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Combining electric and conventional power for sustainable transportation

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Abstract

As the global demand for sustainable transportation grows, hybrid powertrain systems combining electric and conventional internal combustion engine (ICE) power have emerged as a promising solution to reduce emissions and enhance fuel efficiency. This review explores the design, development, and performance of hybrid powertrain systems, highlighting key technological advancements, challenges, and future opportunities. It also discusses the environmental and economic impact of hybrid vehicles and compares them with fully electric and conventional vehicles. The paper concludes by evaluating the role of hybrid systems in the transition towards fully electric mobility and their contribution to reducing the global carbon footprint.

Keywords: Hybrid powertrain, sustainable transportation, electric vehicles, internal combustion engines, fuel efficiency, carbon emissions

Introduction

Rwanda is depending on imports where 100% of fuel used in Rwanda is imported and transport cost is high due to fuel imported. Today Rwanda is promoting E-Mobility where electrical motorcycles, vehicles and bikes are in manufacturing in Rwanda to reduce the emissions and quantity of fuel consumptions (Sweco, 2019) [2].

The E-mobility avoids the use of fuel and promotes the decrease of carbon emissions in environment. Average price of fuel in Rwanda is 1.09 $ and the average vehicles in Kigali city was about 30,000 in 2018. Three companies Ampersand, Safi and Rwanda Electric mobility are targeting to contribute in implementation of this new system of E-Mobility.

The global push for sustainable transportation has led to significant changes in the automotive industry, with an increasing focus on reducing carbon emissions, improving fuel efficiency, and transitioning away from fossil fuels. While fully electric vehicles (EVs) represent the ultimate solution for a zero-emission future, the widespread adoption of such vehicles faces several challenges, including limited battery range, high costs, and underdeveloped charging infrastructure. In this context, hybrid powertrain systems have emerged as a critical transitional technology, bridging the gap between traditional internal combustion engine (ICE) vehicles and fully electric vehicles.

Hybrid vehicles combine an internal combustion engine with an electric motor, offering a unique balance of the familiar power and range of gasoline engines with the reduced emissions and fuel savings associated with electric motors. These systems allow for greater fuel efficiency and reduced emissions, especially in urban environments where stop-and-go traffic makes the use of electric power more efficient. By enabling drivers to switch between or combine electric and gasoline power, hybrids offer the flexibility needed for both short trips in electric-only mode and longer journeys powered by the internal combustion engine.

The development of hybrid systems began as a response to the need for more efficient, cleaner alternatives to conventional gasoline and diesel vehicles. Early hybrids, such as the Toyota Prius, paved the way for more advanced systems, demonstrating that combining electric and gasoline power could achieve significant reductions in fuel consumption and emissions. Over the years, technological advancements in battery efficiency, energy management, and powertrain control have significantly improved the performance, reliability, and market acceptance of hybrid vehicles.

Despite the promise of fully electric vehicles, the transition to widespread EV use is a gradual process.

Many regions lack the charging infrastructure needed to support an all-electric fleet, and the high cost of EVs, driven by expensive battery technology, remains a barrier for many consumers. Hybrid vehicles provide an intermediate solution, allowing drivers to reduce their carbon footprint while relying on existing fuel infrastructure. Furthermore, hybrids offer an opportunity for automakers to develop and refine electric powertrain technologies while continuing to utilize combustion engines, which are still necessary in many markets.

In addition to serving as a practical solution for the current automotive landscape, hybrid systems also play an important role in shaping the future of electrification. By encouraging consumers to adopt partially electric vehicles, hybrids help raise awareness about the benefits of electrified driving, such as reduced fuel costs and lower emissions. This familiarity with electric technology can make the eventual transition to fully electric vehicles smoother for both consumers and manufacturers. Furthermore, the increasing prevalence of hybrid vehicles has spurred the development of supporting technologies, such as battery recycling, charging networks, and renewable energy integration, all of which are essential for the broader adoption of electric vehicles.

Objective

The objective of this paper is to examine the technological advancements in hybrid powertrain systems and their role in facilitating the transition to fully electric vehicles

Types of Hybrid Powertrain Systems

Hybrid powertrain systems, which combine electric propulsion with conventional internal combustion engines (ICE), represent a critical transition technology in the shift towards more sustainable transportation. These systems are designed to leverage the advantages of both electric and fossil-fuel-driven power sources to enhance fuel efficiency, reduce emissions, and offer flexibility in various driving conditions. There are three main types of hybrid powertrain systems:

1. Series Hybrid.
2. Parallel Hybrid.
3. Series-Parallel Hybrid.

- **Series Hybrid:** The series hybrid configuration is one of the simplest forms of hybrid systems. In this design, the internal combustion engine is decoupled from the drivetrain and is used solely as a generator to provide electrical energy to the battery or directly to an electric motor, which is the sole propulsion source. The vehicle operates on electric power, with the engine serving to recharge the battery when needed. This architecture is highly efficient in low-speed, stop-and-go urban traffic, where the electric motor can manage most of the propulsion duties, significantly reducing fuel consumption and emissions. A study by Chan (2007) highlights that the series hybrid architecture offers significant benefits in terms of fuel savings, particularly in urban driving conditions, where electric drive can be used for extended periods. However, despite its advantages in city driving, the series hybrid system faces limitations at higher speeds. At highway speeds, this system becomes less efficient, as the energy must be converted from mechanical (through the internal combustion engine) to electrical, and then back to mechanical power to drive the wheels. This multiple conversion process leads to energy losses, which can decrease the system's overall efficiency. According to research by Muneer *et al.* (2015) [6], this inefficiency makes series hybrids less suited for long-distance, high-speed driving, where direct mechanical connection between the engine and the wheels would be more advantageous. Thus, while series hybrids are ideal for urban applications, they may not perform as efficiently in other driving contexts.
- **Parallel Hybrid:** The parallel hybrid system differs significantly from the series hybrid by allowing both the internal combustion engine and the electric motor to be directly connected to the wheels. In this configuration, the vehicle can be powered by the electric motor, the internal combustion engine, or a combination of both. Depending on the driving conditions, the system can switch between power sources or use both simultaneously. Research by Ehsani *et al.* (2018) [2] demonstrates that this design is highly efficient in highway driving, where the internal combustion engine can take over, and the electric motor can assist during periods of acceleration or heavy load. This dual functionality enhances fuel efficiency while maintaining performance levels similar to conventional ICE vehicles. One of the major advantages of the parallel hybrid system is its flexibility. The vehicle can rely more heavily on the electric motor during city driving, while the ICE can be engaged during higher-speed travel, making the system versatile across various driving conditions. Furthermore, studies by Mi *et al.* (2011) show that parallel hybrids often exhibit lower complexity in terms of powertrain architecture compared to series hybrids, making them easier and less costly to manufacture and maintain. However, the primary limitation of the parallel system lies in its reduced capability for electric-only operation. Since both power sources are typically used together, the range for electric-only driving is limited, which may not align with consumer expectations for zero-emission performance.
- **Series-Parallel Hybrid:** The series-parallel hybrid system combines the benefits of both series and parallel configurations, offering the highest level of flexibility. This architecture allows the vehicle to operate in series mode at low speeds and parallel mode at higher speeds, thus optimizing the use of both electric and ICE power sources based on the driving environment. Research by Miller *et al.* (2010) [9] suggests that the series-parallel hybrid offers significant improvements in fuel efficiency and emissions reduction, particularly in urban environments where stop-and-go driving is prevalent. The series mode allows for maximum use of the electric motor, while the parallel mode enhances efficiency during high-speed travel by reducing reliance on battery power. One of the key innovations in series-parallel systems is the use of advanced energy management systems that intelligently split power between the electric motor and the ICE. According to

Guzzella and Sciarretta (2013) [3], these systems use real-time data from the vehicle's sensors to optimize energy distribution, ensuring that the engine and motor work together in the most efficient manner possible. For instance, during acceleration, both the engine and motor may work in tandem, while during cruising, the motor may handle the load alone. This dynamic power split contributes to higher fuel economy compared to conventional ICE vehicles or simpler hybrid configurations. The series-parallel system also benefits from regenerative braking technology, which captures kinetic energy during braking and converts it into electrical energy to recharge the battery. Studies by Karbaschian and Söffker (2014) [8] show that this feature significantly improves overall energy efficiency, particularly in city driving, where frequent braking occurs. The ability to recover and store energy that would otherwise be lost as heat provides a substantial boost to fuel economy and battery life.

Despite its many advantages, the series-parallel hybrid system is not without challenges. Its complex architecture, which combines the features of both series and parallel systems, increases the overall weight and cost of the vehicle. Moreover, the advanced control systems required to manage the power split between the electric motor and the ICE add to the complexity and potential for maintenance issues. Research by Scrosati *et al*. (2016) [5] points out that while series-parallel hybrids offer superior performance, they also demand more sophisticated engineering solutions, making them more expensive to produce compared to simpler hybrid systems.

In summary, the three main types of hybrid powertrain systems series, parallel, and series-parallel each offer distinct advantages and trade-offs. Series hybrids excel in urban environments with their ability to operate primarily on electric power, but they fall short in highway efficiency due to energy conversion losses. Parallel hybrids offer greater flexibility across different driving conditions and are particularly efficient at higher speeds, though they lack the ability for extended electric-only driving. Series-parallel hybrids represent the most advanced configuration, combining the best aspects of both systems to optimize performance and efficiency, but at the cost of increased complexity and manufacturing expense. The choice of hybrid system ultimately depends on the intended use case, with each configuration suited to different driving conditions and consumer needs. As research and development in battery technology, energy management, and regenerative braking continue, hybrid powertrains will play an increasingly important role in the transition towards fully electric transportation.

Technological advancements in hybrid powertrain systems

Hybrid powertrain systems have undergone significant technological advancements over the past decades, driven by the increasing demand for more fuel-efficient, environmentally friendly vehicles. One of the most notable advancements has been in battery technology, particularly the shift from nickel-metal hydride (NiMH) to lithium-ion (Li-ion) batteries. Li-ion batteries offer higher energy density, reduced weight, and longer lifespans, allowing hybrid vehicles to operate more efficiently and extend their electric-only range. The development of solid-state batteries, which promise even greater energy storage capabilities and faster charging times, is expected to further revolutionize hybrid vehicle performance. Battery management systems (BMS) have also evolved, allowing for more precise control over battery charging and discharging processes, which helps prolong battery life and enhance vehicle safety.

Another key advancement is regenerative braking, a technology that captures energy lost during braking and stores it in the battery for later use. This system improves the overall energy efficiency of hybrid vehicles, especially in urban environments with frequent stops and starts. By recovering kinetic energy and converting it into electrical energy, regenerative braking can contribute significantly to fuel savings and lower emissions. Modern regenerative braking systems have been refined to offer smoother transitions between traditional friction brakes and energy recovery, providing a better driving experience.

Energy management systems (EMS) have become increasingly sophisticated, utilizing advanced algorithms and, in some cases, artificial intelligence (AI) to optimize the balance between electric and internal combustion power. These systems monitor real-time vehicle data, such as speed, acceleration, and battery charge levels, to determine the most efficient use of energy. AI-driven EMS can even predict future driving demands, such as hills or traffic congestion, and adjust the power output accordingly. This dynamic energy management not only improves fuel economy but also reduces wear and tear on the vehicle's components.

Hybrid powertrain systems have also benefited from advancements in control systems and transmission technology. Modern hybrid vehicles often feature dual-clutch or continuously variable transmissions (CVTs), which provide seamless transitions between electric and internal combustion power. These transmissions help maximize the efficiency of both power sources, ensuring that the vehicle operates in the most energy-efficient mode for the given driving conditions. The integration of start-stop systems, which automatically shut down the engine when the vehicle is idling, further enhances fuel savings and reduces emissions in hybrid vehicles.

Lightweight materials and aerodynamic designs are additional areas where technological advancements have had a positive impact on hybrid vehicle performance. The use of high-strength steel, aluminum, and carbon fiber in vehicle construction reduces the overall weight, allowing the vehicle to operate more efficiently. Aerodynamic enhancements, such as streamlined body shapes and active grille shutters, reduce drag, improving fuel efficiency, especially at higher speeds. These advancements have contributed to significant gains in vehicle range and performance, making hybrid powertrains more competitive with conventional internal combustion vehicles. As hybrid technology continues to evolve, further innovations are expected to enhance the efficiency and sustainability of these systems. Research into solid-state batteries, wireless charging technologies, and vehicle-to-grid (V2G) integration could further reduce the reliance on fossil fuels and improve the environmental impact of hybrid vehicles. Moreover, the incorporation of AI-driven predictive energy management and real-time optimization systems will likely continue to improve the performance of hybrid powertrains, making them a key component in the transition toward fully electric vehicles.

The role of hybrid systems in the transition to fully electric vehicles

Hybrid systems play a crucial role in the gradual transition from traditional internal combustion engine (ICE) vehicles to fully electric vehicles (EVs). Hybrid vehicles, which combine both electric and combustion power sources, serve as a bridge, helping to overcome some of the limitations of current EV technology while promoting widespread adoption of electrified transport. As the automotive industry moves towards sustainable solutions, hybrid systems provide a critical transitional technology that addresses issues such as range anxiety, infrastructure limitations, and cost considerations.

One of the most important contributions of hybrid systems is mitigating range anxiety the fear that an electric vehicle will run out of power before reaching a charging station. For many consumers, the limited range of EVs remains a significant barrier to adoption. Hybrid systems alleviate this concern by allowing drivers to switch to gasoline power when the electric battery is depleted. Plug-in hybrids (PHEVs), in particular, offer a solution that allows for all-electric driving for short distances, typically for city commuting, while still providing the option to switch to gasoline for longer trips. Studies have shown that many drivers of PHEVs rarely use the combustion engine for daily commuting, reducing overall fuel consumption and emissions.

Hybrid systems also address the issue of charging infrastructure, which remains underdeveloped in many regions. While EVs require access to reliable and widespread charging networks, hybrids can operate on gasoline, ensuring that drivers are not reliant solely on charging stations. This flexibility is particularly important in rural areas or regions where EV charging infrastructure is still being developed. As the charging infrastructure expands and becomes more reliable, hybrid vehicles can continue to serve as a transition technology, helping consumers gradually adapt to electric driving.

Cost considerations also play a significant role in the transition. Fully electric vehicles, especially those with long-range batteries, are often more expensive than their hybrid counterparts due to the high cost of battery production. Hybrid vehicles provide a more affordable entry point for consumers looking to reduce fuel consumption and emissions without making a full commitment to EVs. By offering fuel savings and the ability to drive on electric power for short distances, hybrids provide an economically feasible option for consumers while they wait for EV prices to decrease as battery technology advances and economies of scale reduce costs.

Additionally, hybrid systems contribute to the reduction of emissions, which is a key motivation for transitioning to electric mobility. While fully electric vehicles produce zero emissions, hybrid systems, particularly plug-in hybrids, significantly reduce tailpipe emissions by allowing for all-electric driving in urban environments. This is especially valuable in cities with high levels of pollution, where the ability to drive emission-free for part of the day can have a meaningful environmental impact. Hybrid vehicles also help reduce fuel consumption and emissions on highways, where the internal combustion engine can operate more efficiently in combination with the electric motor.

Technological advancements in hybrid systems, such as improved battery efficiency, regenerative braking, and intelligent energy management, have made these vehicles more efficient and environmentally friendly. The continued development of these technologies will further enhance the role of hybrids in the transition to EVs. Moreover, hybrid vehicles familiarize consumers with electric driving habits, such as charging the vehicle, managing energy consumption, and utilizing electric-only driving modes. This experience can make the eventual shift to fully electric vehicles more seamless for drivers.

Hybrid vehicles also contribute to the gradual shift in infrastructure required for the widespread adoption of EVs. By increasing the number of electrified vehicles on the road, hybrid systems help drive the demand for charging stations, battery recycling, and renewable energy sources. In this way, hybrids indirectly support the build-out of the necessary infrastructure that will eventually accommodate fully electric vehicles.

Conclusion

In conclusion, hybrid powertrain systems play a pivotal role in the ongoing transition toward fully electric vehicles, offering a balanced approach that integrates both electric and internal combustion technologies. These systems provide a practical solution for addressing range anxiety, infrastructure challenges, and cost concerns, making them an attractive option for consumers during this transitional period. Technological advancements in battery efficiency, energy management, and regenerative braking have significantly improved the performance and environmental impact of hybrid vehicles, positioning them as a key component in reducing fuel consumption and emissions.

While fully electric vehicles represent the future of sustainable transportation, hybrids serve as a crucial intermediary by familiarizing consumers with electrification and driving the demand for supporting infrastructure. As the automotive industry evolves, hybrid systems will continue to bridge the gap between traditional vehicles and the electrified future, helping to accelerate the shift toward cleaner, more sustainable transportation solutions.

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