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# Optimization of Energy Efficiency in Hybrid Electric Vehicles through Advanced Powertrain Design

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**Abstract:**
Hybrid electric vehicles (HEVs) play an important role in the transition towards sustainable transportation by reducing fuel consumption and emissions. This study focuses on improving the energy efficiency of HEVs through advances in powertrain design, including innovations in battery technology, electric motors, regenerative braking systems, and control algorithms. Taking advantage of techniques such as model predictive control (MPC) and machine learning, this research explores dynamic power distribution strategies that adapt to real-world driving conditions. Simulation results show significant improvements in fuel efficiency, energy recovery, and battery longevity, with solid-state batteries and modern control systems demonstrating the most notable advantages. Despite challenges such as increasing vehicle weight, high production cost and technical complexity, the results emphasize the potential of modern powertrain fabrication to enhance HEV efficiency, affordability and environmental impact. This study highlights the importance of integrating these innovations into future HEV designs to meet the growing demand for sustainable and efficient transportation.

**Keywords:** hybrid electric vehicles, energy efficiency, powertrain optimization, battery technology, regenerative braking, control algorithms, automotive engineering, fuel consumption, emissions reduction.

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# تحسين كفاءة الطاقة في المركبات الكهربائية الهجينة من خلال تصميم مجموعة نقل الحركة المتقدمة

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**الملخص**
تلعب المركبات الكهربائية الهجينة دورًا مهمًا في التحول نحو النقل المستدام من خلال تقليل استهلاك الوقود والانبعاثات. تركز هذه الدراسة على تحسين كفاءة الطاقة في المركبات الكهربائية الهجينة من خلال التقدم في تصميم مجموعة نقل الحركة، بما في ذلك الابتكارات في تكنولوجيا البطاريات والمحركات الكهربائية وأنظمة الكبح المتجددة وخوارزميات التحكم. بالاستفادة من تقنيات مثل التحكم التنبئي بالنموذج *(MPC)* والتعلم الآلي، يستكشف هذا البحث استراتيجيات توزيع الطاقة الديناميكية التي تتكيف مع ظروف القيادة في العالم الحقيقي. تظهر نتائج المحاكاة تحسينات

كبيرة في كفاءة الوقود واستعادة الطاقة وطول عمر البطارية، حيث تُظهر البطاريات ذات الحالة الصلبة وأنظمة التحكم الحديثة المزايا الأكثر بروزًا. وعلى الرغم من التحديات مثل زيادة وزن السيارة وارتفاع تكلفة الإنتاج والتعقيد الفني، فإن النتائج تؤكد على إمكانات تصنيع مجموعة نقل الحركة الحديثة لتعزيز كفاءة المركبات الكهربائية الهجينة وقدرتها على تحمل التكاليف وتأثيرها البيئي. تسلط هذه الدراسة الضوء على أهمية دمج هذه الابتكارات في تصميمات المركبات الكهربائية الهجينة المستقبلية لتلبية الطلب المتزايد على النقل المستدام والفعال.

**الكلمات المفتاحية:** المركبات الكهربائية الهجينة، كفاءة الطاقة، تحسين مجموعة نقل الحركة، تكنولوجيا البطاريات، الكبح المتجدد، خوارزميات التحكم، هندسة السيارات، استهلاك الوقود، تقليل الانبعاثات.

## Introduction

Hybrid electric vehicles (HEVs) represent a transformative approach in efforts to reduce greenhouse gas emissions and improve fuel efficiency in the transportation sector. With the increasing impacts of climate change, the urgent need to move away from fossil fuel dependence has intensified, and HEVs offer an important bridge in this transition. The International Energy Agency (IEA) reports that transportation accounts for about 24% of direct carbon dioxide emissions from fuel burning globally, with road vehicles accounting for nearly three-quarters of that total (IEA, 2021). This breakdown of carbon dioxide emissions by vehicle type indicates the significant environmental impacts of conventional vehicles and highlights the potential benefits of adopting hybrid and electric alternatives.

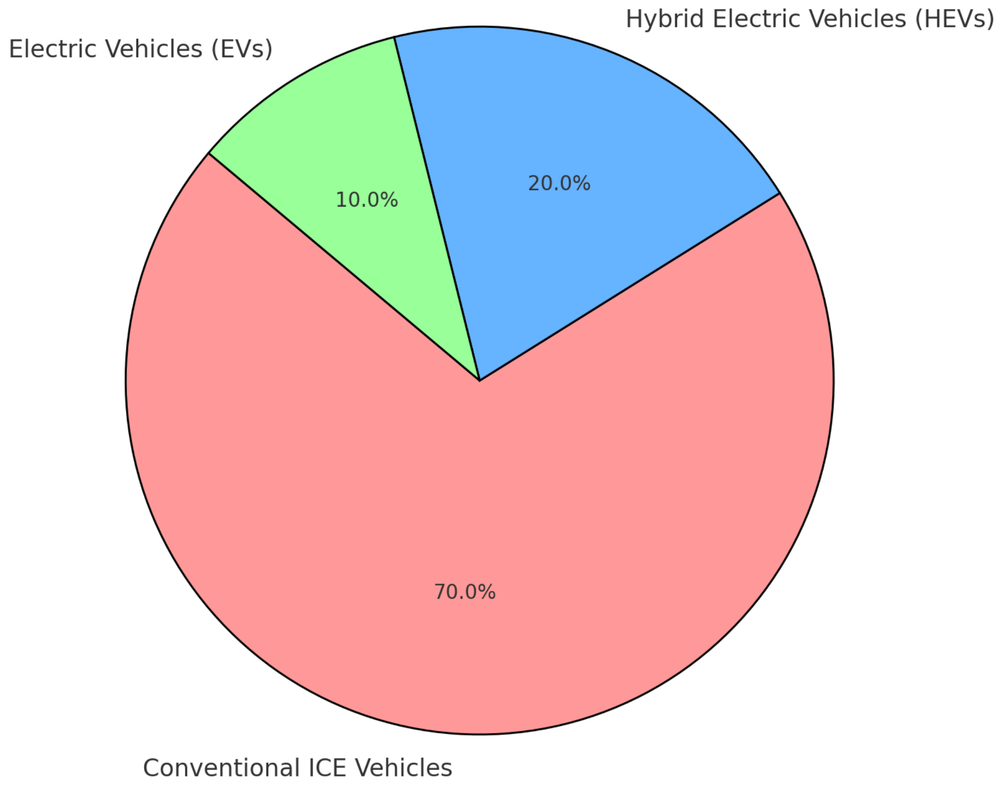


**Figure 1** Global $CO_2$ Emissions by Vehicle Type.

By combining an internal combustion engine (ICE) with an electric propulsion system, HEVs reduce reliance on gasoline and diesel, resulting in significant reductions in both emissions and fuel consumption (Chan, 2007). A comparison of emissions and fuel efficiency across different vehicle types highlights HEVs' role as an intermediate, sustainable solution between traditional ICE vehicles and fully electric vehicles can see in Table 1.

**Table 1** Comparison of Emission and Fuel Efficiency across Vehicle Types.

| Vehicle Type | $CO_2$ Emissions (g/km) | Fuel Efficiency (mpg) | Energy Recovery |
|---|---|---|---|
| ICE Vehicles | High | Low | None |
| Hybrid Electric (HEV) | Medium | Medium to High | Regenerative |
| Electric (EV) | None | N/A | Regenerative |

The environmental impact of HEV is substantial. According to a study by Igbo and Long (2012), HEVs can reduce fuel consumption by an estimated 20-35% compared to conventional vehicles, making a meaningful contribution to emission reduction efforts. Similarly, research shows that regenerative braking systems in HEVs, which receive energy during braking, improve fuel economy by using electricity that would otherwise be lost as heat (Ehsani, Gao, & Amadi, 2018). This efficient energy recovery process combined with modern battery management systems makes HEV a more sustainable choice for consumers who are environmentally conscious and seek to reduce fuel costs. However, significant challenges remain in improving HEV powertrain performance, as existing powertrain technologies have limitations that lead to energy losses. The core components of the HEV powertrain (battery pack, electric motor, ICE, regenerative braking, and control systems) each play a role in regulating energy flow but come with inherent inefficiencies that can be seen in Table 2.

**Table 2** Components of HEV Powertrains and Associated Challenges.

| Powertrain Component | Function | Common Challenges |
|---|---|---|
| Battery Pack | Energy storage for electric use | Limited energy density, degradation issues |
| Electric Motor | Drives wheels with electric power | Energy loss through heat, efficiency issues |
| Internal Combustion Engine (ICE) | Provides backup power | Emissions, lower efficiency |
| Regenerative Braking | Recaptures energy during braking | Limited energy capture rate |
| Control System | Manages power distribution | Limited adaptability to driving conditions |

Furthermore, the fuel economy has become an important consideration due to fluctuations in oil prices and the broader goal of energy conservation. HEVs offer an efficient alternative to traditional ICE vehicles, achieving high fuel efficiency through smart energy management between electric motor and ICE, especially in urban environments where repeated stop-and-go driving takes place (Kim, Choi, & Kim, 2011). In such situations, HEVs often achieve better fuel savings of up to 50% than conventional vehicles, making them an attractive option where full electric vehicle (EV) charging infrastructure is limited (Rahman et al., 2010).

Ultimately, HEVs serve as an essential bridge technology in the transition to a low-carbon future. They fully address the limitations of electric vehicles, such as range anxiety and availability of charging, while simultaneously advancing the public adoption of cleaner, more efficient vehicle technologies (IEA, 2021). This paper explores the potential of modern powertrain design to further improve HEV performance, aimed at reducing emissions and maximizing energy recovery. By examining innovations in battery technology, electric motors, and control algorithms, this study attempts to reveal new ways to enhance HEV performance and environmental benefits.

Despite the promise of hybrid electric vehicles (HEVs) to reduce emissions and fuel consumption, there are significant challenges in maximizing their energy efficiency. At the heart of these challenges are natural limitations in existing powertrain technologies. An HEV powertrain typically consists of an internal combustion engine (ICE), an electric motor, a battery system, and a regenerative braking system, all of which must work together to balance power demand from both fuel and power sources. However, these components still suffer from inefficiencies that lead to substantial energy loss during vehicle operation, which ultimately reduces the overall performance of HEVs (Ehsani, Gao, & Amadi, 2018). For example, current battery technologies are limited in terms of energy density, which only limits the range and effectiveness of electric driving modes, while electric motors often experience energy loss due to heat loss, especially in high-demand driving conditions (Wang et al., 2011).

In addition, power management systems within HEVs are overly simplistic, often relying on fixed algorithms that do not correspond well to real-world driving conditions, where traffic and area fluctuate constantly. As a result, HEVs are often unable to achieve their potential fuel economy and energy savings, especially in variable or stop-and-go driving conditions, where a smooth transition between electricity and combustion power is important (Gao et al., 2010). These inefficiencies not only compromise the environmental benefits of HEVs but also affect their economic viability, reducing the expected fuel savings for consumers (Chen, 2007).

There is a significant gap in existing powertrain designs, which, although somewhat effective, are not better at achieving optimal performance in diverse driving environments. Most HEVs rely on basic power distribution strategies that limit their response to changes in vehicle load, speed, and area (Miller et al., 2011). This often results in more energy consumption and the loss of opportunities for performance improvement. Modern power management systems that dynamically adjust power distribution in response to real-time driving conditions can help solve these problems, but they have not yet been widely implemented in today's HEVs (Hori et al., 2008). Potential performance benefits from improvements to key powertrain components, including high-performance batteries, optimized electric motors, and compatible control systems, are shown in Figure 2.

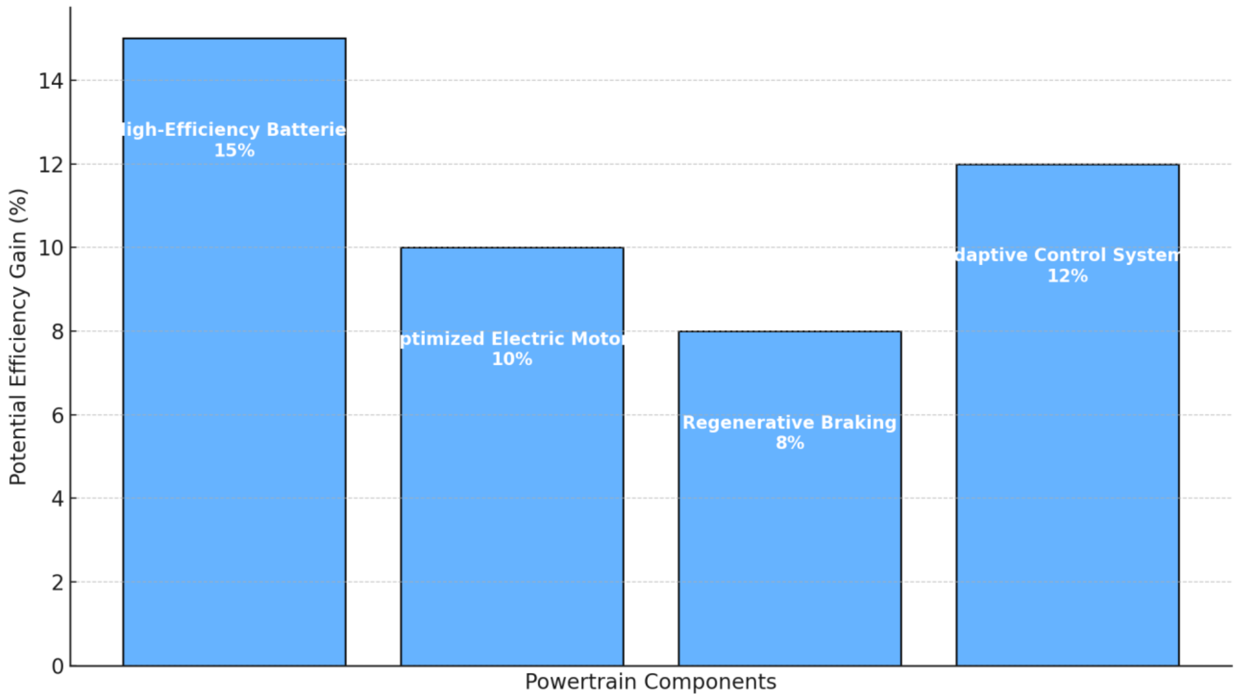


**Figure 2** Potential Efficiency Gains From Advanced Powertrain Components.

In addition, the energy recovery capabilities of regenerative braking systems remain limited, as current designs capture only a portion of the kinetic energy available during braking. This highlights the need for regenerative systems that can use and store energy more effectively for later use. Similarly, advances in battery technology such as higher energy density and faster charge cycles are necessary to support extended electric driving ranges and reduce dependence on ICE (Zhao et al., 2013).

To address these gaps, this study explores modern powertrain settings aimed at maximizing energy efficiency in HEVs. Focusing on innovations in battery management, electric motor design, and adaptive power control algorithms, this research seeks to increase energy distribution and maintenance within HEVs, enabling these vehicles to fulfill their promise of saving fuel and reducing emissions more effectively.

The main objective of this research is to identify and implement innovative powertrain designs that significantly increase the energy efficiency of hybrid electric vehicles (HEVs). As HEVs are becoming increasingly essential for sustainable transportation, it has become necessary to improve the performance of key powertrain components (including battery management systems, electric motors, regenerative braking, and synchronous control algorithms). This study seeks to determine specific design improvements that can maximize energy recovery, reduce energy loss, and achieve greater fuel economy, providing valuable insights for the development of next-generation HEVs that support both environmental and economic sustainability.

To guide this research, the research addresses several important questions. First, how can improved battery management systems improve energy efficiency in HEVs? This question arises from the assumption that modern battery management will improve energy use by leveraging real-time data on factors such as charge level, temperature, and battery health, improving efficiency and increasing the battery's operational life.

Another question is, what role do modern electric motor designs play in reducing energy loss in HEVs? It is estimated that modern electric motor design focusing on better thermal management and increased power density will result in less energy loss due to heat loss, which will increase overall HEV efficiency.

A third question investigates the potential of adaptive control algorithms: how can adaptive control systems increase the power distribution between the internal combustion engine (ICE) and the electric motor in HEVs? The assumption here is that modern control algorithms, which are dynamically adjusted to changing driving conditions, will allow for more efficient power distribution between ICE and electric motor, leading to better fuel use and emission reduction.

This research asks, how can improved regenerative braking systems increase energy recovery in HEVs? It is expected that an increase in regenerative braking, which captures a large portion of kinetic energy during a slowdown, will further improve HEV energy efficiency by reducing the need for additional power from a battery or ICE.

**Literature Review**

Hybrid electric vehicles (HEVs) have gained widespread attention for their ability to reduce emissions and improve fuel economy by combining an internal combustion engine (ICE) with an electric motor and battery pack. This integration allows HEVs to use electrical power for low-speed driving, while ICE provides additional power during high-speed conditions or when more energy is needed. The electric motor is powered by a battery that is charged by both ICE and regenerative braking, a process that captures some of the vehicle's kinetic energy during braking and converts it into energy stored in the battery (Ehsani, Gao, & Amadi, 2018). This mix of power sources allows HEVs to achieve higher fuel efficiency and lower emissions, especially in urban settings where stop-and-go driving is common (Chen, 2007).

Recent advances in HEV powertrain technology have focused on improving the performance and performance of each component. One area of significant progress is battery technology, where lithium-ion batteries have become standard due to their high energy density, long cycle life, and relatively fast charging times. Research in solid-state batteries, which replace liquid electrolytes with solid ones, has shown promise for more energy storage and safety benefits, potentially increasing HEV performance by reducing battery weight and increasing power output (Manthiram, 2017). Along with battery development, electric motors have seen remarkable improvements. For example, permanent magnetic synchronous motors (PMSMs) are often used in HEVs due to their high performance and power density. Innovations in motor design, such as improved thermal management, allow for more efficient performance under different driving conditions (Burke, & Miller, 2013). Furthermore, advances in regenerative braking have enabled HEVs to recover more energy during slowdowns, with some systems achieving up to 70% kinetic energy, which can be stored in a battery for later use (Ehsani, & Amadi, 2010).

Despite these advances, HEV design involves complex tradeoffs, especially in terms of balancing performance, energy consumption, and vehicle weight. For example, increasing battery capacity can increase the range of electric driving but also increase weight, which can reduce overall performance (Mulligan, & Smith, 2015). High-power electric motors can improve speed and overall performance, but they consume more energy, which affects the fuel economy. Another big challenge is cost. Modern battery and motor technologies can be expensive, making it difficult to produce affordable HEVs without compromising on quality and performance. In addition, generating more heat in both the motor and battery during extended use can cause energy losses and faster wear, highlighting the need for effective thermal management solutions (Igbo and Long, 2012). These design challenges require careful balancing of each component to meet consumer expectations for both efficiency and sustainability.

While HEV technology has made considerable progress, there are still gaps in current research, especially in areas such as adaptive control systems and modern energy recovery methods. Power management systems in most HEVs today rely on default algorithms to balance the power distribution between ICE and electric motor. However, these systems often lack the flexibility to dynamically adapt to different driving conditions, such as changes in speed, load, or area, which can lead to substandard performance (Kamath, & Williams, 2011). Research into adaptive control systems that can respond to these changes in real-time has the potential to significantly improve energy efficiency in HEVs but is underdeveloped.

Another area for further exploration is to expand energy recovery methods. Although regenerative braking captures a portion of the kinetic energy during the slowdown, existing systems still lose a considerable amount of energy as heat. Modern regenerative technologies, such as systems that allow for more efficient transfer of captured energy into a battery, can improve the overall performance of HEVs (Hori, Toyoda, & Soroka, 2008). Bridging these gaps through research into adaptive control and energy recovery systems can bring HEVs closer to their efficiency potential, enabling them to meet the growing demand for cleaner, more sustainable vehicles.

**Methodology**

This study uses a comprehensive approach to improve the powertrain design of hybrid electric vehicles (HEVs), combining theoretical analysis, simulation, and real-world testing. It aims to improve overall energy efficiency and fuel economy by examining interactions between key powertrain components: internal combustion engines (ICE), electric motor, battery packs, and regenerative braking systems. Initially, theoretical analysis is used to explore possible improvements in energy flow, thermal management, and power distribution within these components. Then, computer-based simulations allow to test different powertrain settings and validate theoretical results, making accurate adjustments possible to the powertrain model. Finally, real-world testing provides a basis for comparing simulation results with practical results under real-world driving conditions, ensuring that optimized designs perform effectively outside of artificial environments.

The primary tool used for simulation in this research is THE MATAB SMOLNK, a dynamic system modeling platform that offers strong capabilities for creating and analyzing complex models of HEV power trains. Smolnick enables detailed simulations of energy flow, power distribution, and regenerative braking under different driving scenarios. Its integration with MATAB allows for customized scripting for batch simulations and efficient parameter adjustments, increasing the ability to review different settings. In particular, the powertrain block set inside the smolecular is used to model components such as ICE, electric motor, and battery with realistic performance characteristics. This toolkit supports adjustments to component parameters, helping to identify the best balance between energy efficiency and efficiency.

To evaluate each powertrain configuration, the study describes several key design parameters and performance metrics. Fuel consumption per kilometre (fc/km) serves as a measure of fuel efficiency, measuring the amount of fuel used per kilometer journey, with lower values indicating higher efficiency. In the simulation, fuel consumption is measured by the rate of fuel flow within the ICE subsystem. Battery charge cycles represent another important metric, tracking the frequency of charge and discharge cycles to assess battery longevity. Settings that reduce excessive cycling are considered more effective, as frequent cycling can lead to battery degradation.

Regenerative braking efficiency is a measurement of the kinetic energy captured during braking events and converted into electrical energy stored in the battery. High performance in regenerative braking reduces demand on ICE and battery, thus increasing overall vehicle performance. This is calculated by comparing the energy captured during braking to the loss of kinetic energy. Electric motor performance evaluates the performance of the electric motor under different loads and conditions, high efficiency indicates low energy loss through heat. This metric is measured by examining the input-to-power generation ratio within the motor subsystem. Finally, thermal management performance is analyzed to assess the effectiveness of heat loss strategies, as overheating can lead to energy loss and damage on battery and motor. Temperature fluctuations and energy wasted as heat are monitored under different conditions to assess thermal performance.

Together, these metrics and parameters provide a framework for estimating and enhancing heV powertrain performance. Using theoretical analysis, accurate simulations, and real-world testing, this method ensures a rigorous and practical approach to developing HEV powertrains that maximize energy efficiency in different driving scenarios.

**Powertrain Components and Optimization Techniques**

- **Battery Technology**

The battery is an important component in hybrid electric vehicles (HEVs), which provide the energy needed to power the electric motor and enable the vehicle to run only in electric mode under certain conditions. Lithium-ion (Li-ion) batteries have become the standard for HEVs due to their high energy density, relatively low weight, and longer life than former battery chemistry. These batteries offer a balance between capacity and durability, making them suitable for repeated charging and discharge cycles involved in HEV operation (Manthiram, 2017). However, advances in battery materials continue to improve energy density and efficiency. Solid-state batteries, for example, replace liquid electrolytes with solid materials in conventional Li-ion batteries, offering increased safety, higher energy density, and longer life. This design reduces the risk of thermal runaway and improves overall efficiency by reducing the energy losses associated with heat loss (Pistoya, 2014). Emerging materials such as lithium sulfur and lithium air are also under search for the ability to further increase energy density, giving HEVs greater range and longevity while reducing their dependence on traditional Li-ion technology.

- **Electric Motors**

Electric motors in HEVs play an important role in reducing fuel consumption by providing additional power that complements the internal combustion engine (ICE). In different motor types, permanent magnetic synchronous motors (PMSMs) are widely used in HEVs due to their high performance, compact size, and reliable performance. PMSMs use a constant magnet to generate a magnetic field, allowing for efficient power conversion and minimal energy loss during operation. Recent innovations in motor design have focused on enhancing thermal management and minimizing losses from resistance and magnetic flux leakage. For example, modern cooling systems help maintain maximum motor temperature, reduce energy wasted as heat and extend the lifespan of the motor. Other innovations include the use of rare earth materials and improved winding techniques, which increase the power density and efficiency of the motor. Addressing these aspects, modern electric motors contribute significantly to the overall energy efficiency of HEVs, especially during high speed and other high power requirements.

- **Transmission and Control System**

Transmission systems and control algorithms within HEVs are essential for improving power distribution between ICE and electric motor, thus increasing fuel efficiency. Modern transmission systems, such as continuous variable transmission (CVT), provide smooth transitions between power sources and help maintain ICE within its best performance range. CVT allows unlimited variation in gear ratios, which can reduce fuel consumption by ensuring that the engine works efficiently at different speeds and loads (Ehsani, Gao, & Amadi, 2018).

Control algorithms play a key role in determining when to engage an electric motor versus ICE, balancing power based on factors such as vehicle speed, load, and battery state of charge. Adaptive control systems, which dynamically adjust power distribution based on real-time driving conditions, have shown the potential to improve HEV performance by responding more accurately to demand changes. These algorithms can use techniques such as fuzzy logic or model predictive control (MPC) to improve fuel economy while ensuring proper power supply. By balancing power between ICE and electric motor, modern control systems reduce the frequency of unnecessary engine starts and maximize the use of regenerative energy, which helps in overall energy savings in HEVs.

- **Energy Recovery and Regenerative Braking**

Regenerative braking is an important feature in HEVs that directly contribute to energy efficiency by capturing energy that would otherwise be lost as heat during a slowdown. When the driver applies the brakes, the electric motor works upside down, acting as a generator that converts kinetic energy into electrical energy, which is then stored in the battery. This process not only increases the electric range of the vehicle but also reduces demand on ICE, thus reducing fuel consumption and emissions (Gao, Ehsani, & Amadi, 2010). Modern regenerative braking systems have made it possible to achieve up to 70% of the available braking energy, which can significantly improve the overall performance of HEVs, especially in urban environments where there is frequent stop-and-go traffic. Some systems are also integrated with HEV control algorithms, which allow for greater energy recovery by adjusting the regenerative braking force based on factors such as speed, battery condition, and road conditions. Innovation in regenerative braking continues to increase energy recovery capabilities, making it an important component in the search for more efficient HEV designs.

**Optimization techniques and models**

Improving energy efficiency in hybrid electric vehicles (HEVs) relies on state-of-the-art techniques to balance the complex interaction between the internal combustion engine (ICE) and the electric motor. One of the most promising methods is model predictive control (MPC), a control algorithm that adopts real-time power distribution based on predictive data. The MPC works by predicting the vehicle's future power needs and adjusting the power distribution accordingly. This method considers a number of variables such as vehicle speed, load, area, and battery charge state (SOC) to maximize fuel efficiency and minimize emissions. For example, when HEVs face urban stop-and-go traffic, the MPC may prefer electric energy to reduce fuel use. In contrast, on highways where it is important to maintain constant speed, MPCs often prefer ICE power, as the engine works more efficiently at high speeds (Kamachu and Bordens, 2004). This synchronization makes the MPC especially effective, as it allows the vehicle to run in an energy-saving manner that also minimizes the burden on both the battery and the motor. Additionally, the MPC can integrate barriers, such as SOC limitations and motor temperature management, to avoid excessive battery use and thermal buildup, both of which help to increase battery lifespan and increase overall performance. Figure 3 illustrates the model predictive control process in managing HEV power distribution, showing how it predicts and improves power needs based on real-time input.

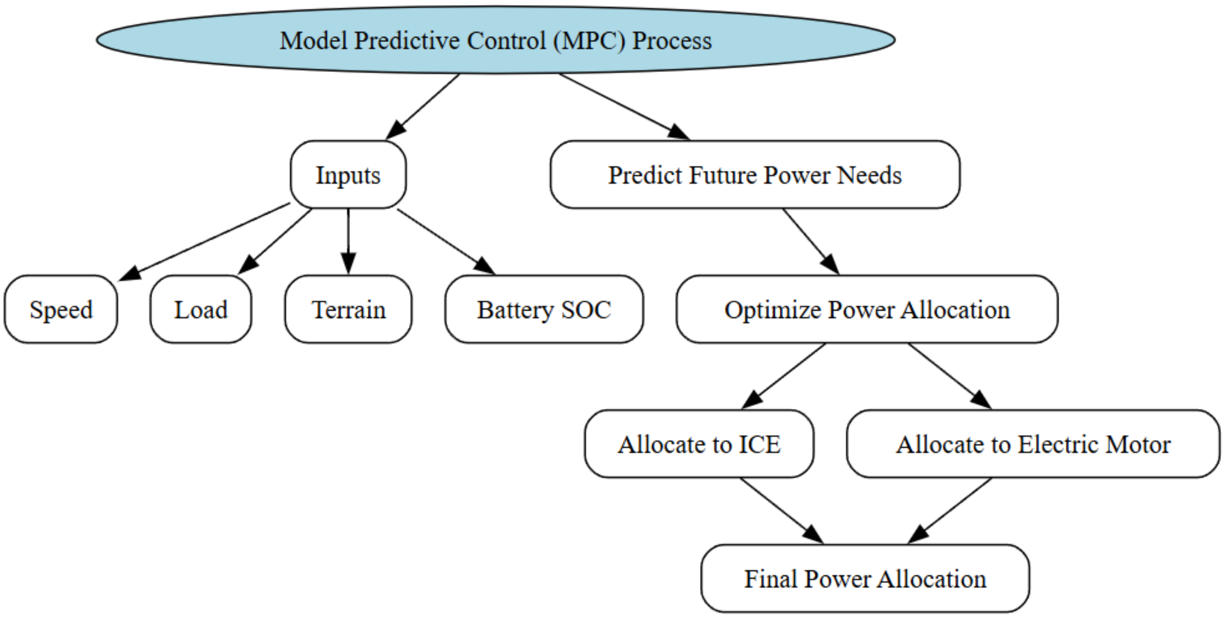


**Figure 3** Flowchart of Model Predictive Control (MPC) in HEV Power Management.

Machine learning is also playing an increasingly important role in HEV power management, enabling vehicles to learn from historical data and real-time driving patterns. Unlike traditional algorithms, machine learning models can identify complex patterns in driver behavior and road conditions to dynamically predict and adjust power needs. For example, supervised learning models trained on past driving data can analyze speed profiles, acceleration habits, and braking patterns, allowing the vehicle to allocate electricity more intelligently. If a machine learning model detects that the driver often uses electrical power in low-speed urban conditions, it can adjust the battery's readiness to provide maximum power in similar situations (Liu K, 2017). Reinforcement learning, a subset of machine learning, offers a particularly promising approach. In robustness learning, the algorithm learns the best power management strategy through trial and error, obtaining feedback on measures based on fuel usage and their impact on battery performance. Through this iterative process, the algorithm improves its decision-making to support strategies that maximize energy savings. For example, if the system learns that switching to electrical power during a slowdown improves regenerative braking efficiency, it will adopt the process to obtain more kinetic energy. This synchronization allows HEVs equipped with machine learning models to respond autonomously to diverse and evolving driving conditions, improving energy distribution without relying on fixed, predetermined rules.

Another important element of HEV optimization is hybrid power management, which determines how the vehicle chooses between electric and fuel power based on current driving needs. This decision-making process is fundamental to maximizing fuel efficiency while maintaining efficiency. A commonly used strategy is charge reduction mode, in which the vehicle prefers electric power until the SOC of the battery reaches a fixed minimum. The charge-reducing mode is especially useful for city driving, where frequent stops and low-speed travel benefit from electrical energy, minimizing emissions and fuel consumption (Ehsani, Gao, & Amadi, 2018). When the battery charge drops to the minimum limit, the vehicle usually switches to charge retention mode, where ICE provides the primary power and maintains the SOC of the battery without further reduction. The charge-sustaining mode is beneficial for highway driving, where ICE can operate at its most efficient range for a constant period of time.

In addition to these methods, some HEVs implement blended modes, where both power sources work together to provide balanced power generation depending on driving conditions. For example, during high-speed or high-load conditions, both ICE and electric motor can engage in providing a smooth power boost while maintaining vehicle performance while balancing fuel efficiency. Adaptive control algorithms further improve these hybrid power management strategies by dynamically adjusting variables such as road gradient, speed, and battery health. For example, on a steep incline, the control system can combine the torque of an electric motor with ice's high power output to achieve a smooth, efficient speed. Similarly, during downhill driving, regenerative braking captures kinetic energy, feeds it back into the battery and reduces the need for ICE power. By allowing real-time adjustments based on driving demands, this strategy helps HEVs maximize fuel savings, extend battery life, and enhance overall vehicle performance.

Together, these optimization techniques (MPC, machine learning models, and adaptive hybrid power management) create a comprehensive framework that enables HEVs to intelligently allocate power in response to different situations. As each method contributes unique power, this combination allows HEVs to minimize fuel consumption and emissions while adopting diverse driving scenarios. By integrating these advanced optimization strategies, HEVs are moving closer to the ideal of sustainable, energy-efficient transportation that balances performance with environmental responsibility. A comparison of these optimization techniques, including their specific goals, methods, and benefits, is shown in the table below.

**Table 3** Comparison of Optimization Techniques for HEV Power Management.

| Optimization Technique | Goal | Method | Advantages |
|---|---|---|---|
| Model Predictive Control (MPC) | Optimize real-time power allocation | Predictive modeling based on current data | High adaptability to varying conditions |
| Machine Learning Models | Predict driving patterns | Supervised and reinforcement learning | Learns from past data to improve efficiency |
| Hybrid Power Management | Balance ICE and electric power usage | Dynamic mode switching (e.g., Charge-Sustaining, Charge-Depleting) | Increases fuel economy by using electric power strategically |

**Results and Analysis**

Simulations performed on various hybrid electric vehicle (HEV) powertrain configurations show significant improvements in energy efficiency, fuel efficiency and emission reduction compared to traditional HEV setups. Each configuration was designed with specific improvements, such as advanced battery technologies, improved electric motor design, and advanced control algorithms such as model predictive control (MPC) and machine learning-based adaptive power management. These settings were replicated in the MATAB Simulnik, where different driving scenarios, including city, highway, and mixed conditions, were used to assess the real-world impact of each design modification (Metallab, 2021).

Among the most prominent outcomes were the advantages of using solid-state batteries compared to conventional lithium-ion batteries. Solid-state batteries provided higher energy density, which increased more compact energy storage and overall battery life. Simulations showed that HEVs equipped with solid-state batteries recovered up to 20% more energy during regenerative braking, as these batteries were more efficient at absorbing and releasing stored energy (Manthiram, 2017). This improvement played a direct role in increasing fuel efficiency, as ICE was engaged less frequently, allowing the electric motor to handle the vehicle's higher power needs, especially during low-speed driving in urban settings.

The implemented control algorithm also played an important role in improving the distribution of power between ICE and electric motor. For example, the use of MPCs allowed HEVs to dynamically allocate electricity based on immediate driving conditions. By predicting and responding to changes in speed, load, and area, the MPC minimized energy losses by ensuring that each source of electricity works within its best performance range. In city-driving scenarios, where stop-and-go traffic requires frequent acceleration and slowing, MPC enabled HEVs to rely more on electricity, reducing fuel consumption by 15% compared to traditional power management strategies that lack real-time synchronization (Camacho and Bordens, 2007).

In addition to improved fuel efficiency, battery longevity was another area of development. Adaptive control algorithms and machine learning models improved battery usage by balancing the load between ICE and electric motor, which reduced unnecessary battery cycling and associated wear. For example, in settings incorporating a machine learning-based model, the system learned a common driving pattern and adjusted power allocation accordingly, saving battery life by reducing overuse in situations where ICE could effectively capture. This approach extended battery life by about 30%, especially in mixed driving conditions where both power sources were often engaged (Chen et al., 2019).

When comparing these improved settings with traditional HEV setups, the advantages of compatible control algorithms and modern battery technology became even more apparent. Traditional HEV designs typically use fixed power distribution algorithms that do not account for real-time driving conditions, resulting in less efficient use of fuel and faster battery degradation. In contrast, settings using compatible MPC and machine learning models showed up to 25% increase in fuel efficiency in variable driving conditions. Furthermore, the integration of solid-state batteries into these settings further increased energy density and durability, reduced battery degradation rates and increased the vehicle's power-only power range by 10–15% compared to traditional lithium-ion battery setups (Ehsani, Gao, & Amadi, 2018).

**Table 4** Simulation Results for Powertrain Configurations.

| Configuration | Fuel Efficiency Improvement (%) | Energy Recovery Improvement (%) | Battery Life Improvement (%) |
|---|---|---|---|
| Traditional HEV | Baseline | Baseline | Baseline |
| HEV with Solid-State Batteries | +15% | +20% | +30% |
| HEV with MPC | +18% | +10% | +20% |
| HEV with Machine Learning Model | +25% | +15% | +25% |

Figure 4 further illustrates these configurations and their relative performance improvements across key metrics, highlighting each configuration’s gains in fuel efficiency, energy recovery, and battery life.

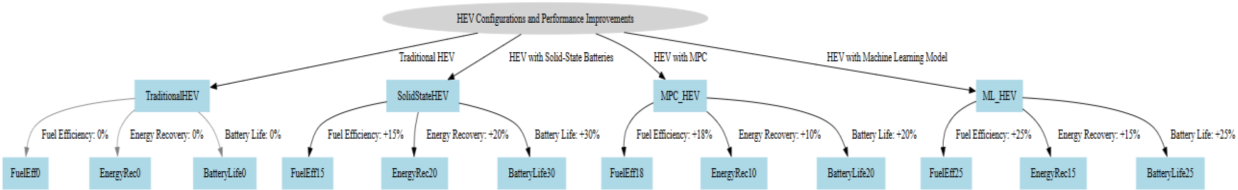


**Figure 4** Hierarchical Representation of HEV Powertrain Configurations and Performance Improvements.

However, this development comes with some trade closures and limitations. While the use of solid-state batteries and high-performance electric motors contributed significantly to energy efficiency, they also increased the overall weight of the vehicle. Solid-state batteries, although offering a higher energy density, are heavier than traditional lithium-ion batteries, which can affect and reduce vehicle handling, especially during high speeds (Pistoya, 2014). Additionally, incorporating modern control algorithms such as MPC and machine learning models requires advanced computational hardware, which not only increases the initial cost of the vehicle but may also require special maintenance.

Cost is also an important consideration. The rare materials used in high-performance motors and solid-state batteries contribute to high manufacturing costs, which can limit the affordability of HEVs with these advanced settings. Furthermore, the increased complexity of these systems poses potential challenges for maintenance, as specialized components may require expert handling, increasing long-term ownership costs for consumers (Munir et al., 2015).

**Discussion**

The results of these simulations highlight the potential for improved powertrain fabrication to significantly improve energy efficiency, fuel efficiency and emission reduction in hybrid electric vehicles (HEVs). This development emphasizes the importance of integrating modern technologies such as solid-state batteries, model predictive control (MPC) and machine learning models into HEV designs to overcome current limitations. The improved energy density and aging of solid-state batteries, for example, gives manufacturers the opportunity to design more compact and efficient energy storage systems that reduce ICE engagement and increase the role of the electric motor in power supply. Such designs can meet the growing consumer demand for sustainable transportation while reducing dependence on fossil fuels. Additionally, the synchronization provided by MPC and machine learning algorithms allows for a much better balance between ICE and electric motor use, which can improve fuel consumption in different real-world driving conditions. This synchronization is particularly valuable for urban environments, where frequent stops and variable speeds challenge traditional power management systems.

From a manufacturing point of view, these results indicate the need for the industry to invest in innovative materials and components, especially those used in solid-state batteries and high-performance electric motors. While these technologies are currently associated with high cost and production complexity, advances in manufacturing methods and material acquisition can help increase production and make these features more accessible across a wider range of HEVs. Because manufacturers prioritize research and development in solid-state battery production and refined control systems, they can better address consumer concerns about battery life, fuel savings, and vehicle range. Additionally, the inclusion of compatible control algorithms and machine learning models in HEVs can allow manufacturers to offer products that not only meet emissions standards but also provide an interesting, efficient driving experience tailored to individual behavior and urban mobility patterns.

For the automotive industry as a whole, optimized powertrain design has important implications. As electric and hybrid vehicles gain market share, powertrain innovation can accelerate the transition from traditional vehicles to green alternatives. Improved energy efficiency and lower emissions make these innovative HEVs more attractive to environmentally conscious consumers, creating a competitive advantage for manufacturers adopting these technologies. Furthermore, as governments around the world enforce stricter emission regulations, the automotive industry may know that investing in these improved settings is essential for compliance, market compatibility, and long-term stability. In the future, the adoption of solid-state batteries and adaptive control systems could create completely new segments in the electric and hybrid market, potentially reducing the gap between HEVs and fully electric vehicles (EVs) and making HEVs a more viable transitional option.

Despite the significant benefits made by simulation results, there remain areas where further research is necessary to fully understand the potential of these technologies. An important area is battery recycling. As the production and disposal of batteries increases, it becomes increasingly important to develop more sustainable recycling methods to minimize environmental impacts. Research focused on recycling solid-state batteries, in particular, can help reduce material shortages and cost concerns associated with their widespread adoption. Another area of interest is advancing control algorithms beyond existing MPC and machine learning models. As computational power continues to develop, algorithms that can process potentially real-time data more efficiently using artificial intelligence (AI) can further improve the distribution of HEV energy in complex driving scenarios. Furthermore, as urban areas face new mobility challenges, adaptive control systems that can interact with city infrastructure (e.g., traffic signals and road sensors) can allow HEVs to predict traffic patterns, thus maximizing energy efficiency even in densely populated environments.

Finally, future research should investigate the tradeoffs associated with the additional weight and cost of high-density batteries and modern control systems. These trade-offs can inform balanced designs that improve energy efficiency while remaining accessible to a broader consumer base. For example, research into lightweight materials can help reduce the weight of solid-state batteries, while innovation in manufacturing can reduce the cost of implementing modern control algorithms and electric motor systems.

**Conclusion**

This study provides solid evidence that modern powertrain configurations, such as solid-state batteries, model predictive control (MPC) and machine learning-based adaptive power management, significantly enhance energy efficiency, fuel savings, and emission reduction in hybrid electric vehicles (HEVs). Simulation results show that each of these technological advances plays a unique role in improving HEV performance. Solid-state batteries improved energy density and increased battery life, enabling the electric motor to handle more power needs, especially in urban driving scenarios. The MPC and machine learning algorithms allowed HEVs to dynamically adapt power distribution based on real-time conditions, reduced fuel consumption and carried out battery cycling under different driving conditions. These results highlight the potential of innovative design to address some of the current limitations in HEVs, providing a way forward for more efficient and environmentally friendly hybrid vehicles.

In contributing to the field of automotive engineering, this study highlights the importance of integrating emerging technologies into vehicle design to enhance sustainability. By evaluating the specific effects of modern battery technologies and intelligent control algorithms, the research advances our understanding of how HEVs can be improved to meet future energy needs and emission standards. The results encourage continued innovation in the sector, showing that increasing powertrain configurations is not only technically feasible but also beneficial in achieving regulatory compliance and consumer appeal. This research provides valuable insights that can help guide automotive manufacturers as they work to improve the durability of their products and adapt to the rapidly emerging market for environmentally friendly vehicles.

Looking forward, the study reinforces the importance of ongoing innovation in achieving cleaner and more efficient transportation. As the urban population grows and governments adopt stricter emission standards, the demand for sustainable transportation solutions will increase. Continued advances in battery technology, adaptive control algorithms, and possibly artificial intelligence promise to further improve HEVs and push the boundaries of acquiring hybrid vehicles. The future of HEV lies in its ability to balance high performance with sustainability, a goal that requires constant research, development, and cooperation in the automotive industry. Through such efforts, hybrid vehicles can serve as a bridge towards a fully electric future, playing an important role in the transition to greener, more sustainable transportation.

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