

# Impact of Powertrain Systems on Automobiles

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**Abstract.** The powertrain system, as the important component of automobiles, profoundly influences vehicle performance, design, and environmental sustainability. This paper provides a comprehensive analysis of the impact of powertrain systems on modern vehicles, examining the evolution from traditional internal combustion engines (ICE) to hybrid, pure electric, and emerging powertrains such as hydrogen fuel cells. It explores how powertrain design dictates key performance metrics including acceleration, top speed, energy efficiency, and driving refinement, while also shaping vehicle morphology, structural layout, and aerodynamic characteristics. Furthermore, the study highlights the role of lightweight materials, intelligent energy management, and integrated design in enhancing overall vehicle efficiency and sustainability. The paper also discusses future trends, including the deep integration of electrification and intelligence, advancements in lightweighting and green manufacturing, and the challenges of achieving full lifecycle carbon neutrality. It concludes that the continued innovation and optimization of powertrain systems are essential for meeting diverse market demands and advancing toward a clean, intelligent, and sustainable automotive industry.

**Keywords:** Powertrain System, Automobile Performance, Vehicle Design.

## 1. Introduction

In the 21st century, the number of automobiles has significantly increased, over 2.3 million electric cars were sold in the first quarter, about 25% more than in the same period last year and cars have become thoroughly integrated into people's lives. Whether for commuting or transportation, they are an indispensable part of daily life. This has likewise contributed to economic progression and an enhancement in the quality of life. However, this has also presented more daunting challenges, such as increasingly severe environmental issues, a gradual depletion of available resources, and intensified market competition. In this complex landscape, automotive companies must pivot their strategic focus from sheer sales volume towards superior quality, environmental sustainability and a more holistic approach to sustainable development.

The powertrain system of an automobile, including internal combustion engine, transmission, and drivetrain in traditional vehicles, along with the battery and electric motor in electric vehicles, is fundamentally the heart of the vehicle. It plays a pivotal role in determining core performance metrics such as acceleration, top speed, gradeability and fuel efficiency. A well-engineered powertrain is also intrinsically linked to the vehicle's ease of operation and riding comfort, thereby directly influencing customer satisfaction and overall brand perception. However, the significance extends far beyond its impact on the fundamental metrics. The selection of a powertrain system imposes critical constraints and poses significant challenges and the overall vehicle design, governing its aerodynamics profile, material selection, internal layout and so on. Therefore, the powertrain is not merely an isolated component but the most important part of vehicle manufacturing, critically influencing both its aesthetic appeal and on-road dynamics.

This paper emphasizes the multifaceted importance of the powertrain in modern automotive engineering. It not only delineates the historical evolution of powertrain system but also focuses on current and future trends. The discussion explores how the powertrain system fundamentally dictates not only traditional performance metrics but also directly influences the vehicle's exterior form, structure architecture and overall performance characteristic. By examining the strengths and limitations of different types of powertrain systems and correlating them with ever-evolving market

demands, the study aims to elucidate the intricate relationship between powertrain development and vehicle design, thereby guiding strategies to meet diverse market requirement.

## **2. Types and Development of Automotive Powertrain System**

The automotive powertrain serves the core of vehicle propulsion, and its technological evolution mirrors the advancement of the entire automotive industry. In recent years, with the introduction of environmental policies and the rise of new energy technologies, the powertrain system has transitioned from the former dominance of traditional internal combustion engines to a diverse technological landscape characterized by the convergence of multiple technologies. Each powertrain system has its own inherent strengths and specific challenges, collectively driving the advancement of the automotive industry toward greater environmental sustainability and operational efficiency. This chapter provides a comprehensive overview of the characteristics and current development status of predominant powertrain systems available in the market, establishing a foundational understanding of automotive propulsion technologies.

### **2.1. Internal Combustion Engine**

For over a century, internal combustion engine which is powered by gasoline and diesel have maintained virtually unrivaled dominance in automotive propulsion systems. The central focus of modern internal combustion engine enhancements lies in optimizing fuel efficiency. Through the utilization of advanced technologies such as direct injection, ultra-high boost pressures, and exhaust gas recirculation, the efficiency of internal combustion engines is being pushed ever closer to their maximum theoretical limits. The widespread application of boosting technologies, particularly turbocharging, has successfully achieved engine downsizing, enabling smaller-displacement engines to deliver power output comparable to that of larger-displacement engines [1]. Simultaneously, it mitigates heat loss while enhancing fuel economy. Conventional transmission systems, such as hydraulic automatic transmissions, dual-clutch transmissions and continuously variable transmissions, continuously improve transmission efficiency, shift smoothness, and response speed through measures like increasing the number of gears and enhancing the strength of transmission belts. These advancements aim to transfer power from the engine to the drive wheels with minimal loss [2].

### **2.2. Hybrid Powertrain System**

Hybrid powertrain systems serve as a pivotal technological bridge between tradition and innovation. By ingeniously integrating conventional internal combustion engines with modern electric motors, these systems leverage their complementary strengths to create powertrain solutions that better align with contemporary demands for efficiency and performance. At its technological core lies the energy management strategy, which constitutes a sophisticated set of intelligent control algorithms [3]. This strategy enables rational allocation of energy consumption, dynamically adjusting the distribution pattern in real-time based on vehicle speed, battery charge level, and external conditions. This approach ensures the engine maintains sustained operation within its optimal efficiency range, thereby enhancing the overall system efficiency. The oil-electric coupling mechanism serves as the physical foundation for implementing this strategy, primarily categorized into three types, such as series hybrid, parallel hybrid and power-split architecture. The series hybrid configuration represents a relatively straightforward powertrain architecture. In this system, the internal combustion engine does not directly drive the wheels but instead operates a generator to produce electricity, which means the vehicle is exclusively propelled by the electric motor. This arrangement allows the engine to maintain operation within its optimal efficiency range consistently, although it suffers from inherent energy conversion losses due to the multiple energy transfer stages. The parallel hybrid configuration also represents a relatively simple structural approach. It supports pure electric drive, pure engine propulsion, and combined power operation where both power sources work together to deliver enhanced performance. This system demonstrates comparatively lower

development complexity. The power-split architecture, also known as series-parallel Hybrid, utilizes complex components such as planetary gear sets to achieve seamless power coupling and free mode switching. This configuration represents the most technically sophisticated hybrid system, while offering the greatest potential for fuel economy.

### 2.3. Pure Electric Powertrain Systems

Pure Electric Powertrain Systems completely eliminate internal combustion engines, utilizing high-capacity battery packs as the energy source to power electric motors for propulsion. The pure electric powertrain has become the dominant mainstream solution in new energy vehicle development. It demonstrates significantly higher energy efficiency compared to internal combustion engines, exceeding 77%. During operation, electric motors provide quieter operation with minimal vibration. Their relatively simple mechanical structure also enables quicker vehicle acceleration. By eliminating the use of fossil fuels that produce exhaust emissions, pure electric vehicles achieve virtually zero direct emissions during operation. The strategic placement of battery packs has revolutionized automotive design. By integrating the battery pack horizontally beneath the chassis floor, manufacturers not only create substantial energy storage capacity but also significantly lower the vehicle's center of gravity. This configuration dramatically enhances handling stability and safety while simultaneously liberating space in both front and rear compartments. This architectural innovation enables a fundamental reimagining of vehicle morphology, giving rise to more spatially efficient automotive architectures.

### 2.4. Emerging Powertrain System

**Table 1.** The feature of different types of powertrain system

Feature	Internal Combustion Engine	Hybrid Powertrain System	Pure Electric Powertrain System	Emerging Powertrain Systems
Primary Energy Source	Gasoline/Diesel	Gasoline/Diesel + Electricity	Electricity	Hydrogen
Key Components	Engine, Fuel Tank, Transmission, Exhaust	Engine, Fuel Tank, Electric Motor, Battery Transmission	Electric Motor, Large Battery Pack, Power Inverter, Onboard Charger	Fuel Cell Stack, Hydrogen Tanks
Propulsion Method	Combustion of Fuel	Combustion of Fuel and Electric Motor	Electric Motor	Electric Motor
Emissions	CO <sub>2</sub> , NO <sub>x</sub> , Particulates	CO <sub>2</sub> , NO <sub>x</sub> (Lower than ICE)	Zero	Zero
Advantages	High Range Mature Tech & Infrastructure Low Initial Cost	Reduced Fuel Consumption No Range Anxiety Regenerative Braking	Zero Emissions Low Operating Cost Low Maintenance	Fast Refueling Long Range
Limitations	High Emissions Fossil Fuel Dependency High Operating Cost	Complex System Higher Cost than ICE Still Uses Fuel	Long Charging Times Limited Range Charging Infrastructure Gaps High Initial Cost	Virtually No Infrastructure Very High Vehicle Cost

In addition to the aforementioned mass-produced technologies, numerous automakers are actively developing emerging powertrain solutions to cater to evolving market demands. Currently the most promising are hydrogen fuel cell vehicles (FCEV). This is essentially an electric vehicle equipped with an on-board power generator. The vehicle is equipped with high-pressure hydrogen tanks. Within the fuel cell stack, hydrogen undergoes an electrochemical reaction with oxygen from the air, producing water and generating electrical current. It offers zero emissions, with water as the only byproduct, while providing rapid refueling (3-5 minutes) and extended driving range. However, it

currently confronts numerous difficulties and challenges. The green production, high-pressure storage, and long-distance transportation of hydrogen pose significant cost challenges [4]. This has resulted in its limited adoption within the automotive sector. Additionally, alternative pathways such as e-fuels and ammonia-based propulsion remain in early-stage R&D status, facing substantial barriers to mass production within a short timeframe.

Through in-depth analysis of these four powertrain types, it becomes evident that automotive propulsion technology is evolving along multiple parallel pathways rather than converging toward a single solution. For the foreseeable future, diverse technological routes will continue to leverage their respective advantages across different market segments—guided by varying consumer demands and policy frameworks—collectively shaping a multifaceted landscape of automotive propulsion systems. All these results are shown in Table 1 [5].

### 3. Impact of Powertrain System on Overall Vehicle Performance

The design of an automotive powertrain system transcends mere component integration and manufacturing processes; it represents the fundamental core that determines the vehicle's essential performance characteristics. A meticulously engineered powertrain system efficiently converts energy into propulsive force, fundamentally governing a vehicle's acceleration capabilities, maximum speed, energy efficiency, and ultimate driving refinement. This chapter is dedicated to examining the specific impacts of powertrain design on four critical dimensions of vehicle performance.

#### 3.1. Acceleration and Power Response

Acceleration performance serves as a direct reflection of a powertrain's capabilities, with its core metrics encompassing 0-100 km/h acceleration time and power response speed. The characteristics of the power source dictate the fundamental nature of its response. Internal Combustion Engines exhibit torque output dependent on rotational speed buildup, characterized by turbo lag phenomena that create perceptible power delivery steps and response delays. In contrast, Pure Electric Powertrain Systems leverage the electric motor's "zero-rpm torque" capability and instantaneous response characteristics, delivering peak torque immediately upon accelerator pedal engagement. This enables seamless linear acceleration without any perceptible delay, achieving exceptionally rapid response times. For hybrid powertrain systems, acceleration performance is determined by the synergistic strategy between the internal combustion engine and electric motor. Sophisticated energy management strategies can instantaneously compensate for the power deficit of the internal combustion engine during rapid acceleration through electric motor intervention, achieving "dual-power synergy" that delivers acceleration capabilities surpassing those of comparable conventional fuel-powered vehicles. Furthermore, transmission system matching is equally critical, as the shift logic and speed of the transmission directly impact the smoothness of the acceleration process.

#### 3.2. Maximum Speed and High-Speed Stability

Maximum speed tests the powertrain's sustained performance under high-load conditions, while high-speed stability is fundamentally linked to the layout configuration of the powertrain system. Power reserve serves as the fundamental cornerstone for achieving higher maximum speeds. According to the formula:

$$P = F * V \quad (1)$$

It is established that the maximum vehicle speed is determined by the net power available from the powertrain after overcoming aerodynamic drag and frictional resistance. This demonstrates that whether an engine possesses high-RPM power capability fundamentally dictates the ceiling of maximum speed.

The layout of the powertrain system serves as the foundational factor influencing vehicle stability. The physical arrangement of the powertrain system significantly impacts the vehicle's center of

gravity, which fundamentally influences stability and handling characteristics. The traditional front-mounted internal combustion engine layout tends to create a nose-heavy weight distribution, which poses significant challenges to high-speed stability. Conversely, pure electric vehicles strategically position their heavy battery packs low in the chassis, significantly lowering the vehicle's center of gravity while substantially enhancing handling stability and perceived safety. Furthermore, fuel cell vehicles typically position their hydrogen tanks beneath the chassis, achieving similarly beneficial center of gravity advantages.

### 3.3. Fuel Economy and Energy Efficiency Management

Driven by dual pressures of environmental concerns and regulatory requirements, energy efficiency has emerged as the central objective in powertrain design. The chosen technical pathway fundamentally dictates the maximum achievable energy efficiency. The selected technical pathway fundamentally determines the upper limit of energy efficiency: from an energy conversion perspective, pure electric systems (>77%) significantly outperform internal combustion engines (<40%), a distinction dictated by their inherent physical principles. The core value of hybrid systems lies in their intelligent energy management, which forces the internal combustion engine to operate consistently within its optimal efficiency range, avoiding low-efficiency operation and thereby substantially enhancing overall energy utilization. Intelligent management serves as the critical enabler for achieving high efficiency. Advanced energy management strategies serve as the system's brain. By dynamically predicting driver intent and real-time road conditions, it intelligently determines when to utilize pure electric drive, when to activate the internal combustion engine, and when to initiate energy recovery. For instance, it prioritizes electric power in congested urban areas, employs highly efficient direct engine drive during highway cruising, and converts each braking event into recoverable electrical energy. This holistic intelligent management approach represents the software core that enhances overall energy efficiency.

### 3.4. Driving Experience

The design of the powertrain system is a critical factor determining a vehicle's driving refinement and perceived quality, directly and tangibly shaping the driver's subjective experience. The important components of the driving experience encompass powertrain refinement, handling and NVH (Noise, Vibration and Harshness). Powertrain refinement significantly influences the quality of the driving experience. It serves as the cornerstone of the driving experience, directly pertaining to the refined smoothness of power delivery. For internal combustion engines, the critical determinant lies in the transmission's shift quality. Subpar powertrain systems can cause noticeable jerkiness during gear changes, adversely affecting the driver's experience. Electric motors, conversely, are free from such issues. Their advantage lies in providing exceptionally smooth operation without any gear shift impacts. However, this very smoothness can potentially induce motion sickness in passengers. Handling refers to a vehicle's responsiveness to driver inputs, which directly impacts driver satisfaction. The high center of gravity characteristic of internal combustion engines adversely affects front-rear weight balance, consequently degrading vehicle handling performance. The strategic placement of battery packs within the chassis lowers the center of gravity, reduces body roll, and enhances stability. Simultaneously, the battery pack functions as a structural member, significantly increasing torsional rigidity. Hybrid powertrain systems combine characteristics of both conventional and electric powertrains. While they may increase overall weight and impact vehicle agility, the flexible placement of electric motors can be utilized to optimize weight distribution. NVH serves as the standard for evaluating a vehicle's acoustic quality and mechanical vibration performance, thereby enhancing ride comfort, premium perception, and driving refinement. The inherent combustion processes and mechanical vibrations of internal combustion engines serve as the primary sources of overall vehicle noise and vibration. In contrast, the near-silent operation of electric motors fundamentally eliminates idle vibrations and acoustic disturbances, establishing the foundation for the tranquil and premium cabin ambiance characteristic of pure electric vehicles. For hybrid

powertrain systems, the seamless execution of mode transitions, such as engine start-stop cycles and power engagement, represents the paramount criterion for evaluating calibration proficiency. Inadequate management of these transitions can induce perceptible jerking and abrupt noise, ultimately degrading the overall driving experience.

## **4. Impact of Powertrain Design on Vehicle Form and Structure**

Automotive design is never solely driven by aesthetics but represents the ultimate embodiment of form follows function. As the heart of the vehicle, the powertrain system, through its type, layout, and performance requirements, fundamentally dictates the vehicle's morphology, structural architecture, and even the design of every exterior detail. This chapter will delve into how powertrain design shapes both the form and internal framework of automobiles.

### **4.1. Powertrain Layout and Body Structure**

The configuration of the powertrain packaging serves as the fundamental determinant of the vehicle's architecture, directly governing the passenger compartment space, handling characteristics, and styling proportions. Traditional internal combustion engine layouts impose significant design constraints. During the era of internal combustion engine vehicles, layouts such as front-engine front-wheel drive (FF), front-engine rear-wheel drive (FR), mid-engine rear-wheel drive (MR), and rear-engine rear-wheel drive (RR) had established distinct design paradigms. The substantial space occupied by the engine, transmission, and driveshaft resulted in forward-shifted passenger compartments, raised cabin floor panels (to accommodate the driveshaft tunnel), and elongated front overhangs (to house the engine and balance weight distribution). Within these imposed by mechanical hardpoints, designers were compelled to execute stylistic innovation under strict limitations. However, the advent of electric powertrain system has enabled a fundamental reshaping. The emergence of pure electric systems represents a structural revolution. The "skateboard" chassis platforms integrate battery packs flat along the underbody, while electric motor placement offers extreme flexibility (front, rear, or dual-motor configurations). This transformation brings several fundamental changes: the miniaturization of mechanical components liberates space around the wheel arches, enabling longer wheelbases within the same overall vehicle length and providing unprecedented spaciousness for the passenger cabin. By eliminating the transmission tunnel, the cabin floor becomes completely flat, enhancing comfort for rear-center passengers. The inherent advantages of electric motors allow for reimagined body proportions—short front overhangs, long wheelbases, and flowing A-pillar lines have become signature modern proportions of electric vehicles, as seen in models like the Tesla Model S and NIO ET7.

### **4.2. Powertrain System and Aerodynamic Shape Optimization**

Aerodynamic performance is directly linked to energy efficiency and high-speed stability. Its design must be harmonized with the thermal management requirements of the powertrain system, while breakthroughs are achieved through the application of new materials. The drag coefficient is a critical factor influencing its driving range. For electric vehicles, every 0.01 reduction in the drag coefficient increases driving range by approximately 1.5-2% [6]. This compels designers to adopt features such as sealed front grilles, flush door handles, streamlined fastback profiles, and underbody panels, prioritizing aerodynamic efficiency above all else. Different powertrain systems have varying cooling requirements. For electric vehicles, the thermal management requirements of the e-drive system and battery pack are relatively modest, necessitating only minimal air intakes for battery and brake cooling. This enables the implementation of sealed front fascias and integrated body styling. In contrast, high-performance internal combustion engine vehicles and hybrids generate substantial heat from the engine and braking systems, requiring large grilles, hood vents, and side fender ducts to ensure adequate cooling. These functional elements, through sophisticated design, have evolved into visual signatures of performance—exemplified by BMW's kidney grilles and Audi's Single frame

design. The application of new materials enables greater diversification in vehicle exterior design. Carbon fiber, valued for its high strength and lightweight properties, is utilized in manufacturing entire roofs, spoilers, and chassis components to achieve extreme weight reduction and lower the center of gravity. Composite plastics and polymer materials are employed to create lighter and more complex aerodynamic components (such as side skirts and diffusers), granting designers enhanced styling freedom.

### **4.3. Powertrain Performance and Lightweight Design Integration**

Ultimate performance stems from robust power output and a lightweight body structure and weight reduction serves as the fundamental means of enhancing handling, acceleration, and energy efficiency. Modern vehicle bodies are no longer constructed from a single grade of steel, but strategically employ diverse material compositions across different structural zones to optimize performance and safety [7]. High-strength steel is typically utilized for the passenger cell structure to ensure crashworthiness. Aluminum alloy, another commonly used material, is widely applied in hoods, doors, and subframes to achieve significant weight reduction while maintaining structural integrity. Carbon fiber, increasingly adopted in recent years, is frequently employed in performance and supercars for both skin panels and structural components. Weight reduction within the powertrain system itself is equally critical. For instance, the adoption of aluminum alloy engine blocks, carbon fiber driveshafts, and integrated electric drive systems (combining motor, controller, and reducer into a single unit) achieves source-level weight reduction.

### **4.4. Design Adaptation Across Three Vehicle Types**

Supercar (e.g. Ferrari SF90 Stradale) is served as a high-performance hybrid supercar; its exterior represents the ultimate expression of functionalism. The massive front lip and side vents direct airflow to cool the brakes and engine, while the complex rear diffuser manages underbody turbulence and generates downforce. Its hybrid powertrain layout (dual front-axle motors + mid-mounted engine) dictates its unique weight distribution and proportions.

Electric Vehicle (e.g. Tesla CyberTracker) has revolutionary wedge-shaped form is entirely enabled by the pure electric powertrain. Without needing engine cooling, it adopts an almost completely sealed monobody construction made of ultra-hard stainless steel. The low center of gravity and rigid structure allow it to break traditional design rules, pursuing extreme drag reduction and maximum structural efficiency.

Hybrid Vehicle (e.g. BMW i8) and its design perfectly blend the requirements of both power sources. The low, flowing body and extensive aerodynamic channels serve both the cooling needs of the 1.5T engine and optimize drag reduction for extended electric range. Its lifelike butterfly doors and complex surface variations demonstrate the avant-garde, technological design language enabled by hybrid systems.

## **5. Future Development Trends and Challenges**

The transformation of automotive powertrain systems is advancing at an unprecedented pace. Its future development will no longer be confined to the substitution of power sources but will deeply integrate with intelligent technologies, materials science, and global carbon reduction goals, presenting a holistic and synergistic development trend. This chapter will explore the core trends and formidable challenges facing powertrain design in the future.

### **5.1. Integrated Design of Powertrain and Exterior under Electrification and Intelligent Technologies**

In traditional automotive design processes, the relationship between powertrain (hardpoints) and exterior design (styling) has often been sequential or even mutually compromising. However, driven by both electrification and intelligent technologies, this paradigm is being fundamentally reshaped.

The integrated design of powertrain and exterior has emerged as a core trend—no longer merely about "adaptation" but rather a "fusion and symbiosis" starting from the underlying architecture and centered on user experience. Modern vehicles have transitioned from being function-driven to experience-driven in their design philosophy. The "skateboard-style" chassis of pure electric systems has now become a mainstream trend, with its flat and modular nature offering unlimited possibilities for upper cabin configurations (e.g., Tesla CyberTracker). Future automotive body styling will focus more on aerodynamic optimization (e.g., active aerodynamic components, virtual side mirrors), cabin space maximization, and personalized user experiences, rather than accommodating mechanical layouts. Intelligently-driven dynamic exterior forms are emerging as a primary future development direction, aimed at achieving deep integration between vehicle morphology and intelligent driving/powertrain management systems. For instance, in high-speed autonomous driving mode, the vehicle can automatically lower its body height and adjust the angles of front and rear spoilers to pursue minimal drag and energy consumption. Or smart surface technologies (such as e-ink-based color-shifting body panels and adaptive light grilles). This technology will enable users to alter the vehicle's appearance based on mood or scenario, realizing a "software-defined" approach to exterior design. The integration of powertrain and exterior design also presents numerous challenges. Integrated design imposes extremely high demands on cross-disciplinary collaboration (mechanical, electronic, software, and design). Simultaneously, balancing the relationships between aerodynamics, sensor visibility, interior space, and aesthetics will pose the core challenge for engineering and design teams. Furthermore, substantial development and production costs as well as government regulations imposed on vehicle morphology will pose additional obstacles to innovative design development.

## 5.2. New Materials, Lightweighting and Energy Efficiency Advancement

In the electric era, the value of weight reduction is further amplified, as it is directly linked to improved energy efficiency and extended driving range. Its development will be closely integrated with new materials and processes. The mixed application of multiple materials has become a trend in the modern automotive industry. Future vehicle bodies will continue to evolve toward multi-material hybrid architectures. High-strength steel ensures the integrity of the safety cell structure, aluminum alloys are widely used in body panels and structural components, while carbon fiber composites are expanding their application in high-performance models and critical parts. Material selection will be optimally distributed based on precise performance-cost-weight analysis. Numerous companies are transforming body manufacturing processes through integrated gigacasting technology [8]. By integrating hundreds of stamped and welded components into one or two large castings, this approach significantly reduces part count, connection points, and production processes. It achieves substantial weight reduction while simultaneously enhancing structural rigidity, production efficiency, and cost reduction. This will become an essential pathway for automotive manufacturers seeking to achieve lightweighting goals in the future. Innovations in battery pack architecture serve as the cornerstone for enhancing energy efficiency. CTC (Cell-to-Chassis)/CTB (Cell-to-Body) technology enables direct integration of battery cells into the vehicle's floor or chassis structure, eliminating the need for traditional modules and battery pack housing. This approach achieves maximized structural efficiency and space utilization, representing a paradigm of synergistic lightweighting and energy efficiency improvements. The process of achieving these objectives will also encounter lots of challenges. Cost control of new materials, reliability of joining processes—particularly for dissimilar material connections—as well as recyclability issues of advanced materials such as carbon fiber, constitute the primary barriers to their widespread adoption.

## 5.3. Green and Low-Carbon & Regulatory Orientation

Future powertrain competition will extend beyond performance and cost to encompass full lifecycle carbon footprint. Regulations will shift from focusing solely on tailpipe emissions to addressing environmental performance across the entire cycle—from manufacturing and usage to recycling. Regulatory frameworks concerning green and low-carbon initiatives are gradually being

refined and increasingly stringent in the whole world. Globally, major markets (China, EU, US) are implementing increasingly stringent emission regulations and carbon neutrality policies. The EU's Carbon Border Adjustment Mechanism (CBAM) and the deepening of China's national carbon market will compel enterprises to calculate and reduce the full lifecycle carbon emissions of their products. Driven by these regulatory frameworks, a growing number of enterprises have been placing increasing emphasis on green and low-carbon manufacturing processes. Some enterprises are adopting renewable energy sources such as photovoltaic systems to power their manufacturing facilities, thereby reducing carbon emissions during production processes. They are also increasing the utilization ratio of low-carbon materials (such as recycled aluminum and recycled steel) and developing battery materials with a low carbon footprint [9]. Efficient battery recycling stands as a critical pathway toward achieving green and low-carbon goals. Through material regeneration technologies (e.g., hydrometallurgy), we can recover precious metals such as cobalt, nickel, and lithium. Establishing a comprehensive battery recycling system and forming a closed-loop supply chain will significantly reduce the environmental burden associated with mining [10]. Establishing an accurate full lifecycle carbon emission accounting system is a complex undertaking. The costs associated with green manufacturing and recycled materials remain relatively high, while the economic viability and scalability of battery recycling still require breakthroughs. Achieving a genuine transition from "gray" to "green" supply chains represents a systemic challenge confronting the entire industry.

In summary, the future development of powertrain systems will constitute a multidimensional optimization process driven collectively by technological advancement, environmental imperatives, and user experience. Successful products will emerge from finding the optimal balance among integrated design, lightweight material processes, and full lifecycle decarbonization. This transformation not only tests automotive manufacturers' technical capabilities but also necessitates a comprehensive reevaluation of their supply chain management, energy strategies, and sustainable development philosophies.

## 6. Conclusion

The rapid development of the automotive industry in the 21st century has increasingly highlighted the critical role of powertrain systems as the core component of vehicles. This paper has provided an in-depth exploration of the multidimensional importance of powertrain systems, reviewing their historical evolution while offering a detailed analysis of current and future trends. From traditional internal combustion engines to hybrid systems, and further to pure electric and emerging hydrogen fuel cell powertrains, each technological pathway demonstrates unique advantages and challenges, collectively driving the automotive industry toward a more environmentally friendly and efficient future.

The selection and design of powertrain systems decisively influence overall vehicle performance, including acceleration capability, top speed, fuel economy, and driving refinement. For instance, electric powertrains deliver instant torque and exceptionally smooth operation, while advanced internal combustion engines continue to achieve higher thermal efficiency through technologies such as turbocharging and variable valve control. Hybrid systems combine the strengths of both, offering optimized energy management for diverse driving conditions. At the same time, the powertrain significantly affects the vehicle's exterior morphology, structural architecture, and aerodynamic characteristics. The adoption of dedicated electric platforms has enabled more flexible cabin layouts, improved space utilization, and bold aerodynamic designs that reduce drag and enhance energy efficiency. Lightweight materials and integrated battery solutions further contribute to overall vehicle mass reduction and safety enhancement.

Looking ahead, powertrain development will increasingly focus on deep integration with intelligent technologies and new material applications, as well as low-carbon sustainability throughout the entire lifecycle. Connectivity and AI-driven energy management will allow real-time

optimization of power distribution based on road conditions, traffic, and user behavior. Furthermore, the use of sustainable materials—such as recycled aluminum, low-carbon steel, and bio-based composites—will help reduce the environmental footprint of manufacturing. The growth of circular economy models, including remanufacturing and component recycling, will also play an essential role in minimizing waste and resource consumption.

In this context, automotive manufacturers must continuously innovate and optimize powertrain designs to meet diverse market demands for high-performance, low-emission vehicles. This includes not only advancing hardware such as batteries, fuel cells, and power electronics but also developing more sophisticated control software and digital services. Additionally, establishing accurate carbon footprint accounting systems, promoting green manufacturing practices, and advancing battery recycling and reuse are crucial for achieving sustainable industry development. Close collaboration across the value chain—from raw material suppliers and energy providers to policymakers and consumers—will be essential in building a resilient and eco-conscious mobility ecosystem.

In summary, the future evolution of powertrain systems will constitute a process of multidimensional optimization and balance. It will require synergistic advances in technology, regulation, infrastructure, and market adaptation. Only through interdisciplinary collaboration and a firm commitment to sustainability can the automotive industry truly fulfill its role in enabling clean, intelligent, and accessible transportation for all.

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