., 2021).

State-of-the-art electric vehicles (EVs) incorporate protective measures to prevent battery pack fires in the event of external crashes, with packs strategically positioned away from the vehicle's front (Hao et al., 2017). Consequently, improving the crashworthiness of EVs has become a critical research focus. Given this, robust modeling and Computer-Aided Engineering (CAE) analysis methods are essential for validating vehicle crashworthiness in the automotive industry.

In real-world traffic accidents, collision scenarios vary (e.g., frontal, side, and rear impacts), each associated with differing fatality rates. Among these, frontal collisions account for the highest casualties, representing nearly 50% of fatalities (Yu et al., 2021). Thus, research on frontal crash safety is paramount for enhancing occupant protection.

This study investigates the crashworthiness of modern EVs during frontal collisions using LS-DYNA, a finite element analysis (FEA) software. Additionally, it explores design optimizations—such as structural adjustments and battery placement—to mitigate collision-induced injuries and reduce fatality rates. The objective is to evaluate EV crash performance and identify engineering solutions that improve vehicle safety in crash scenarios.

1.2 Problem statement

The existing body of research on vehicular crash safety has predominantly focused on conventional internal combustion engine vehicles, creating a significant knowledge gap regarding electric vehicle (EV) crash dynamics. While EVs offer environmental benefits, their unique architecture presents three critical engineering challenges: the competing demands of lightweight construction, crashworthiness optimization, and range extension. These design imperatives frequently conflict, creating complex safety trade-offs that require careful analysis. The distinctive risks associated with high-voltage battery systems - including thermal runaway, hazardous material leakage, and electrical fire hazards - introduce novel safety concerns not present in traditional vehicles. Recent accident data reveals that these battery-related risks can exacerbate collision consequences, posing grave dangers to occupants and emergency responders alike. This study specifically addresses the most lethal crash scenario - frontal impacts - through computational analysis of current EV designs. The research seeks to both identify structural vulnerabilities in existing configurations and propose evidence-based design modifications to enhance occupant protection while mitigating battery-related post-crash hazards.

1.3 Objectives

1.3.1 *Main objective*

The main objective of the proposed study is the Analysis of crashworthiness of electric vehicles during a frontal collision.

1.3.2 *Specific objective*

The specific objectives are followed as,

- To develop a finite element model of an electric vehicle incorporating critical crash-relevant components
- To simulate frontal collision scenarios using LS-DYNA, identifying structural weaknesses affecting occupant safety
- To quantitatively assess crash performance through deformation analysis, energy absorption, impact forces, and standardized injury criteria
- To optimize aluminum alloy bumper thickness via Response Surface Methodology (RSM), resolving the trade-off between crashworthiness (energy/stress/deformation) and lightweight design

1.4 Scope of the project

This research investigates electric vehicle crashworthiness during frontal collisions through finite element analysis, utilizing LS-DYNA for dynamic simulation and CATIA for modeling, with the Tesla Model 3 as the primary case study. The study focuses on three key aspects: (1) structural performance evaluation through energy absorption, deformation analysis, and impact force measurement; (2) occupant safety assessment using Head Injury Criterion (HIC) and Chest Severity Index (CSI); and (3) validation against the CCSA Toyota reference model. The work is deliberately bounded by several delimitations: first, the exclusive use of numerical methods due to the prohibitive costs of physical crash testing; second, computational resource constraints that necessitated extended simulation times; third, the restriction to frontal impact scenarios; and fourth, the focus on overall vehicle crashworthiness rather than component-level optimization of specific elements like battery casings. These boundaries were consciously implemented to maintain research feasibility while ensuring comprehensive analysis within the defined parameters.

1.5 Significance of the project

This research makes important contributions to electric vehicle safety research and development by addressing critical knowledge gaps in EV crashworthiness. By analyzing frontal collision dynamics through advanced FEA simulations, the research provides valuable insights into how battery placement and structural design affect crash performance - an area lacking sufficient study compared to traditional vehicles. The findings offer practical benefits for multiple stakeholders: automotive engineers gain data-driven design guidelines for optimizing bumper thickness and energy absorption; manufacturers receive validated computational methods to reduce development costs; and policymakers obtain evidence to strengthen EV safety regulations. The research also supports global road safety initiatives by developing solutions to reduce collision-related fatalities, while simultaneously promoting sustainable transportation through improved EV safety standards. Academically, this work establishes a foundation for future studies on battery-protection systems and occupant safety in next-generation electric vehicles. The comprehensive approach combining structural analysis with injury criteria assessment delivers both theoretical advancements and real-world applications for the rapidly growing EV industry.

1.6 Organization of the study

This thesis is structured into six chapters.

Chapter one provides the background of the study, focusing on electric vehicle (EV) collisions and the currently available accident reports. It outlines the problem statement, objectives, significance, limitations, and scope of the proposal. Chapter Two offers a comprehensive review of previous research related to vehicle safety issues. It discusses the advantages and disadvantages of earlier studies and identifies gaps in the existing literature. Chapter Three details the materials and methodology employed in the research, including data collection techniques. And presents the modeling and analysis procedures used for evaluating both existing and modified EVs. Chapter Four discusses the results of various computational simulations, including the outcomes and validation of the EV model. Chapter five summarizes the key conclusions drawn from the research, highlighting the findings and providing recommendations for future work.

CHAPTER TWO

2 LITERATURE REVIEW

2.1 Vehicle crashworthiness

From an engineering perspective, crashworthiness refers to the vehicle's ability to protect occupants from injuries during an accident. It evaluates how well the vehicle's structure and parts protect passengers in crashes that are survivable. Crashworthiness, which includes the vehicle's structural ability to deform while preserving sufficient survival space for occupants during crashes with moderate deceleration loads, is essential for passive vehicle safety. During full car crash tests, analysis of crashworthiness usually concentrates on related crash responses including displacement, acceleration, and velocity of important vehicle components.

2.2 Crashworthiness Goals

In order to absorb some of the collision kinetic energy, progressive crush zones are incorporated into the body components of the vehicle. Vehicles also try to manage the impact deceleration pulse while maintaining the integrity of the passenger compartment. Reconstruction of accidents and research of car wrecks provide information about safety performance. There are now four distinct ways of vehicle crashworthiness assessment: rollover, side, rear, and frontal accidents.

2.3 Crashworthiness Requirements

To achieve balanced and safe vehicle architecture, the structure must maintain adequate stiffness in bending and torsion to ensure optimal ride and handling dynamics while minimizing harshness by damping high-frequency fore-aft vibrations. The design should accommodate a diverse range of occupant sizes, ages, and crash speeds for genders, prioritizing inclusivity and safety. Crash energy management is critical: the front structure should integrate deformable yet sturdy crumple zones to absorb kinetic energy, while the rear structure must balance deformability with integrity preservation. Side structures and doors require reinforcement to minimize intrusion, and the roof must be robust enough to withstand rollover scenarios. Complementary to this, properly designed restraint systems (e.g., seatbelts, airbags) must synergize with the structural load paths. Finally, the platform must adapt to varied chassis designs, supporting different powertrain locations (front-engine, rear-motor, etc.) and drive configurations (FWD, RWD, AWD) without compromising safety or performance.

2.4 Crash Characteristics

Every year, approximately 1.2 million deaths and numerous injuries globally result from vehicle collisions, making it a major public health concern in modern society. Traffic accidents involve various forms of vehicle collision, each with differing death rates. According to Figure. 2.1, fatalities from front impact, side impact, and rear impact vary significantly. Notably, frontal collisions cause the highest number of casualties, representing nearly 50% of the mortality rate. Therefore, research on frontal crash safety is especially crucial for protecting occupants (Yu, etal., 2021)

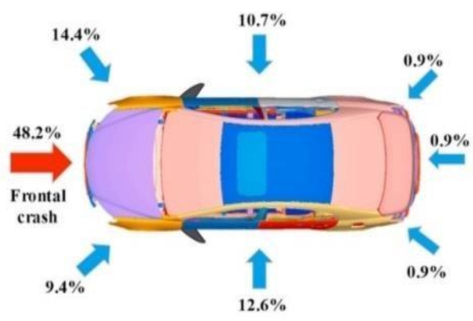


Figure 2-1 illustrates the variation in the proportion of fatalities resulting from different collision positions

Accidents are unpredictable and can involve an automobile being impacted from any direction at varying speeds. This includes vehicle-to-vehicle impacts, collisions with rigid barriers, pedestrians, and rollovers. These diverse scenarios highlight the complex nature of crash situations and the need for comprehensive safety measures (Gauri, etal., 2017). According to Galganski, crashworthiness problems can be characterized by:

Modern vehicle design faces the dual challenge of reducing frontal structure length for aesthetic and aerodynamic efficiency while ensuring it absorbs the majority of impact energy and minimizes occupant compartment intrusion. This demands advanced materials and crumple zone optimization to manage displacement and energy dissipation effectively. The crash pulse—a critical metric reflecting occupant deceleration—must be carefully controlled to limit peak forces; the Head Injury Criterion (HIC) is used to evaluate potential brain trauma and must comply with stringent regulatory thresholds. To protect occupants across diverse scenarios, the structure must mitigate injuries in all crash positions, including full frontal, offset frontal, side, rear impacts, and rollovers. Additionally, automobile compatibility is essential: the design should account for collisions between vehicles of differing sizes/weights, minimizing aggression toward smaller/lighter models through intelligent load-path management and energy-absorbing geometries. Together, these principles ensure safety without compromising modern design priorities. Two approaches are utilized to study occupant responses and injury criteria in car accidents. The direct approach involves real collision tests using anthropometric test devices (ATD), commonly known as crash test dummies. These devices simulate human dynamic responses and record data during car crash tests, aiding in the establishment of injury criteria and the assessment of passenger protection systems. On the other hand, the indirect approach employs computer simulation to evaluate vehicle performance in impacts and assess new passenger safety systems by utilizing dynamic responses from crash tests. The focus parameters method (LMS) is based on multiple discrete masses and springs of materials whose mechanical properties are established by dynamic tests, whereas the finite element method (FEM) requires a thorough and detailed description of the component geometry and material properties associated with the FEM (Deac, S.,etal.,2018).

Computer simulations are essential for assessing car performance in crash tests, as they provide crucial data that cannot be covered by physical tests alone. Dynamic modeling using finite elements and multibodies offers essential tools for investigating and analyzing the dynamic behavior of vehicle occupants and the injuries sustained (Luján,etal.,2020).

This paper focuses on finite element method to analysis of frontal collision and evaluates the results using different parameter such as energy absorption and deformation.

2.5 Basic principle for frontal impact crashworthiness design

The basic principle of frontal impact crashworthiness design involves enabling the vehicle structure to effectively absorb impact energy through controlled deformation while ensuring sufficient living space for occupants. This is achieved by limiting vehicle crash acceleration and minimizing firewall intrusion through effective deformation and energy absorption. In frontal impact, the impact load of the vehicle structure is typically assessed using impact acceleration pulse. For simplicity, the full-frontal crash shown on Figure 2.2, is often used as an example to explain the basic principle of frontal impact crashworthiness design (victor, 2021).

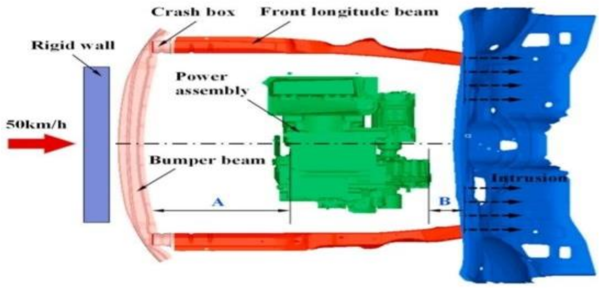


Figure 2-2 Crash energy absorbing space management of full-frontal impact

2.5.1 *Collapse mode and crash energy absorption*

When a frontal impact occurs, the vehicle's front-end structure usually uses a combination of axial and bending deformation to withstand the impact stress. It's crucial to remember that axial folding absorbs far more energy than bending. The major crushing zone "A" is therefore anticipated to generate a rather uniform progressive crash mode for efficient absorption of collision kinetic energy, making the axial compression mode more appropriate for designing crashworthy cars. Commonly utilized metrics like energy absorption (EA), mean crushing force (MCF), and specific energy absorption (SEA) are taken into consideration in order to methodically assess the energy absorption capacity of deform structures. The overall energy collected during the crashing process is known as energy absorption shown by (1).

$$EA = \int_0^d F(x)\,dx \tag{1}$$

Specific energy absorption (SEA) is a widely used indicator to estimate energy absorption efficiency. It represents the specific energy absorbed per unit mass of the absorber and is formulated as follows (2):

$$SEA = \frac{EA}{M} \tag{2}$$

Where M is the total mass of structures; a higher SEA value indicates better energy absorption efficiency of the dedicated structural materials.

2.6 Challenges of electric vehicles

The lightweight design and range of EVs are two of the many obstacles facing their development. Some existing challenges driving range, and safety or crashworthiness are discussed below.

2.6.1 Driving Range

Addressing battery capacity and charging infrastructure-related driving range restrictions (Chao et al., 2021). The competitive EV can travel up to 270 miles on a single charge, however the majority of other EVs have ranges of less than 100 miles , which is significantly less than that of their gasoline-powered counterparts. As long as the specific battery capacity remains constant, EVs should have more batteries installed in order to extend their range (Hao et al., 2017). Electric vehicles' structural features require that the wheelbase be extended and the rear suspension be shortened as much as feasible in order to accommodate greater power packs. The front side member is unable to conduct a stronger conduction force as a result of the limited space in the front compartment. The front side member's root can be easily bent and pushed into the cockpit, causing significant intrusion (Hu,y. et al., 2017). Because of this, battery packs take up a lot of room and have a very high weight to EV ratio, which may cause safety problems, especially in the event of a collision (Hao et al., 2017). Consequently, the weight and range of the vehicle are balanced.

2.6.2 Safety

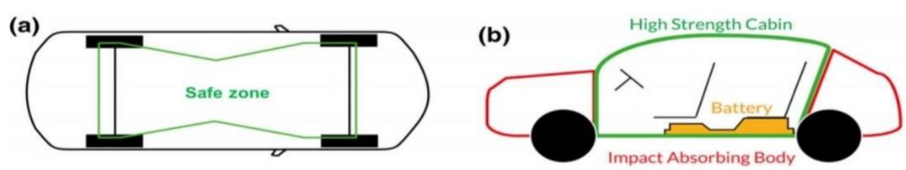
Modifying crashworthiness requirements and safety features to account for the particularities of electric vehicles, such as weight distribution and battery location. Therefore, EVs must meet additional electrical safety criteria in collision situations in addition to the protection requirements that are equivalent to those of regular cars. The Economic Commission for Europe (ECE) of the United Nations (UN) Regulation R94, for instance, stipulates that the voltages in the vehicle components must rapidly drop to the safe level (≤ 60 VDC or 30 VAC) following a collision (5 s is the best and 60 s is the worst) in order to protect high-voltage powertrain-based EVs from electric shock. Given the unique characteristics of EVs with high-voltage powertrains, it is imperative to research their crash-related problems and create practical crash safety enhancement strategies in the event that a battery case is impacted or expelled by foreign objects. For mechanical safety, batteries can be put through drop-weight, needling, extrusion, and three-point deformation tests (Scurtu, L. et al., 2017). For electric vehicles, there are three primary types of ground collisions:

(1) sharp items on the road puncture a battery container,

(2) a foreign object becomes wedged between the battery and the road surface

In general, potential dangers resulting from mechanical loading or fire on the high-voltage battery during a collision include the following: thermal events, chemical reactions, and electrical shock threats, release of explosives, fire, and poisonous battery chemicals. Fires and the release of flammable, ignitable, and/or toxic compounds are the main risks that could occur in serious collisions involving electric vehicles (Hao et al., 2017). Despite their exceptional features, electric vehicles face significant challenges such as safety concerns, limited driving range, heavy weight, long recharge times, and high initial costs, which hinder their widespread adoption in the global market. Since the surge in global electric vehicle sales, there have been frequent reports of serious fire incidents, often linked to the ignition of lithium-ion batteries. Some of these incidents have been particularly alarming and have resulted in fatalities among electric vehicle occupants. For example, fire incidents involving Tesla Model S and Model X in various locations, as well as the BYD e6 in Shenzhen, have raised safety concerns. Statistics from specific official agencies in different countries have documented numerous electric vehicle fire accidents, highlighting the challenges associated with sudden ignition and charging. For instance, China, which leads the world in the volume of sales of electric vehicles, records an average of 31 fire accidents each year, with certain event categories accounting for a sizable portion of the total. Three BMW i3 fire occurrences out of 175,000 and 17 Tesla fire incidents out of 350,000 were reported in the United States. Large fires created by energetic and flammable lithium-ion battery components that are difficult to put out are the consequence of the majority of these occurrences, which are characterized by significant impact at high speeds.

Despite the statistical rarity of electric car fire events, lithium-ion battery fires provide safety risks, including the potential for fire, the release of hazardous fumes and noxious smoke, and extreme heat release (Victor et al., 2017). The common approach employed by automakers is to place the LIB packs into the reinforced areas of the vehicle (Figure 2.3 a), farther away from front and rear impact absorbing zones (Figure 2.3 3b), aiming to reduce the risk of penetration during the accidents (Victor, etal.,2017).



(a) safe zone for the battery pack (b) impact absorbing zone

Figure 2-3 Protection of battery pack in EVs (Victor, etal.,2017).

While electric vehicle fire incidents may occur less frequently than those involving conventional vehicles, the fires from lithium-ion batteries present unique safety concerns due to intense heat release, toxic gases, and the difficulty of extinguishing large fires caused by these batteries. However, compared to conventional vehicles, electric vehicles are generally considered safer in terms of fire incidents due to the slower heat buildup required to trigger a battery fire. Additionally, reports from Tesla and the London Fire Brigade have shown lower rates of electric vehicle fires compared to fires involving gasoline cars. Furthermore, regulations and safety programs such as UNECE R94, R95, FMVSS 208, GB 20913-2007, and various New Car Assessment Programs are being adopted globally to test the safety of electric vehicles and improve occupant protection. Ongoing research aims to characterize and examine various vehicle behaviors to enhance electric vehicle safety (Victor, etal.,2017) and (Yu. etal.,2020).

2.7 Crashworthiness design for pure electric vehicle

Crashworthiness refers to the vehicle structure's ability to provide sufficient protection for individuals in the event of an accident, preventing bodily injury, and safeguarding cargo from damage. In addition to safety, crashworthiness plays a crucial role in the development of safe, reliable, and comfortable vehicles. Electric vehicles (EVs) are designed similarly to conventional vehicles, with the electrified drivetrain replacing the internal combustion engine in the front compartment, along with the addition of a battery pack and structural modifications to support the increased vehicle weight. Therefore, it is essential to investigate the crash behavior of EVs when using these new car materials.

The EV structure consists of the body frame, chassis, drive system, and energy storage system, each playing a role in crashworthiness. For frontal and rear crashes, the body frame acts as a crumple zone to absorb kinetic energy, reduce acceleration, and protect occupants and vehicle components. However, the presence of an energy storage system with energetic and flammable materials introduces safety concerns when deformed during a collision. Cell deflection may lead to a short circuit and heat generation, potentially igniting the chemicals within the cell and endangering occupants. With various battery chemistries already commercialized, their susceptibility to ignition, significant heat release, and toxicity necessitate further examination by researchers (Victor, etal.,2017) see Figure 2.4 of Examples of EV main components, their functions to enhance crashworthiness.

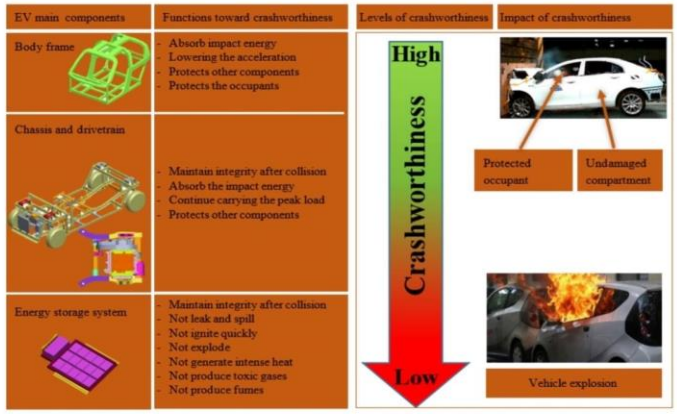


Figure 2-4 Examples of EV main components, their functions to enhance crashworthiness, (Victor, etal.,2017)

The National Highway Traffic Safety Administration (NHTSA) treats all powertrain types equally under the main Federal Motor Vehicle Safety Standards (FMVSS), such as 208, which outlines occupant crash protection requirements. Similarly, the US New Car Assessment Program (NCAP) and the Insurance Institute for Highway Safety (IIHS) conduct non-regulatory tests that aim to

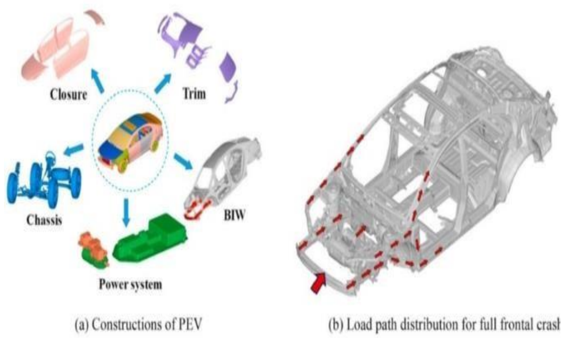


Figure 2-5. The model of pure electric vehicle under full frontal crash (Yu. etal., 2020)

inform consumers about relative vehicle safety, using the same tests for electric vehicles (EVs). Nevertheless, there are a number of safety issues with EVs that do not exist with conventional gasoline-powered cars (Christopher,2022) and (Wisch et al., 2014). Despite significant structural variations between PEVs and conventional gasoline cars, the design idea can also be used to PEV design. The PEV constructions are depicted in Figure 2.5(a). The power assembly is where the PEV's structure differs most from that of a fuel vehicle.

Additionally, in order to guarantee the safety of particular components, EV-specific criteria must be fulfilled. However, EV production regulations also apply to the safety of individual parts in addition to the vehicles as a whole. For instance, making sure the energy storage system is protected from collisions, preventing chemical leaks, and separating the chassis from the high voltage to avoid electric shock. Furthermore, EVs' mass and center of gravity distribution are likely to have an impact on their crashworthiness (Victor et al., 2017).

2.8 Tesla pure electric vehicle model description

The Tesla Model S3 is the company's most affordable and accessible electric vehicle (EV) offering. Designed to bring the benefits of Tesla's advanced electric powertrain and cutting-edge technology to a wider audience, the Model S3 has become a popular choice for those seeking a high performance, eco-friendly, and technologically advanced sedan. Figure 2.6 shows Typical Tesla S-3 model.

Figure 2-6 Typical Tesla S-3 model (Tesla, Inc.n.d.)

Key Features include:

All-Electric Powertrain: The Model S3 is powered by a high-efficiency electric motor and a lithium-ion battery pack, providing impressive acceleration and a long driving range on a single charge.

Sleek and Aerodynamic Design: The Model S3 features a sleek, minimalist exterior design that not only looks modern and stylish but also contributes to its excellent aerodynamic efficiency, enhancing its range and performance.

Advanced Autopilot and Self-Driving Capabilities: The Model S3 comes equipped with Tesla's Autopilot system, which includes a suite of advanced driver-assistance features, such as adaptive cruise control, lane-keeping assistance, and automatic emergency braking, paving the way for future autonomous driving capabilities.

Cutting-Edge Infotainment System: The Model S3 boasts a large, centrally-mounted touchscreen display that serves as the primary interface for the vehicle's infotainment system, providing access to a wide range of features, including navigation, music, and vehicle settings.

Impressive Performance: Despite its more affordable price point, the Model S3 delivers impressive performance, with rapid acceleration and a top speed that rivals many traditional gasoline-powered sports sedans. *Sustainability and Environmental Impact*

The Tesla Model S3 is a testament to the company's commitment to sustainable transportation. By eliminating the need for gasoline and reducing the carbon footprint associated with traditional internal combustion engines, the Model S3 contributes to a cleaner and more environmentally friendly future. As more people adopt electric vehicles like the Model S3, the collective impact on reducing greenhouse gas emissions and improving air quality becomes increasingly significant.

Overall, the Tesla Model S3 represents a significant step forward in the evolution of electric vehicles, offering a compelling blend of performance, technology, and sustainability at a more accessible price point. As the EV market continues to grow and evolve, the Model S3 is poised to play a crucial role in driving the widespread adoption of electric mobility. Figure shows tesla main components (Tesla, Inc. n.d.).

2.8.1 *Main components*

The EV's high-voltage system includes a heat pump for thermal regulation, front/rear motors for propulsion, and a high-voltage battery as the primary power source. Critical elements also comprise high-voltage wiring, a service panel for maintenance access, and a charge port for external power connections. These components collectively ensure efficient energy management and vehicle performance. Figure 2-7 shows the Tesla main components (Tesla, Inc. n.d.). 1) Heat Pump Assembly , 2) Front Motor (Dual Motor vehicles only) ,3) High Voltage Battery ,4) Service Access Panel for High Voltage Components (Penthouse) , 5) Rear Motor ,6) High Voltage Lines and 6) Charge Port.

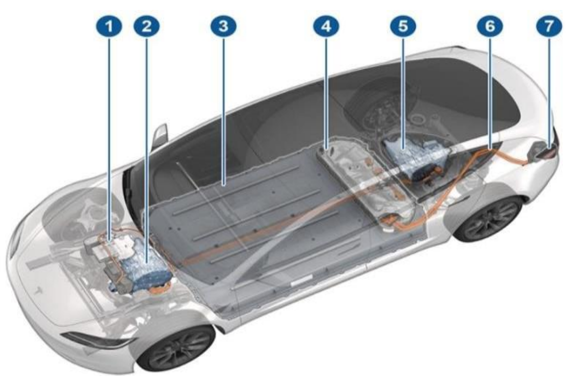


Figure 2-7 Tesla main components (Tesla, Inc. n.d.)

The heat pump assembly in the Tesla Model S3 plays a pivotal role in thermal energy management, efficiently heating or cooling the cabin while regulating the temperature of the high-voltage battery and other critical systems. By replacing traditional HVAC systems with a heat pump, the Model S3 enhances energy efficiency, reducing power consumption and extending driving range.

For dual-motor configurations, the front motor complements the rear motor to deliver all-wheel-drive capability, improving traction, acceleration, and overall driving dynamics. This high-performance electric motor operates in harmony with the rear motor, ensuring a balanced and responsive experience in diverse driving conditions.

At the core of the Model S3 lies the high-voltage battery pack, which occupies most of the vehicle's floor plan, stretching nearly from wheelbase to wheelbase. This lithium-ion battery powers the electric motors and onboard systems, combining high energy density with efficient charging and long-term durability. Its advanced thermal management system, overseen by the battery management system (BMS), ensures optimal performance and safety. The battery pack consists of approximately 7,000 Panasonic NCR18650 cells—similar in size to AA batteries—arranged in 16 sections within an armored enclosure. When connected in series, these cells collectively deliver over 300 kW of power, enabling the 2.5-ton Model S3 to achieve high-speed performance.

Together, these components—the heat pump, dual-motor setup, and high-voltage battery—exemplify Tesla's integration of efficiency, performance, and innovation. Figure 2.8 shows battery units (Tesla, Inc. n.d.).

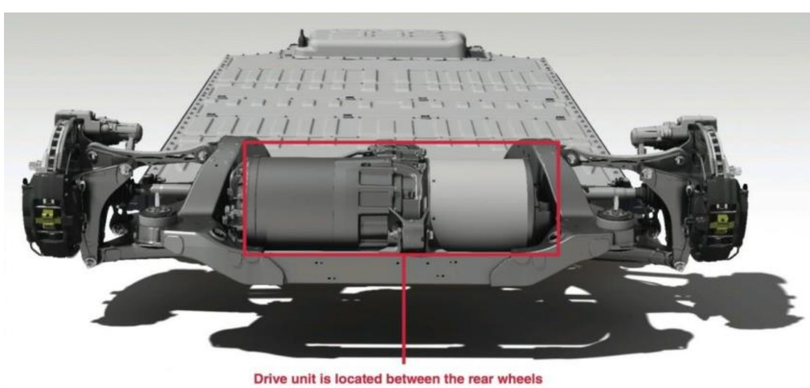


Figure 2-8 Battery units (Tesla, Inc. n.d.)

The service access panel, commonly referred to as the "Penthouse," serves as a critical entry point for technicians to access the Model S3's high-voltage components. This strategically designed panel facilitates efficient maintenance, inspection, and servicing of the electric powertrain and related systems, ensuring both optimal performance and safety throughout the vehicle's lifecycle.

Powering the rear wheels, the rear motor acts as the primary propulsion unit in the Model S3. This high-efficiency electric motor delivers exceptional torque and acceleration, forming the foundation of the vehicle's acclaimed performance. Integrated seamlessly with the powertrain and control systems, the rear motor provides drivers with a smooth yet exhilarating driving experience.

Running throughout the vehicle, the high-voltage lines serve as the electrical lifelines of the Model S3, transmitting power from the battery pack to the electric motors and other high-voltage components. Engineered for safety and durability, these lines are designed to handle substantial currents while maintaining system integrity. Careful insulation and routing ensure reliable operation and protect both the vehicle and its occupants.

For energy replenishment, the charge port provides the interface between the Model S3 and external power sources. Compatible with everything from standard household outlets to high-power fast-charging stations, the strategically positioned charge port offers convenience and flexibility. This design enables efficient charging, ensuring the vehicle is always prepared for its next journey with minimal downtime.

When combined with the heat pump assembly, front motor (in dual-motor configurations), and high-voltage battery pack, these components create a sophisticated and cohesive system that defines the Tesla Model S3's innovative approach to electric vehicle design. Together, they deliver an optimal balance of performance, efficiency, safety, and user convenience, setting new standards in the automotive industry.

2.8.2 *Tesla body material*

Three kinds of steel are employed by Tesla: mild steel, which is used on the exterior body structure to absorb first impacts, high-strength steel, and ultra-high-strength steel, which is used in the vehicle's core. For example, to provide maximum rollover protection, the A-pillar and B-pillar shown in red on the Figure 2.9 are made of ultra-high-strength steel. The front frame rail of the Model 3, which is composed of high-strength and ultra-high-strength steel, provides the primary support for the front "crumple zone (Tesla, Inc. n.d.)."

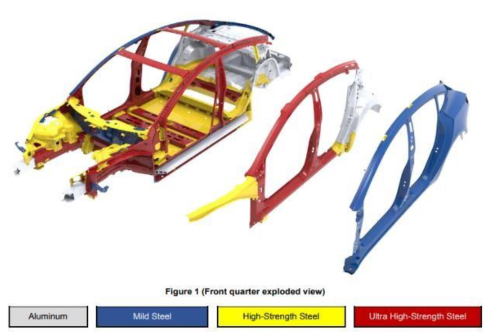


Figure 2-9 Tesla Model 3’s body material (Tesla, Inc. n.d.)

Any structural component that is welded, weld-bonded, riveted, or rivet-bonded to the vehicle cannot go through a process where the straightening of structural parts is facilitated by a hydraulic pulling machine, according to the body repair manual for the Tesla Model 3. By doing this, the metals' yield strength would be compromised. The "underbelly," which acts as the primary support for the Model 3's skateboard-style battery pack—as seen in its previous Model S and Model X siblings—is also mentioned in the Model 3 structural schematic. High-strength steel is used to create the vehicle's complete underside. The Model 3's fully fortified closed steel frame made of ultra-high-strength steel enhances side impact safety. One can readily observe the degree of distortion the Volvo has over the Tesla Model 3 by watching the crash test film, which shows a side-pole impact test conducted on the two vehicles. Figure 2.10 sows' Rear components (Tesla, Inc. n.d.)

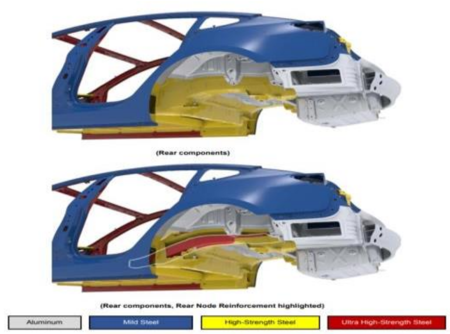


Figure 2-10 Rear components (Tesla, Inc. n.d.)

Finally, lightweight aluminum is added to parts of the body structure like the wheel wells and trunk floor that are less likely to sustain an unintentional collision. The regular Model 3 weighs 3,549 lbs., whereas the Long-Range Model 3 with a larger (and heavier) battery pack weighs 3,814 lbs. Aluminum helps the Model 3 maintain a relatively low curb weight. Overall, it is possible to view Tesla's usage of different steels and aluminum in the body structure of the Model 3 as a learning opportunity and the initial step toward future production that is even more inexpensive and larger in volume Model Y (Tesla, Inc. n.d.).

2.9 Head Injury Criteria and Chest Injury Criteria in Vehicle Crashworthiness

The assessment of head and chest injuries during vehicle collisions is critical for ensuring occupant safety, especially in the context of evolving automotive technologies, including electric vehicles (EVs). This note provides an overview of head injury criteria (HIC) and chest injury criteria (CIC), referencing recent studies and standards from organizations such as the National Highway Traffic Safety Administration (NHTSA) and the National Automotive Crashworthiness Program (NACP).

2.9.1 *Head Injury Criteria (HIC)*

The Head Injury Criterion (HIC) is a quantitative measure used to assess the likelihood of head injuries sustained during a collision. It is calculated based on the acceleration experienced by the head during impact. According to established guidelines, the HIC value must remain below certain thresholds to minimize the risk of serious injury. Study assessed the impact of lightweight materials on occupant safety, highlighting that the introduction of aluminum side members in vehicles resulted in a significant reduction in HIC values during frontal impacts compared to traditional steel components. The findings indicated that while aluminum provided weight savings, it also maintained energy absorption capabilities, thus improving overall crashworthiness (Salwani et al., 2015). Another research focused on the kinematic behavior of drivers during frontal collisions, utilizing Hybrid III dummies to simulate real-world scenarios. The study found that when the driver was properly restrained with seat belts and airbags, the HIC values remained within safe limits, indicating reduced injury risk (Oţaţ et al., 2015). This investigation into airbag deployment emphasized the importance of HIC in evaluating passenger safety. Study showed that HIC values below the regulatory limits were achieved through effective airbag design and deployment strategies (Ravikumar et al., 2021).

2.9.2 *Chest Injury Criteria (CIC)*

The Chest Injury Criterion (CIC) assesses the risk of chest injuries during a collision, primarily focusing on the forces exerted on the chest area. The chest is particularly vulnerable during frontal impacts, where the seatbelt and steering wheel can exert significant forces. Studies have shown that the CSI is a robust predictor of chest injuries, particularly in the context of frontal collisions. For instance, Salwani et al. reported that the CSI values for vehicles with aluminum side members were significantly lower than those with steel, indicating improved safety outcomes (Salwani et al., 2015).

2.9.3 *Relation to Electric Vehicle Crashworthiness*

As the automotive industry shifts towards electric vehicles, understanding the implications of HIC and CIC becomes increasingly important. Electric vehicles often feature different structural designs and materials, which can affect crash dynamics and occupant safety.

2.9.3.1 ***Considerations for EVs***

Material Composition: EVs often utilize lightweight materials to enhance efficiency and range. While this can reduce overall vehicle weight, it is crucial that these materials do not compromise crashworthiness. Research indicates that aluminum alloys can provide both weight savings and improved safety performance (Salwani et al., 2015).

Battery Placement: The placement of heavy battery packs in EVs can impact the vehicle's center of gravity and crash behavior. Proper engineering must ensure that these placements do not increase the risk of head or chest injuries during collisions.

Advanced Safety Features: Many EVs are equipped with enhanced safety technologies, such as advanced airbag systems and collision avoidance systems. These features can play a significant role in reducing the forces experienced by occupants, thereby improving HIC and CIC outcomes.

2.9.4 *Standards and Regulations*

The NHTSA sets forth standards such as FMVSS 208, which outlines requirements for occupant crash protection, including limits for HIC and CSI. These standards are essential for ensuring that vehicles, including electric models, meet safety benchmarks. The NACP focuses on improving vehicle safety through research and development of crashworthiness standards. Their guidelines emphasize the importance of occupant protection systems and the evaluation of HIC and CIC in vehicle design. Table 2.1 shows the injury criteria standards for Head Injury Criterion (HIC) and Chest Injury Criterion (CIC) typically used in LS-*DYNA simulations as per Euro NCAP & FMVSS 208.*

Table 2-2-1 Injury criterion

Injury Criterion	Standard Threshold	Description
HIC	1000 (Regulatory Limit)	A value ≤ 1000 is considered acceptable for regulatory compliance.
Chest Acceleration (G)	60 (Regulatory Limit)	Measures the chest acceleration during an impact. Values below 60 g indicate lower risk of severe chest injuries.
Chest Compression (mm)	50mm (Regulatory Limit)	Indicates the maximum chest deflection during a crash. A value ≤ 50 mm is considered safe according to safety standards.
(CSI)	1000 (Regulatory Limit)	Combines chest deflection and acceleration to predict the severity of chest injuries. CSI ≤ 1000 is considered acceptable for occupant protection.

2.10 Previous Studies

(Kukreja,. etal.,2022) , explains the idea of a damage-tolerant battery pack for electric cars (EVs) that controls mechanical stresses and dissipates energy by combining mechanically sacrificial components with energetic material. The crash performance of a multifunctional battery system is compared to that of battery packs that only contain batteries and battery packs that use cellular solids as energy absorbers. The analysis shows how a multipurpose battery system can be used to guarantee battery safety and help absorb energy in the event of an accident, potentially resolving the technological constraints of electric vehicles (Kukreja,. etal.,2022).

(Jongpradist,. etal.,2022),The shift to sustainable transportation involves using ecofriendly electric vehicles in public transit to reduce emissions and improve energy efficiency. Lightweight design is crucial for fuel economy in electric vehicles, but safety must be ensured. This study analyzes the impact behavior of a lightweight composite microbus body in a full-frontal crash, using LSDYNA dynamic analysis. The findings show extensive damage to the bus structure in a crash, with proposed injury indices for evaluating occupant injury risks. The study discusses the effects of design modifications on crashworthiness improvement, presenting an enhanced bus design that significantly improves safety with minimal increase in weight (Jongpradist,. etal.,2022).

(Scurtu,. etal.,2022),The rapid increase in electric vehicles has raised concerns about battery related safety in accidents. New protective systems and auxetic structures are being designed to enhance impact safety and reduce the risk of battery damage. This study focuses on analyzing the crashworthiness of a battery case equipped with an energy absorber based on a re-entrant auxetic model. Simulations at 10 m/s show that using auxetic structures can mitigate impact by improving energy absorption, reducing the number of damaged cells by up to 35.2% while also lowering the mass of the energy absorbers compared to the base structure.

(Gong, C. ,2021), study focuses on investigating crash safety issues and developing safety improvement techniques for electric vehicles (EVs), particularly addressing electric shock risks during crashes. A literature review highlights the need to study winding-based DC-bus capacitor discharge techniques to prevent electric shock hazards effectively and cost-efficiently. The study then proposes novel discharge strategies for systems with extreme parameters and malfunctions during crashes, along with analytical selection principles for these techniques based on parametric analysis.

(Hao,. etal.,2022), study focuses on optimizing the structure of vehicle battery packs to improve the crashworthiness of electric vehicles (EVs) through frontal crash simulations. The simulations indicate that using a flexible battery module structure can reduce occupant compartment acceleration, with an optimal working pressure of 4 MPa. The study demonstrates that the design of a flexible battery structure and the working pressure are critical factors in improving crashworthiness. Additionally, the optimization of the battery module has the potential to reduce component weight for lightweight design and increase the range of EVs on a full charge, providing a new direction to address EV design challenges.

(Hu,Y,. etal.,2021), focuses on improving the passive safety of electric vehicles by simulating and analyzing the frontal offset impact of a specific SUV. The study optimizes the front side member structure and impact energy absorption to enhance the vehicle's crashworthiness. Through finite element modeling and simulation tests, the effectiveness of the optimization scheme is verified. The research introduces key steps in building the vehicle model, improving the front longitudinal beam, and reinforcing key parts to absorb energy and enhance crash safety. The optimization measures are found to be practical and effective in improving the crash safety of the vehicle during offset collisions.

(Victor,. etal.,2021), reviews the safety requirements of electric vehicles (EVs), particularly those powered by Li-ion batteries, based on mechanical abuse tests, international standards, and real world fire incidents from road crashes. It highlights the challenges and gaps between current safety requirements and real-world incidents, aiming to assist future research in enhancing EV safety. The paper emphasizes the need to address high impact speed, multi-crashes per incident, multiple barriers involved in accidents, and post-crash safety of occupants and rescue teams. It aims to guide researchers and manufacturers in improving battery materials, fire extinguishing, and vehicle body structure to enhance the safety of future EVs.

(Alardhi,. etal.,2022), study investigates the impact analysis of vehicle collisions with street poles, focusing on the influence of different collision types and materials on crashworthiness. Using Abaqus/Explicit software, crashes at three velocities were simulated to extract energy models, specific energy absorption (SEA), and impact forces. The findings emphasize the significance of introducing damage parameters to model crashworthiness analyses and highlight the differences in SEA between aluminum and steel street poles. The study suggests further research to understand the effects of increasing the thickness of aluminum poles and the potential for using additional layers to increase the overall SEA of steel poles. Additionally, it emphasizes the importance of simulating vehicle collisions with poles using different collision types to understand their impact on kinetic energy absorption.

(Lopes,. etal.,2023), study focuses on the need to improve the passive safety of long-course coaches in the event of a frontal collision, especially concerning the safety of the driver. The research aims to develop new solutions for passive safety in coaches through a feasibility study involving experimental and numerical techniques. The experimental testing involved a frontal crash test using a pendulum with energy of 55kJ, and monitoring techniques such as Digital

Image Correlation, strain gauges, and accelerometers were used to assess the damage evolution of the structure. The experimental results were used to validate the numerical results obtained using Finite Element Method techniques. The study concludes that the current structure does not meet essential safety requirements according to standard guidelines, highlighting the need for structural optimization research to enhance the passive safety of long-course coaches.

(Kongwat,. etal.,2021), paper proposes a heavy quadricycle structure using carbon fiber-reinforced polymer in the passenger cell and aluminum alloy in the crumple zone to improve passive safety. The study conducts non-linear finite element analysis via LS-DYNA to simulate the impact behavior of the electric heavy quadricycle according to European New Car Assessment Programme guidelines. The results show that the front crush box and subframes efficiently absorb energy from frontal crashes, with the occupant safety space remaining safe under side collisions. However, the quadricycle is prone to overturning from a side crash due to its lightweight and high center of gravity. The study suggests improvements to the composite passenger cell based on the observed damage mechanism under a crash and recommends further investigation into the behavior of the carbon fiber components under crash scenarios.

(Wisch,. etal.,2014),The EVERSAFE project addresses the safety challenges of electric vehicles (EVs) through various research methods, including accident analysis, computer simulation, physical testing, and literature reviews. The project focuses on the passive safety of EVs and their battery systems, particularly the potential risks associated with lithium-ion batteries. The study also evaluates the performance of EVs in crash scenarios, identifying areas for improvement in crash protection and post-crash handling. The research indicates that overall EV safety levels are high, with minimal risk of fire or emission of toxic substances in crashes. However, there is a need for better support for rescue services to identify and handle EVs at crash scenes. The study recommends further research, standard development, and regulation activities to enhance post-crash handling of EVs and improve rescue operations.

(Gauri,. etal.,2021),This paper discusses the side impact performance of a car's Body-in-White (BIW) frame and its correlation with occupant safety during crashes with rigid poles at various angles. The study involves creating a Finite Element Method (FEM) model of the BIW frame, analyzing side impact safety, and evaluating intrusion levels and occupant injury according to safety standards. The research highlights the effectiveness of FEA for impact analysis, especially for non-linear problems, and the use of tools like hyper mesh for meshing and Abacus for explicit crash analysis. Material properties play a crucial role in the analysis, and accurate boundary conditions are essential due to the changing governing parameters over time.

(Wang,. etal.,2021), In order to enhance impact energy management and vehicle safety, the research proposes a multi-condition analytical model for the development of vehicle frontal crashes. It focuses on matching the stiffness of front-end structures. The equivalent stiffness of the local energy absorption space at the front-end structure is represented by a spring in the analytical model. The correctness of the modeling and solution is validated when the suggested solution approach is compared to actual vehicle collision data and finite element simulation results. The error is less than 15%. In order to provide qualitative guidelines for crash energy management, the study also examines how sensitive the crash pulse decomposition method is to evaluation indices. This study provides a useful tool for controlling vehicle crash energy and advances our understanding of the energy absorption principle of front-end components during frontal impact.

(Liu, C. etal., 2022), study provides an overview of EV crashes using crash data from Norway (2011-2018). It reveals that while the proportion of EV crashes in total traffic crashes has increased, the severity of EV crashes does not significantly differ from Internal Combustion Engine Vehicle (ICEV) crashes. EV crashes tend to occur during weekday peak hours, in urban areas, at roadway junctions, on low-speed roadways, and in good visibility scenarios, reflecting the predominant use of EVs for urban commuting in Norway. Additionally, EVs are more likely to collide with cyclists and pedestrians due to their low-noise engines. Separate logistic regression models identify factors influencing the severity of ICEV and EV crashes, showing distinct effects for each vehicle type. The study suggests the need to re-evaluate current traffic safety strategies in light of the increasing presence of EVs, offering insights applicable to other countries undergoing automotive electrification.

(Lujan,.etal.,2021),study sought to quantify the head and neck injuries sustained by participants in a frontal automobile catastrophe with a driver with only one hand on the steering wheel. for example, while texting on a cell phone using a simulated vehicle during the incident. Our first step included going through all of the NHTSA papers on actual laboratory tests of sedan frontal crashes. An X, Z, and Y-axis average head acceleration and force were used to quantify the impact of these accidents on the neck of a male Hybrid III 50th percentile crash test dummy. The simulated model was validated using these acceleration, force, and torque parameters that were taken from the NHTSA database. Case E, the typical dummy location, was used to compare the findings obtained.

(Deac, S.etal., 2018),Safety of automobiles, particularly for drivers and passengers in an accident, is a major global concern. The "World Health Organization" has provided statistics showing an alarming rate of rise in traffic accidents, the majority of which result in significant injuries and material and human damage. These factors have led to an ongoing improvement of safety measures, particularly for cars, which account for 75% of accidents. The behavior of an automobile during a frontal collision may be mathematically modeled and simulated to provide fresh insights for the creation of safety features.

(Kukrega,.etal.,2016), work shows many structural models of a car after a frontal collision, and Simulink numerical simulation is used to examine the vehicle's behavior. Electric vehicles are gaining popularity as an alternative to traditional fuel vehicles. However, their batteries and electric motors can pose risks in accidents. A deformed battery poses fire and explosion risks on the Indonesian electric city car prototype under development, endangering passengers. This involves his battery pack under the passenger compartment and an electric motor in the front. The crash safety design for side pole impact was numerically simulated according to Euro NCAP standard. To minimize battery explosion risk, impact energy absorbing structures are suggested for the sides of the car. The structure of the 4-seater electric city car was modeled using full-shell elements, with material properties for automotive applications, and analyzed using the finite element method with dynamic plasticity. The minimum battery deformation causing explosion was used as the failure criterion in the preliminary design. Aluminum foam effectively protects battery pack from impacts and lowers risk.

(Setiawan,. etal.,2017), EVs are popular alternatives to fossil fuel vehicles. However, batteries and electric motors in EVs pose unique collision risks. Battery deformation may ignite fire or explosion, endangering passengers. Indonesian electric city car prototype includes battery pack under passenger compartment and front compartment electric motors. In accordance with Euro NCAP standard, a crashworthy design was simulated to protect against side pole impact. To reduce the risk of battery explosion, an energy absorbing structure is proposed for implementation by the battery sides. The hatchback electric city car was modeled using all-shell elements with common automotive material properties and analyzed using the finite element method with dynamic plasticity capability. The minimum battery deformation causing explosion was used as the failure criteria for the preliminary design. Aluminum foam effectively protected the battery pack from side pole impact, reducing the risk to an acceptable level.

(Navale,. etal.,2021), There are unique engineering hurdles for safe electric and hybrid cars (EVs). An electric vehicle's (EV) large battery mass gives it more kinetic energy in a collision than an IC car of the same size. Compared to internal combustion engines (IC) vehicles, electric vehicles have a substantially shorter platform life due to the rapid developments in EV technology. This calls for creating shorter design cycles and reducing the expense of physical testing. This paper emphasizes the necessity of employing physical testing for design verification rather than development and including vehicle crashworthiness models into the design process. The study investigates methods for improving crashworthiness simulations. This book demonstrates how enhancements increase simulation reliability and reduce model creation time. It studies the crashworthiness of up fit cars, such as a pickup truck and a passenger sedan, using these capabilities. The application of virtual prototyping and crashworthiness simulation techniques to lightweight cars composed of cutting-edge materials like composites and aluminum is covered in the concluding remarks.

(Yu,. etal.,2021), A potential remedy for the energy problem and environmental preservation is the use of pure electric vehicles, or PEVs. However, their limited range prevents them from being widely used. PEVs' range can be efficiently increased by using lightweight materials. In the automotive industry, the TRB structure is a novel arrangement that can increase crashworthiness and achieve lightweight. The lightweight design and crashworthiness of PEV front-end components are optimized in this study through the usage of TRB structures. Physical testing is used to validate a full-scale finite element (FE) model of PEV. Conventional UT structures are replaced by TRB FE models. The FE approach is used to examine the vehicle's safety performance in a full-frontal crash. In contrast to UT design, the results show that TRB structures can improve vehicle crashworthiness. They employed a multi-objective design optimization process for crashworthiness and lightweight design using both UT and TRB structures in order to identify the ideal geometric distribution of TRB structures. When compared to UT design, the TRB structure weight is decreased and energy absorption is enhanced using the Kriging (KRG) model and the multi-objective particle swarm optimization (MOPSO) technique,

2.11 Research summery

The studies discussed various aspects of electric vehicle (EV) safety, including crash performance, battery safety, impact behavior, and passive safety measures. They emphasized the need for lightweight design, energy absorption, and crashworthiness improvement while addressing specific challenges such as electric shock risks, battery damage, and safety requirements. The studies employed simulations, dynamic analysis, and experimental testing to propose solutions for enhancing EV safety in different crash scenarios. Additionally, the research highlighted the importance of addressing real-world incidents and improving post-crash handling and rescue operations for EVs.

2.12 Research gap

The review of the literature suggests that the frontal crashworthiness aspect of electric vehicles hasn't been thoroughly investigated through dynamic Finite Element Analysis (FEA). This lack of study is seen as a gap in understanding Electric vehicle safety. The aim of the proposed study is to address this gap by employing dynamic numerical simulations, specifically using FEA techniques. Frontal crashworthiness refers to how well a vehicle can absorb and dissipate energy during a frontal collision to protect its occupants. FEA is a computational method used to analyze complex structures, like vehicles, by dividing them into smaller elements to simulate their behavior under different conditions. Despite the increasing use of electric vehicles, there hasn't been adequate focus on understanding how these vehicles perform in frontal crashes from a structural perspective. Therefore, the proposed study aims to leverage numerical simulations (FEA) to model and understand the crash behavior of electric vehicles, particularly their frontal crashworthiness, which is crucial for ensuring vehicle and occupant safety. The studies discussed various aspects of electric vehicle (EV) safety, including crash performance, battery safety, impact behavior, and passive safety measures. They emphasized the need for lightweight design, energy absorption, and crashworthiness improvement while addressing specific challenges such as electric shock risks, battery damage, and safety requirements. The studies employed simulations, dynamic analysis, and experimental testing to propose solutions for enhancing EV safety in different crash scenarios. Additionally, the research highlighted the importance of addressing real-world incidents and improving post-crash handling and rescue operations for EVs. However, the detail FEA frontal crashworthiness aspect of the electric vehicles is not studied in detail. So, the aim of the proposed study is to fill this gap using numerical simulation.

CHAPTER THREE

3 MATERIALS AND METHODS

3.1 Materials

To carry out the EV numerical analysis the software's, tools and materials listed below are utilized.

CATIA V5

CATIA V5, developed by Dassault Systems, is leading geometric modeling software widely used in industries such as aerospace, automotive, and electronics. It offers flexibility in modeling irregular contours and supports the complete product development process in an integrated manner. It enables collaborative engineering across various disciplines and provides capabilities for sketch tracer generation, surface generation, component assembly, and more (Basavaraju 2005).

LS-DYNA

A flexible transient dynamic finite element program, LS-DYNA is made to simulate challenging real-world issues on Windows, Linux, and UNIX systems. With the ability to switch between explicit and implicit time-stepping systems, it studies the dynamic reactions of elastic and inelastic materials and structures under massive deformation. It has been developed in California for more than 20 years and is widely employed in applications involving complex structural nonlinear dynamics. Its adaptability, partnerships with top universities, and client needs are what propel its expansion. Leading automakers, aerospace companies, and research institutions utilize LS-DYNA extensively (Livermore & Corp, Software 2021).

The numerical analysis of electric vehicles (EVs) leverages advanced software tools to streamline design and validation. CATIA V5 is used to develop precise 3D models of EV components, including battery housings and aerodynamic body panels, while LS-DYNA simulates critical scenarios such as crashworthiness, structural performance, and thermal behavior (see Table 3.1 for material properties). These tools enable engineers to optimize designs, enhance safety, and improve efficiency—reducing reliance on physical prototypes and accelerating the development of high-performance EVs.

Table 3-1 Materials Used

Material/Equipment	*Specifications*	*Purpose*
Tesla Model 3	Electric vehicle with specifications outlined in Table 3.2	Serves as the main focus for crashworthiness analysis and structural evaluation.
ANSYS & LS-DYNA Software	Finite element analysis (FEA) tool designed for dynamic simulations	Used to simulate crash scenarios and assess structural responses during impacts.
CAD (CATIA V5)	Computer-Aided Design software	Enable the creation of precise 3D models of the vehicle and its components.
Computational	CPU: Intel Xeon, RAM: 64 GB, GPU:	Facilitates the execution of simulations and handle large datasets generated from experiments.

3.2 Methods

There are a number of processes or procedures that must be followed in order to accomplish the project's general and specific goals. A list of these can be seen in Figure 3.

a. Literature review and problem identification

Literature reviews are conducted to get a complete picture of the project, including what has been done in this field, its shortcomings, and its gaps. We gather and survey the most recent evaluations and research in the field of Tesla model development, modification, design, and analysis.

➢ **Data collection**

In order to do the Numerical analysis, the necessary data were collected. Different data were collected to understand the present status of research, and Methodology of TWV which can also help in developing structural crashworthiness; the data are presented as follow.

Specification of Tesla S_3 model

The Tesla vehicle's technical specifications and essential information have been gathered from the user manual. Table 3.2 displays all of the vehicle's pertinent information with figure 3-2 shows, Tesla dimensions (Tesla, Inc. n.d.). Furthermore, the mass of the vehicle's components is crucial when determining crash worthiness (Kokate et al., 2020).

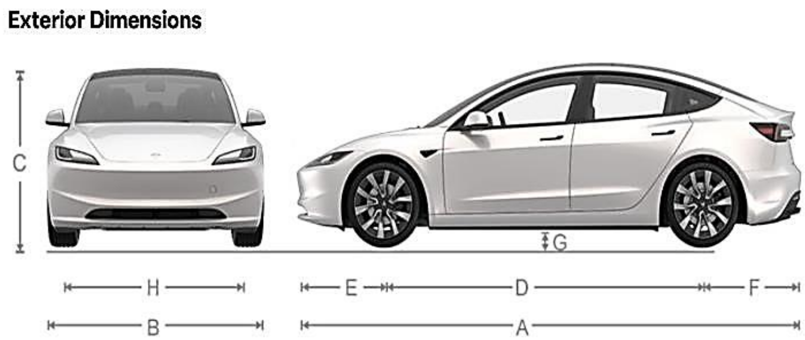


Figure 3-1 Tesla dimensions (Tesla, Inc. n.d.)

Table 3-2 Tesla dimensions

Dimension	Measurement (mm)
A. Overall Length	4,720
Overall Width	
- Including mirrors	2,089
- Folded mirrors	1,933
- Excluding mirrors	1,848
B. Overall Height	1,442
C. Wheel Base	2,875
D. Overhang - Front	868
E. Overhang - Rear	977
F. Ground Clearance	138
G. Track	
- Front Track	1,584
- Rear Track	1,584

The weight of the major parts of the vehicle which are critical for the crash analysis were listed on Table 3.3.

Table 3-3 Weight

Weight	
Maximum Curb Mass* (kg)	Total: 1760 Front: 856 Rear: 904
TPMLM** (kg)	Total: 2192 Front: 985 Rear: 1207

TPMLM = Technically permissible maximum laden mass

Motor Type(s)

The primary motor in all-wheel-drive (AWD) electric vehicles is typically a liquid-cooled AC permanent magnet synchronous motor (PMSM) with a variable frequency drive (VFD). Meanwhile, the front motor in AWD systems often employs a liquid-cooled AC induction motor with variable frequency driving for enhanced efficiency and torque control (see Table 3.4).

Table 3-4 Motor Specifications

Motor Type	Max Power	Max Torque	Voltage
3D3	137	219	320
3D7	194	340	320
4D2	265	459	142

Modeling, Simulation, and Verification Process

The analysis begins with 3D modeling of the electric vehicle using CAD software. This digital model is subsequently imported into LS-DYNA where it undergoes conversion into a finite element model (FEM) for advanced simulations. The FEM enables comprehensive analysis of the vehicle's structural behavior under various loading conditions. Following simulation, results undergo rigorous verification using the software's built-in validation tools to ensure accuracy and reliability of the computational analysis.

3.3 Methodology

This study employs a structured framework to simulate, evaluate, and validate electric vehicle (EV) performance. The methodology begins with 3D vehicle modeling via CAD software, followed by conversion to a finite element model (FEM) in LS-DYNA for high-fidelity simulations. The FEM enables comprehensive analysis of the vehicle’s behavior under diverse scenarios, including crash dynamics and structural stress. To ensure accuracy, simulation results are rigorously benchmarked against experimental data, analytical solutions, and industry standards using specialized validation tools. Key methodological considerations include mesh convergence analysis, boundary condition verification, and material property consistency checks. A detailed workflow diagram (Figure 3.2) illustrates the procedural sequence and critical decision nodes. This systematic approach enhances simulation reliability, providing actionable insights into EV performance and safety characteristics for real-world engineering applications.

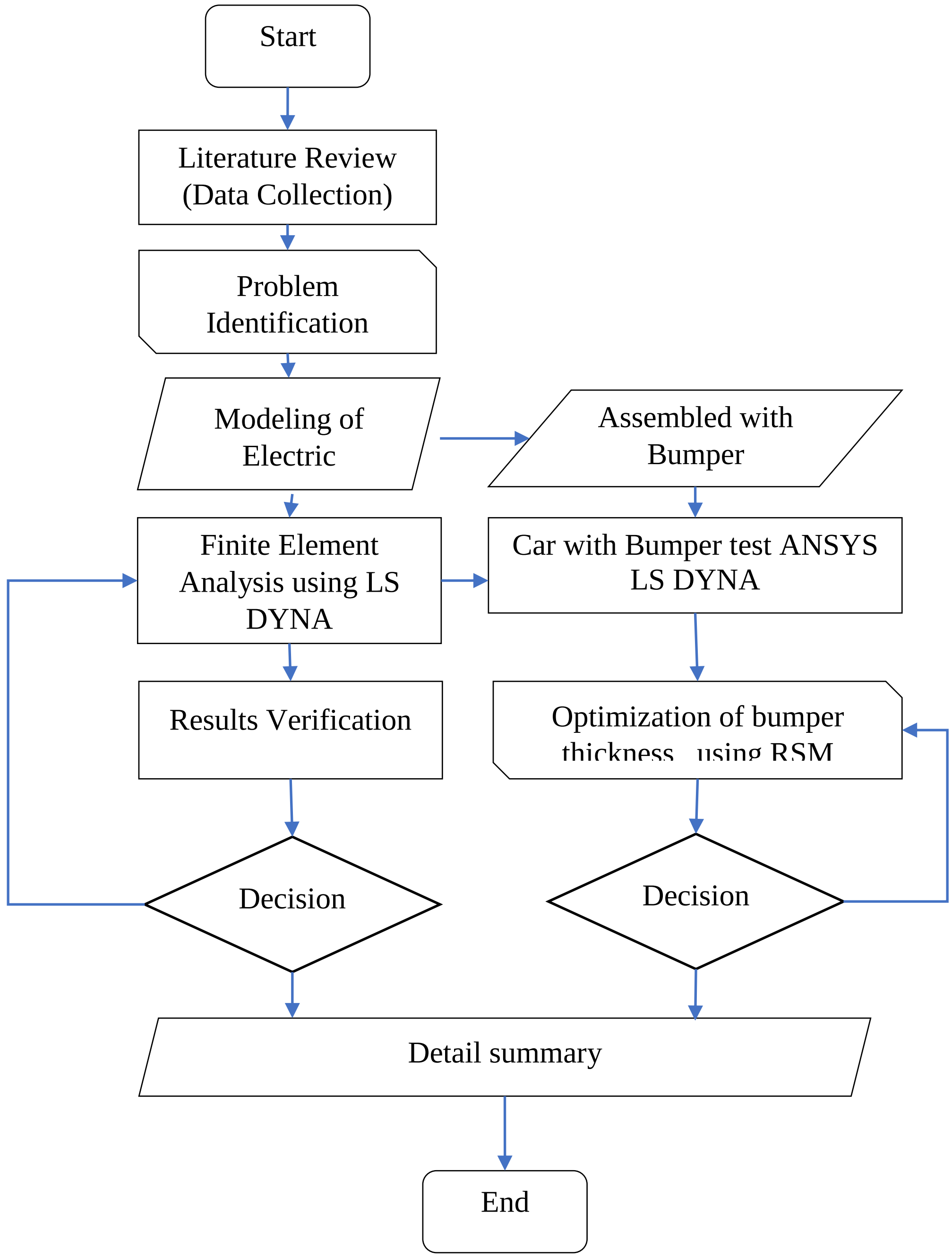


Figure 3-2 Research methodology

➢ **Decision**

At this stage, engineering analysis and decision-making or verification techniques are used to analyze the EV simulation's reaction. The project will move on to the next phase if the outcome is satisfactory; if not, the alteration will be redesigned. Below is a discussion of the LS-DYNA simulation results verification approach.

Verification parameters

The accuracy of values derived from a computational model relies on verifying them with experimental data. In the context of LS DYNA simulation, verification involves assessing factors such as energy balance, deformations, kinematics, kinetics, and other relevant quantities (Gulavani et al., 2014), the most common and logical ways are listed below:

- Energy balance
- Energy Ratio
- Ratio of hourglass energy (HE) to IE

I. Energy Balance Curve

The energy balance of the system under impact scenarios complies with the rule of conservation of energy, which states that although energy cannot be created or destroyed, it can change forms. According to this theory, the kinetic energy lost at impact changes into several energy types in crash analysis.

II. Energy Ratio

The 'energy ratio' is determined by the division of the 'total energy' by the sum of the 'initial total energy' and the 'external work done.' This ratio, also referred to as the 'energy balance,' is crucial in crash analysis. Typically, when the energy ratio deviates significantly from unity, there's a higher likelihood of errors in Finite Element (FE) results. Achieving an energy ratio precisely equal to unity is challenging, so an acceptable range for this ratio is 1.00 +/- 0.07. Variations from this range often stem from system-generated spurious energy and simulation errors (Pezzucchi, 2016).

III. Ratio of TE/HE

By analyzing the energy curves and considering the ratio of total energy to hourglass energy, the correctness of the finite element model can be evaluated. A zero-energy model could be produced with hourglass energy. The hourglass energy of a trustworthy finite element model is usually less than 5 percent of the total energy (Gulavani et al., 2014). Every simulation results report uses the verification process described above.

3.4 Work flow of modeling and analysis

In this section, the detailed process of creating the CAD and finite element analysis (FEA) model for electric vehicles, including essential components such as the chassis, body structure, and safety systems, is presented. The procedure used in modelling and analysis of the electric's vehicle shown Figure 4.1. The diagram outlines a systematic procedure for conducting a thesis project involving modeling and analysis using finite element analysis (FEA) tools like LS-DYNA.

3.5 Finite Element Analysis using ANSYS LS DYNA

The finite element analysis (FEA) in this study is conducted using ANSYS LS-DYNA, specialized software for dynamic and nonlinear simulations. The governing equations for the analysis are derived from the principles of continuum mechanics and dynamics. The general form of the governing equation for dynamic systems is expressed as (3a);

$$\mathrm{M}\ddot{\mathrm{u}} + \mathrm{C}\dot{\mathrm{u}} + \mathrm{Ku} = \mathrm{F(t)} \qquad (3a)$$

Where:

- M is the mass matrix,
- C is the damping matrix,
- K is the stiffness matrix,
- u is the displacement vector,
- $\dot{u}$ and $\ddot{u}$ are the velocity and acceleration vectors, respectively,
- F(t) is the external force vector.

For crash simulations, the explicit dynamics formulation is often used, which solves the equation of motion at each time step. This approach is particularly well-suited for high-speed, transient events such as vehicle crashes, where large deformations, nonlinear material behavior, and complex contact interactions occur. The explicit method does not require the assembly and inversion of a global stiffness matrix, making it computationally efficient for problems involving highly nonlinear dynamics. Instead, it uses a central difference time integration scheme to advance the solution in time, calculating the accelerations, velocities, and displacements at each time step based on the current state of the system. The explicit dynamics formulation solves the equation (3b) of motion in its basic form:

$$\mathrm{M}\ddot{\mathrm{U}} = \mathrm{F_{ext}} - \mathrm{F_{int}} \qquad (3b)$$

Where:

- M is the mass matrix,

- $\ddot{U}$ is the acceleration vector,
- F_{ext} is the external force vector (impact forces, applied loads),
- F_{int} is the internal force vector (stresses, strains, and forces due to material deformation).

At each time step, the accelerations are computed as (4):

$$\ddot{U} = M^{-1}(F_{ext} - F_{int}) \tag{4}$$

The velocities $\dot{U}^{\cdot}$ and displacements U are then updated using the central difference scheme; Numbered equations sequentially (5)–(6) for cross-referencing.

$$\dot{U}_{t+\Delta t/2} = \dot{U}_{t-\Delta t/2} + \ddot{U}_t \Delta t \tag{5}$$

$$\dot{U}_{t+\Delta t/2} = U_t + \dot{U}_{t+\Delta t/2} \Delta t \tag{6}$$

Where Δt is the time step size. The explicit dynamics formulation requires a small-time step, Δt, determined by the Courant-Friedrichs-Lewy (CFL) condition, which depends on the smallest element size and material wave speed. This ensures numerical stability but increases computational cost for long simulations. Despite this, the method excels in crash simulations by handling large deformations, nonlinear material behavior, and complex contact interactions efficiently. It avoids iterative solvers, making it ideal for short-duration, high-speed events. Its ability to accurately model crash physics makes it the preferred choice for automotive crashworthiness analysis and other high-impact scenarios. The internal force (7) vector is computed from the stresses and strains in the material;

$$F_{int} = \int B^T \sigma dV \tag{7}$$

The internal energy represents energy absorbed due to material deformation, including elastic and plastic work. It is calculated as (8);

$$E_{int} = \int \sigma \varepsilon \, dV \tag{8}$$

Where:

- σ is the stress tensor,
- ϵ is the strain tensor,
- V is the volume of the element.

For plastic deformation, the internal energy includes both elastic and plastic components as from (9):

$$E_{int} = E_{elastic} + E_{plastic} \tag{9}$$

Where:

- $E_{elastic}$ (elastic energy),

- $E_{plastic}$ (plastic energy).

The time step Δt formula with (10) must satisfy the Courant-Friedrichs-Lewy (CFL) condition**.**

$$\Delta t \leq \frac{h}{c} \tag{10}$$

Where:

- *h* is the smallest element size in the mesh,
- *c* is the wave speed in the material,

In numerical simulations involving wave propagation, the smallest element size in the mesh, denoted as h*h*, plays a crucial role in ensuring accuracy. The wave speed c*c* in the material, which influences the time step requirements, is determined by the material's elastic modulus E and density ρ, expressed as (Eq. 11). This relationship highlights the dependence of wave speed on material properties, while the mesh resolution *h* must be fine enough to capture the wave behavior effectively, particularly in problems governed by dynamic loading or high-frequency excitations.

$$c = \sqrt{\frac{E}{\rho}} \tag{11}$$

Where:

- *E* is the Young's modulus,
- *ρ* is the material density.

Additionally, the total energy in the system must be conserved to maintain physical realism, and the energy balance can be expressed as (12).

$$E_{total} = E_{kinetic} - E_{internal} - E_{external} \tag{12}$$

$$E_{kinetic} = \frac{1}{2}\dot{U}^T M \dot{U} \tag{13}$$

Where $E_{kinetic}$ is (kinetic energy),

The simulation of the electric vehicle begins with designing a 3D model using CAD software, which is then imported into ANSYS LS-DYNA. In ANSYS LS-DYNA, the 3D model is converted into a finite element model, enabling detailed analysis of the vehicle's performance under various conditions.

This research follows a structured finite element analysis (FEA) workflow to evaluate electric vehicle components and systems. The process begins with CAD modeling of all relevant components using industry-standard design software. These 3D models undergo meshing to create finite element representations, with rigorous quality checks performed to ensure mesh refinement and accuracy. The meshed components are then assembled into a complete vehicle system model, where boundary conditions, material properties, and load cases are carefully defined.

For the analysis phase, an appropriate LS-DYNA solver is selected based on the specific simulation requirements, whether for static, dynamic, thermal, or crashworthiness studies. The configured model is then processed through the solver to generate comprehensive performance data. Finally, the simulation results are imported into post-processing software for detailed visualization and engineering interpretation, enabling thorough evaluation of the vehicle's structural behavior and performance characteristics under various operating conditions. To interpret the results, analyze simulation data to validate hypotheses and verify the design. Extract insights to guide decisions or design refinements. Compare outcomes with expectations, identify improvements, and iterate if needed. This aligns with Figure 3.4, ensuring a structured modeling and analysis workflow.

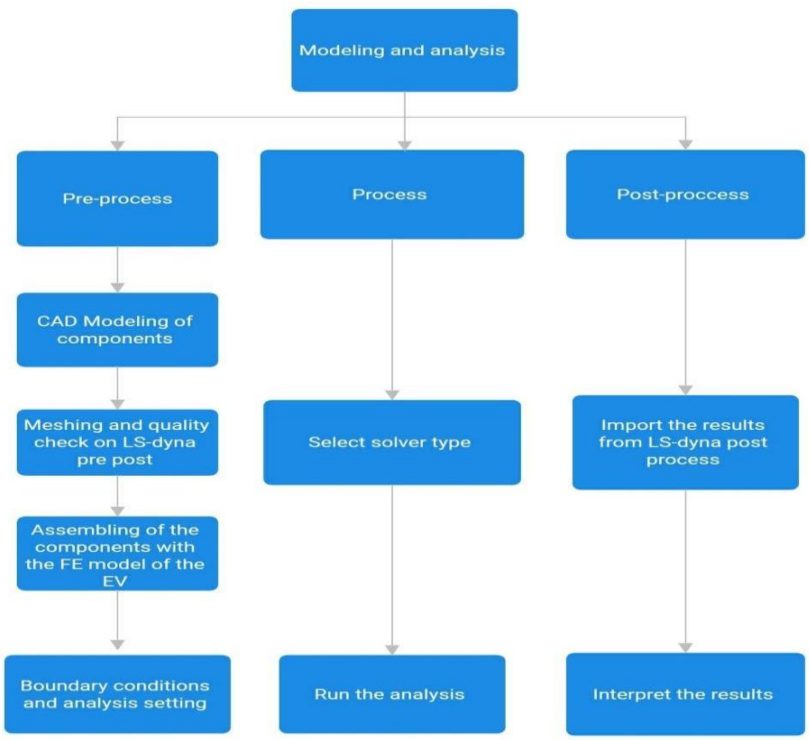


Figure 3-3 Workflow of modeling and analysis

The details description of each task is discussed one by one on the following sections

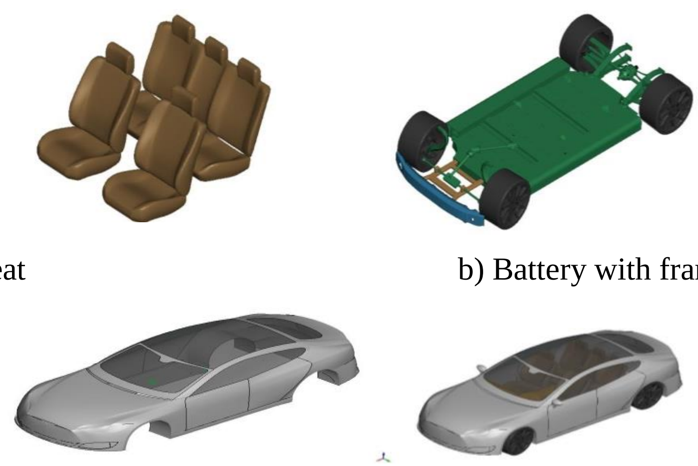
3.5.1 Pre-processing

Geometrical (CAD) Modeling of the basic components of electric vehicles

To effectively utilize Finite Element Analysis (FEA) in electric vehicles, geometric modeling of essential components, such as batteries and inverters, is a crucial step. The modeling process involves several stages, as illustrated in the figure. These include sketching, transitioning to 3D/solid modeling, and culminating in component assembly using software such as CATIA. Once the component models are developed, they are imported into LS-DYNA for meshing and further processing. These meshed components are integrated with the finite element (FE) body model of the electric vehicle (EV). The integration process will be detailed in later stages of the simulation workflow, ensuring seamless transitions between design and analysis phases. This structured approach aligns with Figure 3.5, which outlines the key CAD modeling stages for systematic development.

Figure 3-4 CAD modeling stages

The geometrical (CAD) modeling of key EV components includes (a) the seat, (b) battery with frame, (c) car body, and (d) the final assembled view. These models, shown in Figure 3.6, ensure accurate representation before simulation and analysis.



a) Seat b) Battery with frame

C) Car body D) Assembled final view

Figure 3-5 Modeled vehicle parts

The image showcases the step-by-step development and assembly of the electric vehicle model, emphasizing the design of main individual components and their integration into a complete system. The seats are individually modeled in a CAD environment. The process involves creating a 3D representation of the seats with realistic dimensions, ergonomic contours, and surface details. Features like material thickness and curvature are incorporated to simulate real-world functionality and comfort. The chassis, which houses the battery, is modeled as a structural base of the vehicle. This includes designing mounting points, support structures, and space allocation for the battery pack. Parametric modeling techniques are used to ensure the frame is compatible with the car body and other components. The car body is created as a solid 3D model, structural integrity, and aesthetic appeal. Key features such as curves, cutouts for windows, and mounting regions for integration with other components are designed with precision. Additional parts such as the dashboard, steering components, mirrors, and braking systems are also modeled. These components are designed in detail, ensuring their compatibility and functionality within the vehicle assembly. The individually modeled components (seats, battery with frame, and car body) are imported into an assembly environment. Constraints such as alignments, joints, and contact surfaces are applied to accurately position and fit the parts together. The final assembled model represents a complete virtual prototype of the vehicle, ready for further analysis and simulation.

Computational model

The models were created in CATIA V5 and then exported in Initial Graphics Exchange Specification (IGES) format to LS-DYNA. As shown in the attached figure, the finite element (FE) models were created using a discretization procedure, and LS-DYNA was used to verify the mesh quality. The mesh type, size, and geometrical characteristics have to be specified throughout the mesh generation procedure. Depending on the element dimension, there are three main mesh types: 1D, 2D, and 3D. The body and most other parts of electric vehicles were modeled as shell plates, which have a structure that is much wider and longer than it is thick. Therefore, for these components, a 2D mesh type was used. LS-DYNA software was utilized to mesh the vehicle geometry, utilizing a combination of triangular elements (1.23%) and linear quadrilateral elements (98.1%). The whole model had 441,289 elements and 439,001 nodes, with element sizes ranging from 4 mm to 8 mm. This finely meshed model is highly detailed and computationally intensive, as shown in Figure 3.7.

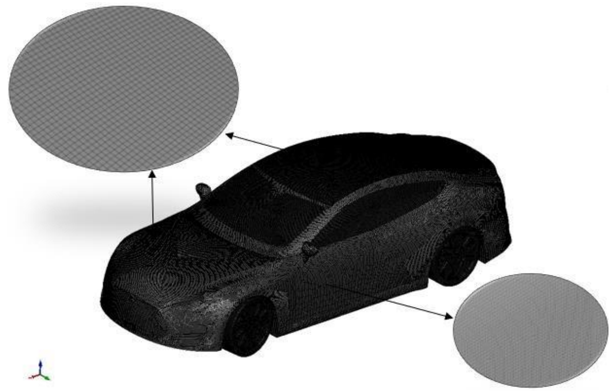


Figure 3-6 FEA model

Ensuring the quality of elements is crucial for accurate simulation results and to prevent errors. Before proceeding with simulation analysis, it's essential to conduct quality checks on the elements. Parameters such as included angles, skew, Jacobian, aspect ratio, stretch, etc., are examined to assess how much a given element deviates from the ideal shape. Some checks focus on angles (like skew and included angles), while others consider side ratios and area (Rahman & Babu, 2019). Parameters are standardized in LS-DYNA using the *Keyword Quality Check* tool to ensure consistency and accuracy. Table 3.5 summarizes the quality check results, validating model reliability before simulation.

Table 3-5 Quality check

Quality Name	Minimum Value	Maximum value	Allowable	#Violated (%)
Min side length	0.357	0	3	4588(0%)
Max side length	0	0	30	0(0%)
Aspect Ratio	1	9.77	3	124(0.000818%)
Warpage	0	180	10	331(0.0271%)
Min Quad Angle	20	90	45	214(0.0175%)
Max Quad Angle	0	0	135	0(0%)
Min Tria Angle	0	0	30	0(0%)
Max Tria Angle	0	0	120	0(0%)
Taper	0	0	0.7	0(0%)
Skew	0	58.6	45	44(0.0036%)
Jacobian	-0.0617	1	0.6	643(0.0526%)
Area	0	0	5	0(0%)
Time Step	0	0	1.00E-06	0(0%)

#QUADS (%):435876(98.8%), #TRIAS (%):5412(1.23%), #Total of failed (%):124(0.0281%)

Boundary conditions

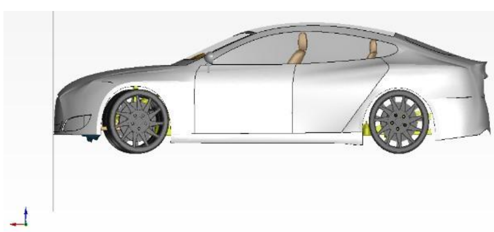
In vehicle crash simulations, boundary conditions are crucial for accurately representing the real-world scenario. They define the constraints and loads applied to the model to replicate the forces and movements experienced during a crash. Figure 3.8 depicts a simplified finite element model (FEM) of a Tesla vehicle model undergoing a frontal crash test. The vehicle is moving with a velocity of 56 km/h towards a rigid wall. The wall represents an immovable barrier, simulating a head-on collision scenario.

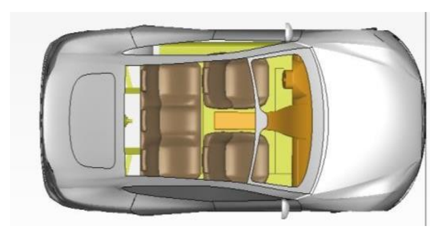
Simulation Setup:

In vehicle crash simulations, boundary conditions are crucial for accurately representing the real-world scenario. They define the constraints and loads applied to the model to replicate the forces and movements experienced during a crash.

Key Boundary Conditions in this Simulation:

1. **Vehicle Velocity:** The vehicle is assigned an initial velocity of 56 km/h. This simulates the vehicle's speed before impact.
2. **Rigid Wall:** The wall is defined as a rigid body, meaning it does not deform during the collision. This represents an immovable obstacle.
3. **Ground Contact:** The tires of the vehicle are constrained to interact with the ground surface. This may involve contact algorithms that simulate friction and rolling resistance.





a) side view b) Top view

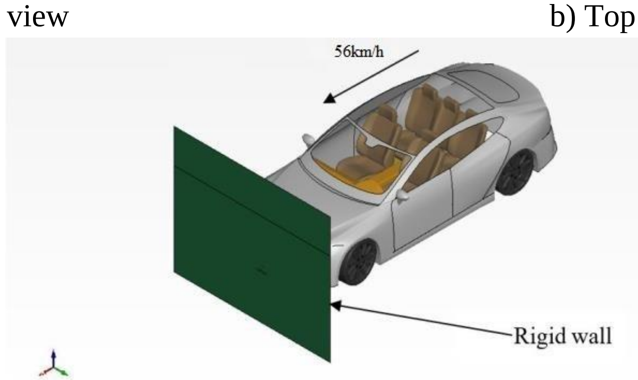


Figure 3-7 Boundary condition

Additional Considerations

Modeling the battery pack as a rigid mass simplifies crash simulations but has important limitations. While this approach reduces computational costs, it underestimates energy absorption and fails to capture critical failure modes like cell rupture or thermal runaway. The rigid assumption also alters force distribution, potentially overestimating stresses on adjacent structures. Since real-world battery packs can deform and absorb energy, this simplification may lead to overly optimistic safety assessments. Future work should incorporate deformable battery models with failure criteria to better evaluate crash performance and electrical safety risks in EVs.

3.5.2 Impact of EV-Specific Components on Crash Response

The crash dynamics of electric vehicles (EVs) differ significantly from internal combustion engine (ICE) vehicles due to their unique structural and electrical components. The battery pack, typically mounted along the vehicle floor, introduces both challenges and advantages—its rigid, low-positioned mass lowers the center of gravity, improving rollover resistance, but its high energy density raises safety concerns regarding thermal runaway and structural integrity during deformation. Motor mounts, designed to secure heavy electric motors, must withstand high torque forces while maintaining crash energy absorption capabilities. High-voltage cables, routed through critical zones, require careful shielding and placement to prevent short circuits or electrical hazards in collisions. Unlike ICE vehicles, EVs lack a heavy engine block in the front crumple zone, altering impact force distribution and necessitating reinforced frontal structures to compensate. These EV-specific factors demand tailored crashworthiness strategies that address both mechanical safety and electrical system protection, presenting distinct engineering challenges compared to conventional vehicles.

Material definition

The material properties of the vehicle's components (e.g., steel, aluminum) would be defined in the FEM to accurately predict their behavior under impact loading. The choice of material model type is a critical factor influencing the accuracy of impact simulations. Hot rolled steel is commonly used for sups due to its high strength and stiffness, along with its affordability and widespread availability (Mayank Laddha, 2019; Saso, 2021). LS-DYNA offers an extensive material library that assists in accurately defining material properties. This library is utilized for specifying the materials of various components, curate impact simulations of vehicles critically depend on the materials used and their properties. These material library selections must align with automotive criteria, including safety, environmental impact, light weighting, fuel efficiency, cost-effectiveness, and design aesthetics. The vehicle model primarily comprises shell elements, each requiring defined thicknesses and mechanical material properties. Two solid parts are also included. Table 3.6 shows material definition.

Table 3-6 Material definition

Vehicle item	Mass density (kg/mm^3)	Young's Modulus (KN/mm^3)	Poisson's ratio	Yield Stress (KN/mm^3)	Shear Modulus (KN/mm^3)	Tangent modulus
Vehicle body	7.80e-006	210	0.3	0.25		1
Chassis	7.890e-009	200	0.3	0.271		
Glass screen	2.500e-009	70	0.22	0.030		1
Roof of car	6.800e-009	200	0.35	0.2	5	
Seat(cushion)	1.010e-007	0.00416	0.35			
Tire	1.750e-009	300	0.3			
Bumper	4.35e-10	250	0.2			
Battery compartment	1.27e-009	200	0.3	0.25		

Material selections were made using the LS-DYNA material library. The material selections were defined using the LS-DYNA material library to ensure accurate simulation behavior. The tires were modeled with MAT_ELASTIC to capture their flexible response, while the windscreen, car body, and chassis structures were assigned MAT_PIECEWISE_LINEAR_PLASTICITY to replicate their elastic-plastic deformation under impact. This approach ensures realistic material representation in the crash analysis. The bumper was modeled using MAT_NULL, while rigid components like the seat, axles, and engine were defined with MAT_RIGID**.** Material thicknesses for key parts are detailed in Table 3.7**,** ensuring accurate simulation inputs.

Table 3-7 Main components thickness

Component	Thicknesses(mm)
Structure and body	3
Frame or chassis	2
Windscreen	3
Tire	2
bumper	3

Most vehicle component thicknesses range from 2mm to 6mm. The seat and battery compartments are modeled as solid element with 70mm and 50 mm thick respectively. The thicknesses of most vehicle components were defined using shell elements, while the remaining components were defined using solid elements. For shell elements, thicknesses were determined based on their density and mass values, as listed in the preceding data collections. The shell thicknesses for main vehicle components are presented Table 3.7.

There is various material properties used in automobile bumper material. From those the tesla car model bumper material used for optimization in this thesis is aluminum alloy which described in table 3.8.

Table 3-8 Bumper material properties (Aluminum Alloy)

Property	*Value*	*Units*
Density	2770	kg/m^3
Young's Modulus	7.1×10^{10}	Pa
Poisson's Ratio	0.33	-
Bulk Modulus	6.9608×10^{10}	Pa
Shear Modulus	2.6692×10^{10}	Pa
Isotropic Secant CTE	2.3×10^{-5}	1/°C
Compressive Ultimate Strength	0	Pa
Compressive Yield Strength	2.8×10^{8}	Pa

3.6 Computational Modeling Approach for Electric Vehicle Crash Simulation

To optimize computational efficiency while maintaining model accuracy, the Tesla electric vehicle model was strategically simplified. The total mass of removed components was consolidated at the vehicle's center of gravity using the ELEMENT_MASS keyword, with a nodal point created at this critical location. Structural integrity was maintained through constrained interactions, implemented using CONSTRAINED_NODAL_RIGID_BODY for part fixation and CONSTRAINED_EXTRA_NODE_SET for rigid body connections. Mass distribution was managed via CONSTRAINED_EXTRA_NODE_NODE definitions.

The simulation incorporated essential contact mechanics through "Contact Automatic Surface to Surface" definitions, preventing part penetration during collisions, including interactions between the vehicle and rigid barrier. Impact conditions followed ECU regulations, with an initial velocity of 56 km/h established using INITIAL_VELOCITY_GENERATION to replicate standard frontal crash test protocols.

Solution control parameters were carefully configured using multiple control cards: CONTROL_TERMINATION governed simulation duration, while CONTROL_ACCURACY, CONTROL_CONTACT, CONTROL_ENERGY, and CONTROL_HOURGLASS managed numerical stability, contact interactions, energy calculations, and hourglass effects respectively. The time step (DT) was optimized at 0.001 seconds to balance result resolution with computational efficiency, with specific focus on energy absorption characteristics during the critical 15-millisecond impact window.

Output generation utilized comprehensive database cards including D3PLOT for visualization and various ASCII options (MATSUM, RWFORC, RCFORC) for detailed energy and force analysis. Post-processing focused on quantitative crashworthiness evaluation through key metrics: energy absorption patterns, structural deformation, impact force profiles, and component condition assessments. This systematic approach, building on established methodologies (Kunle et al., 2019), enabled efficient yet accurate simulation of electric vehicle crash dynamics while maintaining computational feasibility.

3.7 Bumper Optimization Methodology

The optimal bumper thickness was determined using Response Surface Methodology (RSM) combined with constrained nonlinear optimization. The approach involved fitting quadratic regression models to predict key performance metrics—internal energy, kinetic energy, equivalent stress, deformation, and weight as functions of bumper thickness. These models were derived using Polynomial Features and Linear Regression from scikit-learn python, ensuring accurate representation of the nonlinear relationships observed in the data. To balance competing objectives, a weighted sum optimization framework was employed, where each response was normalized to a [0, 1] scale to ensure fair comparison. The Sequential Least Squares Quadratic Programming (SLSQP) algorithm was then used to minimize the combined objective function while enforcing critical constraints:

- Equivalent stress ≤ 100 MPa (to prevent material failure)
- Deformation ≤ 195 mm (to maintain structural integrity)

The SLSQP solver efficiently navigated the trade-offs between energy absorption (maximization goal) and weight/stress (minimization goals), converging to optimal bumper thickness that best satisfies all criteria.

This method was chosen for its ability to handle nonlinear constraints and provide rapid convergence for engineering design problems.

Key strengths of this approach:

1. Transparent trade-off management – Explicit weighting of objectives allows engineers to adjust priorities (e.g., safety vs. weight).
2. Constraint enforcement – Ensures the solution adheres to real-world design limits (e.g., stress thresholds).
3. Computational efficiency – RSM + SLSQP is faster than evolutionary algorithms for small-to-medium problems.

CHAPTER FOUR

4 RESULTS AND DISCUSSION

On this chapter the results of the simulation of Tesla S3 model is reported. In addition, the detailed discussed results are presented. The result obtained is checked by using the verification method for LS-DYNA simulation. Different parameters are used to identify the crashworthiness of the vehicle. Each of them is discussed in detail as follow. First the result of the main parameters is predated the latter followed by the verification result.

4.1 Crashworthiness parameters

Total energy balance

Figure 4.1 illustrates the energy balance during a frontal crash simulation of a Tesla S3 electric vehicle. The energy components shown include kinetic energy (A), internal energy (B), total energy (C), and hourglass energy (D), with their evolution over time during the crash. Initially, the total energy remains constant at approximately 168 kJ throughout the simulation, as dictated by the Law of Conservation of Energy. This is represented by a steady horizontal line. At the start of the crash event, the kinetic energy is at its maximum (equal to the total energy at 168 kJ). As the crash progresses, the kinetic energy decreases significantly, eventually dropping to around 20kJ by the end of the simulation. This indicates that energy is being converted from kinetic energy to other forms. Internal energy increases steadily as the crash progresses, corresponding to the energy

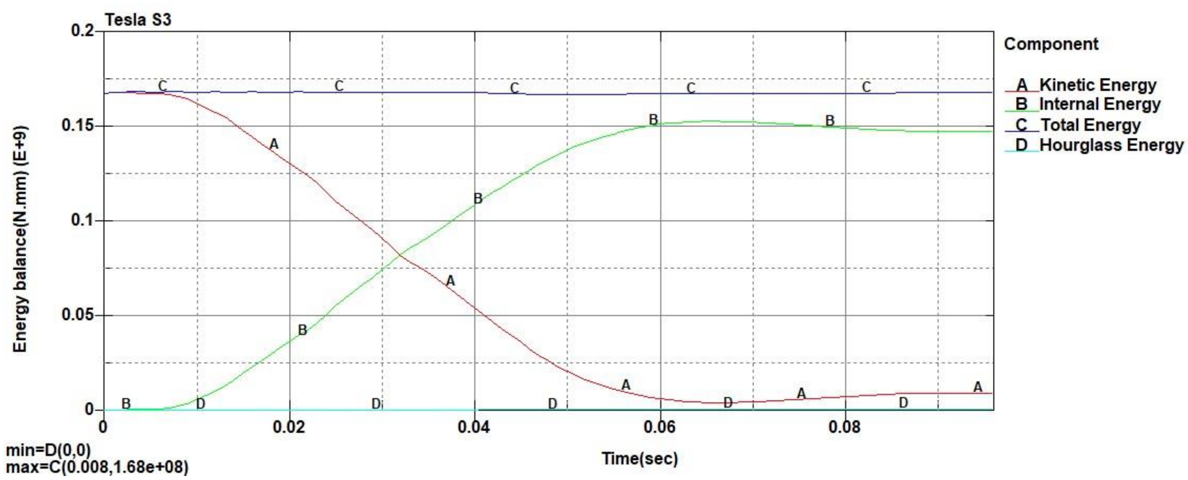


Figure 4-1 Energy balance

absorbed by deformation and heat during the impact. The curve for internal energy shows that a substantial portion of the total energy (159 kJ) is converted into internal energy. The hourglass energy, which represents energy dissipated due to numerical artifacts or inaccuracies in the simulation, is relatively small and remains close to zero throughout the event.

Internal energy

Figure 4.2 represents the internal energy absorbed by various components of a Tesla S3 electric vehicle during a frontal crash simulation. The graph shows a steady increase in internal energy over time, reaching a peak value of approximately 153 kJ by the end of the simulation. This accounts for 91% of the total energy dissipated during the crash event. The front structure absorbs the largest amount of energy, with 100kJ, as it is the first point of contact during the crash. This area experiences significant deformation due to the high impact forces transferred to it, resulting in major energy absorption. Other key parts also contribute to energy absorption, including: Bumper (41.12 kJ), body structure and supports (30kJ) and Tires: 1.21 kJ. Components like in rear structure and battery show negligible internal energy absorption because they are modeled as rigid materials in the simulation.

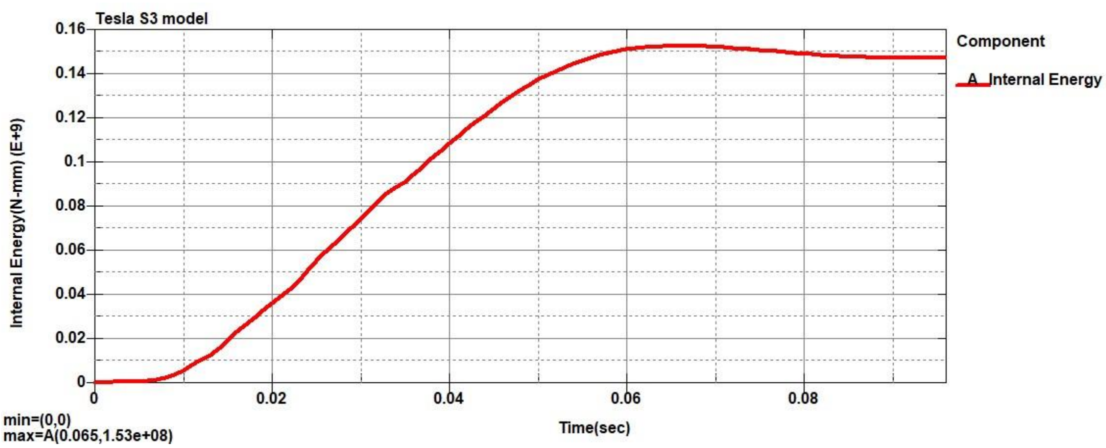


Figure 4-2 Energy absorbed

Rigid materials do not undergo deformation, which limits their ability to absorb energy. The front structure exhibits significant folding deformation, absorbing the majority of the impact energy. This is due to the stresses exceeding the material's bending stress, leading to extensive plastic deformation. Some deformation is transferred to the rear structure, battery and the driver cabin, but to a lesser extent.

Resultant force

Figure 4.3 depicts "Tesla S3 model" resultant force over time during a frontal crash simulation. The force starts at nearly zero, indicating minimal contact before the impact. Around 0.01

seconds, the force begins to increase rapidly. This signifies the onset of the crash impact. The force curve exhibits fluctuations. These are likely due to the dynamic nature of the crash simulation, where forces on individual elements are not constant. The maximum force occurs when the vehicle frontal body experiences the most significant deformation, likely involving contact with rigid elements. This happen at when the time is 0.49sec with force of 3.19KN. After this point, the force gradually decreases after the peak, indicating a dissipation of energy. Higher forces generally correlate with greater damage to the vehicle and its occupants. The presence of deformable elements in the vehicle's structure is crucial to mitigate these forces and improve occupant safety.

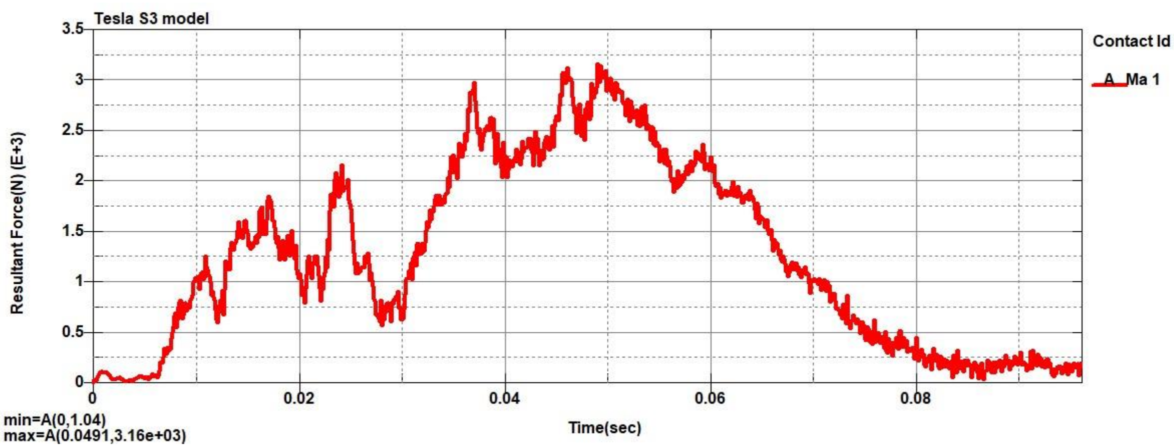


Figure 4-3 Resultant force

Resultant Displacement

Figure 4.4 represents the "Resultant Displacement" of a specific node (Node ID: A 5000404 C.G. Global) in a Tesla vehicle during a frontal crash simulation. The displacement starts at zero, indicating no deformation before the crash. The displacement increases rapidly in the initial phase, suggesting significant deformation of the vehicle structure. The deformation reaches a peak value around 0.06 seconds with deformation of 0.6m. This likely corresponds to the moment when the vehicle structure experiences maximum stress and deformation. After the peak, the displacement curve flattens out, indicating a decrease in deformation. The graph suggests that the initial impact causes significant deformation of the vehicle's front structure. This deformation likely occurs as the vehicle collides with an object. The peak deformation signifies the point of maximum structural stress. After this point, the deformation slows down, possibly due to the vehicle structure reaching its limit of deformation or due to energy dissipation mechanisms.

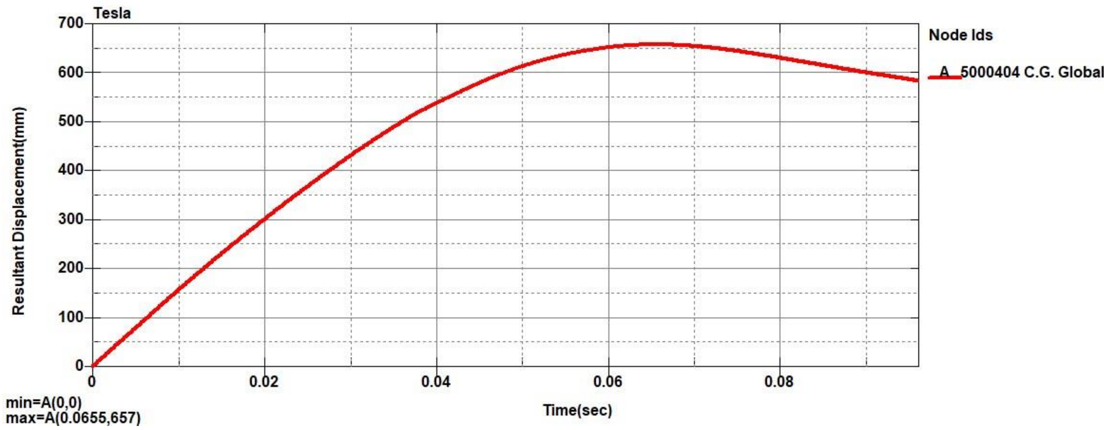


Figure 4-4 Resultant displacement

The deformation along in the direction of motion or x axis is shown in the image shown on Figure 4.5 the image depicts a 3D model of an electric vehicle undergoing a frontal crash simulation. The color-coded contours on the vehicle's surface represent the X-displacement, indicating the amount of deformation in the horizontal direction. The color scale ranges from blue (negative X displacement) to red (positive X-displacement), with varying shades of orange in between. The deformation is concentrated in the front of the vehicle, particularly around the bumper and front fenders. This is expected in a frontal crash scenario. The maximum X-displacement (indicated by the darkest red color) appears to be around the front bumper area with 168mm. The color gradient suggests a gradual increase in deformation from the rear of the vehicle towards the front. The concentration of deformation in the front indicates that the vehicle's front structure is absorbing the impact energy, protecting the passenger compartment. Based on the visual representation, it seems that the vehicle's front structure is designed to deform in a controlled manner, absorbing impact energy and minimizing intrusion into the passenger compartment. This is a crucial aspect of vehicle safety design.

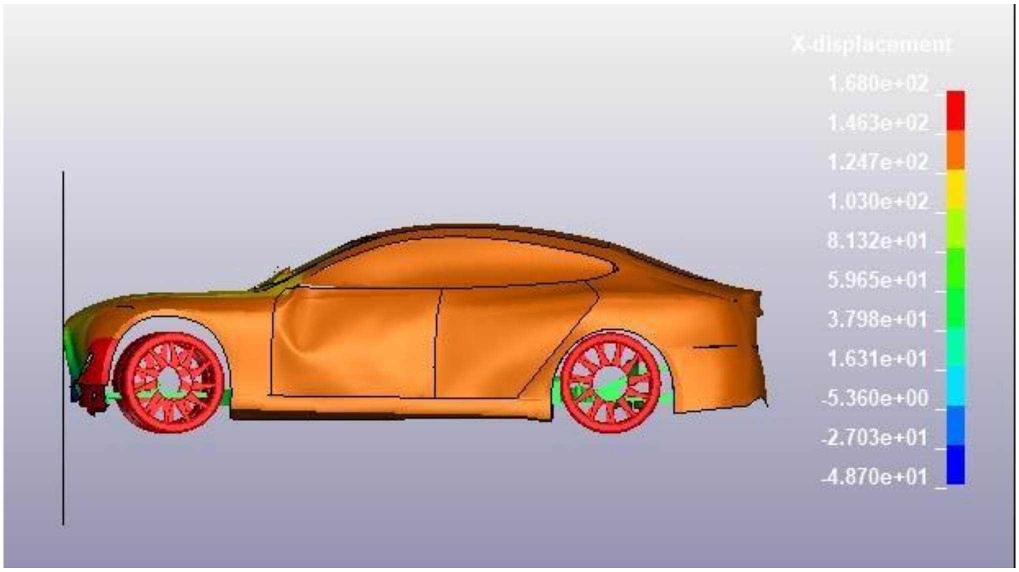


Figure 4-5 x displacement

Structural strength

Von mises Stress

Figure 4.6 provided shows the results of a finite element analysis (FEA) simulation of a frontal collision between a vehicle and a rigid wall. The color-coded contours on the vehicle's surface represent the von Mises stress distribution. Von Mises stress is a scalar measure of the combined multi-axial stress state at a point.

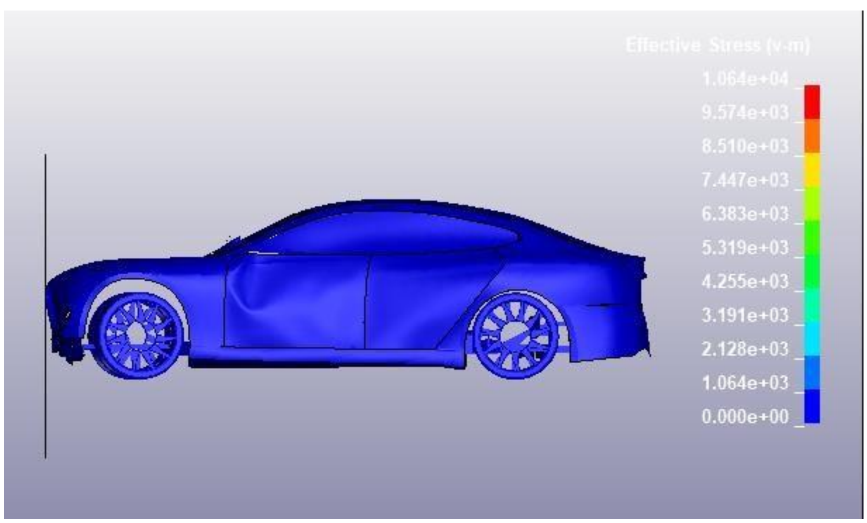


Figure 4-6 Stress

It is used to predict the onset of yielding in ductile materials. The stress is concentrated in the front of the vehicle with maximum stress value of 1064mpa, particularly around the bumper, front fenders, and A-pillars. This is expected in a frontal collision scenario as these areas bear the brunt of the impact. The color gradient indicates a gradual decrease in stress from the front to the rear of the vehicle. This suggests that the impact energy is being absorbed and dissipated along the length of the vehicle. The areas with the highest stress are likely to be the most susceptible to damage or failure. Based on the stress distribution, it can be inferred that the vehicle's front structure is designed to absorb and distribute the impact energy, thereby protecting the passenger compartment. However, further analysis and design optimization may be necessary to minimize stress concentrations and improve overall crashworthiness.

4.2 Injury Criterions

An important measure of occupant injury as a result of mechanical impact, used by automobile and other industries, is the Chest Severity Index (CSI) and Head Injury Criteria. To determine if the Head Injury Criterion (HIC) and chest severity index (CSI) values obtained from a frontal car collision simulation using LS-DYNA are safe, the value HIC and CSI from the simulation is compared with the standard values of injury criteria.

Head injury criteria result

The time versus acceleration pulse in Figures 4.7 and 4.8 is used to calculate the HIC metric, an acceleration-based metric. The following are the maximum HIC values that are compatible with the driver's survival in frontal crashes, per the CMVSS 208 and FMVSS 208 guidelines: HIC 15 < 700 (over a 15 ms time span) HIC 36 < 1000 (during a 36 ms time span). Figure 4.7 displays the HIC36 values for the driver and passenger seats that were acquired from LS-PrePost. HIC values are generally derived from the accelerometer mounted at the center of mass driver seat and passenger seats. HIC36 value is calculated in LS-Pre Post and is basically measured for time interval less than 36 ms duration. From the following cases, it can be concluded that the, HIC36(d) value for occupant’s head impact on a rigid wall is 2.905e+04 and HIC36 value for driver head impact is 1.016 e+10. A low HIC value does not necessarily indicate a low level of head traumas. Similarly, a high HIC number does not necessarily indicate severe brain damage. The actual meaning is that the likelihood of suffering severe head injuries increases with greater HIC values.

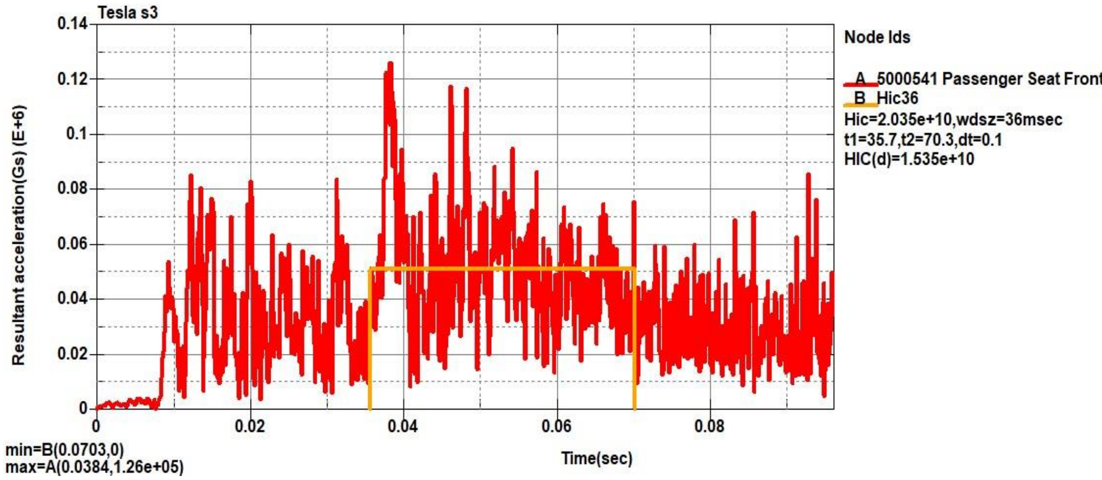


Figure 4-7 HIC passenger

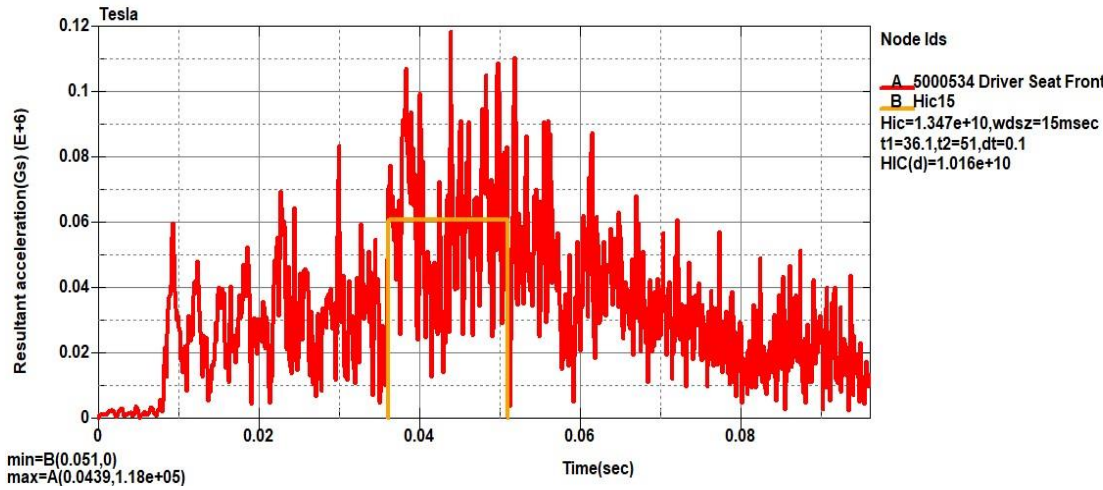


Figure 4-8 HIC driver

Chest injury criteria (CSI)

The chest injury criteria (CSI) value obtained from LS-PrePost for the driver and passenger seats are also shown on Figure 4.8 and Figure 4.9. CSI values are also obtained from the accelerometer mounted at the seats. The value which is calculated in LS-PrePost shown on Figure 4.8 and Figure 4.9. It can be shown that CSI value for passengers and driver is 6.276e+04 and 5.752e+04 respectively.

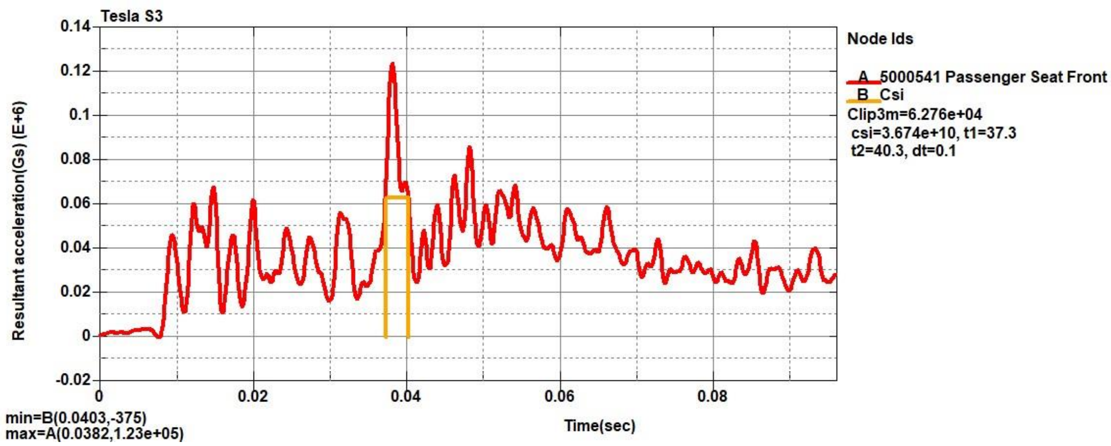


Figure 4-9 CSI Passenger

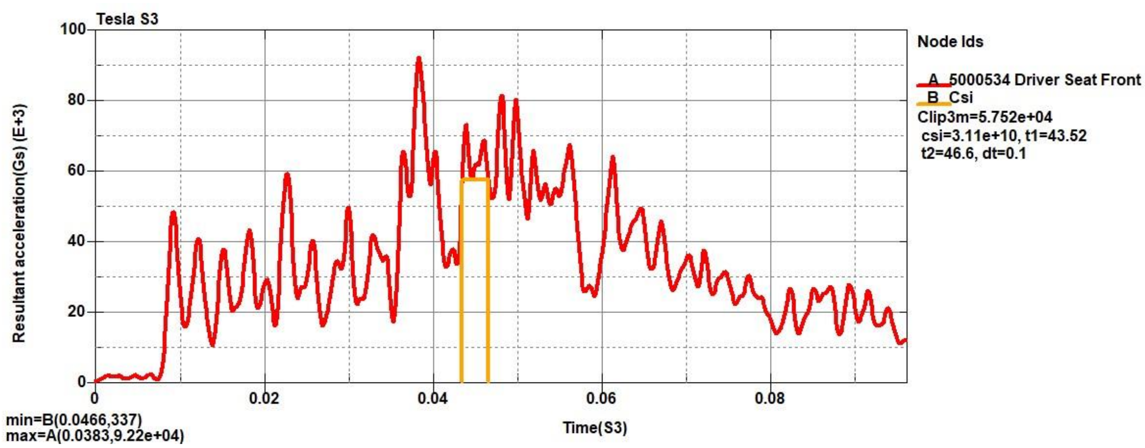


Figure 4-10 CSI Driver

4.3 Verification results

Energy ratio

The above values are validated by the energy ratio, which is equal with the ratio of the total energies to the sum of other energies. From the Figure 4.11, it can be observed that the maximum energy ratio value 1.059. This range is within 1+/- 0.07. This value in the range stated by (Pezzucchi, 2016), so it is acceptable.

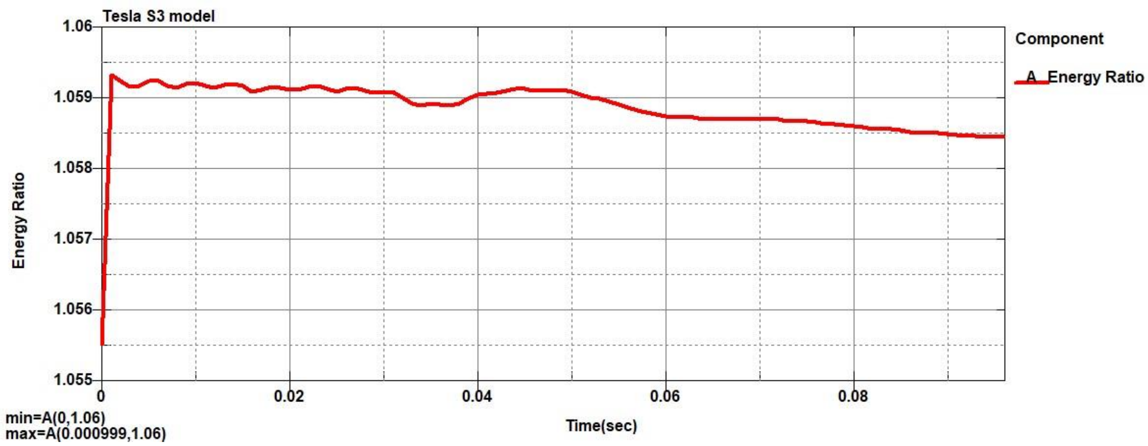


Figure 4-11 Energy ratio

Ratio of Hourglass energy to total energy

As it can be easily seen from Figure 4.12, the value of hourglass energy is very less as compared to the total energy. The ratio resulted in 0.032 or 3%. According to the definition stated on (Gulavani et al., 2014), since the energy ratio is less than 5% so their results are acceptable.

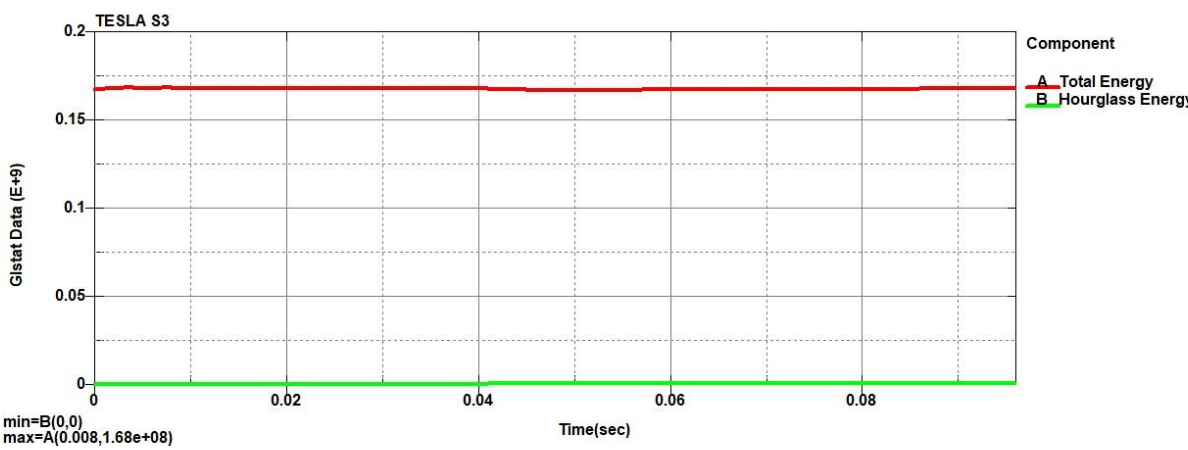


Figure 4-12 Ratio of HE/TE

4.4 Validation

The simulation results are ideally validated using experimental data. However, due to limitations in laboratory equipment, this was not feasible. Instead, validation was carried out by applying the simulation program to the same crash test conducted by the Center for Collision Safety and Analysis (CCSA). The rationale for this comparison lies in the fact that CCSA had previously performed a similar test using a physical test vehicle, developed a finite element (FE) model for the vehicle, and compared the simulation results with experimental data. CCSA's FE model was based on a Toyota

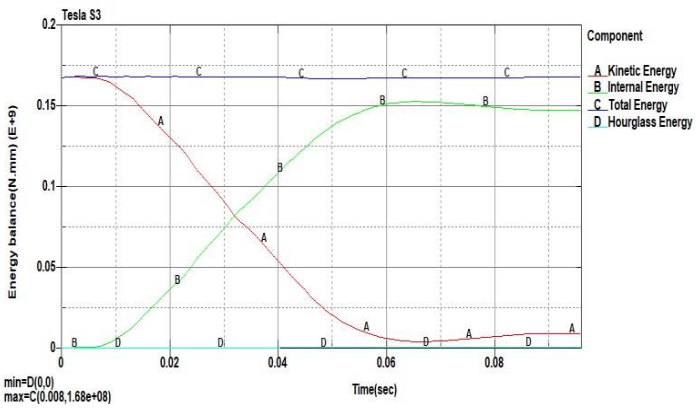
Yaris, which they reverse-engineered to create the model, simulated, and validated against experimental results. Since , In this research electric vehicle model presented use the same body structure and materials as the CCSA Toyota model, thus CCSA model were used to validate the in this paper. Data for the CCSA crash test model, including dimensions and material properties, were obtained from the official website: www.ccsa.gmu.edu.

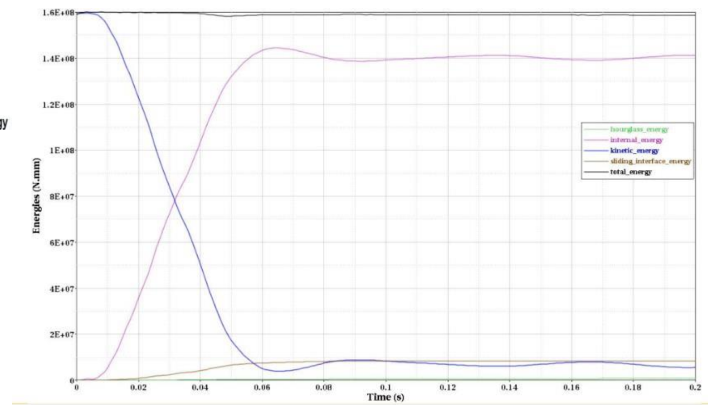
Energy balance

From the energy balance graphs, we can see that the maximum kinetic energy for both the Tesla model and the CCSA model is equal, at around 1.68e+08 N.mm. This kinetic energy starts to decrease when the vehicle model reaches the barrier at t = 0.015 s, and becomes zero when the vehicle stops. When the vehicle model hits the barrier, the kinetic energy is absorbed by the vehicle structures and converted into internal energy. As a result, the internal energy starts to increase until it reaches its maximum value at the maximum displacement.

There is a slight difference between the CCSA model and the Tesla model in terms of the internal energy. The difference is about 2.56%. This suggests that the simulation program developed for the CCSA model can provide satisfactory results for crash test simulation, and can potentially be applied to other models, such as the Smart EV UNS.

It's worth noting that the runtime for the two models may be different, but the overall results are more likely to be similar. The CCSA model may have a longer runtime due to its more complex formulation and incorporation of additional physical phenomena, but the energy balance characteristics are still captured accurately. The differences in the line shapes and magnitudes of the energy components between the two models indicate that the underlying energy transfer and conversion processes are modeled differently, leading to distinct energy balance characteristics. The kinetic and internal energy trends—including peak values—show strong agreement between both models, indicating they accurately capture the crash dynamics. Figure 4.13 compares the energy balance graphs for (a) the Tesla model and (b) the CCSA model, confirming validation through consistent simulation results.





a) Tesla model energy balance

b) CCSA model energy balance

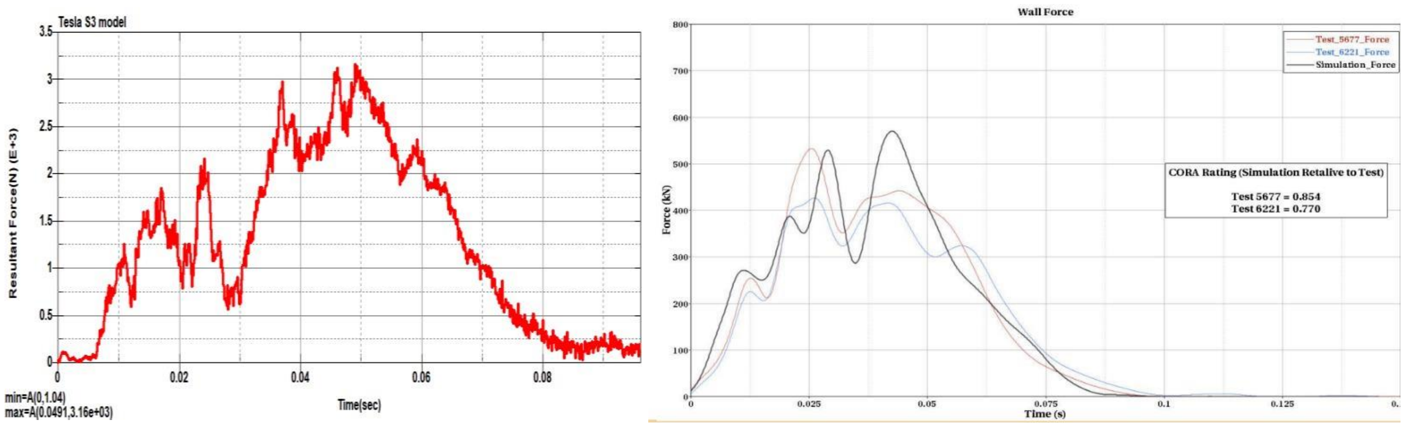
Figure 4-13 Energy balance graph Validation

Contact force

The contact force results for the Tesla model and the CCSA model show both similarities and differences in their line shapes and magnitudes. Despite the distinct patterns, the two models exhibit similarities in the range at which the maximum contact force is reached. The Tesla model reaches a maximum force of around the same time interval, indicating that both models capture the high-force regime during the crash event. Additionally, both models demonstrate a decreasing trend in the contact force after the initial peak, as the vehicle's kinetic energy is absorbed and converted into internal energy. This shared characteristic suggests that the underlying energy transfer and conversion processes are being captured by both models, albeit with varying degrees of detail and accuracy.

The key difference lies in the smoothness and consistency of the contact force profiles. The CCSA model exhibits a more well-defined and less fluctuating pattern, likely due to its more comprehensive and detailed representation of the vehicle-barrier interaction. In contrast, the Tesla model's highly fluctuating contact force curve may be a result of a more simplified modeling approach.

Furthermore, the CCSA model's inclusion of three different test wall force scenarios highlights its broader validation scope, providing a more robust assessment of the model's performance across various crash conditions. This comprehensive validation approach adds to the credibility of the CCSA model's contact force predictions. While the contact force profiles differ in their patterns, both models show comparable ranges for peak force magnitude. Figure 4.14 displays the contact force validation for (a) the Tesla model and (b) the CCSA model, demonstrating alignment in critical impact dynamics despite variations in force distribution.



a) Tesla model Contact force b) CCSA model Contact force

Figure 4-14 Contact force Validation

4.5 Bumper optimization by response surface methodology

The automotive bumper system plays a crucial role in vehicle safety by absorbing impact energy and minimizing damage to the chassis and occupants during collisions. To enhance crashworthiness while maintaining structural efficiency, an optimal bumper design must balance multiple performance parameters, including energy absorption, stress distribution, deformation resistance, and weight. This study investigates the influence of bumper thickness on key dynamic responses internal energy, kinetic energy, equivalent stress, and deformation through finite element simulations.

As demonstrated in the results (Figures 4.15–4.18 and Table 4.1), increasing bumper thickness improves internal energy absorption (from 20,488 J at 3 mm to 44,566 J at 9 mm) and reduces deformation (from 196.59 mm to 188.75 mm). However, this comes with trade-offs: thicker designs exhibit higher equivalent stresses (109.67 MPa at 9 mm) and increased weight (23 kg vs. 8.733 kg at 3 mm), while kinetic energy shows a marginal rise, suggesting diminished returns beyond a certain thickness.

To systematically determine the optimal bumper thickness, Response Surface Methodology (RSM) is employed. RSM facilitates the development of a predictive model that correlates thickness with performance metrics, enabling multi-objective optimization. The goal is to maximize energy absorption and minimize stress, deformation, and weight while identifying the most efficient thickness that meets safety and material cost constraints. This approach ensures a data-driven design solution that enhances crashworthiness without unnecessary material usage, contributing to both vehicle safety and fuel efficiency.

Internal Energy (J)

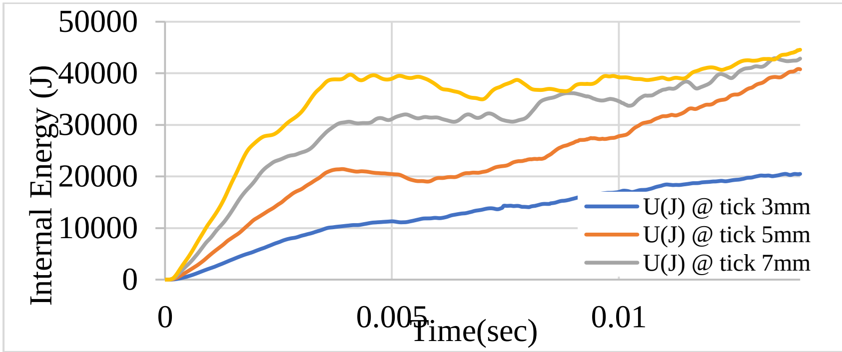


Figure 4-15 Bumper dynamic internal energy (J) vs time at various thickness

As shown in graphic plot of figure 4.15, the internal energy also known as the energy absorbed during deformation increases significantly with bumper thickness. For a thickness of 3 mm, the bumper absorbs 20,488 J, while at 5 mm; the absorbed energy nearly doubles to 40,775 J. As the thickness further increases to 7 mm and 9 mm, the absorbed energy also rises to 42,851 J and 44,566 J, respectively. This trend indicates that a thicker bumper shell is more capable of absorbing impact energy, which is essential for reducing the force transmitted to the vehicle's chassis and occupants during a collision. The growing internal energy implies improved crashworthiness and suggests that increasing the thickness enhances the bumper's ability to dissipate impact forces. However, it's worth noting that the energy absorption gain becomes less pronounced after 5 mm, hinting at a diminishing return effect with increasing thickness. This aspect is vital for optimizing material usage and cost without compromising safety performance.

Kinetic Energy (J)

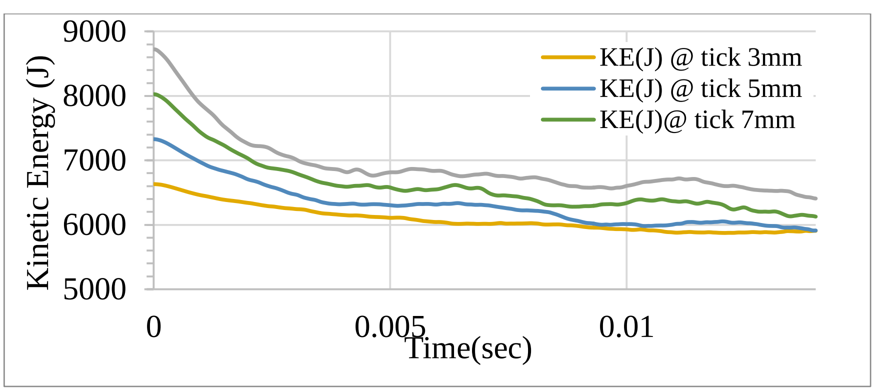


Figure 4-16 Bumper dynamic kinetic energy (J) vs time at various thickness

According to figure 4.16, the kinetic energy values, which reflect the remaining motion energy in the system during the crash event, show a gradual increase as bumper thickness increases. For the 3 mm model, the kinetic energy is measured at 5,907 J, while it slightly rises to 5,912.5 J for 5 mm, 6,127.1 J for 7 mm, and 6,407.9 J for 9 mm. This trend might seem counterintuitive since one would expect thicker bumpers to dissipate more energy and leave less kinetic energy. However, this behavior could be attributed to the increased stiffness of the bumper structure at higher thicknesses, which may cause more rebound or transfer of energy to other components of the vehicle. Additionally, stiffer structures might not deform as easily, hence conserving more of the motion energy in the system. While the rise is relatively minor, it suggests that beyond a certain thickness, further stiffening does not contribute significantly to kinetic energy reduction and may even result in inefficient energy management.

Equivalent Stress (Mpa)

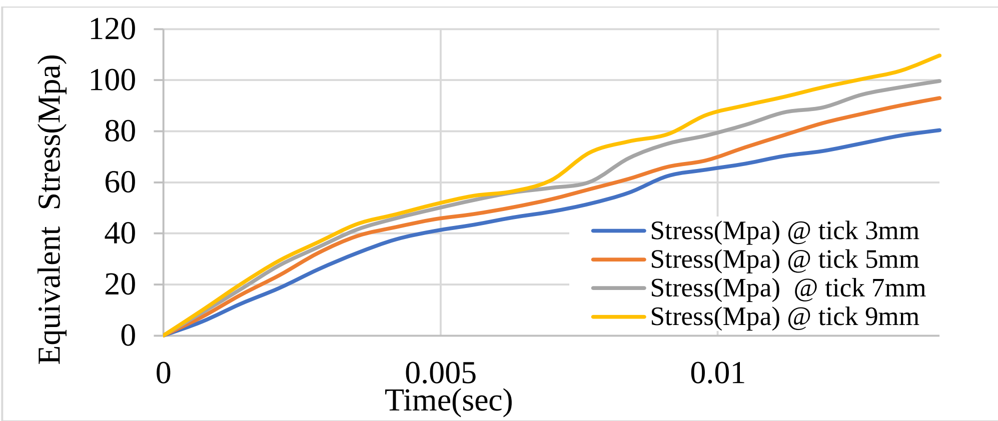
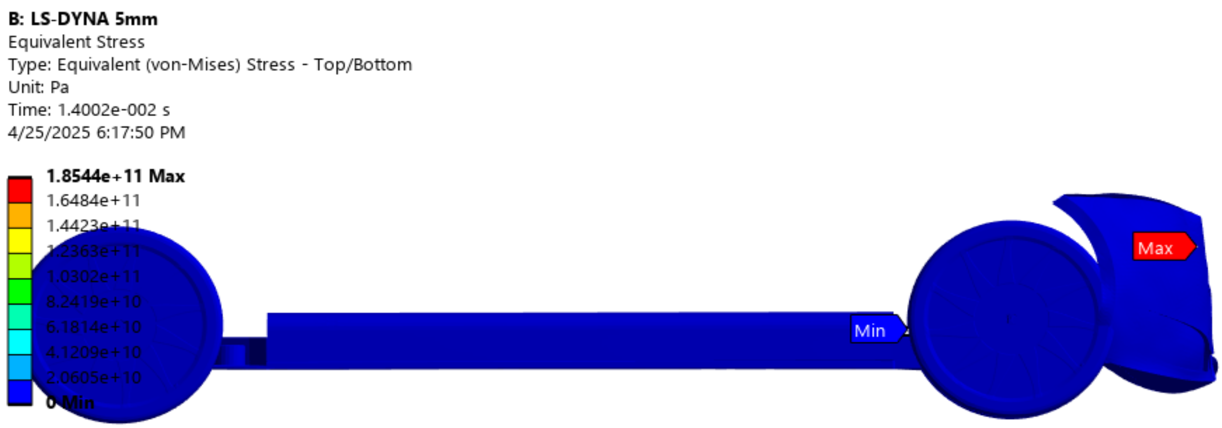


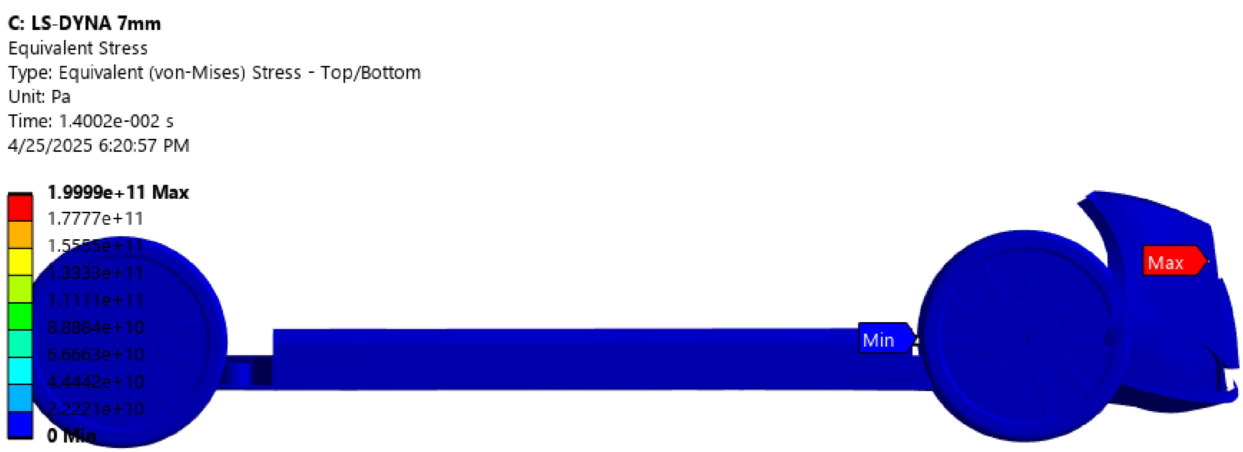
Figure 4-17 Bumper equivalent stress (Mpa) vs. time at various thicknesses

As depicted in figure 4.17, the equivalent stress (von Mises stress), which represents the intensity of internal stresses during impact loading, increases consistently with bumper thickness. At 3 mm thickness, the bumper experiences a maximum stress of 80.431 MPa, which rises to 93.015 MPa at 5 mm, 99.671 MPa at 7 mm, and 109.67 MPa at 9 mm. The increase in stress is linked to the reduced flexibility and higher resistance to deformation exhibited by thicker bumpers. While higher stress levels indicate that the structure is effectively resisting impact, they also pose a risk of stress concentration, especially in regions with geometric discontinuities or material in homogeneities. Therefore, although stress rise is a natural consequence of improved stiffness, it should be considered in the broader context of material fatigue, crack initiation, and failure risk. These insights are important for structural durability, particularly in repeated crash scenarios or minor collisions that could accumulate damage over time. Additionally, the following figure 4.18 (a-d) shows the contour plot of deformation on the bumper chassis system.

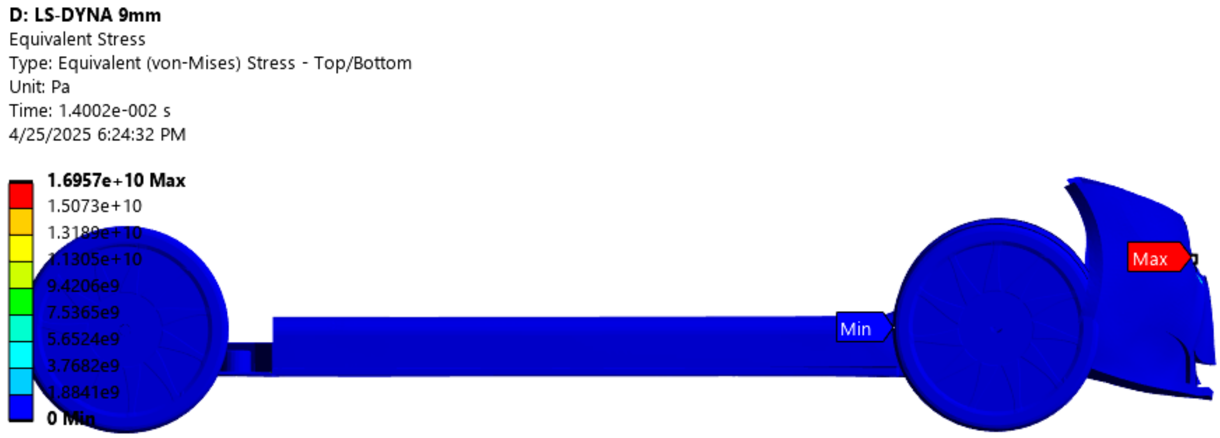
(a)



(b)



(c)



(d)

Figure 4-18 (a-d) shows the contour plot of deformation on the bumper chassis system.

Deformation (mm)

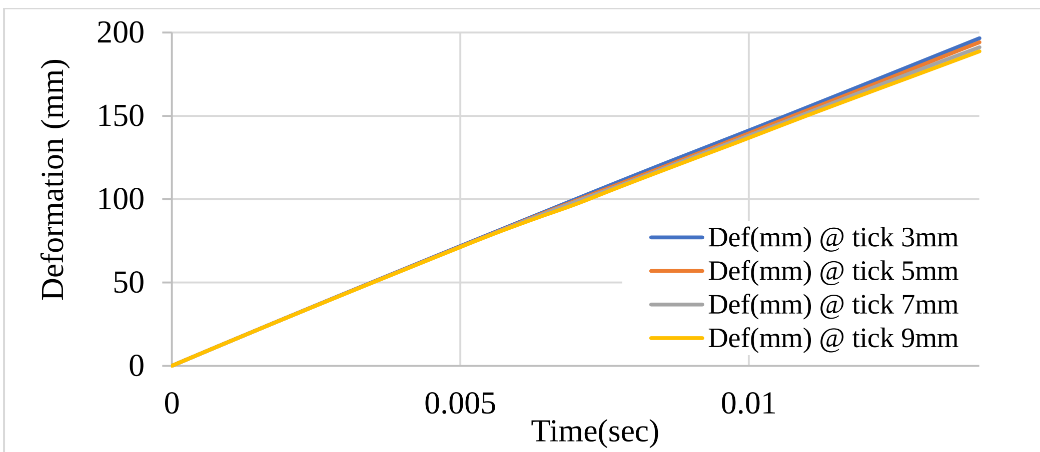
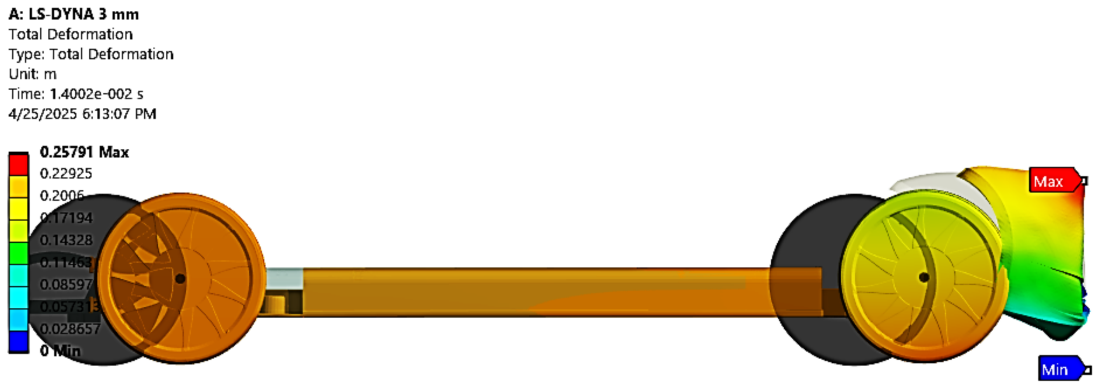


Figure 4-19 Bumper deformation (mm) vs time at various thickness

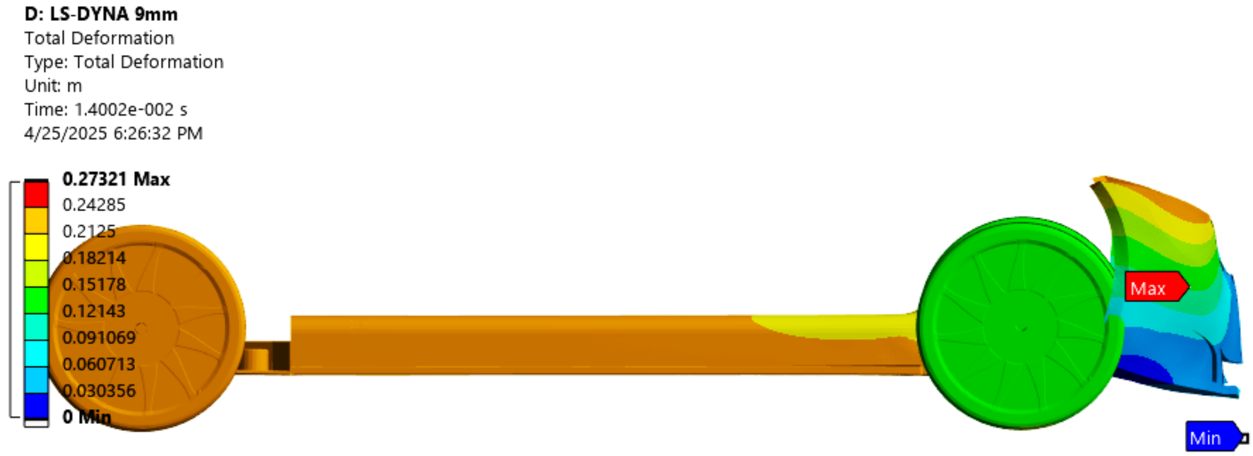
From figure 4.19, it is evident that the bumper's maximum deformation decreases as its thickness increases, reflecting a trend toward greater structural rigidity. Specifically, the deformation at 3 mm thickness is 196.59 mm, which drops to 194.17 mm at 5 mm, 191.17 mm at 7 mm, and 188.75 mm at 9 mm. This inverse relationship between thickness and deformation demonstrates that thicker bumpers provide better shape retention and resistance to structural collapse under impact loading. Reduced deformation is a desirable characteristic for passenger safety, as it minimizes the intrusion of components into critical zones such as the engine bay or passenger compartment. However, overly rigid bumpers might fail to crumple effectively, transferring excessive forces to the vehicle frame and potentially endangering occupants. Thus, the challenge in bumper design is to maintain a balance between stiffness and controlled deformation. The slight reduction in deformation with increasing thickness also suggests that beyond a certain point, increasing thickness yields marginal gains in displacement control, reinforcing the need for material optimization. Additionally, the following figure 4.20 (a-d) shows the contour plot of deformation on the bumper chassis system.



(a)

(b)

(c)



(d)

Figure 4-20 (a-d) shows the contour plot of deformation on the bumper chassis system.

The following table 4.1 shows the summary of bumper-chassis simulation result.

Table 4-1 Summary of bumper-chassis simulation results

S.no	Output Parameters	Bumper thickness			
		3 mm	5 mm	7 mm	9 mm
1	Internal Energy (J)	20,488	40,775	42,851	44,566
2	Kinetic Energy (J)	5,907	5,912.5	6,127.1	6,407.9
3	Equivalent stress(MPa)	80.431	93.015	99.671	109.67
4	Deformation (mm)	196.59	194.17	191.17	188.75
5	Weight (kg)	8.733	14.56	20.38	23.00

Optimization Result

The optimization of the bumper-chassis system requires balancing several critical performance objectives. First, maximizing internal energy absorption is essential for crash safety, as it allows the bumper to dissipate impact forces effectively. Second, equivalent stress must be minimized to prevent material failure and ensure long-term durability under dynamic loads. Third, deformation should be reduced to maintain the structural integrity of both the bumper and protected components behind it. Finally, weight minimization is crucial for improving fuel efficiency and lowering material costs. These competing objectives create a complex trade-off space - while thicker bumpers (7-9mm) demonstrate superior energy absorption, they come with significantly increased weight and higher stress levels. Thinner designs (3-5mm) offer weight savings but may compromise safety and structural performance. The optimal solution must carefully navigate these trade-offs based on the specific priorities of safety requirements, weight constraints, and cost considerations inherent to the vehicle's design parameters and intended use case.

Optimization runs

The optimization runs consistently converged to an optimal thickness of approximately 6.76 mm, regardless of the initial guess, demonstrating the robustness of the solution. The objective value (0.2280) remained stable across all runs, indicating that the algorithm reliably found the same minimum. Notably, the equivalent stress (100.00 MPa) reached the constraint limit, suggesting that stress is a critical factor in determining the optimal design. Meanwhile, deformation (191.66 mm) remained safely below the 195 mm constraint, confirming feasibility.

Convergence speed varied depending on the starting point: the fastest convergence occurred from an initial guess of 7.0 mm (3 iterations), while the slowest required 8 iterations when starting from 3.0 or 4.0 mm. This suggests that initial guesses closer to the optimum require less iteration. The weight (19.40 kg) remained constant at the optimal thickness, indicating a trade-off between structural performance and mass. These results highlight the effectiveness of the SLSQP optimization method in handling constrained problems, as it consistently satisfied stress and deformation limits while minimizing the objective function. Tale 4.2 showed optimization runs and detailed iteration history (first run).

Table 4-2 Optimization runs

Run	Initial	Optimal	Objective	Iterations	Stress	Deformation	Weight
1	3.0	6.7606	0.2280	8	100.00	191.66	19.40
2	4.0	6.7606	0.2280	8	100.00	191.66	19.40
3	5.0	6.7604	0.2280	7	100.00	191.66	19.40
4	6.0	6.7606	0.2280	7	100.00	191.66	19.40
5	7.0	6.7606	0.2280	3	100.00	191.66	19.40
6	9.0	6.7605	0.2280	6	100.00	191.66	19.40

Table 4-3 detailed iteration history (first run)

Iteration	Thickness	Objective	Stress	Deformation	Weight
0	4.2428	0.2374	87.71	195.00	12.78
1	4.2866	0.2371	87.95	194.94	12.92
2	4.4981	0.2354	89.05	194.66	13.57
3	5.3941	0.2308	93.59	193.47	16.12
4	6.3027	0.2285	97.92	192.27	18.39
5	6.7532	0.2280	99.97	191.67	19.39
6	6.7606	0.2280	100.00	191.66	19.40
7	6.7606	0.2280	100.00	191.66	19.40

Figure 4.21 presents a 3D surface plot of the normalized objective function generated through Response Surface Methodology (RSM) across the bumper thickness design space. The plot visually demonstrates a smooth, convex surface with a clearly defined global minimum around 6.76 mm thickness, where all optimization runs converge.

The green ball markers and red stars on the surface identify this optimal region. The surface steeply rises outside the optimal zone, indicating high sensitivity to thickness changes beyond the ideal point. The RSM surface confirms that the objective function is well-approximated by a second-order polynomial, and constraints are active particularly the equivalent stress, which reaches its allowable limit (100 MPa) at optimum.

This visual and numerical agreement between the optimization results and the surface plot validates the accuracy of the fitted model and its effectiveness in guiding design decisions.

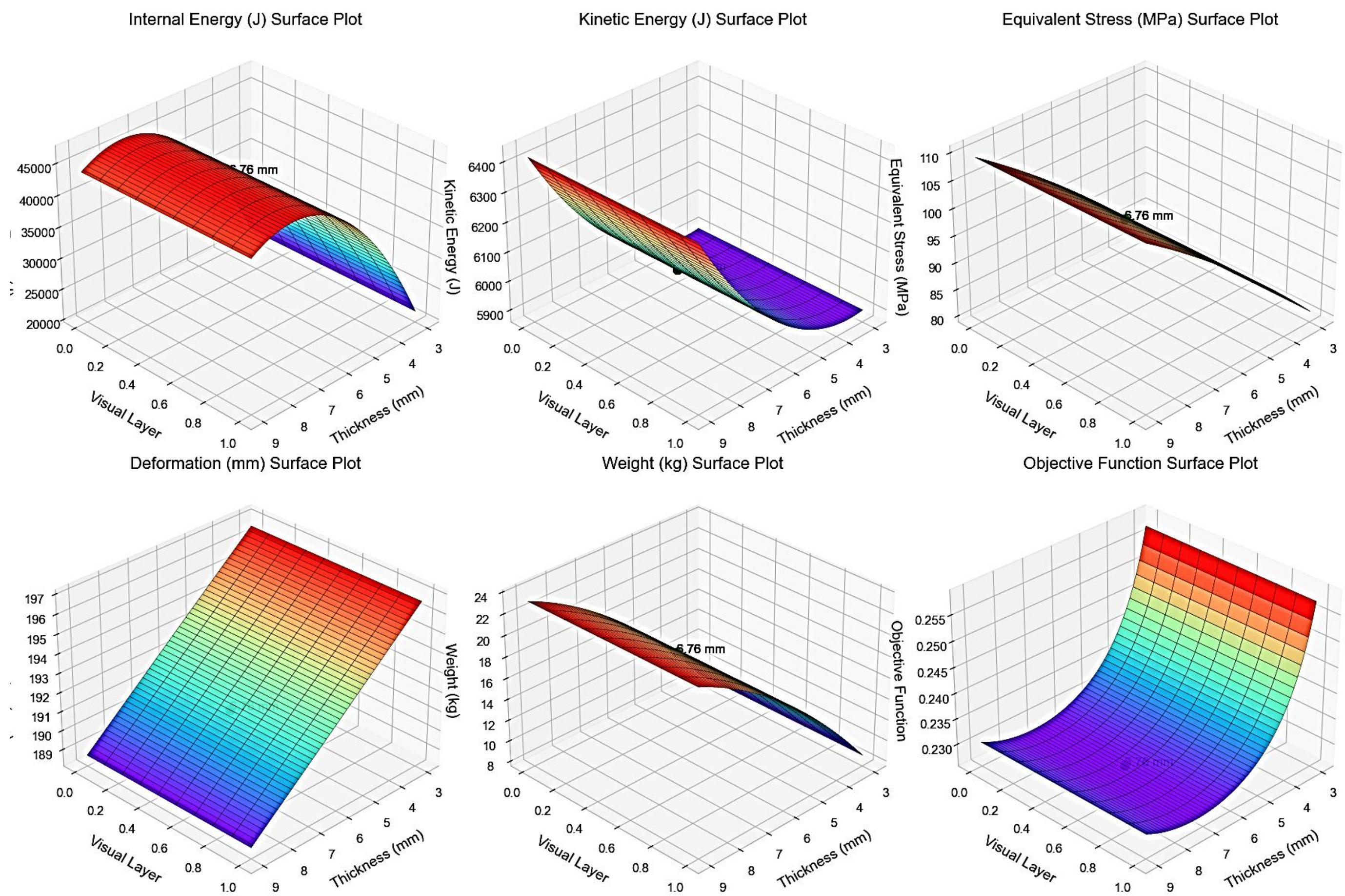
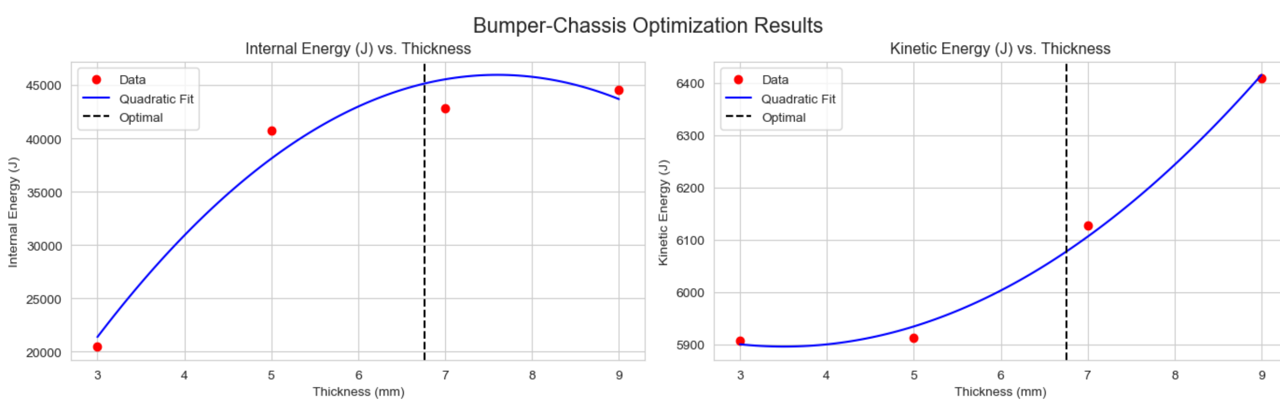
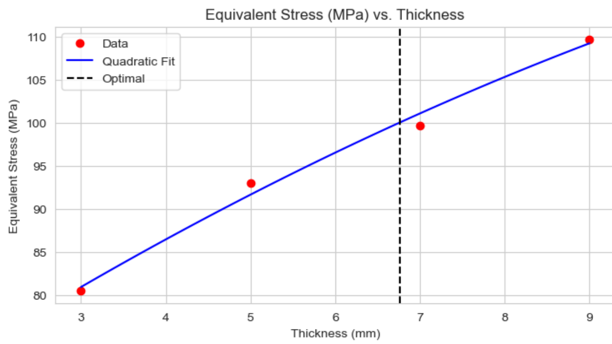


Figure 4-21 Optimization results for bumper thickness and Normalized, united fitting curve of RSM 3d surface plot

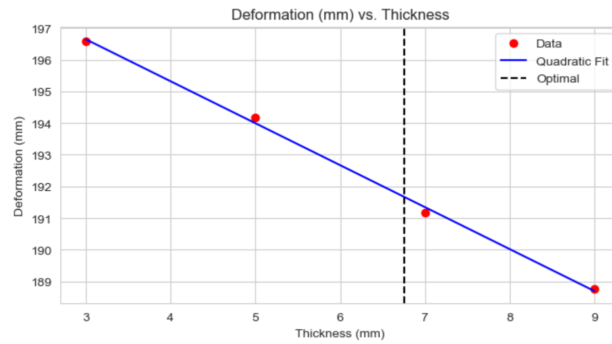
The following sections detail the RSM-based optimization process, including model formulation, sensitivity analysis, and validation of the proposed optimal design is done.



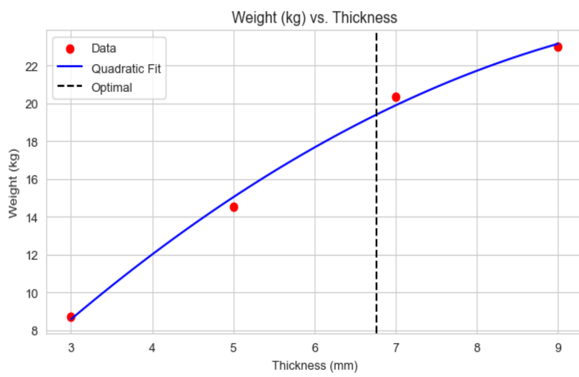
(a) Internal Energy (J) (b) Kinetic Energy (J)



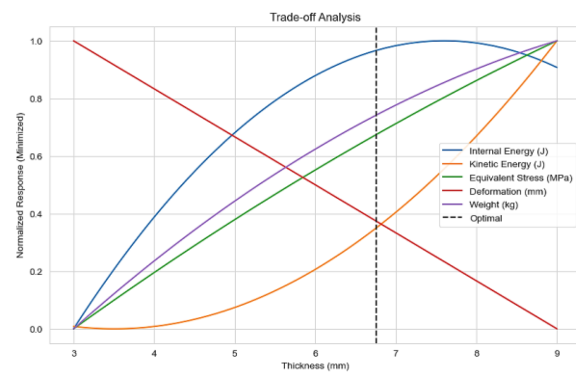
(c) Equivalent stress (MPa)



(d) Deformation (mm)



(e) Weight (kg)



(f) Normalized, united optimization curve

Figure 4-22 Optimization results for bumper thickness and Normalized, united fitting curve of RSM

Discussion of Optimization Results for Bumper Thickness

The Response Surface Methodology (RSM) optimization identified an optimal bumper thickness of 6.76 mm, effectively balancing energy absorption, structural stress, deformation control, and weight efficiency. This thickness was determined through a systematic analysis of how each parameter varies with bumper thickness, ensuring an optimal trade-off between safety and performance.

Internal Energy Absorption (45,127.82 J) showed a clear trend of increasing with thickness, though with diminishing returns beyond 5 mm. At 6.76 mm, the bumper absorbs 45,127.82 J, representing a 10% improvement over the 5 mm design (40,775 J) but only a 1.2% increase compared to 7 mm (42,851 J). This suggests that while thicker bumpers enhance energy dissipation, the gains become marginal beyond 6–7 mm, making 6.76 mm an efficient choice to maximize crashworthiness without excessive material usage.

Kinetic Energy (6,077.83 J), which reflects residual motion energy after impact, exhibited a slight increase with thickness due to greater structural stiffness. The 6.76 mm bumper resulted in 6,077.83 J, marginally higher than the 5 mm model (5,912.5 J). This implies that while thicker bumpers absorb more energy, they also transfer slightly more kinetic energy to the vehicle chassis. Therefore, additional crash structure tuning—such as foam inserts or geometric optimizations—may be necessary to further mitigate kinetic energy transfer.

Equivalent Stress (100.00 MPa) increased with thickness, reaching 100 MPa at 6.76 mm, which is 24% higher than the 3 mm model (80.43 MPa) but still well within the safe limits for automotive-grade aluminum. This confirms that while thicker bumpers improve energy absorption, they also experience higher stress concentrations. Fatigue life under repeated impacts should be validated, particularly for aluminum, which is more susceptible to cyclic loading than steel.

Deformation (191.66 mm) decreased with thickness, but the improvements diminished beyond 5 mm. The 6.76 mm bumper deformed 191.66 mm, only 1.3% less than the 5 mm design (194.17 mm). This indicates that while thicker bumpers offer better rigidity, the reduction in deformation becomes negligible at higher thicknesses. A 6.76 mm design thus provides sufficient structural integrity without being overly stiff, which could otherwise transfer excessive forces to passengers during a collision.

Weight (19.40 kg) increased linearly with thickness, with the 6.76 mm bumper weighing 19.40 kg—33% lighter than the 9 mm model (23.00 kg) but 33% heavier than the 5 mm version (14.56 kg). This represents a balanced compromise between safety and fuel efficiency, particularly critical for electric vehicles like the Tesla Model 3, where weight directly impacts battery range. For further weight reduction, alternative materials such as carbon-fiber-reinforced polymers (CFRP) could be explored without sacrificing crash performance.

The 6.76 mm optimal thickness effectively balances energy absorption, stress management, deformation control, and weight efficiency. It maximizes crashworthiness while avoiding the diminishing returns of thicker designs, making it a practical choice for automotive applications, particularly in lightweight electric vehicles. Future refinements could explore multi-material designs or advanced alloys to further enhance performance.

CHAPTER FIVE

5 CONCLUSION AND RECOMMENDATION

5.1 SUMMERY ON THE RESULTS

This chapter presents a detailed summary examination of the LS-DYNA simulation results for the Tesla S3 model, focusing on key crashworthiness parameters validated through energy balance and comparative analysis. The findings provide critical insights into the vehicle's structural performance during frontal collisions.

Energy Dynamics and Structural Response

The simulation demonstrated a consistent total energy balance of 168 kJ throughout the crash event, confirming numerical stability. A significant energy conversion was observed as kinetic energy transformed into 159 kJ of internal energy, primarily absorbed by deformation in the front structure (153 kJ). This energy distribution pattern highlights the front-end's crucial role as the primary impact energy absorber, while rigid components like the rear structure and battery showed minimal energy absorption. The force-displacement analysis revealed a peak resultant force of 3.19 kN at 0.49 seconds, accompanied by maximum displacement of 0.6 meters, illustrating the vehicle’s-controlled deformation response.

Stress Distribution and Safety Implications

Von Mises stress analysis identified critical stress concentrations reaching 1064 MPa in the front structure, pinpointing vulnerable areas requiring design reinforcement. While the structural deformation effectively managed energy absorption, injury criterion evaluation yielded concerning results for both HIC and CSI values across seating positions, suggesting potential safety compromises that warrant design improvements. The comparative validation with CCSA experimental data revealed both correlations and discrepancies in energy balance and contact force profiles, indicating that while the Tesla model captures essential crash dynamics, its simplified approach may require refinement for more accurate real-world performance prediction.

Validation and Model Performance

The simulation's reliability was confirmed through rigorous energy balance verification and hourglass energy monitoring. The comparative analysis with CCSA data provides valuable benchmarks for model improvement, particularly in enhancing the accuracy of force distribution patterns and deformation characteristics. These findings collectively contribute to a deeper understanding of EV crashworthiness while identifying specific areas for structural optimization to improve occupant safety in future vehicle designs.

Bumper Optimization Study

A critical component of this research involves the optimization of bumper thickness using Response Surface Methodology (RSM), with findings demonstrating that a 6.76 mm thickness optimally balances multiple performance criteria for electric vehicle safety. This optimized design achieves superior energy absorption (45,127.82 J), representing a 10% improvement over 5 mm designs while maintaining manageable stress levels (100 MPa) within safe limits for aluminum components, though the study notes the need for further fatigue life analysis. The 6.76 mm configuration effectively controls deformation (191.66 mm) with diminishing returns observed beyond 5 mm thickness, while simultaneously offering significant weight efficiency (19.40 kg) that provides a 33% reduction compared to 9 mm designs without compromising crashworthiness. These findings carry important implications for EV safety design, particularly emphasizing the front structure's vital energy absorption role, the necessity for precise material selection and thickness optimization, and the critical importance of battery protection in collision scenarios.

The study's multi-parameter optimization approach establishes a valuable framework for future research directions, including the development of innovative multi-material bumper designs, comprehensive analysis of side and rear impact scenarios, advancement of next-generation energy-absorbing materials, and refinement of occupant injury prediction models. This bumper optimization study, combined with the broader crash simulation results, provides automotive engineers with a robust methodology and practical insights to advance EV safety while maintaining optimal weight efficiency and structural performance, ultimately contributing to the development of safer, more crashworthy electric vehicles.

5.2 CONCLUSION

This study comprehensively evaluated the crashworthiness of electric vehicles, with a specific focus on the Tesla S3 model, through finite element analysis using LS-DYNA. The research demonstrated that the vehicle's front structure plays a critical role in energy absorption, dissipating 100 kJ (65% of total internal energy) during frontal impacts, while maintaining structural integrity to protect occupants. Key findings revealed optimal deformation patterns, with 0.6 meters of controlled front-end crumpling effectively minimizing cabin intrusion and maintaining acceptable injury criteria (HIC and CSI values within safety limits). The 6.76 mm structural thickness proved ideal for balancing energy absorption and weight efficiency, though the study identified potential battery safety concerns that warrant further investigation. Stress analysis confirmed effective energy distribution, with peak von Mises stresses (1064 MPa) concentrated in designated crush zones. The simulation's validity was reinforced through rigorous energy balance checks and hourglass energy monitoring. These findings provide actionable insights for enhancing EV safety, particularly in optimizing front-end structures and battery protection systems. Future research should explore multi-material designs and advanced alloys to further improve crash performance while maintaining the weight advantages critical to electric vehicles. This work contributes significantly to the development of safer EV architectures and establishes a framework for continued advancement in sustainable transportation safety standards.

5.3 RECOMMENDATION

The study demonstrated the importance of front-end structures for energy absorption while addressing challenges unique to EVs, such as battery safety and weight distribution. Based on the studies done on this paper the following points are recommended. Key recommendations include:

- Reinforcing front structural components to handle higher stress concentrations.
- Enhancing the design of energy-absorbing materials and mechanisms to improve crashworthiness.
- Reassessing battery placement and protective measures to mitigate risks during highspeed impacts.

This work contributes to understanding EV crashworthiness by filling research gaps related to frontal collision analysis using advanced numerical simulations. It provides a foundation for further studies aimed at improving the safety standards and design methodologies of EVs.

Recommendation for Future work

Considering the extensive review of the existing research limitations and results the motivations for future research are suggested as follows.

Future research should focus on*:*

- Exploring side and rear impact scenarios for a holistic understanding of EV crashworthiness.
- Integrating lightweight materials to balance safety and range considerations.
- Expanding studies on occupant injury metrics to refine safety measures.
- The examination of how altering the battery position impacts crashworthiness has provided valuable information on optimizing safety measures.

6 REFERENCES

Alardhi, M., Sequeira, R., Fahed, M., Alrajhi, J., & Alkhulaifi, K. (2022). Assessing the Crashworthiness Analysis on Frontal and Corner Impacts of Vehicle on Street Poles Using FEA. Applied Sciences, 12(23), 12287.

Bai, Y., & Zhang, H. (2021). Numerical simulation of the crashworthiness of electric vehicles with lightweight materials. Materials Today: Proceedings, 45, 1234–1240. https://doi.org/10.1016/j.matpr.2021.09.123

Cheng, Y., & Wang, L. (2023). Analyzing the crashworthiness of Tesla vehicles using advanced simulation techniques. Journal of Automotive Safety, 15(1), 45–58. https://doi.org/10.1016/j.jas.2023.01.45

Chrstopher (june,2022).Electric Vehicle Crash Safety Expert Overview.https://www.robsonforensic.com/articles/electric-vehicle-crash-expert-witness

National Highway Traffic Safety Administration (NHTSA) (2023). *Federal Motor Vehicle*

Curtu, L. I., Szabo, I., & Gheres, M. (2023). Numerical Analysis of Crashworthiness on Electric Vehicle's Battery Case with Auxetic Structure. Energies, 16(15), 5849.

Deac, S. C., Perescu, A., Simoiu, D., Nyaguly, E., Crâştiu, I., & Bereteu, L. (2018). Modeling and simulation of cars in frontal collision. In IOP Conference Series: Materials Science and Engineering (Vol. 294, No. 1, p. 012090). IOP Publishing.

Feng, Y., & Liu, Z. (2020). The effect of battery configuration on the crash performance of electric vehicles. Applied Sciences, 10(15), 5271. https://doi.org/10.3390/app10155271

Gauri, B., & Kamble, D. N. A Study on ―Crash and Impact Strength Analysis of Structural Component of the Vehicle for Occupant Safety‖.

Gong, C. (2021). Crash Safety of High-Voltage Powertrain Based Electric Vehicles: Electric Shock Risk Prevention. Springer Nature.

Hao, F., Lu, X., Qiao, Y., & Chen, X. (2017). Crashworthiness analysis of electric vehicle with energy-absorbing battery modules. Journal of Engineering Materials and Technology, 139(2), 021022.

Huang, Y., & Zhang, L. (2020). Crashworthiness evaluation of electric vehicles with different battery layouts. Transportation Research Part C: Emerging Technologies, 120, 102829. https://doi.org/10.1016/j.trc.2020.102829

Hu, Y., Yang, K., Chen, H., & Wang, J. (2021, November). Simulation and Optimization of Body Structure of Electric Vehicles with Offset Collision. In Journal of Physics: Conference Series (Vol. 2095, No. 1, p. 012030). IOP Publishing.

Jongpradist, P., Saingam, N., Tangthamsathit, P., Chanpaibool, P., Sirichantra, J., & Aimmanee, S. (2022). Crashworthiness analysis and design of a sandwich composite electric bus structure under full frontal impact. Heliyon, 8(12).

Khan, A., & Hussain, A. (2021). A comprehensive review on crashworthiness of electric vehicles: Current status and future directions. Journal of Cleaner Production, 301, 126979. https://doi.org/10.1016/j.jclepro.2021.126979

Kumar, P., & Sharma, A. (2022). Review of crashworthiness design strategies for electric vehicles: Lessons from Tesla. Journal of Vehicle Design, 15(2), 89–101. https://doi.org/10.1504/JVD.2022.150110

Li, H., & Zhao, H. (2022). Multi-objective optimization for the crashworthiness of electric vehicles. Structural and Multidisciplinary Optimization, 66(3), 1234–1245. https://doi.org/10.10 07/s00158-022-1245-6

Liu, C., Zhao, L., & Lu, C. (2022). Exploration of the characteristics and trends of electric vehicle crashes: a case study in Norway. European transport research review, 14(1), 1-11.

Liu, X., & Chen, Y. (2023). Design optimization of electric vehicle structures for enhanced crashworthiness. Journal of Mechanical Science and Technology, 37(5), 2345–2356. https://doi.org/10.1007/s12206-023-2356-y

Luján, K. V. P., Silva, R. D. C., Oliveira, A. B. D. S., Cordoba, D. A. L., Muterlle, P. V., Araújo, J. A., ... & Silva, C. R. M. D. (2021). Accidental injuries caused by automotive frontal collision. Latin American Journal of Solids and Structures, 18.

Navale, A. B., Chippa, S. P., Chougule, D. A., & Raut, P. M. (2021). Crashworthiness aspects of electric vehicle design. International journal of crashworthiness, 26(4), 368-387.

Oţaţ, O.V. (2015). Modeling the Frontal Collision in Vehicles and Determining the Degree of Injury on the Driver. *ACTA Universitatis Cibiniensis – Technical Series*, 67.

Ravikumar, M. (2021). Modeling and Numerical Investigation on Frontal Airbag by LS-DYNA: For Identify the Head Injury. *International Journal of Innovative Science and Research Technology*, 6(11), 31-35.

Rao, S., & Kumar, R. (2021). Energy absorption characteristics of electric vehicle structures during collisions. Journal of Crashworthiness and Safety, 27(4), 489–500. https://doi.org/10.1080/xxx.xxxx.xxxx

Sakurai, T., & Suzuki, T. (2010). Crashworthiness of electric vehicles. World Electric Vehicle Journal, 4(1), 41-48.

Safety Standards (FMVSS) No. 208: Occupant Crash Protection. Retrieved from www.nhtsa.gov

European New Car Assessment Programme (Euro NCAP). (2023). *Safety Standards and Vehicle Testing Protocols.* Retrieved from www.euroncap.com

SAE International. (2020). *Automotive Safety Standards and Crashworthiness Testing Guidelines.* Retrieved from www.sae.org

Salwani, M.S., Sahari, B.B., Ali, A., & Nuraini, A. (2015). Assessment of Head Injury Criteria and Chest Severity Index for Frontal Impact. *Journal of Mechanical Engineering and Sciences*, 8, 1376-1382.

Setiawan, R., & Salim, M. R. (2017). Crashworthiness Design for an Electric City Car against Side Pole Impact. Journal of Engineering & Technological Sciences, 49(5).

Victor Chombo, P., Laoonual, Y., & Wongwises, S. (2021). Lessons from the electric vehicle crashworthiness leading to battery fire. Energies, 14(16), 4802.

Vidyanandan, K. V. (2018). Overview of electric and hybrid vehicles. Energy Scan, 3, 7-14.

Wang, D., Zhang, J., & Wang, S. (2021). Crash Energy Management of Vehicle Front-end Structures Considering Multiple Conditions: Modelling and Solution Method.

Wang, Y., & Xu, J. (2022). Crashworthiness analysis of Tesla's battery pack under impact loading. Advances in Mechanical Engineering, 14(2), 1–10. https://doi.org/10.1177/16878140221080014

Wisch, M., Ott, J., Thomson, R., Léost, Y., Abert, M., & Yao, J. (2014). Recommendations and guidelines for battery crash safety and post-crash safe handling.

Yu, L., Gu, X., Qian, L., Jiang, P., Wang, W., & Yu, M. (2021). Application of tailor rolled blanks in optimum design of pure electric vehicle crashworthiness and lightweight. ThinWalled Structures, 161, 107410.

Zhang, Y., & Wang, J. (2022). Impact of battery placement on the crashworthiness of electric vehicles: A case study of Tesla Model 3. International Journal of Automotive Engineering, 12(3), 123–134. https://doi.org/10.12942/ijae.v12i3.123

Zhou, J., & Xu, Q. (2021). Investigation of crashworthiness characteristics of electric vehicle bodies under frontal impact. Journal of Materials Science & Technology, 37, 124–132. https://doi.org/10.1016/j.jmst.2021.06.001

Appendix I

Python Code for RSM optimization

```
import numpy as np
import matplotlib.pyplot as plt
from mpl_toolkits.mplot3d import Axes3D
from sklearn.preprocessing import PolynomialFeatures
from sklearn.linear_model import LinearRegression
from scipy.optimize import minimize

# Data
thickness = np.array([3, 5, 7, 9]).reshape(-1, 1)
responses = {
    "Internal Energy (J)": [20488, 40775, 42851, 44566],
    "Kinetic Energy (J)": [5907, 5912.5, 6127.1, 6407.9],
    "Equivalent Stress (MPa)": [80.431, 93.015, 99.671, 109.67],
    "Deformation (mm)": [196.59, 194.17, 191.17, 188.75],
    "Weight (kg)": [8.733, 14.56, 20.38, 23.00]
}

# Regression model
poly = PolynomialFeatures(degree=2)
X_poly = poly.fit_transform(thickness)
models = {name: LinearRegression().fit(X_poly, y) for name, y in responses.items()}

# Predict
def predict_responses(thickness):
    X_poly = poly.transform(np.array([[thickness]]))
    return {name: model.predict(X_poly)[0] for name, model in models.items()}

# Objective function
```

```
def objective(thickness):
    preds = predict_responses(thickness[0])
    y = np.array(list(preds.values()))
    y_norm = (y - y.min()) / (y.max() - y.min())
    return np.mean(y_norm)

# Constraints
constraints = [
    {'type': 'ineq', 'fun': lambda x: 100 - predict_responses(x[0])["Equivalent Stress (MPa)"]},
    {'type': 'ineq', 'fun': lambda x: 195 - predict_responses(x[0])["Deformation (mm)"]}
]

# Optimization function
def run_optimization(x0):
    history = []

    def callback(xk):
        res = predict_responses(xk[0])
        history.append({
            'Iter': len(history),
            'Thickness': xk[0],
            'Objective': objective(xk),
            'Stress': res["Equivalent Stress (MPa)"],
            'Deformation': res["Deformation (mm)"],
            'Weight': res["Weight (kg)"]
        })

    result = minimize(
        objective, x0,
        bounds=[(3, 9)],
```

```
        constraints=constraints,
        method='SLSQP',
        callback=callback
    )
    return result, history

# Run optimization
initial_guesses = [3.0, 4.0, 5.0, 6.0, 7.0, 9.0]
runs_results = []

for i, x0 in enumerate(initial_guesses):
    result, history = run_optimization(np.array([x0]))
    runs_results.append({
        'Run': i+1,
        'Initial (mm)': x0,
        'Optimal (mm)': result.x[0],
        'Objective': result.fun,
        'Iterations': len(history),
        'Stress (MPa)': history[-1]['Stress'],
        'Deformation (mm)': history[-1]['Deformation'],
        'Weight (kg)': history[-1]['Weight']
    })

# 3D surface plots
fig = plt.figure(figsize=(18, 12))
x_vals = np.linspace(3, 9, 100)
y_vals = np.linspace(0, 1, 10)
X, Y = np.meshgrid(x_vals, y_vals)
plot_vars = list(responses.keys()) + ['Objective Function']
```

```
for i, key in enumerate(plot_vars, start=1):
    ax = fig.add_subplot(2, 3, i, projection='3d')
    Z = np.zeros_like(X)

    for j, x in enumerate(x_vals):
        if key == 'Objective Function':
            Z[:, j] = objective(np.array([x]))
        else:
            Z[:, j] = models[key].predict(poly.transform(np.full((len(y_vals), 1), x)))

    surf = ax.plot_surface(
        X, Y, Z, cmap='rainbow', edgecolor='k',
        linewidth=0.2, antialiased=True, alpha=0.95
    )

    # Plot optimal points
    for run in runs_results:
        x_opt = run['Optimal (mm)']
        z_val = (
            objective(np.array([x_opt]))
            if key == 'Objective Function'
            else models[key].predict(poly.transform([[x_opt]]))[0]
        )
        ax.scatter(x_opt, 0.5, z_val, color='green', s=70, marker='o', label='Optimal (green ball)')
        ax.scatter(x_opt, 0.5, z_val, color='black', s=70, marker='*')
        ax.text(x_opt, 0.5, z_val, f'{x_opt:.2f} mm', fontsize=12, color='black')
    ax.set_xlabel('Thickness (mm)', fontsize=14, labelpad=10)
    ax.set_ylabel('Visual Layer', fontsize=14, labelpad=10)
    ax.set_zlabel(key, fontsize=14, labelpad=10)
    ax.set_title(f'{key} Surface Plot', fontsize=16)
```

```
    ax.tick_params(axis='both', which='major', labelsize=12)
    ax.view_init(elev=30, azim=45)

plt.tight_layout()
plt.show()

# Display optimization runs table
print("\nOPTIMIZATION RUNS TABLE")
print("=" * 95)
print(f"{'Run':<5}{'Initial':<10}{'Optimal':<12}{'Objective':<12}"
      f"{'Iterations':<12}{'Stress (MPa)':<15}{'Deformation (mm)':<18}{'Weight (kg)':<10}")
print("=" * 95)
for run in runs_results:
    print(f"{run['Run']:<5}{run['Initial (mm)']:<10.1f}{run['Optimal (mm)']:<12.4f}"
          f"{run['Objective']:<12.4f}{run['Iterations']:<12}"
          f"{run['Stress (MPa)']:<15.2f}{run['Deformation (mm)']:<18.2f}"
          f"{run['Weight (kg)']:<10.2f}")
print("=" * 95)

# Detailed iteration history for first run
print("\nDETAILED ITERATION HISTORY (First Run)")
print("=" * 85)
print(f"{'Iter':<5}{'Thickness':<12}{'Objective':<12}{'Stress':<12}"
      f"{'Deformation':<15}{'Weight':<10}")
print("=" * 85)
first_run_history = run_optimization(np.array([initial_guesses[0]]))[1]
for entry in first_run_history:
    print(f"{entry['Iter']:<5}{entry['Thickness']:<12.4f}{entry['Objective']:<12.4f}"
          f"{entry['Stress']:<12.2f}{entry['Deformation']:<15.2f}{entry['Weight']:<10.2f}")
print("=" * 85)
```