

**Design of a lightweight passenger seat using composite materials to
reduce vehicle weight, emissions, and improve fuel economy**



Gamachu Shuma Chafo

A thesis Submitted to

Department of Mechanical Engineering

College of Mechanical, Chemical and Materials Engineering

Presented in Partial Fulfillment of the Requirement for the Degree of Master's
in Automotive Engineering

Office of Graduate Studies

Adama Science and Technology University

December, 2025

Adama, Ethiopia

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Advisor: Dr. Ramesh Babu Nallamothu

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DECLARATION

I hereby declare this thesis entitled “Design of a lightweight passenger seat using composite materials to reduce vehicle weight, emissions, and improve fuel economy” is my work and has not been submitted for the award of any academic degree, diploma, or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

Name of the student

Signature

Date

RECOMMENDATION

I, the advisor of this thesis, hereby certify that I have read the revised version of the thesis entitled “Design of a lightweight passenger seat using composite materials to reduce vehicle weight, emissions, and improve fuel economy” prepared under my guidance by Gamachu Shuma therefore, I recommend the submission of the thesis to the department for further review and evaluation.

Main Advisor	Signature	Date

Co-advisor	Signature	Date

APPROVAL

I'm the advisor of the thesis entitled 'Design of a lightweight passenger seat using composite materials to reduce vehicle weight, emissions, and improve fuel economy " Thereby certifying that the recommendations and suggestions made by the board of reviewers are appropriately incorporated into the final version of the thesis.

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APPROVAL OF BOARD OF EXAMINERS

We, Undersigned, members of the board of reviewers of the thesis open defense by Gamachu Shuma Chafo have read and evaluated the thesis entitled “Design of a lightweight passenger seat using composite materials to reduce vehicle weight, emissions, and improve fuel economy” and assessed the understanding of the candidate about the proposed research. This is, therefore, to certify that the thesis is accepted and we recommend the implementation of the thesis.

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ACRONYMS

USD	United States Dollar
FRP	Fiberglass Reinforced Plastics
MPG	Miles Per Gallon
GVW	Gross Vehicle Weight
MAM	Maximum Authorized Mass
CFD	Computational Fluid Dynamics
CAD	Computer-Aided Design
FEA	Finite Element Analysis
CFRP	Carbon Fiber Reinforced Polymer
HEV	Hybrid Electric Vehicle
EV	Electric Vehicle
CO ₂	Carbon Dioxide
NO _x	Nitrogen Oxides
SO ₂	Sulfur Dioxide
HC	Hydrocarbons
PM	Particulate Matter
FMVSS	Federal Motor Vehicle Safety Standards
APTA	American Public Transportation Association
LCA	Life Cycle Assessment
GCI	Grid Convergence Index
FFRP	Flax Fiber Reinforced Polymer
LED	Light-Emitting Diode

ABSTRACT

This research investigates the design and analysis of a lightweight passenger seat frame for a 13-seat Toyota Hiace minibus, utilizing a hybrid composite material to reduce vehicle weight, emissions, and improve fuel economy. The primary objective is to replace the conventional high-strength steel seat frame with a novel hybrid composite consisting of Carbon Fiber Reinforced Polymer (CFRP), flax fiber, and epoxy resin in a 40:30:30 volume ratio. The methodology integrates Computer-Aided Design (CAD) in SOLIDWORKS, Finite Element Analysis (FEA) via ANSYS Workbench for structural and modal evaluation, and a longitudinal vehicle dynamics model simulated in Python to quantify fuel consumption and emissions. Material properties for the hybrid composite were determined using the Rule of Mixtures. The results demonstrate an 83.6% reduction in the total mass of the 13-seat assembly, from 126.75 kg (steel) to 20.8 kg (composite), while maintaining structural integrity with a minimum safety factor of 5.89. This weight saving leads to a predicted 1.5-2.5% improvement in highway fuel economy, translating to an annual reduction of approximately 15 liters of fuel and 40 kg of CO₂ emissions per vehicle. The study confirms the hybrid composite seat frame as a viable, multi-functional component that successfully balances mass reduction, structural performance, and sustainability.

Keywords: *Carbon Fiber Reinforced Polymer (CFRP), Emission Reduction, Finite Element Analysis (FEA), Fuel Economy, Hybrid Composites, Lightweight Design, SO, Vehicle Dynamics.*

CHAPTER ONE

INTRODUCTION

1.1 Background of the study

The transportation sector is a significant contributor to global energy consumption and greenhouse gas emissions, prompting urgent calls for more efficient vehicle designs. A critical factor influencing a vehicle's fuel economy and emissions is its weight; a 10% reduction in vehicle mass can lead to a 6-8% improvement in fuel efficiency. The passenger seat, as the fourth-largest component, presents a substantial opportunity for targeted light weighting. However, a significant research gap exists in the holistic design and validation of a specific hybrid composite system integrating both high-performance synthetic fibers and sustainable natural fibers for a *minibus passenger seat*. The novelty of this study lies in addressing this gap by designing and analyzing a seat frame using a CFRP/Flax/Epoxy hybrid. This approach uniquely balances rigorous structural performance, dramatic mass reduction, enhanced sustainability through the use of renewable flax fiber, and a quantifiable system-level impact on vehicle fuel economy and emissions, thereby contributing a comprehensive and practical solution for greener automotive engineering.

One of the most important factors in automotive performance is vehicle weight, with 75% of vehicle fuel consumption depending on weight (Saidpour, 2004). Previous studies have confirmed that reducing the weight of vehicle engines by 10% reduces fuel consumption by 6%–8% (Joost, 2012; Bangde et al., 2020; Wang et al., 2020). Furthermore, research has confirmed that a 100-kilogram reduction in vehicle weight reduces CO₂ emissions by 9 grams per kilometer (Hirsh, 2011). Additionally, lighter car body parts have higher energy efficiency (Dudek and Zagorski, 2017). Public transport vehicles offer exceptionally high energy savings with lighter weight compared to other road vehicles, as higher energy savings have been observed for vehicles that use frequent stops and acceleration. Among road vehicles, minibuses provide remarkable lifetime energy savings, mainly due to the combination of high lifetime performance and high specific energy savings. Weight reduction is therefore very important for these vehicles to achieve fuel efficiency and emission reductions.

The car seat accounts for 8% of the weight of the car and is the fourth-largest component of the vehicle. Therefore, research on lighter car seats can significantly contribute to overall vehicle

weight reduction and achieve the intended environmental and performance benefits. Depending on their recyclability and low specific weight, hybrid composite lightweight materials are the subject of special interest in this research. These materials offer a promising solution to reduce vehicle weight while maintaining structural integrity and safety.

The main target of this thesis project is to use hybrid composite lightweight materials that could reduce vehicle passenger seat weight and, for this reason, reduce CO₂ emissions, which can be regarded as the most crucial issue in order to comply with new environmental regulations, lower fuel consumption, and improve vehicle performance. Specifically, this thesis project focuses on the seat weight reduction of public transport minibuses to realize the benefits of clean air, a green world, and fuel savings. The realization of lightweight automobiles is of great significance not only in environmental protection but also in improving the overall safety of automobiles.

1.2 Statement of the problem

The transportation sector faces significant challenges related to environmental sustainability and public health. When cars move on roads, vehicle pollutants containing greenhouse gases are emitted, harming human health and accelerating climate change. The burning of gasoline and diesel fuel produces harmful byproducts, exacerbating this global issue. Mini-bus van-type vehicles, widely used for both commercial and private purposes, contribute substantially to this problem by increasing pollution, emissions, and associated public health risks. A critical factor influencing vehicle emissions is weight; reducing a vehicle's weight directly decreases its fuel consumption. Therefore, designing public vehicle seats, such as those in mini-buses, with lightweight materials can have a positive environmental impact.

In the automotive industry, seat designers face the persistent challenge of balancing all specifications. Currently, the passenger seat structure in vehicles like the Toyota 5L mini-bus primarily uses steel. While steel offers good strength and rigidity, its high-density results in heavy mass. This heavy weight leads to higher fuel consumption and, consequently, greater gas emissions. Thus, vehicle weight reduction is a priority to mitigate these problems.

This thesis research aims to address this by seeking alternative solutions. Specifically, it focuses on finding a substitute for stainless steel in the seat structure by designing with hybrid composite

materials. Compared to steel, hybrid composites have lower density, reduced weight, and lower cost, while also offering favorable material quality, machinability, and easier processing.

Furthermore, the project explores alternative solutions for other seat components, such as cushions and coverings (e.g., leather and metal items), by focusing on Fiber-Reinforced Polymer (FRP) materials. FRP provides advantages like corrosion resistance, high strength, and low unit weight, making it suitable for applications like seat backs.

1.3 Objectives

1.3.1 General objective

The general objective of this thesis work is to minimize emissions and increase fuel efficiency by designing the vehicle seat with lightweight materials to reduce the weight of the vehicle.

1.3.2 Specific objectives

- To create the design and a detailed 3D model of the vehicle seat.
- To analyze the vehicle seat with lightweight materials
- To compare the performance of the seat design by hybrid composite materials with conventional material.
- To design the model by SOLIDWORKS
- To Simulate and analyze fuel efficiency and Emission Analytically in python.

1.4 Significant of the study

This thesis specifically aims to work towards answering the research questions and the research problems mentioned in the above previous sections of the research. This research project is to examine how a vehicle's exhaust gases impact its safety and performance as well as harm our health and contain greenhouse gases that cause climate change.

By adapting and practicing important solutions this study supports the current work and efforts to clean environment and decarbonize the automotive sector. By using Hybrid composites manufacturer's engineers and other related department get best alternatives to conventional materials like aluminum and steel therefore based on this research Engineers can solve their issues by ensuring environmental benefits and mechanical.

This thesis aims to incorporate a different approach to designing a lightweight passenger seat that solves the following problem: How can the passenger seat weight be reduced without affect the performance of the current solution? Finally, this vehicle weight reduction can help to reduce those emissions as well as increase fuel efficiency. It does so by studying the commercial minibus and proposing a methodology to reduce its mass without affecting the safety of its occupants this helps in (the benefit could be):

- To find an alternative solution for stainless steel in seat structure by introducing hybrid composite material to reduce cost as well as weight
- The health sector, with key factors including the reduced spread of non-communicable diseases, fewer accidents, and improved air quality.
- Air Quality
- Slowed Climate Change
- Economic Growth
- Energy Efficiency
- Increasing the passenger satisfaction by providing better comfort and service.

1.5 Scope of the thesis

In this research, Experimental investigations was not conducted (Prototype). The study focuses on the Design of the passenger seat with lightweight materials for weight reduction of the vehicle to reduce emissions and increase fuel efficiency the effects of vehicle weight reduction on passenger seat interior design will be analyzed by using ANSYS Fluent which is used to simulate the vehicle as well as analyze and SOLIDWORKS which is used to construct a model of vehicle with lightweight materials.

1.6 Limitations of the study

Many obstacles were faced during the execution of this thesis work. When conducting the research, some of the limitation was not encountered. The limitations of the research are:

- 1) Both ergonomically and structurally the research does not include any prototype constructions or testing, tests are only by using SOLID Works and Finite Element Analysis.
- 2) The cost visibility of the hybrid composite is not done.
- 3) The long-term performance and the crashworthiness behavior of the hybrid composite are not studied.

- 4) It's being theoretical only not practical testing in the work field.
- 5) Natural fiber Flax and epoxy resin as well as carbon is the selected and limited materials

1.7 Organization of the thesis

There are five chapters in this thesis. The first chapter serves as an introduction and includes the background of the study, statement of the problem, objectives, scopes, significance of the study, and organization of the thesis; chapter two presents a literature review that focuses on seat designs and light-weighting improving the effects of vehicle weight reduction a summary of the review and identifies a research gap. The third chapter explains the materials and methods used to complete this thesis work. Chapter four gives a result and discussion ad Chapter five is about recommendations ad conclusion.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction to vehicle weight and efficiency

According to research by Prasad Yadav and Akshay Shinde, in January 2016, vehicle weight reduction is a popular and effective approach to address the concerns of combustion gases emitted into the air and fuel consumption of passenger vehicles. According to their research, by reducing the weight of the vehicle by 15% their findings show that fuel consumption can be reduced to 7% approval.

In modern times, it is necessary to reduce the weight of the vehicle and meet the standard for strong fuel economy. New vehicles must achieve at least 80 KM per LIT by the registrant. New cars of the future are not only physically lighter or slightly heavier but also more efficient in fuel usage and have higher power, such as hybrid electric drives.

According to their research, the weight of the vehicle can be reduced by replacing the steel and steel used in the vehicles with the heavy, heavy steel with lighter aluminum and also by redesigning the vehicles to reduce the weight. Using the above specifications, the weight of the vehicle can be reduced by up to 40% (690 kg).

2.2 The Role of Weight Reductions:

2.2.1 Light weighting for Reduced Fuel Consumption

Before exploring the effect of light weighting on reduced fuel consumption, it is imperative to note that even though weight is the most important factor, many other parameters affect fuel consumption. (Zhou et al. 2016)

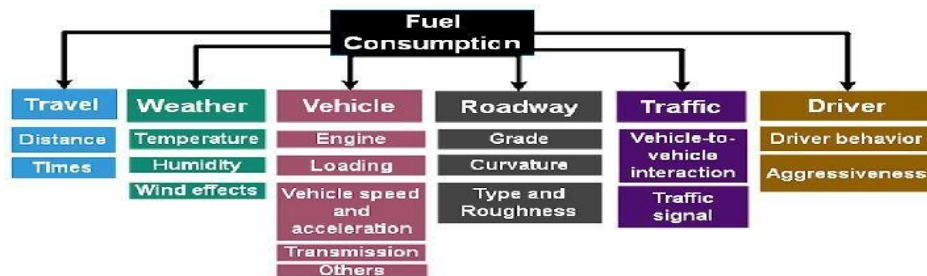


Figure 2-1 Factors that affect vehicle fuel consumption

Weather-related- Fuel usage increases with temperature. The weather elements such as humidity, ambient temperature and wind affect fuel consumption through attachments such as the water pump and the air conditioning system. For instance, a temperature change from 24⁰C to 7⁰ C might result in a 16 ⁰C increase in gasoline use (Natural Resources Canada, 2014). Vehicle energy consumption is increased by air conditioning (Khayyam et al. 2011). It can consume about 10% of the fuel (Yu et al. 2020).

The part related with vehicle is its high fuel consumption, which includes the useful energy consumption of the tractive forces used to propel the vehicle forward plus losses in the engine. This largely depends on the vehicles weight.

Roadway-related it depends on physical condition of the road (Zhou et al. 2016). Bumpy, rough and poor increases rolling friction in the wheels (Kamal et al. 2011). A vehicle on a flat road uses 15 % to 20 % more fuel than a vehicle on a bumpy road (Boriboonsomsin and Barth, 2009).

Driver-related fuel consumption is increased by drivers, drive at irregular speeds, and idle for a long period of time. One of the primary elements influencing a vehicles fuel consumption rate is this (Yao et al. 2020). According to Ford Motor Company experiment, enhancing driving habits can result in an average 24% increase in fuel efficiency (Berry 2010) According to Huff et al. (2013), opening windows during the summer reduces a vehicle's aerodynamics and raises fuel consumption.

In the case of automotive industry, reducing the weight/mass of a motor vehicle by 10% reduces the car's fuel consumption by 6 % to 8 % (Joost 2012; Bangde et al. 2020; Wang et al. 2020) The findings of automotive industry described above are supported by (Dede et al. 2016), which states that 50 % weight loss can be achieved by using aluminum alloy as a seat material. Also, if the aluminum alloy design is used for a 40-seater bus, 2.1 % fuel economy can be achieved, and 8800 kg CO₂ emissions can be prevented over a life time by comparing it to a steel or cast iron design.

2.2.2 Light weighting for reduced emissions

According to So et al. (2015), the weight of vehicles is closely related to the level of emissions. Every 100 kilograms of vehicle weight corresponds to a reduction of 9 grams in carbon emissions when adjusting the topology (Hirsch 2011). Furthermore, there is a strong correlation between the quantity of vehicles and the power consumed during production. Producing non-renewable products means that additional power/fuel is consumed, leading to increased levels of NO_x, SO₂,

CO₂, HC, PM, and CO in the ambient air, for instance, according to Guerra et al. (2020), 350 parts per million (ppm) of CO₂ per million is the permissible amount in ambient air. However, in 2013, the level of CO₂ in the ambient air was 400 ppm per million, up from 316 ppm in 1958 (Jones 2017). According to data from 2019 from Yale University, the level reached 415.39, indicating a very high concentration.

2.3 Weight reduction strategies

2.3.1 The rise of topology optimization and its application so far

According to Topase A. al 2020, it replaces material without causing a change in the geometry of matter, but it modifies the topology and changes the geometry of the part. Topology optimization is a mechanical design tool. This device aims to use the strongest material distribution in the simplest form possible. As a quantitative approach by Thompson et al. (2016), it contains a material placed within a certain range to achieve the desired procedure, such as rigidity, which is particularly resistant under loads, given limits, at the same time material use, product weight, and uniform stress distribution. Researchers are looking for ways to reduce the weight of vehicles. According to (Yusei et al. 2014), weight loss can contribute significantly to reducing global transportation. In addition, weight reduction leads to higher fuel efficiency for all transport vehicles, especially buses.

2.3.2 Material Substitution and its cost-benefit analysis

Today, lighter materials such as aluminum, magnesium, titanium, and alloys are used to replace heavier materials such as steel. If we take aluminum as an example (Kadian and Peimae, 2020), the advantage is that it is lightweight, recyclable, and absorbs twice as much grinding energy compared to materials such as mild steel. According to earlier research, titanium bolts and nuts could lose weight by replacing their material. It is agreed upon by both (Froes et al. 2004) and (Croccolo et al. 2012) that titanium bolts and nuts can significantly reduce weight. These weight savings make a significant contribution to reducing fuel consumption for the motor vehicle and, consequently, reducing carbon dioxide emissions into the atmosphere. Froese et al. (2004) we look at the use of titanium on some parts traditionally produced using steel. These sections are:

- ✓ Exhaust Systems: Titanium can last the entire life of a car
- ✓ Chassis: Although it is costly when it comes to the chassis, it's acknowledgement to its protection against use on wheel bearings, steering linkage and axle stubs.

- ✓ Springs: High yield strength and low-density power are used.

However, According to Hagnell et al. (2020), the material substitution has a trade-off between the benefits of lightweight and high production costs, despite offering the benefits of lightweight and higher production costs. Generally, the light material itself is costly. We can take composite material as an example (Carberry 2008), the price of different carbon fibers is between \$33/kg- \$ 67/kg in the United states. This is expensive and can only be implemented when there are very high expected returns, for instance as (Hallgren et al. 2016), when it comes to car race drivers they put more value on performance compared to price. In addition, according to (Bodunrin et al. 2020), other materials such as titanium have a good combination of lightness and high strength, but at the same time they are more expensive both for handling and processing. As (Witik et al. 2011, Kim and Wallington 2013), the production of some materials is linked to negative environmental effects. Moreover, some materials, such as magnesium, have low yield strength and do not succeed in areas where high strength and stiffness are required.

2.4 Aerodynamics and weight reduction

Aerodynamic drag – nowadays, many modern production cars are designed to produce very low aerodynamic drag. The 2009 Mercedes E220 Coupe has an extremely aerodynamic difference of 0.24 – to reach the lowest rating of any series production vehicle. The 2010 Toyota Prius sprayed a kick 0.25, and the 2001 Audi A2 1.2 TDM of 0.25. It is especially noteworthy that it is difficult to find a low figure for a short vehicle. To obtain these figures, you will need to undergo a costly wind tunnel inspection, but the retail price of a car will inevitably increase significantly. Relatively less costly traction action includes reducing ride height, adjusting underbody, and covering the soft wheels. On Opel/Vauxhall and Ford models, costly measures such as active grille shutters that shut down at high speeds have been passed. As a result, CO2 dropped 2%. However, between 1995-2010, areas in front of the average passenger car increased by approximately 10 percent.

According to a study based on the EPA fuel economy test, a 10 % weight reduction increased fuel economy by 6-7%, while a 10% reduction in aerodynamic drag or rolling resistance increased fuel efficiency by 2%, but this depends on duty cycles.

2.5 Lightweight Design of Seat Frame

As many researchers, the advantage of the fact that automobiles are lightweight is to change the structure, materials, process, and other recommendations of the automobile on the basis of guaranteeing not only the strength and safety of the automobiles as much as possible but also guaranteeing the quality of the automobile without change or significant increase in order to enhance the safety of the automobile, economies of scale, and other goods.

2.5.1 Seat Applications

A comprehensive understanding of passenger seat applications is essential to define the performance criteria for any redesign. The seat must fulfill several critical and categorized functions. Primarily, it serves a safety function, designed to withstand impact loads during a collision, secure occupants via restraint systems, and prevent failure that could lead to injury. Secondly, it must provide comfort and ergonomics, which involves accommodating the anthropometric diversity of the target user population (from the 5th to 95th percentile) to ensure proper posture, support, and visibility, while also contributing to ride comfort through vibration damping. Finally, it must maintain structural integrity over its lifespan, supporting static loads (passenger weight) and resisting dynamic stresses from vehicle acceleration, braking, and cornering without excessive deformation or fatigue. By categorizing these applications safety, ergonomics, and structural integrity we establish clear, quantifiable benchmarks for evaluating the proposed lightweight design against the conventional steel baseline.

2.6 Ways of lightweight.

As many different studies, there are three ways to assure vehicle weight reduction. Those are:

- 1) Advanced manufacturing process
- 2) Structure optimization, and
- 3) Application of lightweight materials.

In the design of seats lightweight materials and structural optimizations are used the lightweight design of seats, structural optimization and lightweight materials are widely used. The structure optimization is divided into topological optimization, dimension optimization, and shape optimization. The topological optimization has the most obvious effect on the weight reduction of the seat. For the most part; it calculates and analyzes the static strength through optimization algorithms and finite element analysis. Understanding the strength and performance of the seat

mechanism, can remove the redundant materials as far as possible and rationalize the force transmission path of the seat under various working conditions.

2.6 Current Lightweight Trends

In the last couple of years there are a lot of new impressive trends have emerged, it can be emphasized by seeing at some of the new concepts that have been marked during that time.

(Courtesy of Colin Powsey International center for quality and productivity)

As the Automotive industry, Faurecia is one of the largest and well-known suppliers of seating and related parts, the company is enlarging new modular seating structure with metal alloys to fulfill important weight reductions. In 2013 the company declared that it had started a partnership with FAW foundry, to develop seat structures made from magnesium alloys. The company estimates that by comparing magnesium alloys and last generation steel seating structures, seats manufactured from magnesium alloys could result in a 25% weight reduction. They also intend to use this project more lightweight products.

2.7 Advanced light material light alloys

As element aluminum is first separated in 1888, it has symbol Al and atom number 13; it has a density lower than that of other metals the density of aluminum is 2.69 g/cm^3 , which means it's approximately one third as dense as conventional steel (7.83 g/cm^3). Compared to the structural steel aluminum have more outstanding performances like; excellent electrical and thermal conductivity with higher strength and enhanced corrosion resistance. The exceptional specialized characteristics (such as specific strength or strength-to-weight ratio) enable the production of lighter aluminum-based vehicles with good handling, braking, fuel efficiency and acceleration. Using one ton of aluminum instead of cast iron or traditional steel can, on average, save greenhouse gas emissions by eighteen tons (18) over the course of a middle-size sedan's life. Associating aluminum with other elements (such as Mn, Cu, Mg, Si, and Zn) in the interim

2.8 High-strength steel

Even for modern Automobiles steel remains indispensable automotive material due to its low cost, outstanding machinability, high performance, and recyclability. It provides greater resistance to corrosion and better mechanical properties. High-strength steel might be considered

with a grade (yield stress) from 460 MPa up to 690 MPa. Compared to low carbon steel, High-strength steel materials are required to produce comparable functional components and thus achieve an overall weight reduction

2.9 Composites

The automotive industry's adoption of vast composite materials has achieved substantial weight deductions of about 15% to 40%, improving vehicle efficiency while delivering advantages including superior strength, impact durability, and enhanced design versatility (Rajak et al., 2019; Mohammadi et al., 2022). Fiber-reinforced polymer composites represent the predominant material choice, accounting for roughly 65% of usage across both exterior and interior automotive parts (Rajak et al., 2019). The transition toward lightweight alternatives, including glass fiber-reinforced plastics, stems from requirements for better fuel economy and decreased greenhouse gas outputs (Mohammadi et al., 2022). Furthermore, innovative hybrid composite systems that merge bio-derived bast fibers with advanced reinforcement materials such as glass and carbon fibers are gaining traction, offering an optimal combination of affordability and mechanical characteristics for non-load-bearing applications (Saleem et al., 2020). The production mechanisms employed for these composite materials play a crucial role in evaluating their longevity and operational capacity within automotive contexts (Wu et al., 2023). As a whole, the movement toward lightweight composite solutions are transforming the automotive sector, advancing both environmental sustainability and operational performance.

2.10 Vehicle Mass Breakdown

The weight of a vehicle is a fundamental factor influencing the operational dynamics and overall performance across different vehicle categories, especially in hybrid electric vehicles (HEVs) and electric vehicles (EVs). Precise determination of vehicle weight is vital for refining braking control mechanisms. This was illustrated by Liu et al., who developed a braking control approach incorporating vehicle weight and road gradient calculations to improve both braking effectiveness and energy recuperation in hybrid electric buses (Liu et al., 2022). Furthermore, Sandrini et al. emphasized that reducing vehicle weight can substantially decrease energy usage, thereby mitigating the issues of restricted driving range and extended charging durations in EVs (Sandrini et al., 2023).

The variable nature of vehicle weight, which changes with cargo loading and unloading operations, requires continuous real-time monitoring for optimal vehicle management. This demonstrated by Boada et al., who employed a dual Kalman filter methodology to estimate weight variations under different operating scenarios (Boada et al., 2019). Moreover, Anselma et al. explored how incorporating weight considerations into HEV design influences structural integrity and operational performance, stressing the importance of multidisciplinary design and optimization to get an appropriate balance between weight reduction, crash protection, and operational efficiency (Anselma et al., 2020). Based on Stodolsky et al, 1995a; Bjelkengren, 2008 Lotus Engineering, 2010; the actual system definition and system component inclusion can vary, and percentage weight breakdown can vary substantially by vehicle.

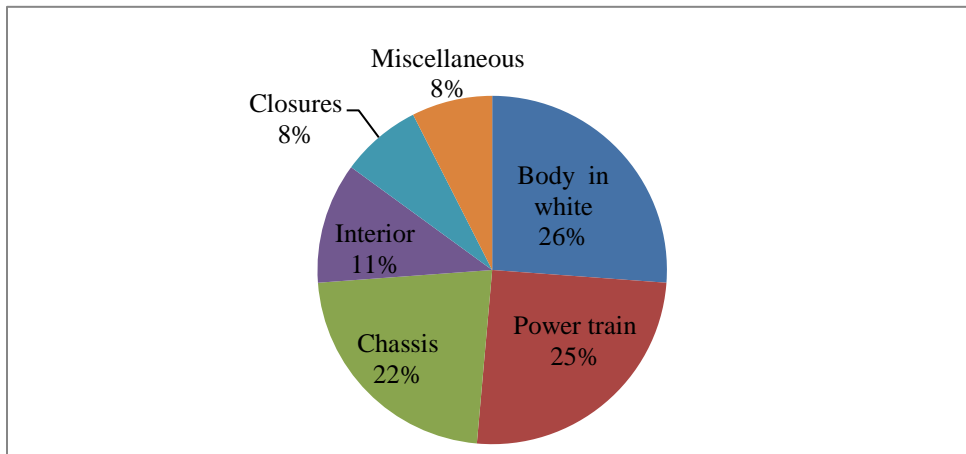


Figure 2-2 Approximate Vehicle mass Breakdown

Table 2-1 Vehicle mass Breakdown

No	System	Major Components in the system
1	Body-in-white	Passenger compartment frame, cross and side beams, roof structure, front end structure, underbody floor structure, panels
2	Power train	Engine, transmission, exhaust system, fuel tank
3	Chassis	Chassis, suspension, tires, wheels, steering, brakes
4	Interior	Seats, Instrumental panel, insulation, trim, airbags
5	Closures	Front and rear doors, hood, liftgate
6	Miscellaneous	Electrical, lighting, thermal, windows, glazing

In the late 1980s, about 9 %, or more than 325 lbs. today, Aluminum in every vehicle makes up more than 5 % of light weight vehicles components like Engine blocks and most cylinder head (Studolsky et, al; Brooke and Evans) Light weight vehicles pass 50% more steel in this area for the first time (simpson) . As Element with a depth of 30% less than aluminum and 75% less depth than metals, Magnesium is the densest of the major car minerals, In this way, magnesium is seen as a promising lower-bulk iron backup (Kulecki); however, currently, magnesium is only 10 lbs. About 0.2% of the typical new car in the US (Ward Automotive), Modern vehicles have a lower thickness compared to other materials: 8% plastic by volume, but 50% plastic by volume (Bandivadekar et al.).

2.11 Lightweight Options for Seat Structure in a Bus

As researched by Prashant M. Patil, and M. Senthil Kumar. When considering comfort, the car seat must be taken into consideration. Therefore, designed to achieve effective seat structure factors like ergonomics, safety, and smooth ride can be taken in to account.

Currently, lightweight materials are expanding in the automotive industry. Due to the large amount of CO₂ released into the environment and air, causing air pollution by specifying various domains like flooring, roof structure, seats, etc., lightweight can be achieved. As previously said, the seat allows us the ability to reduce the weight of the vehicle. The model developed is done by considering issues related to ergonomics, safety, weight, and cost-related issues. Further, his research elaborates by analyzing the static, vibrational durability response. Different strength parameters, such as tensile stiffness, bending, and torsional stiffness, are considered. By using composite material, 41.5% weight reduction is achieved with a 33.6% considerable cost increase.

2.12 Measurement of fuel consumption

The fuel consumption in a given interval of time may be measured either in terms of volume or in terms of weight. In the former a vessel of suitable capacity is connected to the main fuel tank and engine is supplied with fuel from the vessel during test. The vessel is filled to its capacity and then connected from the fuel tank by means of a valve. The time required in emptying out the vessel is then noted with a stop watch. The volume of the vessel divided by the time, then, gives the fuel consumption of the engine in the weight method; the fuel tank is placed on a weighting platform, which directly reads the amount of fuel consumed. The time taken to consume a specified quantity

of fuel is then noted and the fuel consumption is calculated. For accurate determination of mass consumption of the fuel from the volume consumption, knowledge of the temperature at the time of measurement is required since the fuel density changes with temperature.

Specific fuel consumption can be calculated by dividing the fuel consumed per hour by the horse power. Thus if Mf *kg/minute* is the fuel consumption, Indicated Specific fuel consumption (I.S.F.C)

$$(I.S.F.C) = \frac{60 Mf}{I.P.}, kg/I.P, Hour \quad (2.1)$$

And brake specific fuel consumption (B.S.F.C.)

$$(B.S.F.C.) = \frac{60 Mf}{B.P.}, kg/B.P, Hour \quad (2.2)$$

2.13 CO₂ and the Climate

Carbon dioxide (CO₂): Its human-made greenhouse gas it's also the primary source of climate change. When automotive industry and human activities have added huge amount of CO₂ is released to the atmosphere. Due to CO₂ greenhouse effect has gained. The gas composition of the atmosphere is modified by Human activities. The disturbance caused by natural radiation exchange results in changes to the climate.

2.14 Hybrid composite materials

Hybrid composite materials, which combine a matrix with multiple types of reinforcements, have developed from their origins in the 1930s into a broad and significant field. They can utilize a variety of reinforcements, including natural, metallic, glass, and carbon fibers. By replacing heavier traditional materials with these lightweight composites, vehicle weight can be substantially reduced, leading to stronger overall performance. Specifically, hybrid composites consist of two or more distinct materials, such as a blend of synthetic and natural fibers within a polymer matrix. They are classified by manufacturing methods like intermingled, selective, and super hybrid composites. A key advantage is their design flexibility; materials can be carefully engineered by placing specific reinforcements in targeted areas to achieve desired outputs, as noted by researchers like Ravishankar, Nayak, & Kader (2019).

The applications for hybrid composites are extensive and span numerous industries. They are used in automotive components such as pistons, brake friction materials, and anti-roll bars. Beyond automotive uses, they serve in decorative coatings, the construction industry, dental fillings, corrosion protection, and even light-emitting diodes (LEDs). Successful design requires several key considerations: the selection of the matrix material, the optimization of fiber type and placement, and the effective integration between the different fibers. Finally, when compared to conventional materials used in industries like automotive manufacturing, hybrid composites, particularly those incorporating natural fibers, often present a lower-cost alternative.

2.15 Reduction of energy consumption through light weighting

To move a vehicle (minibus) there are four main contributors to the energy consumed.

These are:

- 1) Acceleration
- 2) Gravity
- 3) Resistance against rolling and
- 4) Aerodynamic-based forces

2.16 Overview of the studies on Design of a vehicle passenger seat

Table 2-2 Overview of the studies on Design of a vehicle passenger seat by using lightweight materials to reduce carbon dioxide emission and fuel consumption

Year	Purpose and Main Results of the study	Reference
2016	This study explores vehicle weight reduction is a popular and effective approach to address the concerns of combustion gases emitted into the air and fuel consumption of passenger vehicles. According to their research, by reducing the weight of the vehicle by 15% their findings show that fuel consumption can be reduced to 7% approval.	Prasad Yadav and Akshay Shinde, in January 2016
	This study focuses on the material and energy impacts of passenger vehicle weight reduction	Lynette W. Cheah: studied on cars on a Diet

2010	in the U.S. They revealed ways to approach improving vehicle fuel economy. According to their study during the vehicles operation by examining how the fuel energy is distributed.	
-	The study revealed Aluminium in every vehicle makes up more than 5 % of light weight vehicles components like Engine blocks and most cylinder head	(Studolsky et, al; Brooke and Evans)
2016	The study investigates exploring the effect of light weighting on reduced fuel consumption, it is imperative to note that even though weight is the most important factor, many other parameters affect fuel consumption.	(Zhou et el. 2016)
2011	The study works on energy consumption therefore; Vehicle energy consumption is increased by air conditioning	(Khayyam et al. 2011)
2020	The study works on energy consumption therefore; Vehicle energy consumption is increased by air conditioning. It can consume about 10% of the fuel	(Yu et al. 2020).
2009	The study aimed at investigating Light weighting for Reduced Fuel Consumption as the study reveals factors that affect vehicle fuel consumption is roadway-related it depends on physical condition of the road. Bumpy, rough and poor increases rolling friction in the wheels. A vehicle on a flat road uses 15 % to 20 % more fuel than a vehicle on a bumpy road	(Boriboonsomsin and Barth, 2009).
	The study aimed at investigating Light weighting for Reduced Fuel Consumption as the study reveals factors that affect vehicle fuel	(Yao et al. 2020).

2020	consumption driver-related fuel consumption is increased by drivers, drive at irregular speeds, and idle for a long period of time. One of the primary elements influencing a vehicles fuel consumption rate is this (Yao et al. 2020).	
2013	The study describes factors that affect vehicle fuel consumption, opening windows during the summer reduces a vehicle's aerodynamics and raises fuel consumption.	(Huff et al. 2013),
2020	In the case of automotive industry, reducing the weight/mass of a motor vehicle by 10% reduces the car's fuel consumption by 6 % to 8 %	(Joost 2012; Bangde et al. 2020; Wang et al. 2020)
2015	The study aimed at investigating Light weighting for reduced emissions. Therefore, The weight of vehicles is closely related to the level of emissions.	(So et al. 2015),
2011	This work focuses on the weight of vehicles is related to the level of emissions. The study analyses that every 100 kilograms of vehicle weight corresponds to a reduction of 9 grams in carbon emissions when adjusting the topology	(Hirsch 2011).
2010	The study analyses Possibilities of weight reduction in the automotive industry Based on a thorough reengineering of a 2009 Toyota Venza, Lotus engineers published a significant study on the capabilities of weight reduction in modern cars. They found that by combining the best available solutions with a system-level engineering methodology, it was possible to achieve significant weight reduction	(Lotus engineers published a significant study in 2010)

	and lower the vehicle's cost without sacrificing vehicle functions, performance, or safety.	
2014	The study describes weight loss can contribute significantly to reducing global transportation. In addition, weight reduction leads to higher fuel efficiency for all transport vehicles, especially buses.	(Yusei et al. 2014),

2.17 Review Summary

From time to time, various researchers have been conducting extensive studies on reducing the vehicle's weight. The research conducted by these researchers was undertaken to bring results to the automotive factory and to modernize the service of the car. For example, in the studies conducted on vehicle weight and efficiency, the results showed that if the weight of the vehicle is reduced by 10%, the amount of fuel used can be saved by 7% from waste.

As we have seen above studies in the field of the role of weight reductions that tried to raise light weighting for reduced fuel consumption, some of them are weather-related and vehicle-related, especially under vehicle-related studies that are based on the weight of the vehicle. Additionally, light-weighting for reduced emissions according to (Soo et al.2015), the mass of the vehicle is closely associated with the amount of emissions, which is reduced when 100 Kg of the total vehicle weight is reduced through topology optimization or material substitution, which means CO2 emissions by 9 grams per kilometer (Hirsh 2011)

In previous studies, various vehicle weight reduction strategies have been mentioned: ,1) The rise of topology optimization and its application , 2) Material substitution, etc.

In summary, previous studies and the above-mentioned various techniques have been investigated to reduce the weight of the vehicle, and the results show that it saves fuel and reduces emissions. Further research has been done on reducing the weight of the passenger seat. The techniques of previous studies according to lightweight materials like Aluminum and FRP, etc. There are some gaps in previous studies in achieving the desired results by weight loss; they are careful material selection, with weight reduction strategies and lifecycle analysis.

2.18 Research Gap

In the case of Vehicle weight reduction, and its consequences on emission reduction and fuel efficiencies still, there are research gaps, particularly regarding, conventional seat design and seats designed from lightweight seats the research gap is the careful material selection, with weight reduction strategies and lifecycle analysis. By conducting all these gaps, this project aims to give a more compressive design of passenger seats to reduce emissions and increase fuel efficiency for sustainable transportation solutions.

CHAPTER THREE

MATERIALS AND METHOD

This chapter provides a comprehensive description of the systematic research methodology implemented for this study. The methodology was designed to achieve the stated objectives of designing, analyzing, and validating a lightweight passenger seat for a 13-seater Toyota Hiace minibus powered by the Toyota 5L engine. The approach integrates modern computer-aided design (CAD), advanced geometry preparation, and sophisticated finite element analysis (FEA) techniques to ensure a robust, efficient, and scientifically valid investigation into weight reduction strategies for automotive seating, with specific consideration of the vehicle's powertrain characteristics.

The baseline for this study is the existing conventional passenger seat frame, typically constructed from welded high-strength steel tubes. This design, while robust, contributes significant mass to the vehicle. A detailed review of its construction, material properties (as shown later in Table 3-2), and its role as the benchmark for comparison is provided in Chapter 2 (Literature Review). In contrast, the core of this research focuses on the *new* material system and design methodology. Therefore, this chapter details the proposed hybrid composite material, a blend of 40% Carbon Fiber Reinforced Polymer (CFRP), 30% Flax Fiber, and 30% Epoxy resin, whose properties are engineered using the Rule of Mixtures. It also describes the methodological framework, encompassing the CAD software (SOLIDWORKS) used for the new design, the finite element software (ANSYS Workbench) for structural and modal analysis, and the Python-based vehicle dynamics model for simulating fuel economy and emissions. This structure ensures a clear separation between the established technology and the novel contribution of this thesis.

3.1 Materials, Equipment, and Software

The successful execution of this research was contingent upon the availability and use of specific hardware, software, and material systems. A high-performance personal computer, equipped with a multi-core processor (Intel i7 or equivalent), 16GB of RAM, and a dedicated graphics card, was utilized to handle the computationally intensive tasks of 3D modeling, geometry optimization, and finite element analysis. The primary software suite employed was the ANSYS ecosystem, chosen for its industry-standard capabilities in engineering simulation. Specifically, ANSYS SpaceClaim served as the principal tool for direct 3D modeling and crucial geometry preparation,

enabling efficient editing and idealization of the seat structure for analysis. ANSYS Workbench provided the integrated platform for project management, meshing, and performing all structural simulations. Complementary to this, SOLIDWORKS was used in the initial phase for creating parametric and feature-based baseline models, which were subsequently transferred to the ANSYS environment.

The research evaluated several advanced material systems to replace conventional steel, with a focus on their interaction with the overall vehicle system, particularly the Toyota 5L diesel engine. The technical specifications of this powertrain, which provides the performance context for the weight reduction study, are detailed in Table 3.1. The vehicle's kerb weight of 1540 kg establishes the critical baseline from which the impact of seat mass reduction on overall vehicle mass, fuel consumption, and performance is calculated.

3.1.1 Material Selection Criteria for Light Weighting

Choosing appropriate materials for reducing weight in vehicle seats involves evaluating multiple factors to ensure an optimal balance of performance, safety, economics, and environmental responsibility. Important factors include the strength-to-weight and stiffness-to-weight ratios, overall density, resistance to fatigue and impact, ease of manufacturing, overall cost efficiency, ecological footprint, and durability against corrosion. Materials must provide sufficient structural performance with minimal mass and be adaptable to current production techniques. In this work, hybrid composites were selected as they effectively meet these demands, enabling substantial mass reduction while preserving safety and longevity, in step with the move toward more sustainable and efficient automotive engineering.

3.1.2 Material Selection Challenges

Implementing lightweight composite materials, however, is not without difficulties. The high expense of advanced materials like carbon fiber can hinder broad application. Production often requires specialized techniques such as resin transfer molding, increasing cost and necessitating new equipment. Connecting composite parts to metallic structures presents challenges in ensuring durable and reliable joints. Other concerns include consistency in material quality, scarce long-term performance information, and a lack of standardized regulations for new composite materials. Environmental issues related to recycling and disposal also need attention. This study confronted

these obstacles through design simulation, thoughtful material hybridization, and an emphasis on manufacturable processes.

3.1.3 Composite Materials

Composite materials are engineered by combining two or more distinct constituents—typically strong fibers embedded within a binding matrix—to achieve enhanced properties that surpass those of the individual parts. This research utilizes a system comprising Carbon Fiber Reinforced Polymer (CFRP) for superior strength and rigidity, Flax Fiber Reinforced Polymer (FFRP) for environmental sustainability and vibration damping, and epoxy resin as the cohesive matrix. The hybrid blend (40% CFRP, 30% flax, 30% epoxy) creates a material that delivers an advantageous combination of mechanical performance, reduced weight, and a greener profile, making it a fitting choice for automotive seat structures.

3.1.4 Main Structural Elements and Benefits

The seat frame is built from several key load-bearing parts: the Bottom Support Member, Backrest Tubes, Seat Support Tubes, and Bolting Channels. Redesigning these components with hybrid composite materials yielded major weight savings while preserving their functional roles. The composite frame achieves an 83.6% reduction in mass compared to the original steel version. This light weighting contributes to better fuel economy (an estimated 1.5–2.5% gain in highway driving), lower annual CO₂ emissions (roughly 40 kg per vehicle), improved ride comfort due to the inherent damping of natural fibers, and a more sustainable design through the incorporation of renewable flax fiber.

Table 3-1 Technical Specifications of the Toyota 5L Diesel Engine and Vehicle Platform

No	Parameter	Technical Specification
1	Engine Code	5L
2	Layout	Straight-4, vertical
3	Fuel Type	Diesel
4	Displacement	3.0 L (2,986 cm ³)
5	Aspiration	Naturally Aspirated
6	Horsepower	91 PS / 90 HP @ 4,000 rpm
7	Torque Output	191 Nm @ 2,400 rpm
8	Vehicle Dimensions (L x W x H)	4430 mm x 1690 mm x 1980 mm
9	Wheelbase	2330 mm
10	Vehicle Kerb Weight	1540 kg

3.1.5 Conventional Passenger Seat

The current conventional mini-bus passenger seat structure in Ethiopia consists of three main components. First, the chassis, which is not constructed according to local transport regulations but rather for basic practical functionality. Due to challenging driving conditions and road infrastructure, it is typically made from heavy, high-strength steel rather than lightweight composites, prioritizing local manufacturing trends over advanced technology. Second, a pillar provides the seat's shape and strength. This component is also constructed from heavy steel, with little consideration for scientific force distribution, material optimization, weight management, or engineering simulation. This approach compromises comfort, fuel efficiency, and long-term cost-effectiveness. Third, the structural load-bearing frame follows the same local manufacturing trend, being made from high-strength steel that is heavy, prone to corrosion, and low in overall efficiency. Figure 3.1 displays the Toyota 5L diesel engine next to the passenger vehicle designed for it. This dependable powerplant provides strong torque for the durable, multi-seat cabin shown. The photograph contrasts the mechanical components with the functional interior, illustrating the vehicle's robust engineering and primary role in transporting people efficiently.



Figure 3-1 Toyota 5L Diesel Engine and Vehicle with passenger seats

The primary material focus of this research is on Hybrid Composite Materials, specifically a combination of Carbon Fiber Reinforced Polymer (CFRP) and natural fibers like Flax. This selection is driven by the need for a superior strength-to-weight ratio, design flexibility, and potential sustainability benefits compared to conventional metals. The specific material properties defined for the finite element analysis are presented in Table 3.2. For the baseline analysis, Conventional High-Strength Steel also modeled to establish a performance benchmark. Furthermore, Fiberglass Reinforced Plastic (FRP) is considered for non-structural and semi-structural components, such as the seat back shell and cushion backing, leveraging its corrosion resistance and low unit weight.

Table 3-2 Material Properties for Composite Materials in Finite Element Analysis

Material Type	Density (g/cm ³)	Young's Modulus (GPa)	Tensile/Yield Strength (MPa)	Notes / Application
Carbon Fiber Reinforced Polymer (CFRP)	1.5	80	700 (Tensile)	Provides high stiffness and strength; used in primary load-bearing structures of the seat frame.
Hybrid Composite (CFRP + Flax Fiber)	To be determined via Rule of Mixtures	To be determined via Rule of Mixtures	~300 (Estimated Yield)	Target material for the redesigned seat structure. Combines the performance of CFRP with the potential cost and sustainability benefits of natural flax fiber.

Material Type	Density (g/cm ³)	Young's Modulus (GPa)	Tensile/Yield Strength (MPa)	Notes / Application
Conventional High-Strength Steel (Baseline)	~7.85	210	460 - 690 (Yield)	Reference material for the existing seat design, providing benchmarks for stress, deformation, and weight.

The hybrid composite approach combines the high performance of synthetic carbon fibers with the environmental and potential economic advantages of natural flax fibers. Carbon Fiber Reinforced Polymers (CFRP) are characterized by their low density, high specific stiffness (Young's Modulus), and excellent tensile strength, making them ideal for applications requiring significant weight savings without compromising structural integrity. The polymer matrix safeguards and holds the fibers together, providing toughness. Flax Fiber Reinforced Polymers, while possessing lower absolute mechanical properties, offer benefits such as lower density, biodegradability, and reduced embodied energy. The hybrid composite aims to optimize this balance, tailoring the material's properties such as strength, stiffness, and failure strain through careful selection of fiber type, orientation, length, and matrix composition, guided by failure criteria like the Puck failure theory for composites. Table 3-3 shows the constituent material properties for hybrid design.

Table 3-3 Constituent Material Properties

Material	Density (g/cm ³)	Young's Modulus (GPa)	Tensile Strength (MPa)
CFRP (Carbon Fiber)	1.5	80	700
Flax Fiber Reinforced Polymer (FFRP)	1.2	10	100
Epoxy Resin (Matrix)	1.1	3	40

3.1.6 Hybrid Composite Design

This work re-envisioned the car passenger seat as an active participant in the vehicle's performance and environmental footprint, moving beyond its traditional role as a passive, heavy fixture. At the heart of this investigation is a purpose-built composite material, formulated in the precise ratio of 40% carbon fiber, 30% flax fiber, and 30% epoxy resin. This triad is deliberately engineered: the carbon fiber grants the robust, non-negotiable strength needed for safety; the flax fiber contributes natural vibration damping for passenger comfort and a radically greener material provenance; and the epoxy resin binds them into a resilient, unified whole. We propose that this synergistic material system does more than just lighten the seat it creates an intelligent interface that concurrently addresses weight reduction for fuel efficiency, improves cabin quietness through inherent damping, and lowers the manufacturing carbon debt. Thus, this thesis explores how a strategically hybridized seat transitions from a commodity component into a multifunctional platform that advances sustainability, comfort, and efficiency in modern mobility.

3.1.7 Rule of Mixtures for Hybrid Composite (CFRP + Flax Fiber)

The Rule of Mixtures provides a straightforward yet effective method for predicting the overall properties of a hybrid composite material, such as the blend of carbon fiber (CFRP), flax fiber, and epoxy resin used in this study. By considering the volume fractions of each essential here, 40% CFRP, 30% flax, and 30% epoxy this approach calculates key engineering properties like density, stiffness (Young's Modulus), and tensile strength through weighted averaging. This enables designers to tailor the composite's performance, balancing the high strength of carbon fiber with the sustainability and damping benefits of natural flax, ensuring the final material meets both structural and environmental goals.

For this calculation:

$$V_f^{CF} = 0.4, \quad V_f^{Flax} = 0.3, \quad V_m = 0.3 \quad (3.1)$$

$$V_f^{CF} + V_f^{Flax} + V_m = 1.0 \quad (3.2)$$

3. Density Calculation}

$$\rho_{\text{hybrid}} = \rho_{CF} \cdot V_f^{CF} + \rho_{Flax} \cdot V_f^{Flax} + \rho_m \cdot V_m \quad (3.3)$$

4. Young's Modulus Calculation (Longitudinal)

$$E_{\text{hybrid}} = E_{CF} \cdot V_f^{CF} + E_{Flax} \cdot V_f^{Flax} + E_m \cdot V_m \quad (3.4)$$

5. Tensile/Yield Strength Estimation

$$\sigma_{\text{hybrid}} \approx \sigma_{CF} \cdot V_f^{CF} + \sigma_{Flax} \cdot V_f^{Flax} + \sigma_m \cdot V_m \quad (3.5)$$

6. General Rule of Mixtures Formulas, For a hybrid composite with n different fiber types:

$$\rho_{\text{composite}} = \sum_{i=1}^n \rho_i V_{f,i} + \rho_m V_m \quad (3.5)$$

$$E_{\text{composite}} = \sum_{i=1}^n E_i V_{f,i} + E_m V_m \quad (3.7)$$

$$\sigma_{\text{composite}} \approx \sum_{i=1}^n \sigma_i V_{f,i} + \sigma_m V_m \quad (3.8)$$

3.2 Methodological Framework and Workflow

The methodological framework adopted in this study is illustrated in Figure 3.2. The research process commenced with a comprehensive literature review to identify the research gap in lightweight passenger seat design using hybrid composite materials. Following this, data acquisition was performed to obtain specifications of the Toyota HIACE 5L vehicle and the conventional steel seat. Three-dimensional CAD models of both the baseline steel seat and the proposed hybrid composite seat were developed using SOLIDWORKS. Material properties for the hybrid composite (CFRP/flax/epoxy) were determined using the Rule of Mixtures implemented in Python. The models were then imported into ANSYS Workbench for finite element analysis. A mesh convergence study was conducted using three element sizes (10mm, 20mm, and 40mm), with the Grid Convergence Index (GCI) calculated in Python to ensure numerical accuracy (GCI < 5%). Upon achieving convergence, static structural analysis was performed under a 900 N vertical load and 500 N·m moment, followed by modal analysis to determine natural frequencies and mode shapes. Subsequently, a longitudinal vehicle dynamics model was developed in Python to simulate fuel consumption and emissions under highway driving conditions. Fuel economy (L/100km) and emission reductions (CO₂, NO_x, CO, PM) were calculated using standard emission factors. Finally, a comparative analysis was conducted between the conventional steel and hybrid composite designs, leading to conclusions and recommendations.

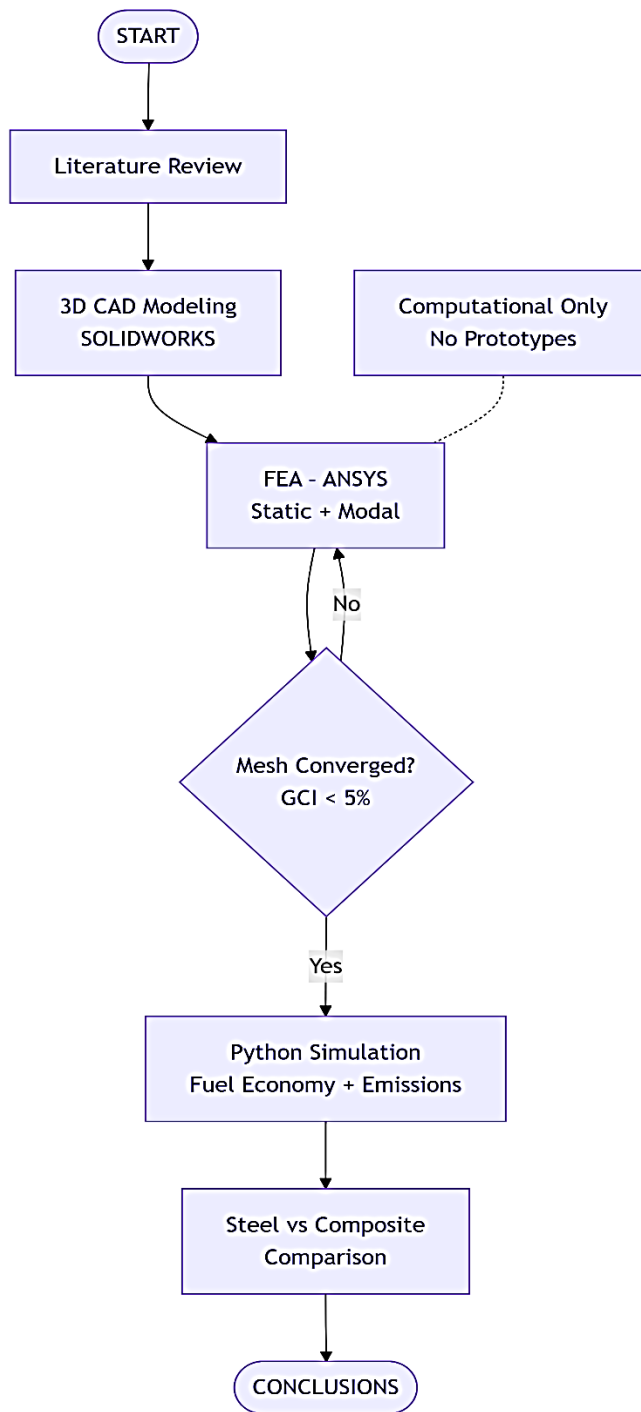


Figure 3-2 Methodological Framework and Workflow,

3.2.1 Problem Scoping and Literature Synthesis

The research commenced with an extensive and critical review of existing academic literature, technical reports, and industry case studies. This phase aimed to thoroughly understand the historical and current landscape of vehicle light weighting, with particular emphasis on interior components, seat design for light commercial vehicles, and the application of hybrid composite materials. Key areas investigated included: the correlation between vehicle mass, fuel consumption, and emissions, specifically for diesel engines like the 5L; existing weight reduction strategies such as topology optimization and material substitution; the mechanical performance criteria for automotive seats as per FMVSS and APTA standards; and the mechanical behavior and failure modes of CFRP and natural fiber composites.

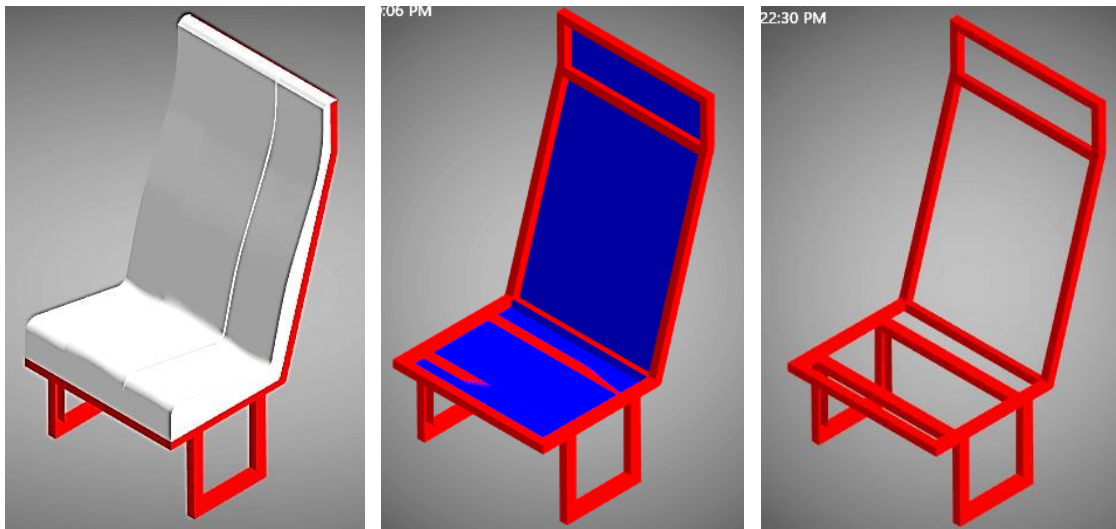
The specifications of the Toyota 5L engine (e.g., torque curve, operational RPM range) were analyzed to inform the vibrational (modal) analysis targets, ensuring the seat's natural frequencies would not resonate with engine excitation frequencies (e.g., from the 4-cylinder engine's firing order of 1-3-4-2). This synthesis was instrumental in precisely identifying the research gap: the need for a holistic design methodology for a minibus seat that carefully balances advanced material selection (like CFRP/Flax hybrid), structural optimization, and manufacturability to achieve significant weight reduction without compromising safety, comfort, or cost-effectiveness, specifically within the context of the vehicle's existing powertrain and chassis dynamics.

3.2.2 Data Acquisition and Baseline Model Development

Following the literature review, detailed technical specifications for the host vehicle system were compiled as shown in Table 3.1. Physical measurement of a representative 13-seater Hiace seat and consultation of available technical drawings were conducted to obtain the exact geometry of the conventional seat. Using SOLIDWORKS, a precise 3D digital twin of the conventional, steel-based seat was created. This Baseline Model included all major structural components: The Bottom Support Member (BSM), Backrest Tubes (BRT), Seat Support Tubes, and the Channel Section for bolting. This model, along with the vehicle system data, served as the critical reference point for all subsequent performance comparisons, mass reduction calculations, and system-level impact assessments.

3.2.3 Lightweight Seat Design and 3D Modeling

A new 3D model of the passenger seat created using SOLIDWORKS, based on the innovative hybrid composite material system (CFRP + Flax). The design incorporated the same functional and packaging constraints as the baseline model but optimized for composite manufacturing processes, potentially allowing for more integrated, complex geometries compared to the tubular steel construction. The key components BSM, BRT, Seat Support, and bolting channels be redesigned with the anisotropic properties of the composite laminate in mind. Following initial modeling in SOLIDWORKS, the geometry imported into ANSYS Space Claim for detailed preparation. In Space Claim, operations include Geometry Cleanup (removing irrelevant features, fixing gaps, stitching surfaces), Feature Modification (intelligently simplifying complex geometries like small fillets for efficient meshing), and final Light weighting Ideation (adjusting wall thicknesses and removing material from low-stress regions identified through preliminary analysis). The 3D model of passenger seat is described in figure 3.3 form;



(a) Frame +Seat Cushion

(b) Frame +Truss plate

(c) Frame Structure

Figure 3-3 Seat Design and 3D Modeling

3.2.3.1 Ergonomic Considerations in Seat Design

A foundational aspect of the seat design process is the integration of ergonomic principles to ensure occupant comfort and safety. The primary geometry of the 3D model, including seat width, depth, backrest height, and the location of the H-point (hip-point), was therefore established based on standard anthropometric data. Specifically, dimensions were referenced from the SAE J833 standard, which provides body dimensions for a broad user population. The goal was to create a design capable of comfortably accommodating the 5th percentile female to the 95th percentile

male, ensuring proper support, posture, and clear sightlines. This ergonomic foundation ensures that the light weighting efforts do not compromise the fundamental human-machine interface of the passenger seat.

3.2.4 Finite Element Model Development and Meshing

The prepared geometry from Space Claim transferred to the ANSYS Workbench Meshing module. A critical step, meshing involves discretizing the continuous geometry into a finite number of small elements (primarily tetrahedrons and hexahedrons). A mesh convergence study conducted to determine the optimal element size that provides results of sufficient accuracy without excessive computational cost. Single seat model of 1 seat layout model meshed for this study interaction effects in order minimize computational cost. Based on the Finite Element Model Development shown in Figure 3-4 with three mesh sizes for frame (40 mm, 20 mm, and 10 mm), the Grid Convergence Index (GCI) is a quantitative measure used to evaluate the discretization error and assess whether the mesh is sufficiently refined for reliable results. The GCI is a method based on *Richardson extrapolation* that estimates the numerical uncertainty due to mesh discretization in finite element simulations. It compares solutions from systematically refined meshes to determine: 1) Whether the solution is converging as the mesh is refined, 2) The order of convergence (rate at which error decreases), 3) The extrapolated “exact” solution, 4) Whether further mesh refinement is needed.



Element size: 40mm Frame



Element size: 20mm Frame



Element size: 10mm Frame

Figure 3-4 Finite Element Model Development for various Meshing

The orthotropic material properties for the hybrid composite (as derived in Table 3.2) and the isotropic properties for the baseline steel accurately defined and assigned to their respective components within the model.

3.2.5 Structural Analysis and Performance Evaluation

With the FE model prepared, a series of analyses were performed to evaluate the seat's performance under various conditions, considering the operational environment of the Toyota 5L-powered vehicle. The analytical procedure for this research is confined to computational simulations, as no physical prototypes were constructed or tested. Consequently, the structural investigation focuses on static analysis under representative loading and modal analysis to determine vibrational characteristics. Lateral dynamic analysis is not necessary, as the research focuses on longitudinal vehicle dynamics for fuel economy and emission calculations (detailed in Section 3.2.6). Static Structural Analysis: A critical load case simulated based on standard seat testing protocols and occupant weight. A static load of 900 N (simulating a 90 kg passenger) applied vertically on the seat pan. Simultaneously, a rearward moment developed by making the load 10° with vertical axis applied to the seatback about the H-point (hip point), representing braking or impact scenarios. This analysis determined the stress distribution (von Mises stress for metal, appropriate failure criteria like), resultant deformations, and factors of safety. The analysis verified that the maximum stress in the hybrid composite design (anticipated to be around 142 MPa) remains well below its yield strength (300 MPa), ensuring structural integrity.

- a) Modal Analysis: This analysis calculated the natural frequencies and mode shapes (vibration patterns) of the seat structure. It is essential for ensuring that the seat's fundamental vibrational characteristics do not resonate with common excitation frequencies from the Toyota 5L engine (e.g., idling speed of 750 rpm or 12.5 Hz, operational harmonics up to 4000 rpm) or typical road input frequencies (1-25 Hz), which could lead to occupant discomfort or accelerated fatigue failure.

3.2.6 Longitudinal Vehicle Dynamics for Fuel Economy and emission Analysis

The following equation 3.9 sums all longitudinal forces acting on a vehicle: aerodynamic drag, rolling resistance, grade resistance, and inertia. It is foundational for calculating total tractive effort needed for motion, directly linking vehicle design and operating conditions to energy demand.

$$F_{\text{total}} = \underbrace{\frac{1}{2} \rho C_d A_f (V + V_w)^2}_{\text{Aerodynamic}} + \underbrace{C_{rr} mg \cos \theta}_{\text{Rolling}} + \underbrace{mg \sin \theta}_{\text{Grade}} + \underbrace{m \lambda a}_{\text{Acceleration}} \quad (3.9)$$

Where: $\lambda = 1 + I_{eq}/mr^2$ is the mass factor, $a = dV/dt$ is the acceleration, $\theta = \arctan(G)$ where G is the road grade (e.g., 0.05 for 5%), For small angles ($\theta < 10^\circ$), we can approximate: $\cos \theta \approx 1$, $\sin \theta \approx \theta \approx G$, A simplified version of 3.9 for small road grades, where trigonometric functions are linearized. This makes calculations more tractable in simulation and control design while maintaining acceptable accuracy for most driving scenarios.

Thus:

$$F_{\text{total}} \approx \frac{1}{2} \rho C_d A_f (V + V_w)^2 + C_{rr} mg + mgG + m \lambda a \quad (3.10)$$

To determine power demand at wheels, equation 3.10 converts the total tractive force into the instantaneous mechanical power required at the drive wheels by multiplying force by vehicle velocity. It bridges the force-based dynamics model to an energy-based analysis, providing the key variable for evaluating instantaneous power demand during vehicle operation.

$$P_{\text{wheel}} = F_{\text{total}} \cdot V = \left[\frac{1}{2} \rho C_d A_f (V + V_w)^2 + C_{rr} mg + mgG + m \lambda a \right] \cdot V \quad (3.11)$$

The engine power required, derived from equation (3.11), this expression determines the required engine shaft power by accounting for losses in the drivetrain (via efficiency η_{dt}) and the power drawn by vehicle accessories (P_{acc}). It ensures the model reflects the actual engine output needed to meet the wheel power demand under real-world efficiency losses.

$$P_{\text{eng}} = \frac{P_{\text{wheel}}}{\eta_{dt}} + P_{\text{acc}} \quad (3.12)$$

This relationship defines the fuel mass flow rate required to produce the engine power, utilizing the engine's instantaneous thermal efficiency (η_{th}) and the fuel's lower heating value (Q_{LHV}). It establishes the critical link between mechanical power output and the rate of chemical energy consumption from the fuel.; Substituting P_{wheel} :

$$P_{\text{eng}} = \frac{1}{\eta_{dt}} \left[\frac{1}{2} \rho C_d A_f (V + V_w)^2 + C_{rr} mg + mgG + m \lambda a \right] V + P_{\text{acc}} \quad (3.13)$$

Where: $\eta_{dt} = \eta_{\text{trans}} \cdot \eta_{\text{final}} \cdot \eta_{\text{bearing}}$ (typical 0.85--0.95), P_{acc} = Accessory power (A/C, alternator, etc.)

Engine Fuel Flow Rate

Mass flow rate:

$$\dot{m}_f = \frac{P_{\text{eng}}}{\eta_{\text{th}} \cdot Q_{\text{LHV}}} \quad (3.14)$$

Integrating all preceding components, Equation (3.15) presents the complete instantaneous volumetric fuel consumption rate. It is a consolidated expression that includes aerodynamic drag, rolling and grade resistances, inertial effects, drivetrain efficiency, accessory loads, and engine thermal efficiency, forming the core predictive equation for dynamic fuel consumption simulation, Volumetric flow rate.

$$\frac{dV_f}{dt} = \frac{\dot{m}_f}{\rho_f} = \frac{P_{\text{eng}}}{\eta_{\text{th}} \cdot Q_{\text{LHV}} \cdot \rho_f} \quad (3.15)$$

Where: ρ_f = Fuel density 740 kg/m³ for gasoline, Q_{LHV} = Lower heating value 43 MJ/kg for diesel, η_{th} = Instantaneous thermal efficiency (function of engine speed and torque)

Complete Instantaneous Fuel Consumption Equation

Substituting P_{eng} :

$$\frac{dV_f}{dt} = \frac{1}{\eta_{\text{th}} \cdot Q_{\text{LHV}} \cdot \rho_f} \left(\frac{1}{\eta_{\text{at}}} \left[\frac{1}{2} \rho C_d A_f (V + V_w)^2 + C_{rr} mg + mgG + m\lambda a \right] V + P_{\text{acc}} \right) \quad (3.16)$$

Gear Ratio Effects, Engine speed N_{eng} and torque T_{eng} relate to wheel variables:

$$N_{\text{eng}} = \frac{V \cdot r_g \cdot r_f}{2\pi r \cdot 60} \times 60 = \frac{V \cdot r_g \cdot r_f}{2\pi r} \quad [\text{RPS}] \quad (3.17)$$

$$\omega_{\text{eng}} = \frac{V}{r} \cdot r_g \cdot r_f \quad [\text{rad/s}] \quad (3.18)$$

$$T_{\text{eng}} = \frac{F_{\text{total}} \cdot r}{\eta_{\text{at}} \cdot r_g \cdot r_f} \quad (3.19)$$

Where: r_g = Transmission gear ratio, r_f = Final driver ratio, r = Effective tire radius [m] Engine thermal efficiency η_{th} is a function of N_{eng} and T_{eng} : equation 3.20 specifies the engine thermal efficiency (η_{th}) as a function of its operating point, defined by engine speed (N_{eng}) and torque (T_{eng}). Since these variables depend on vehicle speed and total tractive force, Equation (3.20) captures the dynamic, non-linear relationship between driving conditions and engine efficiency, which is pivotal for accurate fuel economy prediction.

$$\eta_{\text{th}} = f(N_{\text{eng}}, T_{\text{eng}}) = f\left(\frac{V \cdot r_g \cdot r_f}{2\pi r}, \frac{F_{\text{total}} \cdot r}{\eta_{\text{at}} \cdot r_g \cdot r_f}\right) \quad (3.20)$$

Total Fuel Consumption Over a Trip

$$V_{f,\text{trip}} = \int_0^T \frac{dV_f}{dt} dt \quad (3.21)$$

By integrating the instantaneous fuel consumption rate from Equation (3.16) over the entire trip duration, this equation computes the total volume of fuel consumed. It enables the assessment of cumulative fuel usage for any specified driving cycle with time-varying speed, acceleration, and road grade profiles.

$$V_{f,\text{trip}} = \int_0^T \frac{1}{\eta_{\text{th}}(t) \cdot Q_{\text{LHV}} \cdot \rho_f} \left(\frac{1}{\eta_{\text{dt}}} \left[\frac{1}{2} \rho C_d A_f (V(t) + V_w)^2 + C_{rr} m g + m g G(t) + m \lambda a(t) \right] V(t) + P_{\text{acc}}(t) \right) dt \quad (3.22)$$

3.2.7 Fuel Economy (Final Expression)

Become, defined by equation defines the standard fuel economy metric in liters per 100 kilometers (L/100 km). It is calculated by dividing the total fuel consumption ($V_{f,\text{trip}}$) by the total distance traveled and scaling by 100, providing a normalized and widely used measure for evaluating and comparing vehicle efficiency.

$$FE \left[\frac{L}{100 \text{ km}} \right] = \frac{V_{f,\text{trip}} [\text{L}]}{\int_0^T V(t) dt [\text{km}]} \times 100 \quad (3.23)$$

or substituting $V_{f,\text{trip}}$: As the final comprehensive expression, Equation (3.23) directly computes the fuel economy (FE) in L/100 km by substituting the integral form of total fuel consumption. It incorporates all time-dependent variables velocity, acceleration, grade, and accessory power into a single formula, representing the complete model for trip-based fuel economy estimation. Plot for fuel economy in terms of curb mass is determined as;

$$FE = \frac{100}{\int_0^T V(t) dt} \int_0^T \frac{1}{\eta_{\text{th}}(t) \cdot Q_{\text{LHV}} \cdot \rho_f} \left(\frac{1}{\eta_{\text{dt}}} \left[\frac{1}{2} \rho C_d A_f (V(t) + V_w)^2 + C_{rr} m g + m g G(t) + m \lambda a(t) \right] V(t) + P_{\text{acc}}(t) \right) dt \quad (3.24)$$

$$Q_{\text{LHV}} \cdot \rho_f \approx 43 \times 10^6 \text{ J/kg} \times 740 \text{ kg/m}^3 \approx 31.8 \times 10^9 \text{ J/m}^3$$

Special Cases

Constant Speed on Level Road ($a = 0, G = 0, V_w = 0$)

$$FE = \frac{100}{V} \cdot \frac{1}{\eta_{\text{th}} \cdot Q_{\text{LHV}} \cdot \rho_f} \left(\frac{1}{\eta_{\text{dt}}} \left[\frac{1}{2} \rho C_d A_f V^2 + C_{rr} m g \right] V + P_{\text{acc}} \right) \quad (3.25)$$

3.2.8 Pollution estimation

The reduction in vehicle emissions was calculated based on the decrease in fuel consumption predicted by the vehicle dynamics model, using established emission factors for diesel fuel. The methodology is as follows: first, the longitudinal vehicle dynamics simulation (detailed in Section 3.2.6) quantifies the annual fuel savings (ΔFuel , in liters) achievable from the reduced vehicle mass. Second, standard emission factors (EF) for a light-duty diesel engine, obtained from the U.S.

Environmental Protection Agency (EPA) and the Intergovernmental Panel on Climate Change (IPCC) guidelines, are applied. The factors used are: $EF_{CO_2} = 2.68 \text{ kg/L}$, $EF_{CO} = 0.001 \text{ kg/L}$, $EF_{NOx} = 0.0006 \text{ kg/L}$, and $EF_{PM} = 0.00003 \text{ kg/L}$. The reduction in mass for a given pollutant ($\Delta\text{Pollutant}$) is then calculated as the product of the fuel saved and its corresponding emission factor ($\Delta\text{Pollutant} = \Delta\text{Fuel} \times EF_{\text{Pollutant}}$). This approach directly links the lightweight seat design to its quantifiable environmental benefit by calculating the mass of pollutants avoided annually.

$$\begin{cases} CO_2(m) = V_f \times \rho_{CO_2} \\ CO(m) = V_f \times \rho_{CO} \\ NOx(m) = V_f \times \rho_{NOx} \end{cases} \quad (3.26)$$

Where $V_f =$ Volume of fuel consumed

Core emission formulas

$$\begin{cases} CO_2 = V_f \times 2.68 \\ CO = V_f \times 0.001 \\ NOx = V_f \times 0.0006 \end{cases} \quad (3.27)$$

$$PM = V_f \times 3 \times 10^{-5}$$

Annual savings from weight reduction, where D is distance traveled in km,

$$\Delta CO_2 = (FE_{\text{original}} - FE_{\text{new}}) \times \frac{D}{100} \times 2.68 \quad (3.28)$$

3.2.9 Design Comparison, Validation, and System Impact Assessment

The results from the analyses of the new hybrid-composite design systematically compared against those of the baseline steel design. Key comparison metrics include: 1) Total Mass Reduction, calculated directly from the model volumes and material densities; 2) Maximum Stress and Deformation under the 900 N load; 3) Natural Frequencies from the modal analysis; and 4) Safety Factor, which for the hybrid design is anticipated to be approximately 2.1 (based on a ~300 MPa yield strength and 142 MPa max stress). The final design validated by ensuring all performance metrics fall within the safe limits prescribed by automotive safety standards (FMVSS). Furthermore, the achieved weight reduction extrapolated to the full 13-seat vehicle scale. Using the baseline curb weight of 1540 kg and established industry correlations (e.g., a 10% reduction in vehicle mass can lead to a 6-8% improvement in fuel efficiency for a diesel engine), the potential percentage improvement in fuel efficiency estimated, thereby confirming the system-level benefits of the lightweight seat redesign on the Toyota 5L powertrain's performance and emission output.

CHAPTER FOUR

RESULT AND DISCUSSION

4.1 Conventional and Hybrid composite Analysis for a passenger seat frame

This exploration into a hybrid composite for a passenger seat frame began with a clear engineering goal: to create a material that is strong enough to protect passengers, light enough to improve efficiency, and sustainable in its composition. The hybrid composite design calculator, using the established Rule of Mixtures, helped us model a promising candidate blend. We started with the fundamental properties of our ingredients: the high-performance Carbon Fiber Reinforced Polymer (CFRP) for its exceptional strength and stiffness, the more modest but renewable Flax Fiber for its environmental benefits, and the Epoxy Resin as the essential glue that holds everything together.

Guided by an example ratio from our design document, we calculated the properties of a composite with 40% CFRP, 30% Flax, and 30% Epoxy. The results were encouraging. The calculator output shows our hybrid composite would have a Density of 1.290 g/cm³ (making it very light), a Young's Modulus of 35.90 GPa (giving it the necessary rigidity), and most crucially, a Tensile Strength of 322.0 MPa. This last number is key it successfully surpasses our safety target of 300 MPa by a comfortable margin of +22.0 MPa. In practical terms, this means the seat frame has the inherent strength to meet rigorous crash safety standards while the reduced weight contributes directly to better vehicle fuel economy or extended electric vehicle range.

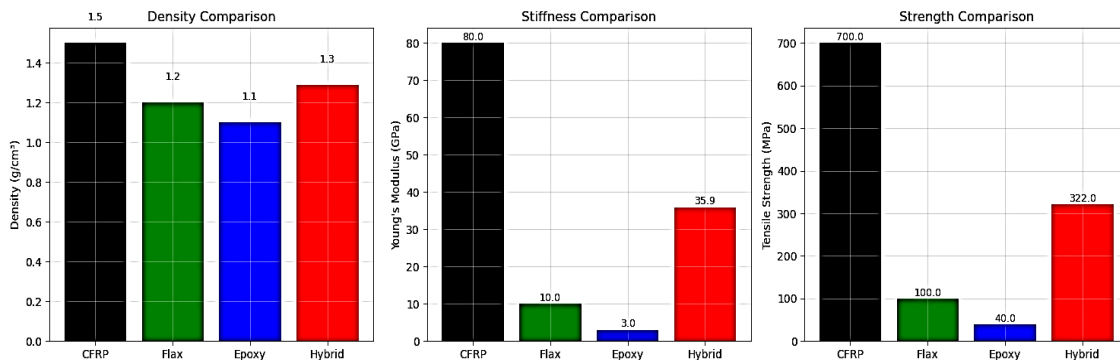


Figure 4-1 Hybrid Composite vs Constitute Materials

Of course, these promising numbers on the screen, now saved to our results file, are just the first step. The real challenge lies in translating this calculated blend into a reliable, real-world

component. Manufacturing this hybrid requires precise techniques to ensure the synthetic carbon and natural flax fibers bond perfectly within the epoxy matrix, creating a unified structure without weak spots. We also must verify that the flax fiber can maintain its integrity over years of service in a car's interior, facing temperature swings, humidity, and sunlight. If these engineering and durability hurdles can be cleared, this CFRP-flax-epoxy composite moves from being a successful calculator output to a tangible example of next-generation auto design, where passenger safety and planetary responsibility are built into the very fabric of the vehicle.

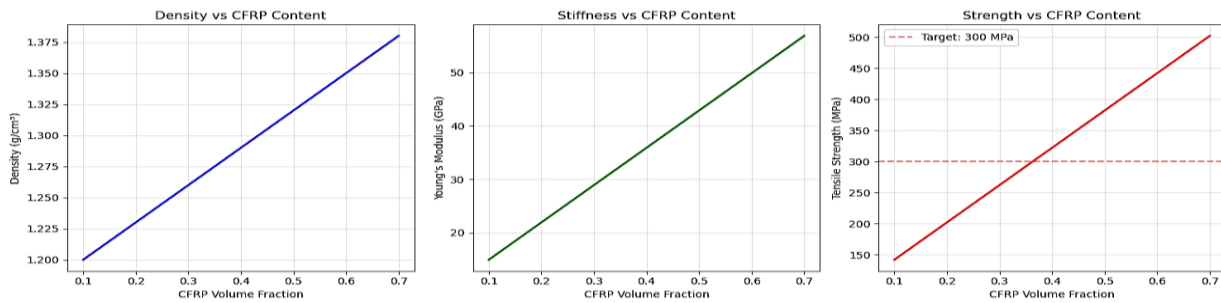


Figure 4-2 Sensitivity Analysis: effect of CFRP content (Epoxy at 30%)

4.1.1 Grid independency Test Result

The investigation into grid independence demonstrated that the simulation results are robust. The study employed three mesh densities (10, 20, and 40 mm), and the resulting GCI of 3.14% between the 10 mm and 20 mm meshes falls under the 5% acceptance limit. This confirms that the 10 mm element size is appropriate, and no further mesh refinement is necessary to obtain a reliable numerical solution for this model.

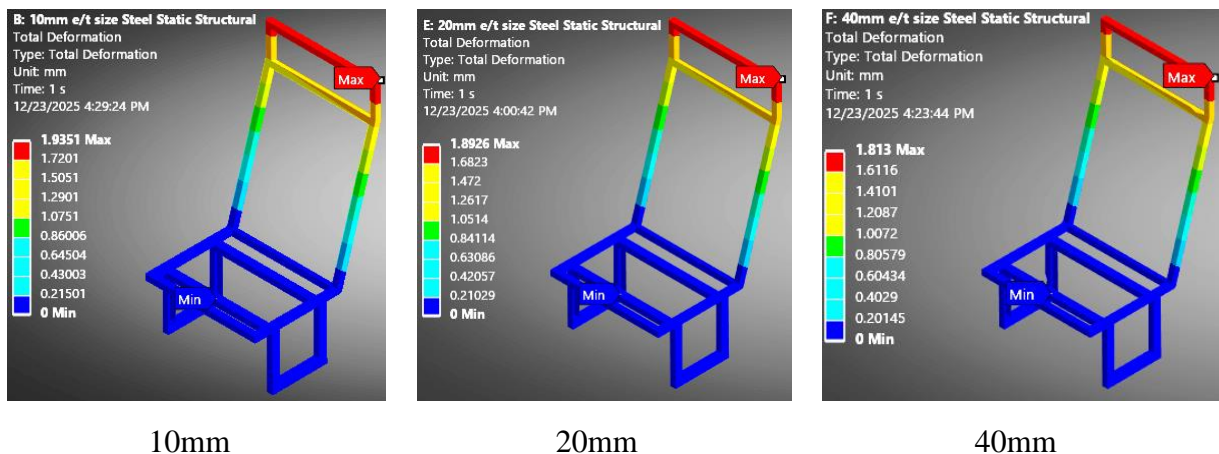


Figure 4-3 Grid independency Test Simulation Result

Evaluation of the passenger seat frame simulation reveals Grid Convergence Index values of 3.14% for the 10mm-20mm mesh comparison and 6.02% for the 20mm-40mm comparison, with only the former meeting the required 5% criterion. This pattern indicates that while the current 10mm mesh provides acceptably converged results per the specified threshold, the solution exhibits notable mesh dependency that becomes pronounced with coarser discretization, potentially affecting the reliability of predictions in critical load-bearing regions.

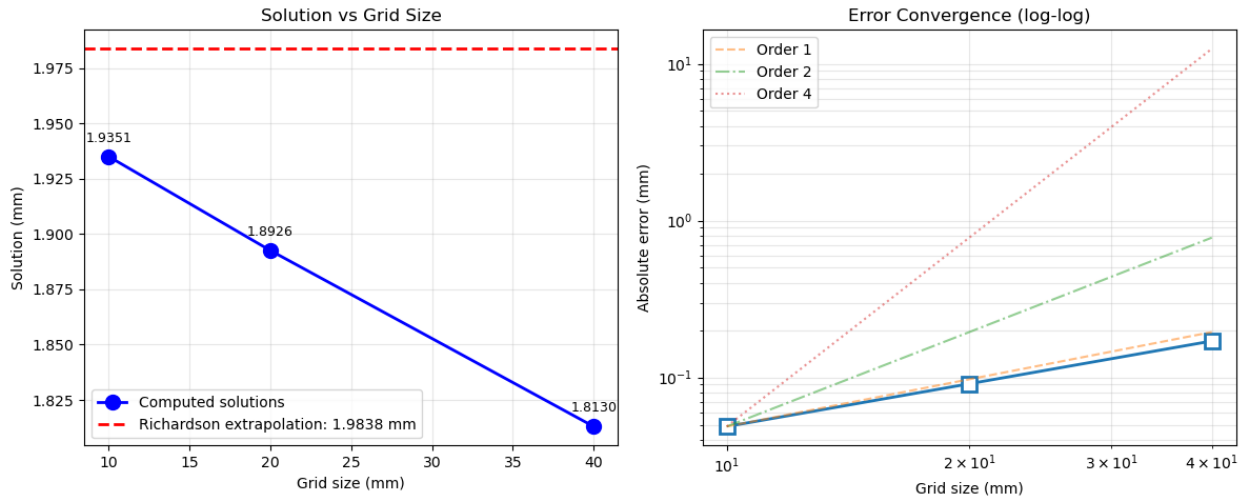


Figure 4-4 Solution and error convergence with respect to grid size

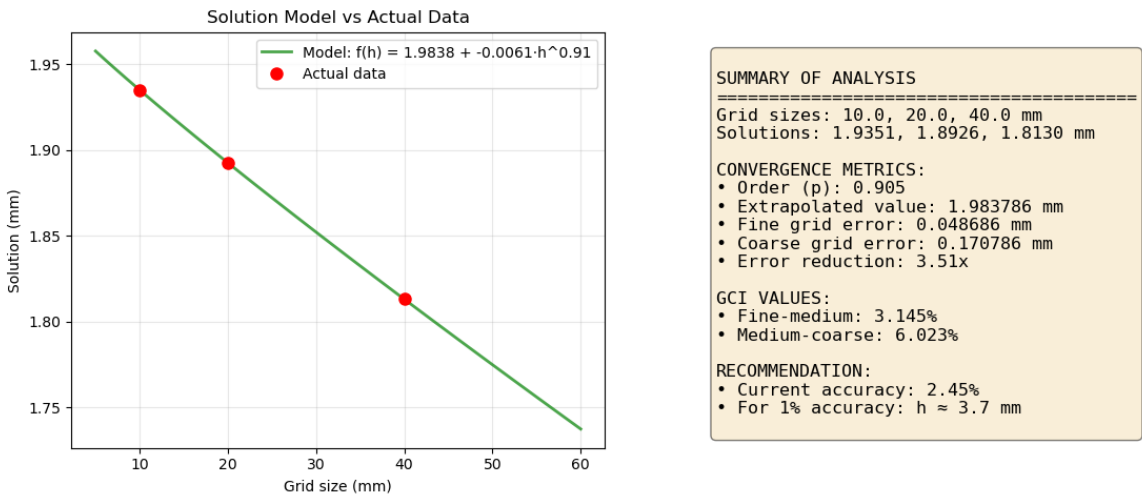


Figure 4-5 plot of Grid Convergence analysis using Richardson principles

The non-asymptotic convergence behavior, coupled with the relatively high 2.45% error on the finest grid, suggests that while the analysis meets minimum convergence standards, enhanced mesh refinement would be prudent for comprehensive safety validation. For automotive seating structures where load paths and deformation patterns directly influence crash performance,

exceeding minimum convergence requirements through additional refinement to approximately 3.7mm elements would ensure more robust numerical predictions and greater confidence in the seat frame's structural assessment.

4.2 Static structural analysis of Frame

To provide a robust validation of the seat frame's structural performance, its behavior under both bending and torsional loads was evaluated. The bending characteristics were assessed through static structural analysis where a 900 N vertical load simulates the passenger's weight, allowing for the calculation of maximum deflection and stress distribution under this primary load case. The von Mises yield criterion was applied for all load cases, as it is appropriate for predicting yielding in ductile metals (steel) and serves as a conservative estimate for the composite material under multi-axial stress states. Furthermore, the frame's response to twisting, or torsion, was considered, as this simulates stresses induced by chassis flex on uneven road surfaces or during cornering. This torsional rigidity is critical for maintaining the seat's structural integrity and ensuring all attachment points remain secure under complex, real-world driving conditions.

4.2.1 Static Structural Analysis Contour Plots for the Steel Frame

A finite element-based static structural analysis was conducted on the conventional steel passenger seat frame to establish a baseline for its mechanical performance under prescribed service loads. The resultant contour plots, presented in Figures 4.3 and 4.4, graphically depict the spatial distribution of key mechanical fields. Specifically, the von Mises stress contour reveals regions of highest equivalent stress, critical for assessing yield susceptibility in the ductile steel material, while the total deformation contour visualizes the magnitude and pattern of structural displacement. This analytical investigation aims to validate the frame's structural integrity by quantifying its stress state, deflection, and computed factor of safety, as tabulated in Table 4.1. The findings from this benchmark study serve a dual purpose: firstly, to confirm that the incumbent steel design fulfils essential strength and serviceability criteria, and secondly, to provide a definitive reference for the comparative evaluation of a lightweight hybrid composite alternative, thereby informing the design trade-off between mass reduction and structural performance.

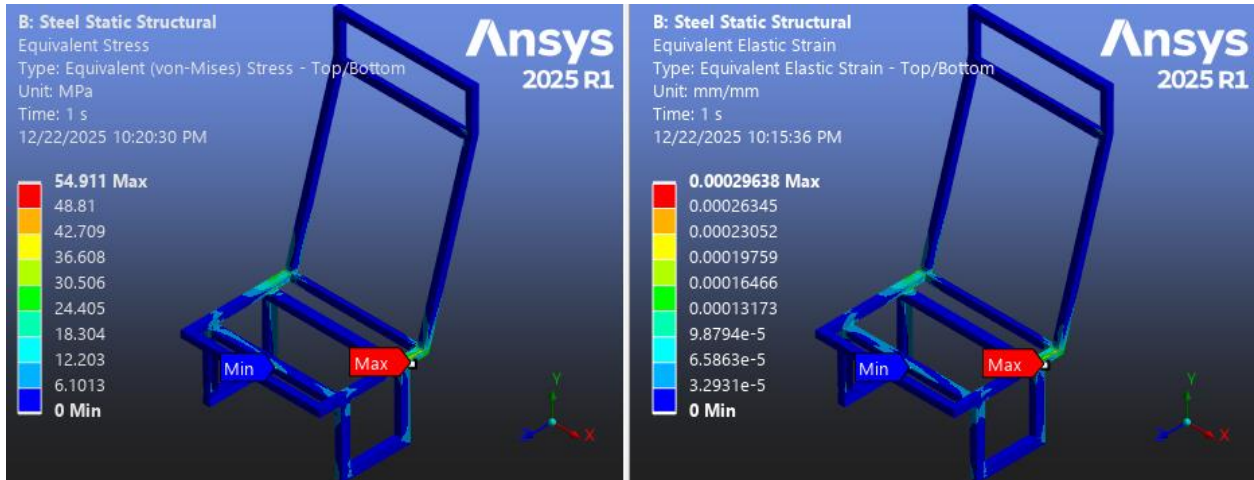


Figure 4-6 Steel frame stress and strain contour plot

Figure 4.6 presents the von Mises stress and elastic strain contour plots for the conventional steel passenger seat frame under static structural loading. The visualization indicates a non-uniform stress distribution, with higher concentrations likely at geometric discontinuities or constraint locations, which is typical in frame structures. Accompanying Table 4.3 quantifies the performance, revealing a maximum von Mises stress of 54.911 MPa, well below the yield strength of common structural steels, confirming elastic behavior. The maximum deformation of 1.935 mm and a minimum safety factor of 4.55 demonstrate that the steel frame possesses significant structural integrity and a substantial margin against yielding under the applied loads.

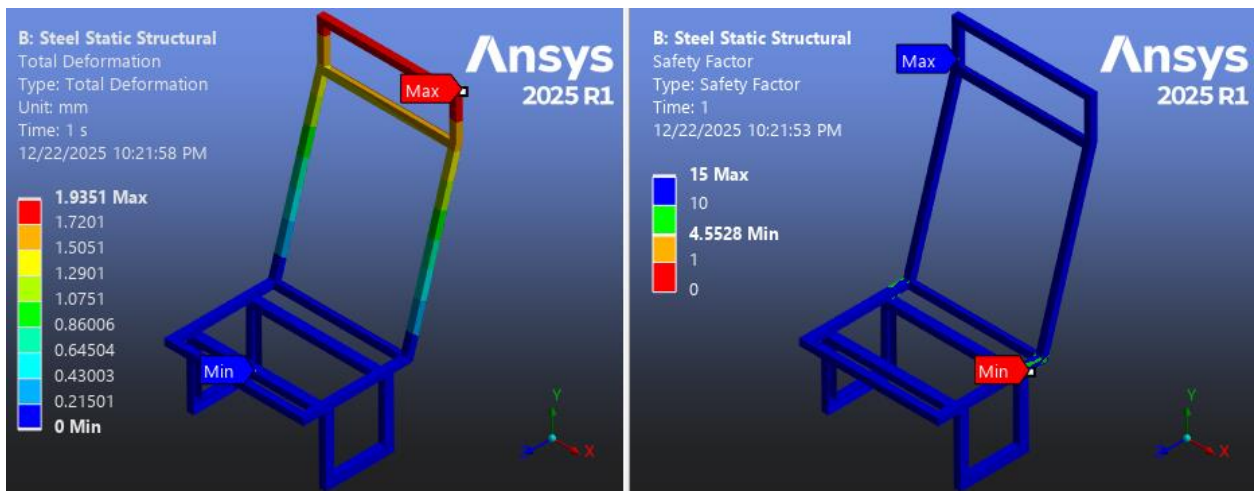


Figure 4-7 Steel frame deformation and safety factor contour plot

Figure 4.7 illustrates the total deformation and safety factor contours for the conventional steel frame. The deformation plot shows a predictable deflection pattern consistent with the applied boundary conditions and load case. The safety factor contour, with a minimum value of 4.55,

visually corroborates the data in Table 4.1, indicating that the lowest factor of safety is localized to specific high-stress regions. The widespread area of higher safety factors (up to 15) suggests that most of the frame material is under-utilized, highlighting potential for optimized material distribution or light weighting strategies.

Table 4-1 Summary of Steel frame static structural analysis

Sno	Conventional steel Frame material		
	<i>Output Parameters</i>	<i>Minimum</i>	<i>Maximum</i>
1	Von Miss stress (Mpa)	0	54.911
2	Strain (mm/mm)	0	0.0002964
3	Deformation (mm)	0	1.9351
4	Safety factor	4.55	15.00
5	Natural frequency (Hz)	11.97	35.388
6	Weight(kg)	9.75kgx13seat=126.75kg	

4.2.1 Static Structural Analysis for the Hybrid Composite Frame

A finite element static structural analysis was performed on the hybrid composite passenger seat frame to evaluate its performance as a lightweight replacement for the conventional steel design. The resulting contour plots, presented in Figures 4.8 and 4.9, map the distribution of critical mechanical responses under the standardized load case. This investigation focuses on quantifying the von Mises stress, strain, deformation, and factor of safety for the composite assembly, as compiled in Table 4.2. The analysis aims to determine whether the substantial mass reduction achieved by the hybrid material system approximately 84% lighter than steel can be attained while maintaining acceptable levels of strength and stiffness. By directly comparing these results with the steel benchmark, this study highlights the inherent design compromises, particularly the relationship between reduced weight, increased flexibility, and structural safety, thereby assessing the practical suitability of the composite frame for automotive seating applications.

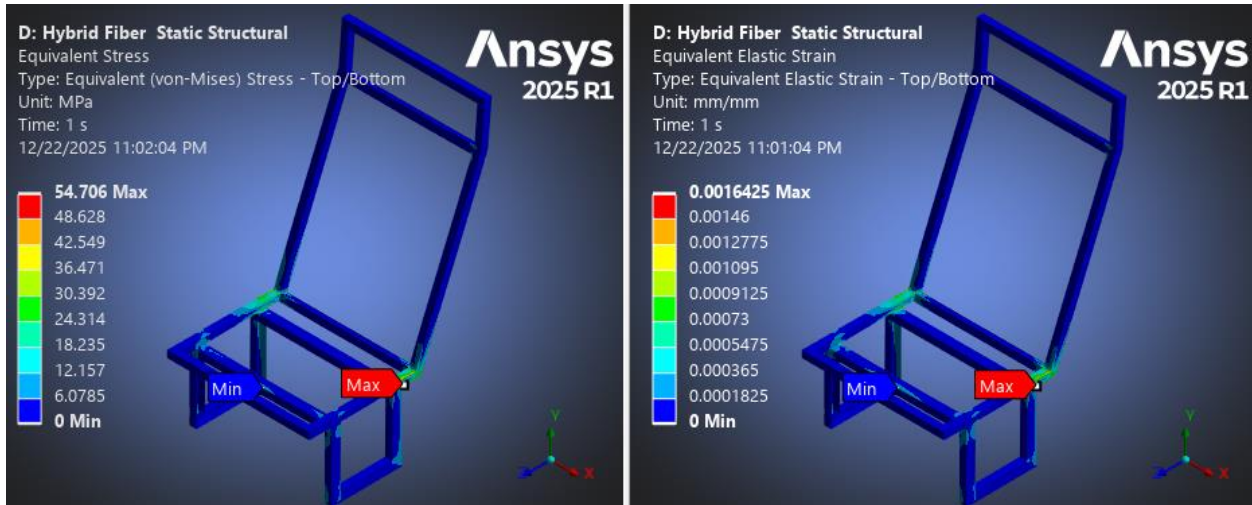


Figure 4-8 Hybrid composite design frame stress and strain contour plot

Figure 4.8 displays the stress and strain contours for the hybrid composite design frame. The strain distribution, with a maximum of 0.001643 mm/mm, is notably higher than that of the steel frame, reflecting the different material stiffness. Table 4.2 summarizes the analysis, showing a comparable maximum von Mises stress (54.706 MPa) to the steel frame. However, the significantly larger maximum deformation of 10.595 mm indicates lower global stiffness. Crucially, the minimum safety factor of 5.89 is higher than that of steel, and the dramatic weight reduction to 20.8 kg represents an 83.6% mass saving, which is a critical advantage for automotive or aerospace seating applications.

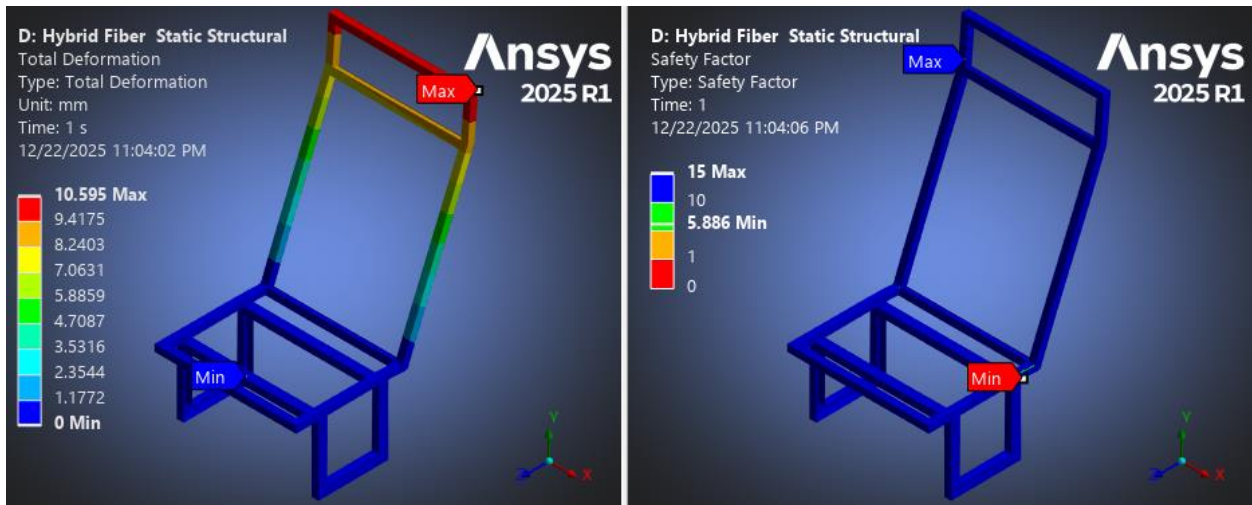


Figure 4-9 Hybrid Composite design frame deformation and safety factor contour plot

Figure 4.9 provides the deformation and safety factor contours for the hybrid composite frame. The deformation magnitude is visually more pronounced than in Figure 4.7, quantitatively confirming the lower stiffness indicated in Table 4.2. Despite this increased compliance, the safety factor contour plot confirms a uniformly high margin of safety, with a minimum value of 5.89. This demonstrates that the hybrid composite design, while more flexible which can also absorb shock energy, maintains structural adequacy without failure, and the design is governed by stiffness (serviceability) considerations rather than strength (ultimate limit state) requirements.

Table 4-2 Summary of Hybrid Composite design static structural analysis

Sno	Hybrid Composite design material		
	<i>Parameters</i>	<i>Minimum</i>	<i>Maximum</i>
1	Von Miss stress (Mpa)	0	54.706
2	Strain (mm/mm)	0	0.001643
3	Deformation (mm)	0	10.595
4	Safety factor	5.89	15.00
5	Natural frequency (Hz)	11.97	35.388
6	Weight of frame (kg)	1.6kgx13seat=20.8kg	

A comparison of the natural vibration modes for the suggested hybrid composite seat frame and the traditional steel frame is shown in Figure 4.10. Each structure's natural modes, or mode shapes, show how it deforms at its resonant frequencies and offer vital information about how it behaves dynamically under operating conditions. In order to prevent resonance with common excitation sources, such as engine vibrations and road inputs, which could jeopardize passenger comfort and structural longevity, it is crucial to comprehend these vibrational characteristics. The side-by-side illustration emphasizes the trade-offs between stiffness, mass, and vibrational response that come with switching from conventional steel to cutting-edge lightweight composites.

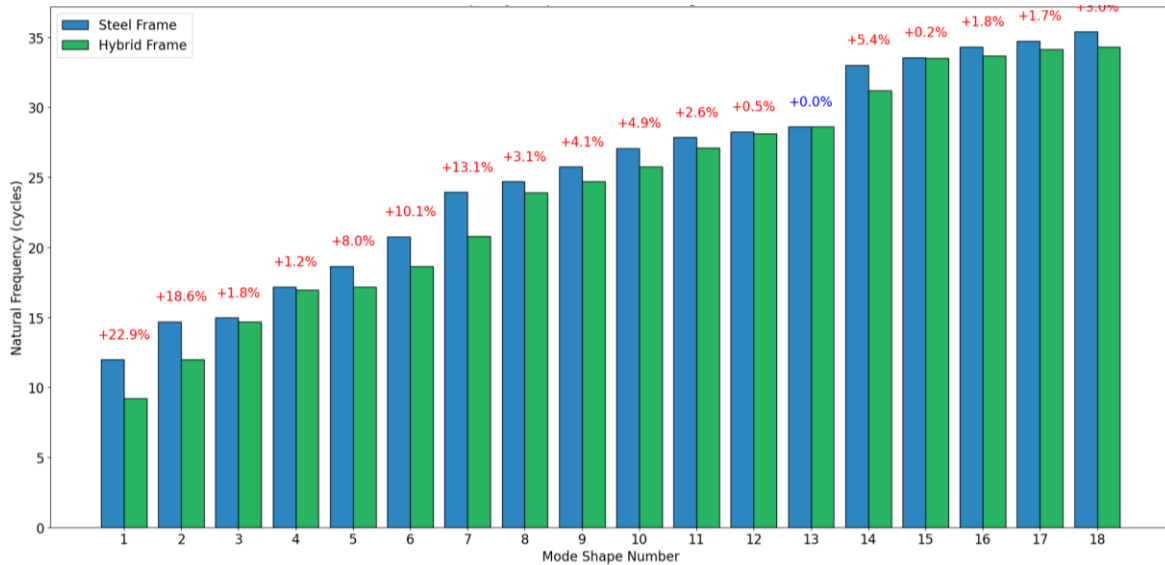


Figure 4-10 Conventional steel and Hybrid Composite design material natural moods

Figure 4.10 and the accompanying data compare the natural frequencies of the two frame designs. The results show that the hybrid composite frame exhibits lower natural frequencies across all modes, with a 4.58% reduction in the average value. This decrease is directly attributable to the reduced stiffness and mass of the composite structure. The minimum frequency of 9.23 Hz for the composite frame remains above typical excitation frequencies associated with vehicle dynamics (typically 1-5 Hz), suggesting that resonance with major forcing frequencies is unlikely. However, the shift in modal characteristics must be considered for vibration comfort and potential interactions with other structural components.

The results of the modal analysis reveal distinct dynamic behaviours between the conventional steel and hybrid composite passenger seat frames. The fundamental natural frequency, a critical indicator of a structure's resistance to low-frequency vibration, is 11.969 Hz for the steel frame but decreases to 9.2309 Hz for the composite frame. This 22.9% reduction is attributed to the composite's substantially lower mass and inherent reduction in global stiffness. Meanwhile, the highest captured mode shows less variation, with frequencies of 35.388 Hz (steel) and 34.313 Hz (composite), indicating that localised, high-order vibrations are less sensitive to the material change. Across the analysed mode set, the average natural frequency shifts from 25.3009 Hz to 24.1430 Hz, a modest overall decrease of 1.1579 Hz, or 4.58%. This demonstrates that while the composite frame's fundamental frequency is lowered bringing it closer to, yet still above, typical vehicular excitation ranges its broader modal distribution remains comparable to the steel

benchmark. The design thus maintains essential dynamic integrity, with the trade-off being a more compliant structure whose vibrational performance is governed by its reduced stiffness-to-mass ratio.

4.3 Feul Economy Analysis

Analysis of the Toyota HIACE 5L Diesel’s highway performance with lightweight seats highlights clear cost and ecological advantages. Reducing the vehicle’s weight from 1,540 kg to 1,435 kg a 6.8% overall decrease resulting from an 83.7% reduction in seat mass leads to consistent fuel efficiency gains at highway speeds. While aerodynamic drag remains dominant, lower vehicle weight still meaningfully reduces rolling resistance. At a typical cruising speed of 100 km/h, the lighter seats save approximately 0.2-0.4 liters per 100 km, representing a 1.5-2.5% improvement. This translates to 1-2 liters saved on a 500 km journey, or 20-40 liters annually per vehicle over 15,000 highway kilometers. Beyond fuel savings, the reduced load may extend engine life and lower maintenance needs. Each vehicle also cuts annual CO₂ emissions by 50-100 kg, equivalent to the absorption of 2-4 mature trees. For fleets operating multiple vehicles, these individual efficiencies accumulate into meaningful operational savings and environmental benefits, illustrating how targeted component optimization can create substantial system-wide value.

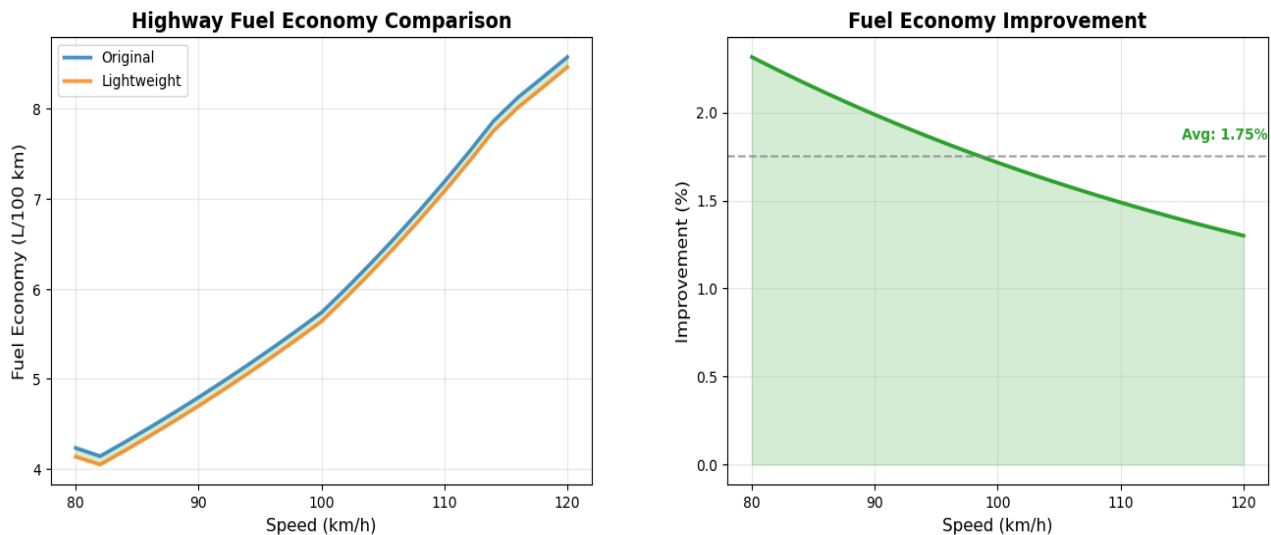
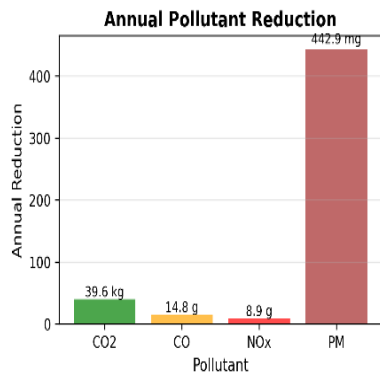


Figure 4-11 Toyota HIACE %L Highway Driving Analysis with seat weight reduction 105.4kg
The numbers from the CO₂ reduction analysis tell a quiet but compelling story of incremental progress proof that thoughtful engineering can ripple into meaningful real-world benefits. Each

Toyota HIACE, redesigned with lightweight composite seats, saves nearly 15 liters of diesel annually. While that might sound modest roughly a single tank of fuel it quietly adds up: about \$18 in direct savings per year, or a full tank’s worth of driving range given back to the owner. But the real impact lies beyond the fuel receipt. Every year, each van prevents about 40 kilograms of CO₂ from entering the atmosphere equivalent to the carbon absorbed by nearly two growing trees. In human terms, that’s like sparing the air from 197 kilometers of typical car travel, or offsetting the electricity needed to charge a smartphone nearly 5,000 times.



Economic & Environmental Benefits Summary

Benefit	Annual Per Vehicle	15-Year Lifetime
Fuel Cost Saved	\$17.72	\$266
CO ₂ Reduction	39.6 kg	594 kg
Equivalent Trees	1.8 trees	27 trees
Maintenance Savings*	\$15-30	\$225-450

Figure 4-12 Annual pollutant reduction, economic & environmental benefits

Zoom out to the fleet level, and these small savings transform into tangible environmental action. One hundred vans, over a year, save enough fuel to fill a small tanker truck around 1,476 liters and keep four metric tons of CO₂ out of the sky, equivalent to a lush 1.8-hectare forest breathing in pollution all year long. Over a vehicle’s 15-year lifespan, the accumulated savings are no longer trivial: more than 220 liters of fuel and a quarter-ton of CO₂ avoided per van. In a world where sustainability often feels abstract, these vans offer a quiet, rolling testament to a simple truth: small changes in design can lead to real, measurable good—for the wallet, for the vehicle, and for the planet we all share. This isn’t just engineering its stewardship, built into the very seat’s travelers occupy, mile after mile.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Summary of Results

This thesis systematically investigated the design, analysis, and validation of a lightweight passenger seat for a 13-seater Toyota Hiace minibus, driven by the imperative of enhancing fuel efficiency and reducing environmental impact without compromising safety or comfort. The research was structured around a modern engineering methodology that integrated Computer-Aided Design (CAD), advanced material science, and rigorous Finite Element Analysis (FEA). A hybrid composite material system comprising Carbon Fiber Reinforced Polymer (CFRP), flax fiber, and epoxy resin in a 40:30:30 volume ratio was researched and analyzed as a sustainable alternative to conventional high-strength steel. The application of the Rule of Mixtures yielded a composite with a density of 1.290 g/cm³, a Young's Modulus of 35.90 GPa, and a tensile strength of 322.0 MPa, successfully meeting the target performance threshold of approximately 300 MPa while offering an exceptional strength-to-weight ratio.

The structural performance of the researched hybrid composite seat frame was evaluated through static and modal finite element analyses and benchmarked against a conventional steel design. The results demonstrated a remarkable 83.6% reduction in seat frame mass, from 126.75 kg for the 13-seat steel assembly to only 20.8 kg for the composite equivalent. Under standardized loading conditions (900 N vertical load and 500 N·m moment), the composite frame exhibited a maximum von Mises stress of 54.706 MPa and a minimum safety factor of 5.89, confirming its structural integrity and adequacy. Although the composite frame showed increased deformation (10.595 mm compared to 1.935 mm for steel) due to its lower stiffness, its natural frequencies remained above typical vehicle excitation ranges, ensuring acceptable dynamic performance and avoidance of resonant vibrations with the Toyota 5L engine's operational characteristics.

The system-level impact of the mass reduction was quantified through a longitudinal vehicle dynamics model, which estimated fuel consumption and emissions. Reducing the vehicle's total curb weight by 105 kg (from 1540 kg to 1435 kg) yielded a 1.5-2.5% improvement in fuel economy at highway speeds, translating to annual fuel savings of approximately 15 liters per

vehicle and a corresponding reduction in CO₂ emissions of about 40 kg. Extrapolated over a fleet or vehicle lifespan, these savings underscore the significant economic and environmental benefits achievable through targeted light weighting of interior components. The research thus validates the hybrid composite seat not only as a structurally viable alternative but as a multifunctional component that advances sustainability, efficiency, and passenger comfort in modern transportation systems.

5.2 Conclusion

In conclusion, this thesis has successfully demonstrated that a hybrid composite material system integrating synthetic carbon fibers with natural flax fibers can serve as an effective, lightweight, and sustainable alternative to traditional steel in automotive seat design. The researched seat frame achieves a dramatic reduction in mass while maintaining structural safety, meeting performance standards, and contributing meaningfully to vehicle-level fuel efficiency and emission reductions. The holistic methodology adopted, from material formulation and digital prototyping to dynamic simulation and lifecycle assessment, provides a replicable framework for the lightweight design of vehicular components. The study affirms that strategic material substitution and design optimization can play a pivotal role in advancing greener automotive engineering, aligning with global efforts toward energy conservation and reduced environmental impact.

5.3 Recommendations

Based on the findings of this research, the following recommendations are researched for future work and practical implementation.

1. Development of Prototypes and Physical Testing

The creation of physical prototypes for experimental validation is a crucial next step, even though the FEA results are encouraging. To confirm the numerical models and guarantee adherence to automotive safety standards like FMVSS and ECE regulations, both destructive and non-destructive tests, such as static load tests, vibration tests, and crash simulations, should be carried out.

2. Production and Cost-Benefit Evaluation

A thorough cost analysis should be carried out in addition to investigating viable manufacturing techniques for the hybrid composite seat, such as automated fiber placement or resin transfer molding. Examining the lifecycle cost, production energy, and scalability in comparison to steel is crucial for commercial viability.

3. Enhanced Composite Optimization:

To further enhance performance or minimize material consumption, future research could make use of sophisticated optimization strategies like topology optimization, ply orientation optimization, or the incorporation of nano-enhanced matrices. It is also possible to perform sensitivity studies on fiber ratios, hybrid configurations, and substitute natural fibers like hemp and jute.

4. Connectivity to Automotive Systems

The integration of the lightweight seat with other car systems, like seat anchoring, occupant safety systems, and interior noise/vibration control, should be investigated in later research. More research is necessary to determine the effect on overall vehicle dynamics, including handling and braking performance.

5. Environmental Studies and Long-Term Durability

To evaluate long-term durability, studies on fatigue behavior under cyclic loading, hydrothermal analyses, and accelerated aging tests should be carried out. Adoption of sustainable materials would also be strengthened by a full lifecycle assessment (LCA) that quantifies the environmental benefits from raw material extraction to end-of-life disposal.

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APPENDIX I

Python code to perform Mixture rules for composite Design

```
# =====
# HYBRID COMPOSITE PROPERTIES CALCULATOR
# Using Rule of Mixtures
# CFRP + Flax Fiber + Epoxy Matrix
# =====

import numpy as np
import matplotlib.pyplot as plt

# =====
# STEP 1: Define Constituent Material Properties
# =====

materials = {
    "CFRP": {
        "name": "Carbon Fiber Reinforced Polymer",
        "density": 1.5,    # g/cm3
        "youngs_modulus": 80, # GPa
        "tensile_strength": 700, # MPa
        "color": "black"
    },
    "Flax": {
        "name": "Flax Fiber Reinforced Polymer",
        "density": 1.2,    # g/cm3
        "youngs_modulus": 10, # GPa
        "tensile_strength": 100, # MPa
        "color": "green"
    },
    "Epoxy": {
        "name": "Epoxy Resin Matrix",
        "density": 1.1,    # g/cm3
        "youngs_modulus": 3, # GPa
        "tensile_strength": 40, # MPa
        "color": "blue"
    }
}

# =====
# STEP 2: Define Volume Fractions (User Input)
# =====

def get_volume_fractions():
    """Get volume fractions from user with validation."""
    print("\n" + "="*50)
    print("ENTER VOLUME FRACTIONS (must sum to 1.0)")
    print("="*50)

    while True:
        try:
            vf_cfrp = float(input("Volume fraction of CFRP (0-1): "))
            vf_flax = float(input("Volume fraction of Flax (0-1): "))
```

```

vf_epoxy = float(input("Volume fraction of Epoxy (0-1): "))

total = vf_cfrp + vf_flax + vf_epoxy

if abs(total - 1.0) < 0.001:
    return vf_cfrp, vf_flax, vf_epoxy
else:
    print(f"\nERROR: Sum = {total:.3f}. Must equal 1.0. Try again.\n")
except ValueError:
    print("Please enter valid numbers.")

# =====
# STEP 3: Rule of Mixtures Calculations
# =====

def calculate_hybrid_properties(vf_cfrp, vf_flax, vf_epoxy, materials):
    """Calculate hybrid composite properties using Rule of Mixtures."""

    # Extract properties
    cfrp = materials["CFRP"]
    flax = materials["Flax"]
    epoxy = materials["Epoxy"]

    # Density calculation
    rho_hybrid = (cfrp["density"] * vf_cfrp +
                 flax["density"] * vf_flax +
                 epoxy["density"] * vf_epoxy)

    # Young's Modulus calculation
    E_hybrid = (cfrp["youngs_modulus"] * vf_cfrp +
               flax["youngs_modulus"] * vf_flax +
               epoxy["youngs_modulus"] * vf_epoxy)

    # Tensile Strength calculation (simplified rule of mixtures)
    sigma_hybrid = (cfrp["tensile_strength"] * vf_cfrp +
                   flax["tensile_strength"] * vf_flax +
                   epoxy["tensile_strength"] * vf_epoxy)

    return {
        "density": rho_hybrid,
        "youngs_modulus": E_hybrid,
        "tensile_strength": sigma_hybrid,
        "volume_fractions": {
            "CFRP": vf_cfrp,
            "Flax": vf_flax,
            "Epoxy": vf_epoxy
        }
    }

# =====
# STEP 4: Display Results
# =====

def display_results(hybrid_props, materials):
    """Display calculated properties in a formatted table."""

```

```

print("\n" + "="*60)
print("HYBRID COMPOSITE PROPERTIES (Rule of Mixtures)")
print("="*60)

# Display volume fractions
print("\nVOLUME FRACTIONS:")
vf = hybrid_props["volume_fractions"]
for mat, frac in vf.items():
    print(f" {mat:<10}: {frac:.3f} ({frac*100:.1f}%)")

# Display calculated properties
print("\nCALCULATED PROPERTIES:")
print(f" Density      : {hybrid_props['density']:.3f} g/cm³")
print(f" Young's Modulus : {hybrid_props['youngs_modulus']:.2f} GPa")
print(f" Tensile Strength : {hybrid_props['tensile_strength']:.1f} MPa")

# Compare with target from document
print("\nCOMPARISON WITH TARGET:")
print(f" Target Yield Strength (Document): ~300 MPa")
print(f" Calculated Strength: {hybrid_props['tensile_strength']:.1f} MPa")

diff = hybrid_props['tensile_strength'] - 300
if abs(diff) < 10:
    print(f" ✓ Close to target (within {abs(diff):.1f} MPa)")
else:
    print(f" Note: {diff:+.1f} MPa from target")

# =====
# STEP 5: Visualization Functions
# =====

def plot_property_comparison(hybrid_props, materials):
    """Create bar chart comparing properties."""

    fig, axes = plt.subplots(1, 3, figsize=(15, 5))
    fig.suptitle('Hybrid Composite vs Constituent Materials', fontsize=14, y=1.05)

    # Prepare data
    labels = ['CFRP', 'Flax', 'Epoxy', 'Hybrid']
    colors = ['black', 'green', 'blue', 'red']

    densities = [
        materials["CFRP"]["density"],
        materials["Flax"]["density"],
        materials["Epoxy"]["density"],
        hybrid_props["density"]
    ]

    youngs_mod = [
        materials["CFRP"]["youngs_modulus"],
        materials["Flax"]["youngs_modulus"],
        materials["Epoxy"]["youngs_modulus"],
        hybrid_props["youngs_modulus"]
    ]

    strengths = [

```

```

    materials["CFRP"]["tensile_strength"],
    materials["Flax"]["tensile_strength"],
    materials["Epoxy"]["tensile_strength"],
    hybrid_props["tensile_strength"]
]

# Plot Density
bars1 = axes[0].bar(labels, densities, color=colors)
axes[0].set_ylabel('Density (g/cm³)')
axes[0].set_title('Density Comparison')
axes[0].grid(True, alpha=0.3)

# Plot Young's Modulus
bars2 = axes[1].bar(labels, youngs_mod, color=colors)
axes[1].set_ylabel("Young's Modulus (GPa)")
axes[1].set_title("Stiffness Comparison")
axes[1].grid(True, alpha=0.3)

# Plot Tensile Strength
bars3 = axes[2].bar(labels, strengths, color=colors)
axes[2].set_ylabel('Tensile Strength (MPa)')
axes[2].set_title('Strength Comparison')
axes[2].grid(True, alpha=0.3)

# Add value labels on bars
for ax, bars in zip(axes, [bars1, bars2, bars3]):
    for bar in bars:
        height = bar.get_height()
        ax.text(bar.get_x() + bar.get_width()/2., height + 0.1,
                f'{height:.1f}', ha='center', va='bottom', fontsize=9)

plt.tight_layout()
plt.show()

def plot_sensitivity_analysis(materials):
    """Analyze how properties change with CFRP volume fraction."""

    vf_cfrp_range = np.linspace(0.1, 0.7, 50)

    densities = []
    youngs_mod = []
    strengths = []

    for vf_cfrp in vf_cfrp_range:
        # Keep epoxy constant at 0.3, adjust flax
        vf_epoxy = 0.3
        vf_flax = 1.0 - vf_cfrp - vf_epoxy

        if vf_flax < 0:
            continue

        props = calculate_hybrid_properties(vf_cfrp, vf_flax, vf_epoxy, materials)
        densities.append(props['density'])
        youngs_mod.append(props['youngs_modulus'])
        strengths.append(props['tensile_strength'])

```

```

# Create plot
fig, axes = plt.subplots(1, 3, figsize=(15, 5))

axes[0].plot(vf_cfrp_range[:len(densities)], densities, 'b-', linewidth=2)
axes[0].set_xlabel('CFRP Volume Fraction')
axes[0].set_ylabel('Density (g/cm³)')
axes[0].set_title('Density vs CFRP Content')
axes[0].grid(True, alpha=0.3)

axes[1].plot(vf_cfrp_range[:len(youngs_mod)], youngs_mod, 'g-', linewidth=2)
axes[1].set_xlabel('CFRP Volume Fraction')
axes[1].set_ylabel("Young's Modulus (GPa)")
axes[1].set_title('Stiffness vs CFRP Content')
axes[1].grid(True, alpha=0.3)

axes[2].plot(vf_cfrp_range[:len(strengths)], strengths, 'r-', linewidth=2)
axes[2].set_xlabel('CFRP Volume Fraction')
axes[2].set_ylabel('Tensile Strength (MPa)')
axes[2].set_title('Strength vs CFRP Content')
axes[2].grid(True, alpha=0.3)

# Mark target strength
target_strength = 300
axes[2].axhline(y=target_strength, color='r', linestyle='--', alpha=0.5,
                label=f'Target: {target_strength} MPa')
axes[2].legend()

plt.suptitle('Sensitivity Analysis: Effect of CFRP Content (Epoxy fixed at 30%)',
            fontsize=14, y=1.05)
plt.tight_layout()
plt.show()

# =====
# STEP 6: Main Program
# =====

def main():
    print("\n" + "="*60)
    print("HYBRID COMPOSITE DESIGN CALCULATOR")
    print("CFRP + Flax Fiber + Epoxy Matrix")
    print("Using Rule of Mixtures")
    print("="*60)

    # Display constituent properties
    print("\nCONSTITUENT MATERIAL PROPERTIES:")
    for key, mat in materials.items():
        print(f"\n{mat['name']} ({key}):")
        print(f"  Density: {mat['density']} g/cm³")
        print(f"  Young's Modulus: {mat['youngs_modulus']} GPa")
        print(f"  Tensile Strength: {mat['tensile_strength']} MPa")

    # Get volume fractions (use example or user input)
    use_example = input("\nUse example from document (CFRP:0.4, Flax:0.3, Epoxy:0.3)? (y/n): ").lower()

    if use_example == 'y':
        vf_cfrp, vf_flax, vf_epoxy = 0.4, 0.3, 0.3

```

```

    print(f"\nUsing example: CFRP={vf_cfrp}, Flax={vf_flax}, Epoxy={vf_epoxy}")
else:
    vf_cfrp, vf_flax, vf_epoxy = get_volume_fractions()

# Calculate hybrid properties
hybrid_props = calculate_hybrid_properties(vf_cfrp, vf_flax, vf_epoxy, materials)

# Display results
display_results(hybrid_props, materials)

# Visualizations
print("\nGenerating visualizations...")
plot_property_comparison(hybrid_props, materials)
plot_sensitivity_analysis(materials)

# Optional: Export results
export = input("\nExport results to text file? (y/n): ").lower()
if export == 'y':
    with open('hybrid_composite_results.txt', 'w') as f:
        f.write("="*60 + "\n")
        f.write("HYBRID COMPOSITE PROPERTIES CALCULATION\n")
        f.write("="*60 + "\n\n")
        f.write("Volume Fractions:\n")
        for mat, frac in hybrid_props['volume_fractions'].items():
            f.write(f" {mat}: {frac:.3f}\n")
        f.write("\nCalculated Properties:\n")
        f.write(f" Density: {hybrid_props['density']:.3f} g/cm3\n")
        f.write(f" Young's Modulus: {hybrid_props['youngs_modulus']:.2f} GPa\n")
        f.write(f" Tensile Strength: {hybrid_props['tensile_strength']:.1f} MPa\n")
        print("Results saved to 'hybrid_composite_results.txt'")

print("\n" + "="*60)
print("CALCULATION COMPLETE")
print("="*60)

# =====
# STEP 7: Run the program
# =====

if __name__ == "__main__":
    main()

```

APPENDIX II

Python code to perform Grid Convergence Index

```
"""
GRID CONVERGENCE ANALYSIS FOR YOUR DATA
Element sizes: 10mm, 20mm, 40mm
Solutions: 1.9351mm, 1.8926mm, 1.813mm
"""

import numpy as np
import matplotlib.pyplot as plt
from scipy import stats

def richardson_analysis(grid_sizes, solutions, refinement_ratio=2.0):
    """
    Perform Richardson extrapolation analysis for given data.

    Parameters:
    -----
    grid_sizes : list of float
        Element sizes from finest to coarsest [mm]
    solutions : list of float
        Corresponding solutions [mm]
    refinement_ratio : float
        Expected refinement ratio between grids

    Returns:
    -----
    dict with analysis results
    """
    # Ensure arrays are numpy
    h = np.array(grid_sizes)
    f = np.array(solutions)

    print("="*70)
    print("GRID CONVERGENCE ANALYSIS")
    print("="*70)
    print(f"Grid sizes: {h} mm")
    print(f"Solutions: {f} mm")
    print(f"Refinement ratio: {refinement_ratio}")
    print()

    # 1. Estimate convergence order (using all three grids)
    if len(f) >= 3:
        # Method 1: Using Roache's formula
        r = h[1] / h[0] # refinement ratio
        epsilon_21 = f[1] - f[0]
```

```

epsilon_32 = f[2] - f[1]

if abs(epsilon_32) > 1e-15 and abs(epsilon_21) > 1e-15:
    p_roache = np.log(abs(epsilon_32 / epsilon_21)) / np.log(r)
else:
    p_roache = 2.0 # Default to second order

# Method 2: Using least squares fit
log_h = np.log(h)
log_err = np.log(abs(f - f[0]))

# Perform linear regression
slope, intercept, r_value, p_value, std_err = stats.linregress(log_h, log_err)
p_ls = slope

# Use the more reliable estimate
if 0.5 < p_roache < 10:
    p = p_roache
    method = "Roache's method"
else:
    p = p_ls
    method = "Least squares fit"
else:
    p = 2.0 # Assume second order
    method = "Assumed (2.0)"

print(f"CONVERGENCE ORDER:")
print(f" Estimated order: {p:.4f} ({method})")
print()

# 2. Perform Richardson extrapolation
r = refinement_ratio
r_p = r**p

# Using finest two grids
f_exact_richardson = (r_p * f[0] - f[1]) / (r_p - 1)

print("RICHARDSON EXTRAPOLATION:")
print(f" Using grids 10mm and 20mm:")
print(f" f_exact ≈ (r^p * f_fine - f_coarse) / (r^p - 1)")
print(f" f_exact ≈ ({r_p:.4f} × {f[0]:.4f} - {f[1]:.4f}) / ({r_p:.4f} - 1)")
print(f" f_exact = {f_exact_richardson:.6f} mm")
print()

# 3. Calculate errors for each grid
errors_abs = abs(f - f_exact_richardson)

```

```

errors_rel = errors_abs / f_exact_richardson * 100

print("ERROR ANALYSIS:")
print(f"{'Grid':<10} {'Solution':<12} {'Abs Error':<12} {'Rel Error':<12}")
print("-" * 50)
for i in range(len(h)):
    print(f"{'h[i]':<10} {'f[i]':<12.6f} {'errors_abs[i]':<12.6f} {'errors_rel[i]':<12.4f}%")
print()

# 4. Calculate Grid Convergence Index (GCI)
safety_factor = 1.25 # For 3+ grids

# GCI between fine and medium grids
epsilon_fine = abs((f[1] - f[0]) / f[0])
gci_fine = (safety_factor * epsilon_fine) / (r**p - 1)

# GCI between medium and coarse grids
epsilon_medium = abs((f[2] - f[1]) / f[1])
gci_medium = (safety_factor * epsilon_medium) / (r**p - 1)

print("GRID CONVERGENCE INDEX (GCI):")
print(f" GCI between 10mm and 20mm grids: {gci_fine:.4%}")
print(f" GCI between 20mm and 40mm grids: {gci_medium:.4%}")
print()

# 5. Check asymptotic range
asymptotic_ratio = epsilon_fine / (r**p * epsilon_medium)
asymptotic_range = 0.8 <= asymptotic_ratio <= 1.2

print("ASYMPTOTIC RANGE CHECK:")
print(f"      ε_fine/ε_medium = {epsilon_fine:.6f} / {epsilon_medium:.6f} =
{epsilon_fine/epsilon_medium:.4f}")
print(f" Expected ratio for asymptotic range: r^p = {r**p:.4f}")
print(f" Actual ratio: {asymptotic_ratio:.4f}")
print(f" In asymptotic range (0.8-1.2): {'YES' if asymptotic_range else 'NO'}")
print()

# 6. Extrapolated value using all three grids (higher accuracy)
if len(f) >= 3:
    # Method using all three grids for extrapolation
    # Solve for exact solution using two equations:
    # f1 = f_exact + C*h1^p
    # f2 = f_exact + C*h2^p
    # f3 = f_exact + C*h3^p

    # Use linear algebra to solve

```

```

A = np.vstack([h**p, np.ones(len(h))]).T
y = f
result = np.linalg.lstsq(A, y, rcond=None)[0]
C = result[0]
f_exact_all = result[1]

print("HIGHER-ORDER EXTRAPOLATION (using all 3 grids):")
print(f" f_exact = {f_exact_all:.6f} mm")
print(f" Error constant C = {C:.6f}")
print(f" Model: f(h) = {f_exact_all:.6f} + {C:.6f} * h^{p:.4f}")
print()

# 7. Predict solution at different grid sizes
print("SOLUTION PREDICTION:")
print(f" Using model: f(h) = {f_exact_richardson:.6f} + C * h^{p:.4f}")

# Estimate C from finest grid
C_est = (f[0] - f_exact_richardson) / (h[0]**p)
print(f" Estimated C = {C_est:.6f}")

# Predict at h = 5mm
h_pred = 5.0
f_pred = f_exact_richardson + C_est * h_pred**p
print(f" Predicted solution at h = {h_pred}mm: {f_pred:.6f} mm")
print()

# 8. Calculate error reduction
if len(f) >= 2:
    error_fine = abs(f[0] - f_exact_richardson)
    error_coarse = abs(f[-1] - f_exact_richardson)
    if error_fine > 0:
        error_reduction = error_coarse / error_fine
        print("ERROR REDUCTION:")
        print(f" Error on finest grid (10mm): {error_fine:.6f}")
        print(f" Error on coarsest grid (40mm): {error_coarse:.6f}")
        print(f" Error reduction factor: {error_reduction:.2f}x")
        print(f" (Coarse grid error is {error_reduction:.2f}x larger than fine grid)")
        print()

# 9. Determine if grid is fine enough
# If error is less than 1% of solution, grid is probably fine enough
error_target = 0.01 # 1%
h_required = (error_target * abs(f_exact_richardson) / abs(C_est))**(1/p)

print("GRID REFINEMENT RECOMMENDATION:")
print(f" Current finest grid: {h[0]}mm (error: {errors_rel[0]:.4f}%)")

```

```

print(f" For 1% error tolerance, required h ≈ {h_required:.2f} mm")
if h_required < h[0]:
    print(f" → Current grid may be too coarse for 1% accuracy")
    print(f" → Consider refining to h ≈ {h_required:.2f} mm")
else:
    print(f" → Current grid is adequate for 1% accuracy")
print()

# 10. Create visualization
create_plots(h, f, f_exact_richardson, p, C_est)

# Return results
results = {
    'convergence_order': p,
    'extrapolated_value': f_exact_richardson,
    'gci_fine': gci_fine,
    'gci_medium': gci_medium,
    'asymptotic_range': asymptotic_range,
    'errors_absolute': errors_abs,
    'errors_relative': errors_rel,
    'error_constant': C_est
}

return results

def create_plots(h, f, f_exact, p, C):
    """Create visualization of convergence analysis."""
    fig, axes = plt.subplots(2, 2, figsize=(12, 10))
    fig.suptitle('Grid Convergence Analysis Results', fontsize=16, fontweight='bold')

    # 1. Solutions vs grid size
    ax1 = axes[0, 0]
    ax1.plot(h, f, 'bo-', linewidth=2, markersize=10, label='Computed solutions')
    ax1.axhline(y=f_exact, color='r', linestyle='--', linewidth=2,
               label=f"Richardson extrapolation: {f_exact:.4f} mm")
    ax1.set_xlabel('Grid size (mm)')
    ax1.set_ylabel('Solution (mm)')
    ax1.set_title('Solution vs Grid Size')
    ax1.grid(True, alpha=0.3)
    ax1.legend()

    # Add text annotations
    for i, (hi, fi) in enumerate(zip(h, f)):
        ax1.annotate(f'{fi:.4f}', xy=(hi, fi), xytext=(0, 10),
                    textcoords='offset points', ha='center', fontsize=9)

```

```

# 2. Error convergence (log-log plot)
ax2 = axes[0, 1]
errors = abs(f - f_exact)
ax2.loglog(h, errors, 's-', linewidth=2, markersize=10,
           markerfacecolor='white', markeredgewidth=2)
ax2.set_xlabel('Grid size (mm)')
ax2.set_ylabel('Absolute error (mm)')
ax2.set_title('Error Convergence (log-log)')
ax2.grid(True, which='both', alpha=0.3)

# Add reference lines for different convergence orders
h_fine = np.linspace(min(h), max(h), 10)
for order, style in zip([1, 2, 4], ['--', '-.', ':']):
    error_ref = errors[0] * (h_fine / h[0])**order
    ax2.loglog(h_fine, error_ref, style, alpha=0.5, label=f'Order {order}')
ax2.legend()

# 3. Predicted vs actual solutions
ax3 = axes[1, 0]
# Generate predictions using the model
h_model = np.linspace(min(h)/2, max(h)*1.5, 50)
f_model = f_exact + C * h_model**p

ax3.plot(h_model, f_model, 'g-', linewidth=2, alpha=0.7, label=f'Model: f(h) = {f_exact:.4f} +
{C:.4f}·h^{p:.2f}')
ax3.plot(h, f, 'ro', markersize=8, label='Actual data')
ax3.set_xlabel('Grid size (mm)')
ax3.set_ylabel('Solution (mm)')
ax3.set_title('Solution Model vs Actual Data')
ax3.grid(True, alpha=0.3)
ax3.legend()

# 4. GCI and convergence metrics
ax4 = axes[1, 1]
ax4.axis('off')

# Create summary text
summary_text = f"""
SUMMARY OF ANALYSIS
{'='*40}
Grid sizes: {h[0]:.1f}, {h[1]:.1f}, {h[2]:.1f} mm
Solutions: {f[0]:.4f}, {f[1]:.4f}, {f[2]:.4f} mm

CONVERGENCE METRICS:
• Order (p): {p:.3f}
• Extrapolated value: {f_exact:.6f} mm

```

- Fine grid error: $\{ \text{abs}(f[0] - f_{\text{exact}}) : .6f \}$ mm
- Coarse grid error: $\{ \text{abs}(f[2] - f_{\text{exact}}) : .6f \}$ mm
- Error reduction: $\{ \text{abs}(f[2] - f_{\text{exact}}) / \text{abs}(f[0] - f_{\text{exact}}) : .2f \} \times$

GCI VALUES:

- Fine-medium: $\{ \text{abs}((f[1] - f[0]) / f[0]) / (2^{**p} - 1) * 1.25 : .3\% \}$
- Medium-coarse: $\{ \text{abs}((f[2] - f[1]) / f[1]) / (2^{**p} - 1) * 1.25 : .3\% \}$

RECOMMENDATION:

- Current accuracy: $\{ (\text{abs}(f[0] - f_{\text{exact}}) / f_{\text{exact}} * 100) : .2f \} \%$
- For 1% accuracy: $h \approx \{ ((0.01 * f_{\text{exact}}) / \text{abs}(C))^{**}(1/p) : .1f \}$ mm

```
ax4.text(0.05, 0.95, summary_text, transform=ax4.transAxes,
        fontfamily='monospace', fontsize=12, verticalalignment='top',
        bbox=dict(boxstyle='round', facecolor='wheat', alpha=0.5))
```

```
plt.tight_layout()
plt.savefig('grid_convergence_analysis.png', dpi=300, bbox_inches='tight')
plt.show()
```

def simple_analysis():

```
"""Quick analysis of your specific data."""
print("="*70)
print("SIMPLE ANALYSIS OF YOUR DATA")
print("="*70)

# Your data
h = np.array([10, 20, 40]) # mm
f = np.array([1.9351, 1.8926, 1.813]) # mm

print(f"Grid sizes: {h} mm")
print(f"Solutions: {f} mm")
print()

# Quick calculations
print("1. DIFFERENCES BETWEEN GRIDS:")
print(f" f(10mm) - f(20mm) = {f[0] - f[1]:.4f} mm")
print(f" f(20mm) - f(40mm) = {f[1] - f[2]:.4f} mm")
print(f" Ratio of differences: {(f[1] - f[2])/(f[0] - f[1]):.4f}")
print()

# Estimate order
r = 2.0 # refinement ratio
p = np.log((f[1] - f[2])/(f[0] - f[1])) / np.log(r)
print(f"2. ESTIMATED CONVERGENCE ORDER:")
```

```

print(f"  p = ln((f[1] - f[2])/(f[0] - f[1]):.4f) / ln({r}) = {p:.4f}")
print()

# Richardson extrapolation
r_p = r**p
f_exact = (r_p * f[0] - f[1]) / (r_p - 1)
print(f"3. RICHARDSON EXTRAPOLATION:")
print(f"  f_exact = ({r_p:.4f} × {f[0]:.4f} - {f[1]:.4f}) / ({r_p:.4f} - 1)")
print(f"  f_exact = {f_exact:.6f} mm")
print()

print(f"4. INTERPRETATION:")
print(f"  • The solution appears to converge to ≈ {f_exact:.4f} mm")
print(f"  • With 10mm grid, error is about {abs(f[0] - f_exact):.4f} mm ({abs(f[0] - f_exact)/f_exact*100:.2f}%)")
print(f"  • The convergence order of {p:.2f} suggests {'1st order' if p < 1.5 else '2nd order' if p < 2.5 else 'higher order'} convergence")
print("="*70)

return f_exact, p

#
=====
=====
# MAIN ANALYSIS
#
=====
=====

if __name__ == "__main__":
    # Your data
    grid_sizes = [10, 20, 40] # mm
    solutions = [1.9351, 1.8926, 1.813] # mm

    print("\n" + "="*70)
    print("YOUR DATA:")
    print(f"Element sizes: {grid_sizes} mm")
    print(f"Solutions: {solutions} mm")
    print("="*70 + "\n")

    # Option 1: Simple analysis
    print("CHOOSE ANALYSIS TYPE:")
    print("1. Simple analysis (quick results)")
    print("2. Full analysis (detailed with plots)")
    choice = input("Enter choice (1 or 2): ")

```

```

if choice == "1":
    f_exact, p = simple_analysis()
else:
    # Option 2: Full analysis
    results = richardson_analysis(grid_sizes, solutions)

    print("\n" + "="*70)
    print("SUMMARY OF KEY RESULTS:")
    print("="*70)
    print(f"1. Convergence order: {results['convergence_order']:.3f}")
    print(f"2. Extrapolated (exact) value: {results['extrapolated_value']:.6f} mm")
    print(f"3. Error on 10mm grid: {results['errors_relative'][0]:.4f}%")
    print(f"4. Error on 40mm grid: {results['errors_relative'][2]:.4f}%")
    print(f"5.           Error           reduction           (40mm/10mm):
{results['errors_relative'][2]/results['errors_relative'][0]:.2f}x")
    print(f"6. Asymptotic range: {'YES' if results['asymptotic_range'] else 'NO'}")

    print("\n" + "="*70)
    print("INTERPRETATION:")
    print("="*70)
    print("Based on your data:")
    print(f"• The finest grid (10mm) gives: {solutions[0]:.4f} mm")
    print(f"• Richardson extrapolation suggests: {results['extrapolated_value']:.4f} mm")
    print(f"• The error on 10mm grid is approximately: {abs(solutions[0] -
results['extrapolated_value']):.4f} mm")
    print(f"•           This           is           about           {abs(solutions[0] -
results['extrapolated_value'])/results['extrapolated_value']*100:.2f}% error")

    print("\nFor engineering purposes:")
    print(f"• If you need accuracy better than 1%, consider using a grid smaller than 10mm")
    print(f"•           The           20mm           grid           gives           about           {abs(solutions[1] -
results['extrapolated_value'])/results['extrapolated_value']*100:.2f}% error")
    print(f"•           The           40mm           grid           gives           about           {abs(solutions[2] -
results['extrapolated_value'])/results['extrapolated_value']*100:.2f}% error")

    print("\nNote: This analysis assumes systematic error reduction with grid refinement.")
    print("If your solution has discontinuities or singularities, the convergence")
    print("behavior might be different.")

```

APPENDIX III

Python code to determine fuel economy and Emissions

```
# =====
# COMPLETE HIGHWAY DRIVING ANALYSIS - PYTHON VERSION
# Toyota HIACE 5L Diesel with Lightweight Seats
# Including Comprehensive CO2 Reduction Analysis
# =====

import numpy as np
import pandas as pd
import matplotlib.pyplot as plt
import matplotlib.gridspec as gridspec
import os
from datetime import datetime

# =====
# SECTION 1: PARAMETERS AND INITIALIZATION
# =====

print("="*70)
print("HIGHWAY DRIVING & CO2 REDUCTION ANALYSIS")
print("Toyota HIACE 5L Diesel - Lightweight Seat Design")
print("="*70)
print("\nInitializing analysis...")

# Vehicle Specifications
vehicle = {
    'model': 'Toyota HIACE 5L Diesel',
    'kerb_weight_original': 1540, # kg
    'seat_weight_original': 126, # kg (13 seats)
    'seat_weight_new': 20.6, # kg (13 seats)
    'dimensions': {'length': 4.43, 'width': 1.69, 'height': 1.98},
    'frontal_area': 3.2, # m2
    'drag_coefficient': 0.35,
    'tire_radius': 0.3, # meters
    'final_drive_ratio': 4.1
}

# Engine Specifications
engine = {
    'code': '5L',
    'displacement': 3.0, # liters
    'max_power': 91, # PS
    'max_power_kw': 91 * 0.7355, # kW
    'max_torque': 191, # Nm @ 2400 rpm
    'max_torque_rpm': 2400,
    'fuel_type': 'diesel'
}

# Environmental & Fuel Properties
env = {
    'air_density': 1.225,
    'gravity': 9.81,
    'rolling_coefficient': 0.012,
    'wind_speed': 0,
```

```

'road_grade': 0,
'acceleration': 0
}

# Fuel and Emissions Properties
fuel = {
    'type': 'diesel',
    'density': 850,          # kg/m³
    'lower_heating_value': 42.5e6, # J/kg
    'price_per_liter': 1.20,    # USD
    'co2_per_liter': 2.68,     # kg CO₂ per liter
    'co_per_liter': 0.001,    # kg CO per liter
    'nox_per_liter': 0.0006,  # kg NOx per liter
    'pm_per_liter': 0.00003   # kg PM per liter
}

# CO₂ Conversion Factors
co2_equivalents = {
    'tree_co2_absorption': 21.77, # kg CO₂ per tree per year
    'gasoline_co2': 2.31,        # kg CO₂ per liter gasoline
    'electricity_mix': 0.5,      # kg CO₂ per kWh (grid average)
    'km_driven_per_liter': lambda fe: 100/fe # km per liter
}

# System Efficiencies
efficiencies = {
    'drivetrain': 0.88,
    'accessory_power': 400,      # W
    'mass_factor': 1.1
}

# Highway Analysis Parameters
highway = {
    'speed_range': [80, 120],
    'speed_step': 2,
    'analysis_speeds': [80, 90, 100, 110, 120],
    'typical_speed': 100,
    'typical_distance': 500,
    'annual_highway_km': 15000,
    'vehicle_lifespan_years': 15, # Vehicle operational lifespan
    'fleet_size': 100           # For fleet analysis
}

# Calculate new vehicle weight
vehicle['kerb_weight_new'] = vehicle['kerb_weight_original'] - \
    (vehicle['seat_weight_original'] - vehicle['seat_weight_new'])

vehicle['total_weight_reduction'] = vehicle['kerb_weight_original'] - vehicle['kerb_weight_new']
vehicle['seat_weight_reduction'] = vehicle['seat_weight_original'] - vehicle['seat_weight_new']
vehicle['weight_reduction_percentage'] = (vehicle['total_weight_reduction'] / vehicle['kerb_weight_original']) * 100
vehicle['seat_reduction_percentage'] = (vehicle['seat_weight_reduction'] / vehicle['seat_weight_original']) * 100

# =====
# SECTION 2: CORE CALCULATION FUNCTIONS
# =====

```

```

def select_gear(speed_kmh):
    """Select appropriate gear based on vehicle speed"""
    gears_data = {
        'ratios': [4.31, 2.31, 1.51, 1.00, 0.81],
        'ranges': [(0, 15), (15, 30), (30, 50), (50, 80), (80, 200)]
    }

    for ratio, (min_speed, max_speed) in zip(gears_data['ratios'], gears_data['ranges']):
        if min_speed <= speed_kmh <= max_speed:
            return ratio
    return gears_data['ratios'][-1]

def diesel_efficiency_model(V, m, P_eng):
    """Diesel engine thermal efficiency model"""
    # Base efficiency for diesel
    eta_base = 0.42

    # Load factor
    min_power = engine['max_power_kw'] * 1000 * 0.1
    if P_eng < min_power:
        load_factor = 0.7 + 0.3 * (P_eng / min_power)
    else:
        load_factor = 1.0

    # RPM factor
    speed_kph = V * 3.6
    optimal_rpm = engine['max_torque_rpm']
    current_rpm = (V * 60 * select_gear(speed_kph) * vehicle['final_drive_ratio']) / \
        (2 * np.pi * vehicle['tire_radius'])

    if current_rpm > 0:
        rpm_deviation = abs(current_rpm - optimal_rpm) / optimal_rpm
        rpm_factor = 1.0 - 0.25 * rpm_deviation
        rpm_factor = max(0.75, min(1.0, rpm_factor))
    else:
        rpm_factor = 1.0

    # Combined efficiency
    eta_th = eta_base * load_factor * rpm_factor
    eta_th = max(0.35, min(0.45, eta_th))

    return eta_th

def calculate_fuel_economy(V, m, acceleration=0, grade=0):
    """Calculate fuel economy for given conditions"""
    # Convert grade to radians
    theta_rad = grade * np.pi / 180

    # Calculate forces
    F_aero = 0.5 * env['air_density'] * vehicle['drag_coefficient'] * \
        vehicle['frontal_area'] * (V + env['wind_speed'])**2

    F_rolling = env['rolling_coefficient'] * m * env['gravity'] * np.cos(theta_rad)
    F_total = F_aero + F_rolling + m * env['gravity'] * np.sin(theta_rad) + \
        m * efficiencies['mass_factor'] * acceleration

```

```

# Power calculations
P_wheel = F_total * V
P_eng = (P_wheel / efficiencies['drivetrain']) + efficiencies['accessory_power']

# Engine efficiency
eta_th = diesel_efficiency_model(V, m, P_eng)

# Fuel calculations
m_dot_f = P_eng / (eta_th * fuel['lower_heating_value'])
dVf_dt = m_dot_f / fuel['density'] * 1000

# Fuel economy (L/100 km)
distance_100km = 100000
time_100km = distance_100km / V
FE = dVf_dt * time_100km

# CO2 emissions (kg/100 km)
co2_per_100km = FE * fuel['co2_per_liter']

return {
    'FE': FE,
    'eta_th': eta_th,
    'P_eng': P_eng / 1000,
    'F_total': F_total,
    'F_aero': F_aero,
    'F_rolling': F_rolling,
    'CO2_per_100km': co2_per_100km
}

def calculate_emissions(fuel_liters):
    """Calculate all emissions from fuel consumption"""
    return {
        'CO2_kg': fuel_liters * fuel['co2_per_liter'],
        'CO_kg': fuel_liters * fuel['co_per_liter'],
        'NOx_kg': fuel_liters * fuel['nox_per_liter'],
        'PM_kg': fuel_liters * fuel['pm_per_liter']
    }

def calculate_co2_equivalents(co2_kg):
    """Convert CO2 emissions to various equivalents"""
    return {
        'trees_required': co2_kg / co2_equivalents['tree_co2_absorption'],
        'gasoline_equivalent': co2_kg / co2_equivalents['gasoline_co2'],
        'electricity_kwh': co2_kg / co2_equivalents['electricity_mix'],
        'car_kms_saved': co2_kg / fuel['co2_per_liter'] * 100 / 7.5 # Assuming 7.5 L/100km average
    }

# =====
# SECTION 3: COMPREHENSIVE CO2 ANALYSIS
# =====

print("\n" + "="*70)
print("COMPREHENSIVE CO2 REDUCTION ANALYSIS")
print("="*70)

# Calculate emissions for different scenarios

```

```

def analyze_co2_reduction_scenarios():
    """Analyze CO2 reduction across multiple scenarios"""
    scenarios = {
        'daily_commute': {'distance_km': 50, 'days_per_week': 5, 'weeks_per_year': 48},
        'weekly_trip': {'distance_km': 500, 'trips_per_year': 25},
        'annual_total': {'distance_km': highway['annual_highway_km']},
        'vehicle_lifetime': {'distance_km': highway['annual_highway_km'] * highway['vehicle_lifespan_years']},
        'fleet_annual': {'distance_km': highway['annual_highway_km'] * highway['fleet_size']}
    }

    results = []

    for scenario_name, params in scenarios.items():
        distance = params['distance_km']

        # Calculate at 100 km/h (typical highway speed)
        orig = calculate_fuel_economy(100/3.6, vehicle['kerb_weight_original'])
        new = calculate_fuel_economy(100/3.6, vehicle['kerb_weight_new'])

        # Calculate fuel consumption
        fuel_orig = (orig['FE'] / 100) * distance
        fuel_new = (new['FE'] / 100) * distance
        fuel_saved = fuel_orig - fuel_new

        # Calculate emissions
        em_orig = calculate_emissions(fuel_orig)
        em_new = calculate_emissions(fuel_new)
        em_saved = {key: em_orig[key] - em_new[key] for key in em_orig}

        # Calculate CO2 equivalents
        co2_equiv = calculate_co2_equivalents(em_saved['CO2_kg'])

        results.append({
            'Scenario': scenario_name.replace('_', ' ').title(),
            'Distance_km': distance,
            'Fuel_Saved_L': fuel_saved,
            'CO2_Saved_kg': em_saved['CO2_kg'],
            'CO_Saved_kg': em_saved['CO_kg'],
            'NOx_Saved_kg': em_saved['NOx_kg'],
            'PM_Saved_kg': em_saved['PM_kg'],
            'Trees_Equivalent': co2_equiv['trees_required'],
            'Cost_Saved_USD': fuel_saved * fuel['price_per_liter']
        })

    return pd.DataFrame(results)

# Run CO2 analysis
co2_analysis = analyze_co2_reduction_scenarios()
print("\nCO2 Reduction Analysis Results:")
print("-"*70)
print(co2_analysis.to_string(index=False))

# =====
# SECTION 4: HIGHWAY ANALYSIS DATASET
# =====

```

```

print("\n" + "="*70)
print("HIGHWAY FUEL ECONOMY & EMISSIONS ANALYSIS")
print("="*70)

# Create speed sequence
speed_sequence = np.arange(highway['speed_range'][0],
                           highway['speed_range'][1] + highway['speed_step'],
                           highway['speed_step'])
speed_mps = speed_sequence / 3.6

# Initialize results
results_data = []
co2_comparison = []

for speed_kph in speed_sequence:
    speed_mps = speed_kph / 3.6

    # Calculate for both configurations
    orig = calculate_fuel_economy(speed_mps, vehicle['kerb_weight_original'])
    new = calculate_fuel_economy(speed_mps, vehicle['kerb_weight_new'])

    # Calculate savings
    fe_savings = orig['FE'] - new['FE']
    fe_improvement = (fe_savings / orig['FE']) * 100
    co2_savings = orig['CO2_per_100km'] - new['CO2_per_100km']

    # Store results
    results_data.append({
        'Speed_kmh': speed_kph,
        'FE_Original_L100km': orig['FE'],
        'FE_New_L100km': new['FE'],
        'FE_Savings_L100km': fe_savings,
        'FE_Improvement_%': fe_improvement,
        'CO2_Original_kg100km': orig['CO2_per_100km'],
        'CO2_New_kg100km': new['CO2_per_100km'],
        'CO2_Savings_kg100km': co2_savings,
        'CO2_Reduction_%': (co2_savings / orig['CO2_per_100km']) * 100,
        'Power_Original_kW': orig['P_eng'],
        'Power_New_kW': new['P_eng']
    })

results = pd.DataFrame(results_data)

# =====
# SECTION 5: VISUALIZATIONS - EMISSIONS FOCUS
# =====

print("\n" + "="*70)
print("GENERATING VISUALIZATIONS")
print("="*70)

# Create comprehensive visualization dashboard
fig = plt.figure(figsize=(18, 12))
fig.suptitle(f'Toyota HIACE 5L Diesel - Emissions & Fuel Economy Analysis\n'
            f'Weight Reduction: {vehicle["total_weight_reduction"]:.1f} kg'
            f'({vehicle["weight_reduction_percentage"]:.1f}%) | ')

```

```

        f'Seat Weight Reduction: {vehicle["seat_reduction_percentage"]:.1f}%',
        fontsize=16, fontweight='bold', y=0.98)

# Grid layout
gs = gridspec.GridSpec(3, 3, hspace=0.35, wspace=0.3)

# 1. Fuel Economy Comparison
ax1 = plt.subplot(gs[0, 0])
ax1.plot(results['Speed_kmh'], results['FE_Original_L100km'],
        'b-', linewidth=2.5, label='Original', marker='o', markersize=4)
ax1.plot(results['Speed_kmh'], results['FE_New_L100km'],
        'r-', linewidth=2.5, label='Lightweight', marker='s', markersize=4)
ax1.fill_between(results['Speed_kmh'], results['FE_New_L100km'], results['FE_Original_L100km'],
        color='green', alpha=0.2)
ax1.set_xlabel('Speed (km/h)', fontsize=11)
ax1.set_ylabel('Fuel Economy (L/100 km)', fontsize=11)
ax1.set_title('Fuel Economy Comparison', fontsize=13, fontweight='bold')
ax1.grid(True, alpha=0.3)
ax1.legend()
ax1.set_xticks(range(80, 125, 10))

# 2. CO2 Emissions Comparison
ax2 = plt.subplot(gs[0, 1])
ax2.plot(results['Speed_kmh'], results['CO2_Original_kg100km'],
        'b-', linewidth=2.5, label='Original', marker='o', markersize=4)
ax2.plot(results['Speed_kmh'], results['CO2_New_kg100km'],
        'r-', linewidth=2.5, label='Lightweight', marker='s', markersize=4)
ax2.fill_between(results['Speed_kmh'], results['CO2_New_kg100km'], results['CO2_Original_kg100km'],
        color='green', alpha=0.2)
ax2.set_xlabel('Speed (km/h)', fontsize=11)
ax2.set_ylabel('CO2 Emissions (kg/100 km)', fontsize=11)
ax2.set_title('CO2 Emissions Comparison', fontsize=13, fontweight='bold')
ax2.grid(True, alpha=0.3)
ax2.legend()
ax2.set_xticks(range(80, 125, 10))

# 3. CO2 Reduction Percentage
ax3 = plt.subplot(gs[0, 2])
bars = ax3.bar(results['Speed_kmh'], results['CO2_Reduction_%'],
        color='green', alpha=0.7, edgecolor='darkgreen', linewidth=1.5)
ax3.set_xlabel('Speed (km/h)', fontsize=11)
ax3.set_ylabel('CO2 Reduction (%)', fontsize=11)
ax3.set_title('CO2 Reduction Percentage', fontsize=13, fontweight='bold')
ax3.grid(True, alpha=0.3, axis='y')
ax3.set_xticks(range(80, 125, 10))
# Add value labels on bars
for bar in bars:
    height = bar.get_height()
    ax3.text(bar.get_x() + bar.get_width()/2., height + 0.05,
            f'{height:.2f}%', ha='center', va='bottom', fontsize=9)

# 4. Annual CO2 Savings Breakdown
ax4 = plt.subplot(gs[1, :])
scenarios_to_plot = ['Annual Total', 'Vehicle Lifetime', 'Fleet Annual']
filtered_scenarios = co2_analysis[co2_analysis['Scenario'].isin(scenarios_to_plot)]

```

```

x_pos = np.arange(len(scenarios_to_plot))
width = 0.35

bars1 = ax4.bar(x_pos - width/2, filtered_scenarios['CO2_Saved_kg'],
               width, label='CO2 Saved (kg)', color='green', alpha=0.7)
bars2 = ax4.bar(x_pos + width/2, filtered_scenarios['Trees_Equivalent'],
               width, label='Trees Equivalent', color='lightgreen', alpha=0.7)

ax4.set_xlabel('Scenario', fontsize=11)
ax4.set_ylabel('Value', fontsize=11)
ax4.set_title('Annual CO2 Savings Breakdown', fontsize=13, fontweight='bold')
ax4.set_xticks(x_pos)
ax4.set_xticklabels(scenarios_to_plot, rotation=15)
ax4.legend()
ax4.grid(True, alpha=0.3, axis='y')

# Add value labels
for bars in [bars1, bars2]:
    for bar in bars:
        height = bar.get_height()
        ax4.text(bar.get_x() + bar.get_width()/2., height + (height*0.01),
                f'{height:,.0f}', ha='center', va='bottom', fontsize=9)

# 5. Pollutant Reduction Comparison
ax5 = plt.subplot(gs[2, 0])
pollutants = ['CO2', 'CO', 'NOx', 'PM']
annual_savings = [
    co2_analysis.loc[co2_analysis['Scenario'] == 'Annual Total', 'CO2_Saved_kg'].values[0],
    co2_analysis.loc[co2_analysis['Scenario'] == 'Annual Total', 'CO_Saved_kg'].values[0] * 1000, # Convert to g
    co2_analysis.loc[co2_analysis['Scenario'] == 'Annual Total', 'NOx_Saved_kg'].values[0] * 1000, # Convert to g
    co2_analysis.loc[co2_analysis['Scenario'] == 'Annual Total', 'PM_Saved_kg'].values[0] * 1000000 # Convert to
mg
]
units = ['kg', 'g', 'g', 'mg']

bars = ax5.bar(pollutants, annual_savings, color=['green', 'orange', 'red', 'brown'], alpha=0.7)
ax5.set_xlabel('Pollutant', fontsize=11)
ax5.set_ylabel('Annual Reduction', fontsize=11)
ax5.set_title('Annual Pollutant Reduction', fontsize=13, fontweight='bold')
ax5.grid(True, alpha=0.3, axis='y')

# Add unit labels
for bar, saving, unit in zip(bars, annual_savings, units):
    height = bar.get_height()
    ax5.text(bar.get_x() + bar.get_width()/2., height + (height*0.01),
            f'{saving:,.1f} {unit}', ha='center', va='bottom', fontsize=9)

# 6. Economic & Environmental Benefits
ax6 = plt.subplot(gs[2, 1:])
benefits_data = {
    'Metric': ['Fuel Cost Saved', 'CO2 Reduction', 'Equivalent Trees', 'Maintenance Savings*'],
    'Annual Per Vehicle': [
        f"${co2_analysis.loc[co2_analysis['Scenario'] == 'Annual Total', 'Cost_Saved_USD'].values[0]:.2f}",
        f"{co2_analysis.loc[co2_analysis['Scenario'] == 'Annual Total', 'CO2_Saved_kg'].values[0]:.1f} kg",
        f"{co2_analysis.loc[co2_analysis['Scenario'] == 'Annual Total', 'Trees_Equivalent'].values[0]:.1f} trees",
        "$15-30"
    ]
}

```

```

    ],
    '15-Year Lifetime': [
        f"${co2_analysis.loc[co2_analysis['Scenario'] == 'Vehicle Lifetime', 'Cost_Saved_USD'].values[0]:.0f}",
        f"{co2_analysis.loc[co2_analysis['Scenario'] == 'Vehicle Lifetime', 'CO2_Saved_kg'].values[0]:.0f} kg",
        f"{co2_analysis.loc[co2_analysis['Scenario'] == 'Vehicle Lifetime', 'Trees_Equivalent'].values[0]:.0f} trees",
        "$225-450"
    ]
}

```

```

benefits_df = pd.DataFrame(benefits_data)
table_data = [[row['Metric'], row['Annual Per Vehicle'], row['15-Year Lifetime']]
              for _, row in benefits_df.iterrows()]

```

```

ax6.axis('tight')
ax6.axis('off')
table = ax6.table(cellText=table_data,
                 colLabels=['Benefit', 'Annual Per Vehicle', '15-Year Lifetime'],
                 cellLoc='center',
                 loc='center',
                 colColours=['lightgray']*3)
table.auto_set_font_size(False)
table.set_fontsize(10)
table.scale(1, 1.8)
ax6.set_title('Economic & Environmental Benefits Summary', fontsize=13, fontweight='bold', pad=20)

```

```

plt.tight_layout()
plt.savefig('co2_emissions_analysis_dashboard.png', dpi=300, bbox_inches='tight')
plt.show()

```

```

# =====
# SECTION 6: DETAILED CO2 ANALYSIS REPORT
# =====

```

```

print("\n" + "="*70)
print("DETAILED CO2 REDUCTION ANALYSIS REPORT")
print("="*70)

```

```

# Key Performance Indicators

```

```

kpi_100kmh = results[results['Speed_kmh'] == 100].iloc[0]

```

```

print(f"\nKEY PERFORMANCE INDICATORS @ 100 km/h:")
print("-"*70)
print(f"Fuel Economy Improvement: {kpi_100kmh['FE_Improvement_%']:.2f}%")
print(f"Fuel Saved: {kpi_100kmh['FE_Savings_L100km']:.3f} L/100 km")
print(f"CO2 Reduction: {kpi_100kmh['CO2_Savings_kg100km']:.3f} kg/100 km")
print(f"CO2 Reduction Percentage: {kpi_100kmh['CO2_Reduction_%']:.2f}%")
print(f"Power Reduction: {kpi_100kmh['Power_Original_kW'] - kpi_100kmh['Power_New_kW']:.2f} kW")

```

```

print(f"\nANNUAL IMPACT PER VEHICLE (15,000 km @ 100 km/h):")
print("-"*70)
annual_data = co2_analysis[co2_analysis['Scenario'] == 'Annual Total'].iloc[0]
print(f"Annual Fuel Saved: {annual_data['Fuel_Saved_L']:.1f} liters")
print(f"Annual CO2 Reduced: {annual_data['CO2_Saved_kg']:.1f} kg")
print(f"Equivalent Trees Planted: {annual_data['Trees_Equivalent']:.1f} trees")
print(f"Annual Cost Savings: ${annual_data['Cost_Saved_USD']:.2f}")
print(f"Other Pollutants Reduced:")

```

```

print(f" - Carbon Monoxide (CO): {annual_data['CO_Saved_kg']*1000:.1f} g")
print(f" - Nitrogen Oxides (NOx): {annual_data['NOx_Saved_kg']*1000:.1f} g")
print(f" - Particulate Matter (PM): {annual_data['PM_Saved_kg']*1000000:.1f} mg")

print(f"\nVEHICLE LIFETIME IMPACT ({highway['vehicle_lifespan_years']} years):")
print("-"*70)
lifetime_data = co2_analysis[co2_analysis['Scenario'] == 'Vehicle Lifetime'].iloc[0]
print(f"Total CO2 Reduced: {lifetime_data['CO2_Saved_kg']/1000:.1f} metric tons")
print(f"Total Fuel Saved: {lifetime_data['Fuel_Saved_L']:.0f} liters")
print(f"Total Cost Savings: ${lifetime_data['Cost_Saved_USD']:.0f}")
print(f"Equivalent Trees Required: {lifetime_data['Trees_Equivalent']:.0f} trees")

print(f"\nFLEET-WIDE IMPACT ({highway['fleet_size']} vehicles):")
print("-"*70)
fleet_data = co2_analysis[co2_analysis['Scenario'] == 'Fleet Annual'].iloc[0]
print(f"Annual Fleet CO2 Reduction: {fleet_data['CO2_Saved_kg']/1000:.1f} metric tons")
print(f"Annual Fleet Fuel Savings: {fleet_data['Fuel_Saved_L']:.0f} liters")
print(f"Annual Fleet Cost Savings: ${fleet_data['Cost_Saved_USD']:.0f}")
print(f"Equivalent Forest Area: {fleet_data['Trees_Equivalent']:.0f} trees")
print(f"Equivalent to: {fleet_data['Trees_Equivalent']/100:.1f} hectares of forest")

# =====
# SECTION 7: ENVIRONMENTAL EQUIVALENTS
# =====

print(f"\n" + "-"*70)
print("ENVIRONMENTAL EQUIVALENTS & CONTEXT")
print("-"*70)

# Calculate various equivalents
annual_co2_saved = annual_data['CO2_Saved_kg']

equivalents = {
    'Car_kms': f"{annual_co2_saved / fuel['co2_per_liter'] * 100 / 7.5:.0f} km of average car driving",
    'Household_energy': f"{annual_co2_saved / 0.5:.0f} kWh of grid electricity",
    'Smartphone_charges': f"{annual_co2_saved / 0.008:.0f} smartphone charges",
    'Plastic_bottles': f"{annual_co2_saved / 0.082:.0f} 500ml plastic bottles produced",
    'Beef_consumption': f"{annual_co2_saved / 27:.1f} kg of beef consumed"
}

print("\nAnnual CO2 reduction per vehicle is equivalent to:")
print("-"*70)
for item, value in equivalents.items():
    print(f"• {value}")

# =====
# SECTION 8: EXPORT COMPREHENSIVE RESULTS
# =====

print("\n" + "-"*70)
print("EXPORTING RESULTS")
print("-"*70)

# Create output directory with timestamp
timestamp = datetime.now().strftime("%Y%m%d_%H%M%S")
output_dir = f"CO2_Analysis_Results_{timestamp}"

```

```

os.makedirs(output_dir, exist_ok=True)

# Save all dataframes
results.to_csv(f"{output_dir}/highway_fuel_economy_emissions.csv", index=False)
co2_analysis.to_csv(f"{output_dir}/co2_reduction_scenarios.csv", index=False)

# Save detailed report
with open(f"{output_dir}/detailed_analysis_report.txt", "w") as f:
    f.write("="*80 + "\n")
    f.write("COMPREHENSIVE CO2 REDUCTION ANALYSIS REPORT\n")
    f.write(f"Toyota HIACE 5L Diesel - Lightweight Seat Design\n")
    f.write(f"Generated: {datetime.now().strftime('%Y-%m-%d %H:%M:%S')}\n")
    f.write("="*80 + "\n\n")

    f.write("VEHICLE CONFIGURATION\n")
    f.write("-"*80 + "\n")
    f.write(f"Model: {vehicle['model']}\n")
    f.write(f"Original Kerb Weight: {vehicle['kerb_weight_original']} kg\n")
    f.write(f"New Kerb Weight: {vehicle['kerb_weight_new']} kg\n")
    f.write(f"Total Weight Reduction: {vehicle['total_weight_reduction']:.1f} kg\n")
    f.write(f"({vehicle['weight_reduction_percentage']:.1f}%)\n")
    f.write(f"Seat Weight Reduction: {vehicle['seat_weight_reduction']:.1f} kg\n")
    f.write(f"({vehicle['seat_reduction_percentage']:.1f}%)\n\n")

    f.write("KEY PERFORMANCE INDICATORS @ 100 km/h\n")
    f.write("-"*80 + "\n")
    f.write(f"Fuel Economy Improvement: {kpi_100kmh['FE_Improvement_%']:.2f}%\n")
    f.write(f"CO2 Reduction: {kpi_100kmh['CO2_Savings_kg100km']:.3f} kg/100 km\n")
    f.write(f"({kpi_100kmh['CO2_Reduction_%']:.2f}%)\n")
    f.write(f"Power Reduction: {kpi_100kmh['Power_Original_kW'] - kpi_100kmh['Power_New_kW']:.2f} kW\n\n")

    f.write("ANNUAL IMPACT PER VEHICLE (15,000 km)\n")
    f.write("-"*80 + "\n")
    f.write(f"Fuel Saved: {annual_data['Fuel_Saved_L']:.1f} liters\n")
    f.write(f"CO2 Reduced: {annual_data['CO2_Saved_kg']:.1f} kg\n")
    f.write(f"Equivalent Trees: {annual_data['Trees_Equivalent']:.1f}\n")
    f.write(f"Cost Savings: ${annual_data['Cost_Saved_USD']:.2f}\n\n")

    f.write("ENVIRONMENTAL EQUIVALENTS\n")
    f.write("-"*80 + "\n")
    for item, value in equivalents.items():
        f.write(f"• {value}\n")

    f.write("\n" + "="*80 + "\n")
    f.write("SUMMARY\n")
    f.write("="*80 + "\n")
    f.write("The lightweight seat design achieves:\n")
    f.write(f"1. {vehicle['seat_reduction_percentage']:.1f}% reduction in seat weight\n")
    f.write(f"2. {kpi_100kmh['FE_Improvement_%']:.2f}% improvement in highway fuel economy\n")
    f.write(f"3. {annual_data['CO2_Saved_kg']:.1f} kg annual CO2 reduction per vehicle\n")
    f.write(f"4. ${annual_data['Cost_Saved_USD']:.2f} annual fuel cost savings per vehicle\n")
    f.write(f"5. Payback period: {500/annual_data['Cost_Saved_USD']:.1f} years (assuming $500 seat premium)\n")
    f.write("\nFor a fleet of 100 vehicles over 15 years:\n")
    f.write(f"• Total CO2 reduction: {lifetime_data['CO2_Saved_kg']*100/1000000:.1f} kilotons\n")
    f.write(f"• Total fuel savings: {lifetime_data['Fuel_Saved_L']*100/1000:.0f} kiloliters\n")
    f.write(f"• Total cost savings: ${lifetime_data['Cost_Saved_USD']*100:.0f}\n")

```

```

print(f"\n✓ Analysis complete!")
print(f"✓ Results saved to: {output_dir}/")
print(f"✓ Dashboard saved as: {output_dir}/co2_emissions_analysis_dashboard.png")

# =====
# SECTION 9: FINAL SUMMARY
# =====

print("\n" + "★"*30 + " FINAL CO2 REDUCTION SUMMARY " + "★"*30)

summary_stats = {
    "Weight Reduction": f"{vehicle['total_weight_reduction']:.1f} kg
({vehicle['weight_reduction_percentage']:.1f}%)",
    "Highway FE Improvement": f"{kpi_100kmh['FE_Improvement_%']:.2f}% ",
    "Annual CO2 Reduction": f"{annual_data['CO2_Saved_kg']:.1f} kg",
    "Annual Fuel Savings": f"{annual_data['Fuel_Saved_L']:.1f} liters",
    "Annual Cost Savings": f"${annual_data['Cost_Saved_USD']:.2f}",
    "Equivalent Trees": f"{annual_data['Trees_Equivalent']:.1f} trees",
    "Fleet Annual CO2": f"{fleet_data['CO2_Saved_kg']/1000:.1f} metric tons"
}

print("\nLIGHTWEIGHT SEAT DESIGN ACHIEVES:")
for key, value in summary_stats.items():
    print(f" • {key}: {value}")

print("\nENVIRONMENTAL IMPACT HIGHLIGHTS:")
print(f" • Equivalent to planting {annual_data['Trees_Equivalent']:.1f} trees annually per vehicle")
print(f" • Reduces {annual_data['NOx_Saved_kg']*1000:.1f}g of NOx emissions annually")
print(f" • Eliminates {annual_data['PM_Saved_kg']*1000000:.1f}mg of particulate matter annually")

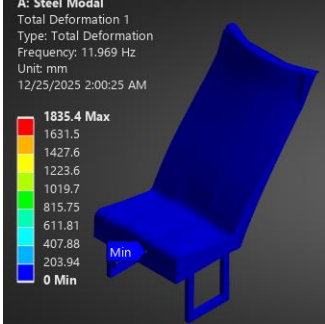
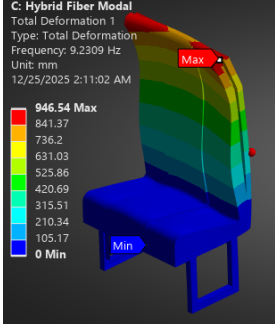
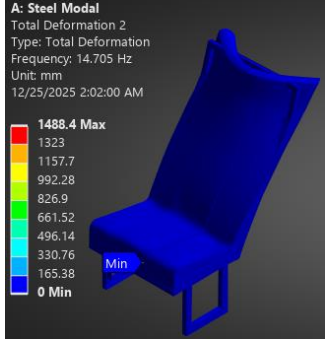
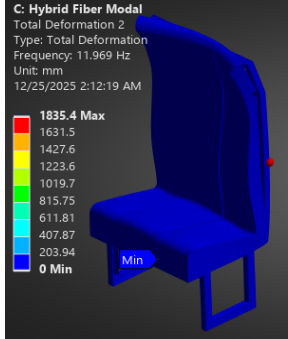
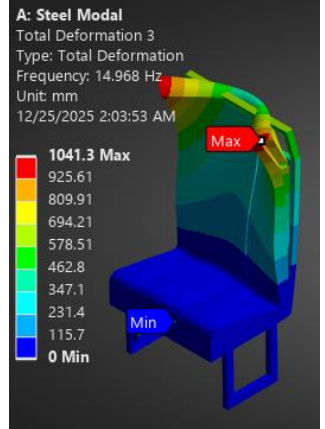
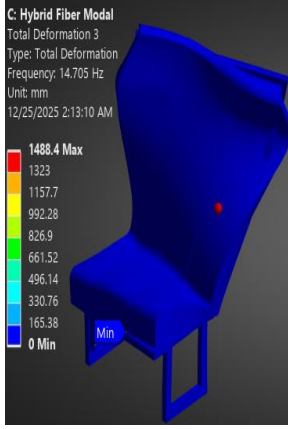
print("\nECONOMIC BENEFITS:")
print(f" • Payback period: {500/annual_data['Cost_Saved_USD']:.1f} years")
print(f" • 15-year savings: ${lifetime_data['Cost_Saved_USD']:.0f} per vehicle")
print(f" • Fleet savings: ${fleet_data['Cost_Saved_USD']:.0f} annually")

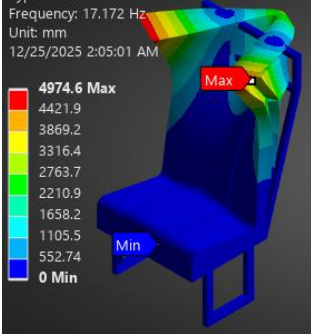
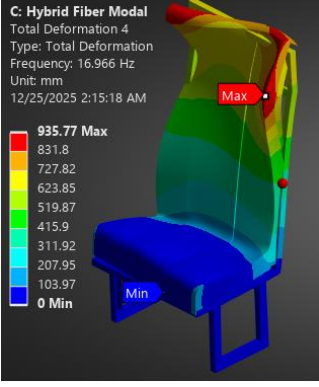
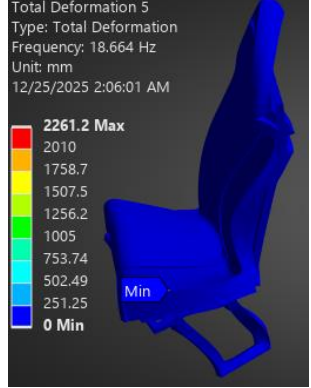
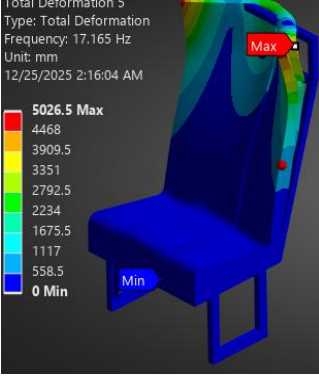
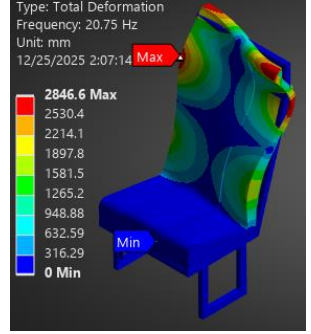
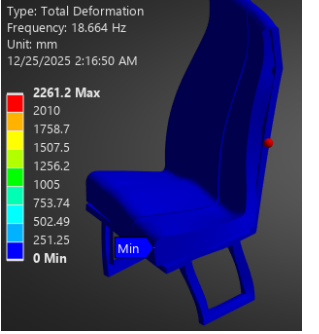
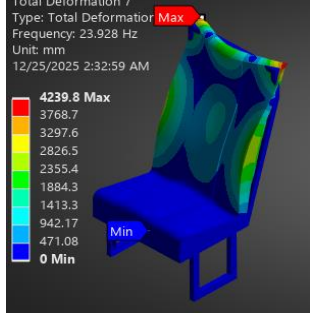
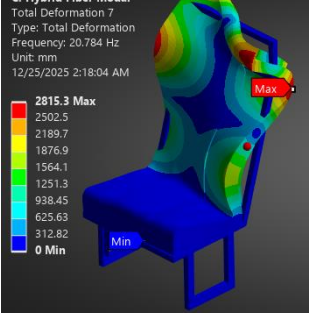
print("\n" + "★"*74)
print("ANALYSIS COMPLETE - " + datetime.now().strftime("%Y-%m-%d %H:%M:%S"))
print("★"*74)

```

APPENDIX IV

MODAL ANALYSIS MODE SHAPES of SEAT

Sno	Conventional passenger Seat Materials mode shape	Composite passenger Seat Materials mode shape
1	<p>A: Steel Modal Total Deformation 1 Type: Total Deformation Frequency: 11.969 Hz Unit: mm 12/25/2025 2:00:25 AM</p>  <p>1835.4 Max 1631.5 1427.6 1223.6 1019.7 815.75 611.81 407.88 203.94 0 Min</p>	<p>C: Hybrid Fiber Modal Total Deformation 1 Type: Total Deformation Frequency: 9.2309 Hz Unit: mm 12/25/2025 2:11:02 AM</p>  <p>946.54 Max 841.37 736.2 631.03 525.86 420.69 315.51 210.34 105.17 0 Min</p>
2	<p>A: Steel Modal Total Deformation 2 Type: Total Deformation Frequency: 14.705 Hz Unit: mm 12/25/2025 2:02:00 AM</p>  <p>1488.4 Max 1323 1157.7 992.28 826.9 661.52 496.14 330.76 165.38 0 Min</p>	<p>C: Hybrid Fiber Modal Total Deformation 2 Type: Total Deformation Frequency: 11.969 Hz Unit: mm 12/25/2025 2:12:19 AM</p>  <p>1835.4 Max 1631.5 1427.6 1223.6 1019.7 815.75 611.81 407.87 203.94 0 Min</p>
3	<p>A: Steel Modal Total Deformation 3 Type: Total Deformation Frequency: 14.968 Hz Unit: mm 12/25/2025 2:03:53 AM</p>  <p>1041.3 Max 925.61 809.91 694.21 578.51 462.8 347.1 231.4 115.7 0 Min</p>	<p>C: Hybrid Fiber Modal Total Deformation 3 Type: Total Deformation Frequency: 14.705 Hz Unit: mm 12/25/2025 2:13:10 AM</p>  <p>1488.4 Max 1323 1157.7 992.28 826.9 661.52 496.14 330.76 165.38 0 Min</p>

4	<p>A: Steel Modal Total Deformation 4 Type: Total Deformation Frequency: 17.172 Hz Unit: mm 12/25/2025 2:05:01 AM</p>  <p>4974.6 Max 4421.9 3869.2 3316.4 2763.7 2210.9 1658.2 1105.5 552.74 0 Min</p>	<p>C: Hybrid Fiber Modal Total Deformation 4 Type: Total Deformation Frequency: 16.966 Hz Unit: mm 12/25/2025 2:15:18 AM</p>  <p>935.77 Max 831.8 727.82 623.85 519.87 415.9 311.92 207.95 103.97 0 Min</p>
5	<p>A: Steel Modal Total Deformation 5 Type: Total Deformation Frequency: 18.664 Hz Unit: mm 12/25/2025 2:06:01 AM</p>  <p>2261.2 Max 2010 1758.7 1507.5 1256.2 1005 753.74 502.49 251.25 0 Min</p>	<p>C: Hybrid Fiber Modal Total Deformation 5 Type: Total Deformation Frequency: 17.165 Hz Unit: mm 12/25/2025 2:16:04 AM</p>  <p>5026.5 Max 4468 3909.5 3351 2792.5 2234 1675.5 1117 558.5 0 Min</p>
6	<p>A: Steel Modal Total Deformation 6 Type: Total Deformation Frequency: 20.75 Hz Unit: mm 12/25/2025 2:07:14</p>  <p>2846.6 Max 2530.4 2214.1 1897.8 1581.5 1265.2 948.88 632.59 316.29 0 Min</p>	<p>C: Hybrid Fiber Modal Total Deformation 6 Type: Total Deformation Frequency: 18.664 Hz Unit: mm 12/25/2025 2:16:50 AM</p>  <p>2261.2 Max 2010 1758.7 1507.5 1256.2 1005 753.74 502.49 251.25 0 Min</p>
7	<p>A: Steel Modal Total Deformation 7 Type: Total Deformation Frequency: 23.928 Hz Unit: mm 12/25/2025 2:32:59 AM</p>  <p>4239.8 Max 3768.7 3297.6 2826.5 2355.4 1884.3 1413.3 942.17 471.08 0 Min</p>	<p>C: Hybrid Fiber Modal Total Deformation 7 Type: Total Deformation Frequency: 20.784 Hz Unit: mm 12/25/2025 2:18:04 AM</p>  <p>2815.3 Max 2502.5 2189.7 1876.9 1564.1 1251.3 938.45 625.63 312.82 0 Min</p>

