

# Assessing Advanced Lightweight Materials for Automotive Applications: A Comparative Analysis

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**Abstract-** The automotive industry's pursuit of enhanced fuel efficiency, reduced emissions, and improved performance has driven significant innovation in lightweight materials. This paper presents a comprehensive comparative review of advanced lightweight materials, evaluating their evolution, current trends, and sustainability implications. Beginning with a historical overview, the study traces the transition from traditional steel-dominated structures to the adoption of aluminum alloys and polymer composites in the late 20th century. Recent advancements (2010–present) are critically examined, focusing on advanced high-strength steels (AHSS), magnesium alloys, carbon fiber-reinforced polymers (CFRPs), and emerging bio-based composites. A systematic comparative analysis evaluates these materials across key parameters, including mechanical properties (strength-to-weight ratio, durability), manufacturability, and cost-effectiveness. The review highlights trade-offs, such as CFRPs' superior lightweight potential versus high production costs, and AHSS's balance of affordability and performance. Environmental impact and sustainability are central to the discussion, emphasizing life cycle assessments (LCAs), recyclability, and energy consumption during production. Findings reveal that while innovative materials like magnesium alloys and bio-composites show promise in reducing ecological footprints, challenges in scalability and end-of-life management persist. The study concludes that a multi-material design approach, tailored to specific automotive components, may optimize performance and sustainability. This review synthesizes critical insights for researchers and industry stakeholders, advocating for continued innovation in material science and collaborative policies to accelerate the adoption of eco-efficient solutions.

**Keywords:** lightweight materials, automotive applications, comparative analysis, environmental sustainability, advanced composites.

## 1. INTRODUCTION

The automotive industry stands at a pivotal juncture, compelled by stringent environmental regulations, consumer demand for fuel efficiency, and the global

imperative to reduce greenhouse gas emissions. Lightweight materials have emerged as a cornerstone of modern vehicle design, offering a pathway to reconcile performance enhancements with sustainability goals. Historically, the sector relied heavily on conventional steel due to its durability and cost-effectiveness. However, the oil crises of the 1970s and evolving emission standards catalyzed a paradigm shift, prompting the exploration of alternatives such as aluminum alloys and polymer composites. Over the past decade, this evolution has accelerated, driven by breakthroughs in material science, manufacturing technologies, and a growing emphasis on circular economy principles.

Today, advanced lightweight materials—including advanced high-strength steels (AHSS), magnesium alloys, carbon fiber-reinforced polymers (CFRPs), and bio-based composites—are redefining automotive engineering. These materials promise exceptional strength-to-weight ratios, corrosion resistance, and design flexibility, yet their adoption is tempered by challenges such as high production costs, manufacturing complexities, and unresolved recycling pathways. Moreover, the environmental benefits of lightweighting must be balanced against the ecological footprint of material production, necessitating rigorous life cycle assessments (LCAs) to evaluate true sustainability.

This paper provides a systematic evaluation of these advanced materials, contextualizing their development, comparing their performance, and analyzing their environmental implications. By synthesizing historical trends, recent innovations (2010–present), and sustainability metrics, the study aims to address critical gaps in existing research, which often prioritizes technical performance over holistic ecological impact. The analysis underscores the necessity of a multi-material strategy, where material selection is tailored to component-specific

requirements to optimize both vehicle efficiency and environmental outcomes.

The findings of this review are intended to guide researchers, engineers, and policymakers in navigating the complexities of material selection, fostering innovation, and aligning automotive advancements with global sustainability targets. Through this lens, the paper contributes to the ongoing discourse on eco-efficient mobility solutions in an era of climate-conscious industrialization.

## 2. HISTORICAL DEVELOPMENT OF LIGHTWEIGHT MATERIALS

The historical development of lightweight materials in the automotive industry can be traced back to the early 20th century when iron and steel dominated vehicle manufacturing as shown in fig.1. These traditional materials, while strong and relatively inexpensive, presented significant limitations in terms of weight, which became a pressing concern as fuel efficiency and performance took center stage in automotive design. The heavy reliance on steel constrained the potential for innovation in design and manufacturing, thus prompting the automotive industry to seek alternatives that would alleviate these burdens while still adhering to performance and safety standards [1].

As environmental concerns and governmental regulations began to shape industry practices, manufacturers turned their attention to lightweight materials starting in the latter part of the 20th century. Early innovations, particularly the introduction of aluminum, began to pave the way for a shift in automotive design. Aluminum's lightweight nature, combined with its resistance to corrosion and

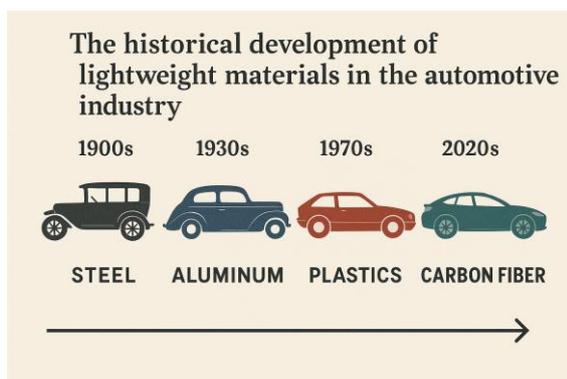


Fig.1 Material used in car Manufacturing.

notable strength, presented an appealing alternative to traditional steels, altering not only weight distribution but also improving fuel efficiency to meet emerging regulatory standards.

The use of composite materials as shown in fig. 2 also emerged during this transitional phase. With advances in material science, manufacturers began experimenting with synthetic polymers and fibers, which could be engineered to provide optimal strength-to-weight ratios. These materials permitted greater flexibility in design while maintaining structural integrity. Such innovations were particularly vital as the automotive sector sought to enhance vehicle performance without compromising safety, which had become a non-negotiable requirement. Notably, "Automotive lightweighting is crucial due to regulatory pressures, environmental concerns, and performance requirements (extended EV range). Lightweight composites offer significant weight reduction without compromising structural integrity or safety"[2].

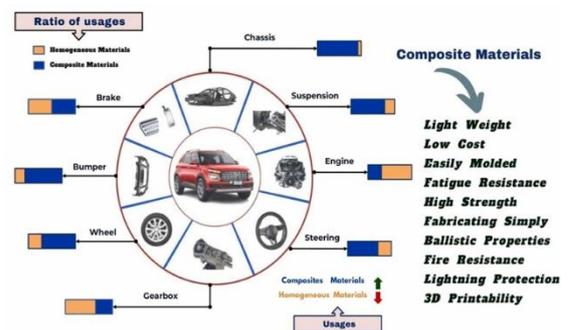


Fig. 2 Composite material for car manufacturing [21]

Between 2000 and 2010, the automotive industry experienced a revolution in material science that further propelled the use of lightweight materials. Advances in composites, including natural fiber reinforced polymer composites, began to gain traction. These materials not only provided enhanced mechanical properties but also presented an environmentally friendly alternative to conventional materials. "Natural fiber reinforced polymer composites (NFRPCs) offer a promising alternative to traditional materials because of their environmentally friendly nature and good mechanical properties" [3]. The growing interest in sustainability also paralleled the industry's embrace of lightweight materials, as manufacturers

increasingly recognized the role these materials could play in reducing vehicular emissions.

Moreover, the continued development of new alloys demonstrated the potential of lightweight materials in not only meeting but exceeding existing performance metrics. With ongoing research and investment, various lightweight materials started to demonstrate enhanced durability and resistance, thus addressing manufacturers' concerns about long-term usability. One significant transformation was highlighted through studies indicating that "A 10% reduction in vehicle weight can lead to a 6-8% decrease in fuel consumption for ICE vehicles, while for electric vehicles (EVs), lightweighting is crucial to offset battery weight and increase range" [4]. This data underscored the economic and environmental impetus for lightweight materials, prompting OEMs (Original Equipment Manufacturers) to integrate these advancements into their designs.

Adoption of lightweight materials also posed specific challenges for automotive manufacturers. The transition required a reevaluation of existing manufacturing processes, as traditional assembly lines were often optimized for heavier materials. This led to increased costs and necessitated investment in new technologies, production techniques, and workforce training. Nevertheless, the opportunities presented by lightweight materials, such as improved vehicle performance and compliance with stricter emissions regulations, ultimately outweighed these transition costs for many manufacturers.

Despite the challenges, the decade from 2000 to 2010 marks an essential period in the historical development of lightweight materials. The automotive sector began to adopt these materials not only as a response to environmental demands but also as a strategic decision to enhance vehicle performance and broader market competitiveness. With projections indicating that "the global lightweight material market is expected to reach \$126.76 billion by 2030, indicating a strong trend towards the adoption of lightweight materials in the automotive sector" [4], it becomes evident that this transition not only reshaped manufacturing practices but also set a foundation for future innovations.

This historical overview of lightweight materials highlights a transformative period in the automotive sector, characterized by a shift from established

practices reliant on traditional materials to innovative designs featuring composites and alloys. As manufacturers navigated the complexities of adapting to new materials, they also opened the door to future possibilities in automotive engineering, thereby paving the way for continued advancements that address the multifaceted challenges of modern mobility and sustainability. The interplay between material science and automotive design continues to evolve, shaping the future trajectory of vehicle manufacturing and performance.

### 3. RECENT TRENDS IN LIGHTWEIGHT MATERIALS (2010-PRESENT)

The automotive sector has undergone a significant transformation regarding the use of lightweight materials since 2010. This transformation has been driven by various factors, including the need to comply with stricter fuel economy and emissions regulations, coupled with technological advancements in material science and manufacturing techniques. [10] Key innovations such as 3D printing and advanced casting methods have emerged to enhance the application of lightweight materials, shifting paradigms in automotive production.

One of the most notable manufacturing innovations in recent years is the rise of additive manufacturing, commonly known as 3D printing. This technology allows for the creation of complex geometries previously unattainable through traditional manufacturing processes. As a result, automotive designers can now fabricate components that reduce overall vehicle weight while maintaining structural integrity. The implications of this innovation are profound; it leads to more efficient production cycles and enables customization at scales that were previously uneconomical. 3D printing technologies are increasingly integrated into the production lines of automotive manufacturers, thus changing the dynamics of how components are designed and manufactured.

In addition to 3D printing, advanced casting techniques, such as die casting and sand casting, have gained momentum in the industry. These methods help produce lightweight components by using new alloys that minimize weight while maximizing strength.[11] Manufacturers are experimenting with magnesium alloys and aluminum-lithium composites, which prove to

exhibit remarkable strength-to-weight ratios. These trends lead to performance enhancements that help automotive manufacturers achieve fuel efficiency goals mandated by regulatory bodies while also responding to market demands for lighter and more efficient vehicles.

Moreover, the introduction of nanotechnology has significantly influenced the mechanical properties of lightweight materials in the automotive sector. By integrating nanomaterials into composites, manufacturers can enhance the performance characteristics of lightweight materials such as polymers and metals. The incorporation of nanoparticles in matrix materials has been shown to improve tensile strength, impact resistance, and thermal stability. Such enhancements are critical as they allow automotive producers to meet evolving standards without compromising the safety and performance of their vehicles.

To illustrate how leading automotive manufacturers have adopted lightweight materials, we can consider various case studies. For instance, Ford has positioned itself at the forefront of this movement with its use of aluminum in the F-150 series, which resulted in substantial weight reduction while increasing payload and fuel efficiency. Furthermore, Audi has developed its "Audi Space Frame" technology, which incorporates both aluminum and high-strength steel to create lightweight structures that do not sacrifice safety. [12] These strategies have allowed these manufacturers not only to improve their products but also to enhance their competitiveness in an increasingly rigorous market landscape.

The influence of regulatory standards established post-2010 cannot be overlooked as they have played a crucial role in shaping the selection and use of lightweight materials in automotive manufacturing. Stricter fuel economy targets and emissions regulations, such as those stipulated by the Corporate Average Fuel Economy (CAFE) standards in the United States, have necessitated greater reliance on lightweight materials. As manufacturers strive to meet these regulations, the integration of alternative materials becomes increasingly attractive, facilitating a shift away from traditional components toward advanced composites and metals that help achieve compliance while boosting performance.

Sustainability has also become a focal point for discussion regarding lightweight materials. Environmental assessments have evolved, highlighting the importance of lifecycle impacts as manufacturers seek to understand the ecological footprint of their material choices. The development and integration of recycled materials into lightweight composites are breaking new ground; for instance, "The introduction of recycled carbon fiber significantly enhances the mechanical and thermal properties of polyamide 6,6 composites, challenging traditional metallic components in terms of performance and sustainability" [5]. Such innovations signify a commitment to enhancing the sustainability credentials of vehicles while offering performance equal to, if not better than, traditional materials.

Additionally, studies demonstrate that lightweight materials significantly reduce vehicle emissions throughout their lifecycle, particularly when optimized for energy efficiency during production. These advances mean that lightweight materials are no longer simply a performance enhancement but are increasingly viewed as a necessary component of an automotive manufacturer's responsibility toward sustainability and environmental stewardship.

In summary, the recent trends in lightweight materials from 2010 to the present showcase a dynamic interplay of technological innovation, regulatory influence, and a growing emphasis on sustainability. As manufacturers continue to adopt and experiment with lightweight materials such as advanced composites and metals, they are not only improving the efficiency and performance of their vehicles but also addressing the crucial concerns surrounding environmental impact. These developments mark a pivotal era in automotive engineering, one that is likely to define the future landscape of the industry.

#### 4. COMPARATIVE ANALYSIS OF LIGHTWEIGHT MATERIALS

The automotive industry has increasingly turned to lightweight materials as a pivotal factor in enhancing vehicle efficiency and performance. This chapter systematically compares various advanced lightweight materials—including aluminum, composites, magnesium alloys, and bio-composites—highlighting their mechanical properties, cost-effectiveness, and environmental

impacts. Through this analysis, stakeholders can make informed decisions on material choices that optimize automotive design and performance. [13]

Aluminum has been a staple in the lightweight materials domain, prized for its favorable strength-to-weight ratio, corrosion resistance, and ease of fabrication. The mechanical properties of aluminum allow for significant weight reductions in vehicle structures, contributing to improved fuel efficiency. As noted, "AHSS can achieve a 50% weight reduction compared to mild steel, leading to a 5% decrease in GHG emissions"[6]. This statement illustrates the substantial benefits that aluminum and other advanced high-strength steels (AHSS) bring to the table in terms of both safety and sustainability. The ability to use lighter materials without sacrificing structural integrity allows manufacturers to meet performance and regulatory standards more effectively.

Composites, particularly those reinforced with synthetic fibers, have gained prominence for their exceptional strength-to-weight ratios. These materials are often tailored to match specific performance criteria demanded by auto manufacturers. The shift toward composite materials also aligns with the industry's push for sustainability. For instance, the potential environmental gains from substituting synthetic fibers with natural fibers in composites can be significant; "Substituting 50% of synthetic fibers with natural fiber composites in North America could reduce CO<sub>2</sub> emissions by 3.07 million tons and crude oil consumption by 1.19 million m<sup>3</sup>"[7]. This capability to provide environmental benefits while enhancing mechanical performance is crucial in maintaining competitive advantage.

Emerging materials such as magnesium alloys are noteworthy for their lower density compared to aluminum, making them attractive alternatives when weight reduction is necessary. These alloys are becoming increasingly viable in automotive applications due to their mechanical properties, which can rival that of more traditional materials while offering up to 30% weight savings. [14] However, the cost remains a significant factor; while magnesium alloys present a promising option, their production expenses often deter widespread adoption.

A comprehensive cost-benefit analysis is essential for evaluating the overall effectiveness of lightweight materials in automotive manufacturing. Although upfront costs can be higher for lightweight materials, the long-term advantages—such as enhanced fuel efficiency and reduced maintenance expenses—are substantial. As highlighted, "The economic aspect is a significant driver of lightweighting initiatives. Although lightweight materials may have higher upfront costs, the potential long-term advantages such as fuel efficiency, enhanced performance, and reduced maintenance expenses make them more appealing" [2]. This perspective emphasizes that cost-effectiveness should be measured not only in initial investment but also in long-term operational savings and environmental gains.

Lifecycle assessments (LCA) play a critical role in comparing the environmental impacts of lightweight materials, as they evaluate the material's footprint from production to disposal. These assessments often reveal that while the manufacturing phase for materials such as composites may involve higher energy inputs, their operational efficiencies during vehicle use can lead to overall lower emissions across their lifespans [16]. Such evaluations become particularly important in the context of growing regulatory scrutiny, which increasingly demands that manufacturers address their environmental impacts comprehensively.

Regulatory standards are another influencing factor that shapes the selection and application of lightweight materials in automotive design. In recent years, global frameworks aimed at reducing greenhouse gas emissions and increasing fuel economy have catalyzed the adoption of lightweight materials [17]. Manufacturers must navigate an evolving landscape of regulations while ensuring that their material selections align with both safety and sustainability benchmarks. Regulatory changes often necessitate updates to production practices, material sourcing strategies, and design philosophies, all of which can directly impact the attractiveness of various lightweight materials.

In summary, the comparative analysis of lightweight materials reveals intricate connections among their mechanical properties, cost implications, and environmental impacts. Each category of material has distinct advantages and limitations that must be understood in the context of the automotive

industry's ever-changing landscape. For stakeholders involved in material selection, the integration of these insights will be crucial for making choices that not only enhance vehicle performance but also align with regulatory and environmental goals. Through this comprehensive approach, the analysis seeks to enhance the dialogue surrounding the optimal material choices for the future of automotive design and manufacturing.

## 5. ENVIRONMENTAL IMPACT AND SUSTAINABILITY

The automotive industry faces increasing scrutiny regarding its environmental impact, particularly concerning the materials it employs for vehicle manufacturing. Lightweight materials, while promising significant benefits in terms of efficiency and performance, necessitate careful consideration of their entire lifecycle, from resource extraction and production processes to end-of-life recyclability. Lifecycle assessments (LCAs) serve as critical tools in this evaluation process [18]. These assessments help identify the environmental consequences of lightweight materials at each stage, allowing manufacturers to make informed choices that align with sustainability objectives.

A comprehensive LCA of lightweight materials must consider various factors, such as the energy consumption associated with material extraction and processing. For instance, metals like aluminum, while beneficial for reducing vehicle weight, require significant energy for production. However, the "high-strength lightweight aluminum alloys significantly reduce vehicle weight while enhancing performance and efficiency, crucial for meeting modern fuel economy standards"[8]. This illustrates the importance of balancing the material's environmental costs with its performance advantages. As manufacturers aim to meet regulatory standards that enforce lower emissions and higher fuel efficiency, LCAs become essential in guiding these decisions effectively.

Current environmental regulations play a pivotal role in shaping material choices in automotive design. Stringent national and international emissions standards compel manufacturers to prioritize lightweight materials that reduce the overall carbon footprint of vehicles. By integrating lighter components, manufacturers can achieve compliance with regulations such as the Corporate

Average Fuel Economy (CAFE) standards in the United States. Strategies to navigate these regulations include adopting advanced materials which simultaneously meet safety and performance standards. According to Wu and Zhang, the ability to "reduce CO<sub>2</sub> emissions by 5 g/km for every 100 kg reduction in vehicle weight highlights the critical role of lightweight materials in sustainability efforts within the automotive sector"[8]. This underscores the necessity of adopting lightweight solutions not merely for performance gain but as a strategic response to regulatory demands.

Additionally, the incorporation of recycled materials has gained traction as a sustainable practice within the automotive sector. Utilizing recycled components reduces reliance on virgin materials, significantly lowering the ecological footprint of vehicles. An exemplary case is the use of recycled carbon fibers in automotive composites, which enhance "mechanical properties of lightweight composites in automotive applications, addressing both performance and sustainability requirements" [5]. The integration of recycled materials not only optimizes the use of resources but also adds a layer of sustainability that conventional materials often lack.

The comparison of carbon footprints among various lightweight materials during their lifecycle reveals critical insights for manufacturers aiming to improve their sustainability practices. Aluminum, composites, and metals like magnesium each present unique advantages and challenges in terms of lifecycle emissions [19]. Heavy reliance on aluminum might yield short-term fuel efficiency benefits, yet its manufacturing phase poses higher initial emissions compared to some synthetic composites. Understanding these dynamics enables manufacturers to strategically select materials that align with both performance goals and environmental mandates.

Innovative practices within the automotive industry are imperative for enhancing sustainability initiatives related to the use of lightweight materials. Research and development activities aim to create new composites and manufacturing processes that further reduce energy consumption and waste. These innovations can lead to lighter, more efficient vehicles while also lessening the overall environmental impact. For example, as manufacturers investigate alternative binders and

resin formulations in composite materials, they can potentially decrease the harmful emissions associated with traditional processes.

Moreover, as technology advances, so too does the potential for utilizing new lightweight materials that not only fulfill performance standards but also appear sustainable [20]. Materials such as bio-composites, which leverage renewable resources, can provide a viable path toward achieving lower environmental footprints. This revolutionary shift in focus necessitates continuous dialogue among manufacturers, researchers, and policymakers to cultivate practices that ultimately lead to a more sustainable automotive industry.

In conclusion, the exploration of lightweight materials in the automotive sector reveals a complex interrelation between environmental impacts and sustainability. By assessing the lifecycle of materials, adhering to regulatory mandates, integrating recycled components, and fostering innovative practices, the automotive industry can navigate the challenging landscape of modern sustainability. As the sector continues to evolve, a thorough understanding of these dynamics will be essential in championing the dual objectives of performance enhancement and environmental stewardship.

## 6. CONCLUSION

The exploration of lightweight materials in the automotive industry has revealed a profound impact on vehicle performance, efficiency, and environmental sustainability. The synthesis of findings underscores those lightweight materials—such as aluminum, composites, and innovative bio-based options—are crucial for enhancing automotive performance. These materials not only facilitate significant weight reductions, contributing to improved fuel economy, but also play a pivotal role in reducing greenhouse gas emissions. As one study noted, "Lightweight materials are crucial for improving fuel efficiency, reducing greenhouse gas emissions, and enhancing vehicle performance. The automotive industry faces pressure to adopt more eco-friendly technologies" [9]. This statement highlights the urgency and necessity of integrating advanced materials within the automotive sector, especially against the backdrop of increasing regulatory pressures and consumer expectations for sustainability.

Cost implications remain an essential consideration in the adoption of lightweight materials. While the initial investment for advanced materials may be higher, their long-term benefits, including enhanced fuel efficiency and reduced operational costs, render them economically viable. The automotive industry has recognized that such materials, though sometimes costly upfront, yield savings through decreased fuel consumption and maintenance expenses. "The economic aspect is a significant driver of lightweighting initiatives. Although lightweight materials may have higher upfront costs, the potential long-term advantages such as fuel efficiency, enhanced performance, and reduced maintenance expenses make them more appealing" [2]. This perspective bolsters the argument that cost-effectiveness evaluations must account for both immediate and enduring advantages, essential for informing stakeholders' decision-making processes.

Environmental impacts associated with lightweight materials further emphasize their alignment with sustainability goals. Lifecycle assessments (LCAs) demonstrate that adopting these materials can contribute to reduced emissions throughout their lifecycle, including production, usage, and disposal phases. The implementation of sustainable practices, such as the introduction of recycled components, adds another layer of environmental benefits. By utilizing recycled materials and bio-composites, manufacturers reduce reliance on virgin resources while addressing performance and sustainability requirements simultaneously. "Substituting 50% of synthetic fibers with natural fiber composites in North America could reduce CO<sub>2</sub> emissions by 3.07 million tons and crude oil consumption by 1.19 million m<sup>3</sup>" [7]. This potential for substantial environmental benefit aligns with the automotive sector's ongoing commitment to corporate social responsibility and sustainable innovation.

Emerging applications of lightweight materials in automotive design present a fertile ground for future research. Current advancements indicate that new materials and innovative manufacturing techniques, including additive manufacturing and advanced casting, are reshaping vehicle architecture and efficiency. These innovations require further exploration, particularly in terms of their implications for material choices, manufacturing processes, and the overall sustainability of automotive production. There is a clear indication that interdisciplinary approaches—bridging

materials science, engineering, and environmental studies—are vital for enhancing the integration of lightweight materials in automotive manufacturing practices. Comprehensive exploration of these avenues can advance our understanding of how to optimize material use and production methodologies.

In summary, the accumulated evidence highlights the multifaceted benefits of lightweight materials in the automotive sector. By synthesizing findings regarding their effectiveness, cost implications, and lifecycle impacts, this conclusion establishes a framework for understanding how these materials align with industry innovations and sustainability goals. The automotive industry's future sustainability efforts hinge on further research into new materials, innovative applications, and strategies that enhance collaboration across disciplines, thus ensuring ongoing advancements that meet the evolving demands of performance, cost efficiency, and environmental stewardship.

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