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A STUDY ON THE TECHNICAL CHARACTERISTICS OF HYBRID VEHICLE SYSTEM CONFIGURATIONS

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Abstract. When examining the historical development process, it becomes evident that significant advancements in the field of transportation have occurred since the invention of the wheel and the widespread application of steam engines, leading to the emergence of various alternative approaches aimed at addressing existing challenges in this sector. While technological progress has brought numerous advantages, it has also given rise to certain drawbacks. Despite the continued dominance of internal combustion engine vehicles in the automotive sector, changing economic, environmental, and technological conditions have prompted a shift toward alternative solutions. The fact that fuels used in internal combustion engines are predominantly petroleum-based results in the depletion of these finite resources and may lead to serious energy problems in the future. Moreover, the combustion of petroleum-based fuels releases harmful gaseous emissions into the atmosphere, significantly adversely affecting both the environment and human health. However, at the current stage, consumers are generally unwilling to compromise the performance characteristics of their vehicles in the name of environmental responsibility. In this context, hybrid electric technology can serve as a short-term transitional solution and play a key role as a pathway toward future zero-emission transportation technologies.

Keywords: *hybrid vehicle, fuel efficiency, regenerative braking, energy transmission*

Introduction. The transport sector is one of the key fields that plays a significant role in the social and economic development of modern society. At present, the vast majority of vehicles in operation worldwide are powered by internal combustion engines (ICE). However, the energy conversion efficiency of these engines is relatively low, and only about 30–40% of the fuel consumed is converted into useful mechanical work [1]. The remaining energy is mainly lost through heat dissipation, mechanical friction, and the processes required to overcome resistive forces acting against the motion of the vehicle.

The growing demand for energy, the limited availability of conventional petroleum-based fuel resources, and their negative environmental impacts have made it necessary to seek more efficient and environmentally friendly alternatives in the transport sector. In this context, hybrid vehicles, which integrate different power sources, are considered a promising approach that serves as a transitional solution between current technologies and future sustainable transportation systems.

Methods. According to expert forecasts, the production and use of hybrid vehicles are expected to increase in the coming years. At the same time, the reliable operation, maintenance, and repair of these vehicles require special attention. Since the structural characteristics and modern mechanisms of hybrid vehicles differ from those of conventional vehicles, it is considered essential to enhance the knowledge and professional skills of specialists working in this field.

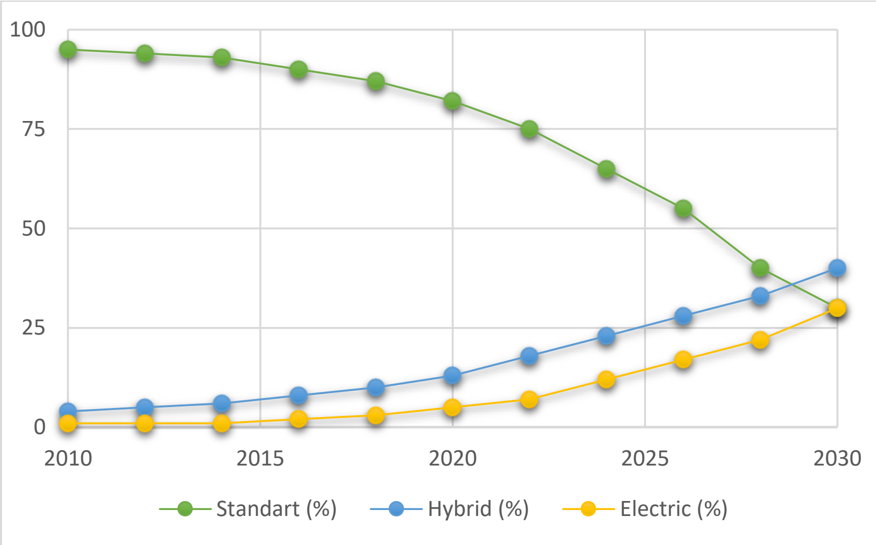

Figure 1. Changes in the annual sales shares of vehicles by engine type [2]

The trend depicted in Figure 1 is clearly evident. Analysis of the graph indicates that by 2030, the market share of conventional vehicles is projected to decline slightly from 25%, while the share of electric vehicles is expected to rise to a nearly comparable level. Notably, the most significant increase in demand is anticipated for hybrid vehicles. According to projections, approximately 50% of the remaining market is expected to be captured by hybrid electric vehicles. This factor constitutes one of the primary justifications for the comprehensive examination of hybrid electric vehicles in this study. The intensification of the energy crisis and environmental pollution has highlighted the urgency of replacing conventional fuel-powered vehicles in the transportation sector with alternative technologies, particularly electric vehicles. According to statistical data, in 2020, the transportation sector in the United States accounted for 27% of total greenhouse gas emissions, with more than 97% of these emissions attributable to carbon dioxide (CO_2) emissions from fossil fuel-powered vehicles. These figures are reflected in the 2022 reports of the U.S. Environmental Protection Agency (EPA) [3, 4]. Globally, the transportation sector is also considered one of the primary sources of atmospheric pollutants and greenhouse gases.

Existing scientific studies indicate that electric vehicles, due to their low CO_2 emissions, cause less environmental harm and play a significant role in achieving sustainable development goals. The adoption of alternative energy sources and new technological solutions is considered essential for combating climate change and ensuring the protection of the environment and atmospheric air [5].

Within this context, the article examines the structural design, key technical components, and operating principles of hybrid vehicles. The study analyzes the integration of hybrid systems with internal combustion engines and electric drivetrains, the management of energy flows, and the advantages offered by this technology compared to conventional vehicles. In particular, the role of hybrid vehicles is emphasized in terms of reducing fuel consumption, minimizing emissions, and enhancing operational efficiency.

Discussion. In the contemporary period, an analysis of automobile technologies used as land-based vehicles reveals the existence of three distinct vehicle technologies, classified according to the method of engine propulsion and the type of energy source employed. A schematic representation of this classification is presented in Figure 2.

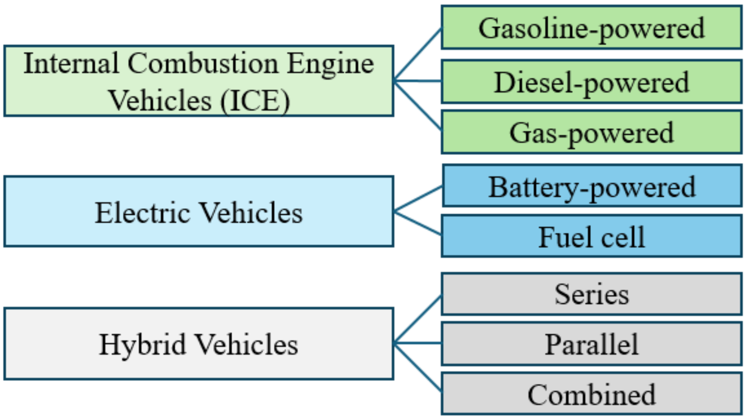

Figure 2. Vehicles classified by power source

Internal combustion engine (ICE) vehicles derive their energy from carbon-based fossil fuels. In this case, the motion of the engine is powered by the energy stored in the fuel (such as gasoline, diesel, etc.) contained in the fuel tank.

In electric vehicles, the electrical energy supplied by the battery is converted into mechanical energy and transmitted to the wheels, thereby enabling motion. Electric vehicles do not have an internal combustion engine; to store energy and facilitate propulsion, they employ a battery, an electric motor, a generator, mechanical transmission elements, and power management systems. Based on the energy source, electric vehicles can be classified into two main categories: battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs).

Hybrid electric vehicles (HEVs) are equipped not only with an internal combustion engine (ICE) but also with an independently operating electric motor and a battery storage system that can be charged from an external source. During operation, these vehicles can utilize the electric motor alone, the ICE alone, or both power units simultaneously, depending on energy efficiency requirements. This approach contributes to reduced fuel consumption and provides economic advantages. In certain hybrid models, it is also possible to generate electricity through a regenerative braking system, which recharges the batteries. Additionally, hybrid vehicles are considered an environmentally superior alternative due to their lower CO_2 emissions and reduced noise levels. Based on powertrain configurations, hybrid vehicles can be categorized into four main types: series, parallel, series-parallel, and plug-in hybrids [6].

In series hybrid systems, power transmission is not directly from the internal combustion engine (ICE) to the wheels; instead, the ICE drives a generator (Figure 3). The electrical energy produced by the generator is directed, via a converter, either to charge the battery pack or to power the electric motor. In such hybrid configurations, the ICE typically has a lower power rating, but compared to parallel hybrid systems, series hybrids employ batteries with higher capacities. The increased battery capacity contributes to a higher production and overall cost of series hybrid vehicles relative to parallel hybrid models. Additionally, series hybrid vehicles are considered more suitable for urban driving conditions, which are often characterized by frequent stops and low-speed operation. In series hybrid configurations, there is no direct mechanical connection between the ICE and the wheels. This feature allows the engine to be positioned at any structurally convenient location. The system does not require classical mechanical transmission elements, including gearboxes or drive shafts. Moreover, even when the ICE operates within a low-speed range, effective regulation of the vehicle’s driving speed remains possible.

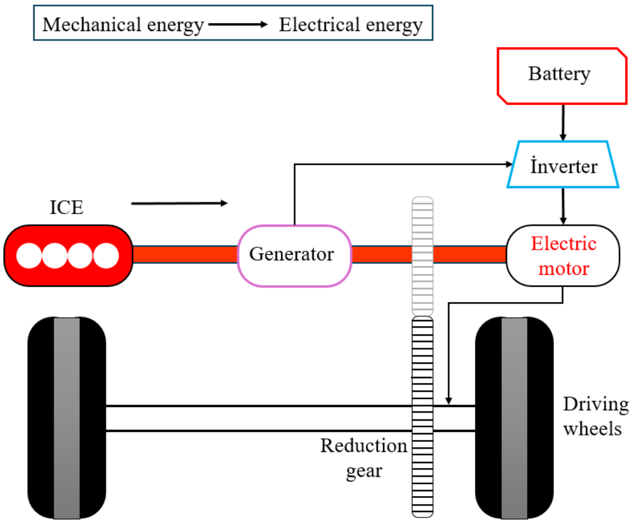

Figure 3. Series hybrid configuration

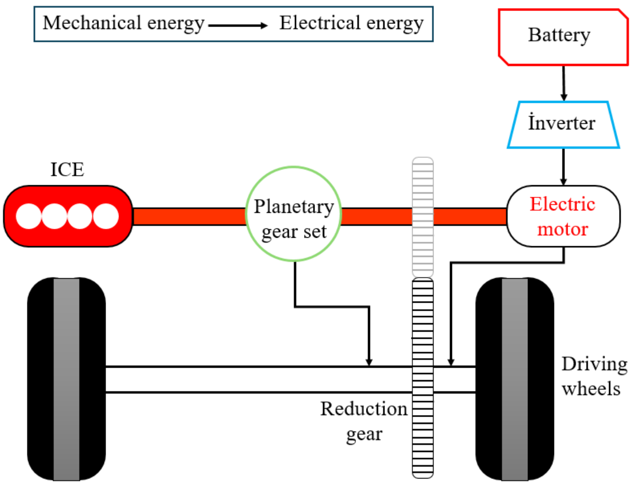

Figure 4. Parallel hybrid configuration

In parallel hybrid systems, both the electric motor and the internal combustion engine (ICE) are capable of transmitting power directly to the wheels (Figure 4). These configurations are typically equipped with relatively low-capacity batteries. The ICE can also drive the generator, which facilitates the charging of the batteries. However, the efficiency of parallel hybrid systems is considered limited in urban driving conditions, which are often characterized by frequent stops and low-speed operation.

Series–parallel hybrid vehicles can operate in either parallel or series hybrid mode, depending on the driving conditions (Figure 5). These systems provide flexible control across various speed ranges and operate efficiently both at high speeds and during low-speed driving.

Hybrid vehicles can be classified into several main categories based on the operating principles of their powertrains [7]. This classification allows for a comparative assessment of the technical capabilities, energy efficiency, and potential applications of different hybrid systems. Let us analyze the systems presented in this classification.

Micro hybrids are not considered hybrid vehicles in the classical sense, as these systems do not possess a second independent energy source. Nevertheless, the electrical system in such vehicles plays a more significant role compared to conventional vehicles. In particular, "start-stop" systems operate efficiently to recover energy during braking, which is especially beneficial in dense traffic conditions.

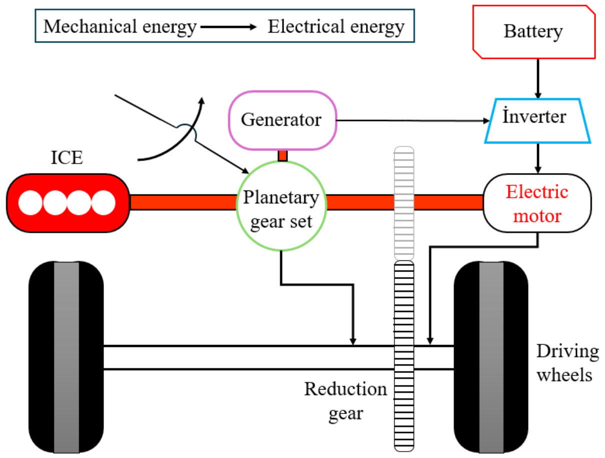

Figure 5. Series–parallel hybrid configuration

Mild hybrids (MHEVs) are equipped with an electric motor that serves as an auxiliary energy source. Although these vehicles cannot operate solely on electric power, the electric motor efficiently performs generator and starter functions. Since the electric motor is primarily positioned between the internal combustion engine (ICE) and the transmission, its functional capabilities are limited. During acceleration, the electric motor supports the powertrain by providing additional torque, while the battery is mainly charged during low- and mid-speed operation. This technology is widely employed by manufacturers such as Honda, BMW, and Mercedes-Benz.

Full hybrids (FHEVs) have the capability to operate solely on electric power for certain periods. These vehicles are considered technically more advanced and are associated with higher production costs. The full hybrid concept is realized either through the structural enhancement of mild hybrid systems (e.g., Porsche and Volkswagen models) or through the implementation of an entirely new design approach (e.g., Toyota and Lexus).

Plug-in hybrids (PHEVs) are distinguished by their ability to charge the battery pack from an external electrical grid. In these vehicles, the energy supply can be provided both from an external source and through the vehicle's internal combustion engine (ICE) and generator, which significantly extends the driving range in electric mode.

Table 1. Advantages and Disadvantages of Hybrid Vehicles

Hybrid Type	Advantages	Disadvantages
Micro Hybrids	Limited fuel savings through start-stop and regenerative braking	No electric-only driving capability, limited hybrid functionality
Mild Hybrids (MHEV)	Additional power during acceleration, reduced emissions	Absence of full electric driving mode
Full Hybrids (FHEV)	Electric-only driving, high energy efficiency	High cost and technical complexity
Plug-in Hybrids (PHEV)	External charging and extended electric driving range	High battery and infrastructure requirements

Results. As a result of the conducted scientific research and comparative analyses, the following conclusions have been drawn:

1. It has been determined that, although series hybrid systems exhibit high energy efficiency in urban driving conditions, they are characterized by high production costs. Parallel hybrids are distinguished by their structural simplicity and compactness, but they are limited in terms of independent electric driving capability. Series–parallel systems, on the other hand, combine

the advantages of both approaches, providing the most flexible operational performance across various speed and load ranges.

2. Analyses confirm that hybrid vehicles serve as a decisive technological solution for reducing fuel consumption and CO_2 emissions. These systems play a crucial transitional role, acting as a bridge between internal combustion engine vehicles and fully electric vehicles.
3. As a result of the study, it is deemed appropriate that future research efforts focus on optimizing the operation of hybrid powertrains, improving energy management strategies, and advancing the technical performance of battery technologies.

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