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Performance Evaluation of a Plug-in Hybrid Powertrain on Compression Ignition Engine in Terms of Energy Consumption Using Intelligent Cruise Control

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Abstract

One of the contemporary trends is to emphasize the benefits of using hybrid drives over conventional ones. Due to the growing popularity of this category of drives, research on the optimization of energy consumption is becoming increasingly popular. The paper presents research on a selected plug-in hybrid drive unit of one of the most popular vehicle manufacturers in the European Union. The research process itself was based on the assessment of the use of active DISTRONIC cruise control as a tool that can influence the optimization of energy consumption of the tested drive unit. The experiment was conducted in real road conditions. Analyses were carried out for several drive system configuration modes: hybrid, E-mode, E-save and charging. The results of the experiment indicated the most optimal drive setting mode on expressways. These analyses emphasize the significant role of intelligent systems as a tool that allows for the optimization of energy consumption of vehicles equipped with plug-in hybrid units. The presented research is dedicated to users of this category of vehicles, while at the same time providing an answer to the question of how to effectively use the described drive unit in real operating conditions.

Keywords

hybrid vehicle, energy consumption, electromobility, intelligent systems, active cruise control, research, analysis

1 Introduction

Currently, passenger cars are the most important means of individual transport. All participants in the automotive market have no doubt that this trend will remain unchanged for some time. However, increasing requirements for the reduction of harmful emissions into the environment and, consequently, the implementation of increasingly restrictive EURO exhaust emission standards and the promotion of the idea of electromobility have forced manufacturers to introduce new drive solutions. As a result, the market offer has been supplemented by vehicles equipped with hybrid drive units. This global trend in the automotive market has sparked a scientific discussion on the assessment of the energy efficiency of this category of drives. Analyzing the literature on the subject regarding research on energy consumption by hybrid vehicles, most of them focus on research in the area of vehicles powered by a petrol engine. For example, in an article by Dang et al. (2025) a strategy for supporting the energy balance for plug-in hybrid electric vehicles (PHEV) was proposed, depending on the interaction between information, energy and transport networks.

The aim of the research in the cited article was to optimize the energy balance in PHEV vehicles in terms of economic benefits. Urooj and Nasir (2024) presents a comprehensive review of energy management for selected hybrid vehicle models. The cited studies revealed gaps in existing energy optimization strategies. Similar research topics were discussed in Ghode and Digalwar (2024). The authors proposed analyses of a model of vehicle charging station connected to photovoltaic installation. This system effectively managed energy consumption during charging. A similar model was analyzed in Nirmala and Venmathi (2024), and Majumder et al. (2019). The presented model was to ensure maximum efficiency of energy resource use by using solar panels in this process.

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Other studies focused on the possibility of using artificial intelligence methods to manage energy consumption in a hybrid vehicle (Mosammam et al., 2024). The neural network algorithm proposed by the researchers was to control the battery charging times and temperature, delaying the process of its consumption, leading to an increase in the vehicle range. In Dong et al. (2024). The authors proposed a strategy for gear shifting and braking while driving a plug-in hybrid vehicle to reduce energy consumption. An improved energy management method for hybrid vehicles equipped with planetary gears was proposed in Yin et al. (2024). The presented method simplistically improves the traditional approach to optimal control by predicting energy management by introducing a differentiable module. A novel deep learning approach for energy management in a hybrid vehicle was also proposed in Huang et al. (2024). In this case, the training dataset included emission test cycles, loads, and driving styles, using dimensionality and noise reduction to control parameters. As postulated by the authors, the long short-term memory (LSTM) prediction model with attention mechanism predicts the power demand, outperforming five other deep learning models. The study showed excellent performance, achieving a root mean square error (RMSE) of 4.9761, which exceeds the RMSE values of the other studied models ranging from 7.9497 to 9.1933. In real-world driving conditions, a mean absolute error (MAE) of 3.965 and an RMSE of 5.908 were achieved, highlighting the model's adaptability and predictive accuracy despite data contamination. Such robustness makes it a valuable tool in research into the development of energy management systems for hybrid vehicles. Yang et al. (2024) proposed a new configuration of plug-in hybrid vehicle, which they named dual hybrid (DH)-PHEV. This model is based on a dual rotor engine (DRM) and a hybrid energy storage system (HESS). In order to improve the all-round efficiency and reduce the battery charge/discharge ratio, a comprehensive energy management strategy (CEMS) is proposed. First, a torque allocation strategy is proposed based on the configuration of DH-PHEV, the operating characteristics of DRM and the operating states of HESS. The torque allocation for DRM is optimized based on sequential quadratic programming. Second, the power allocation between battery and super capacitor is optimized based on dynamic programming (DP) to reduce the battery charge/discharge ratio and minimize the energy consumption. CEMS for DH-PHEV is proposed based on the optimization results of DP and torque allocation of DRM. Finally, the feasibility and adaptability of DH-PHEV and CEMS configurations are verified. The results show that the CEMS adaptability in different driving cycles is excellent. The all-round efficiency and battery charge/discharge ratio are effectively optimized. In the case of WLTC tests and 16 real vehicle driving cycles, the pure electric range for DH-PHEV was improved by 1.07% and 4.36%, respectively. In Selvakumar (2021) and Chan (2002), the development trends of hybrid and electric vehicles were presented. An attempt was made to determine the directions of development of this category of drives. The analysis showed that electric vehicles powered by the battery alone are burdened with certain limitations – technological, infrastructural and economic, such as range, availability of charging stations, charging cost. On this basis, the authors postulate that in these circumstances, the most reasonable solution is a plug-in hybrid vehicle. The analysis of the available literature on the subject showed that there is a lack of studies regarding the evaluation of the hybrid drive system in a plug-in vehicle powered by diesel oil in terms of energy consumption. There is a lack of publications describing the possibilities of optimizing energy consumption using intelligent active safety systems – active cruise control, which modern vehicles are equipped with. The presented study is therefore an attempt to fill the gap in the literature on the subject in the field of energy consumption research, indicating for the first time how the use of active cruise control of the DISTRONIC type as a tool that can influence the optimization of the energy consumption process of the tested drive unit. Zöldy and Zsombók (2019) note that although electromobility is developing dynamically, most studies focus on aspects such as cybersecurity or navigation of autonomous vehicles, omitting issues related to fuel consumption and vehicle range management. To address this gap, the aim of their work was to develop a predictive fuel consumption model that takes into account various external factors affecting vehicle energy efficiency. Zsombók (2024) examines the energy consumption and environmental impact of modern passenger cars, especially in the dynamic and unpredictable environment of urban transport, where fuel consumption and vehicle emissions can vary significantly. A thorough understanding of such fluctuations is crucial for developing innovative, efficient and environmentally friendly vehicle technologies.

Therefore, this article has many important implications, both practical and theoretical. The aim of the research is to evaluate the performance of a plug-in hybrid drive system in a diesel vehicle in terms of energy consumption using intelligent cruise control. The article is organized as follows. Section 2 contains a detailed description of the research object and the method of conducting the research. Section 3 describes the results of experimental research and their interpretation. In turn, Section 4 discusses the results obtained by the authors and contains conclusions from the research – indicating their limitations. At the same time, it sets future directions of research in relation to the impact of intelligent systems from the area of active safety on the increase in energy efficiency of plug-in hybrid units.

2 Material and methods

The aim of this article was to present an analysis of the energy consumption of a plug-in hybrid vehicle Mercedes-Benz 300 de from 2019. The tests were carried out on a road section outside the urban agglomeration. The road conditions were stable, with windless weather and no precipitation and a dry road surface. The ambient temperature was about 16 °C. As observations of market reality indicate, hybrid vehicles powered by diesel are not as common as their counterparts, whose combustion engine is powered by petrol. One of the leading brands in this market is Mercedes-Benz. The company offers a hybrid vehicle, the C class 300 de model. The drive system of this vehicle consists of a 2.0 L diesel engine with a power of 143 kW and an electric motor with a power of 90 kW. The battery capacity in the vehicle is 13.5 kWh. According to the manufacturer's data, the fuel consumption of this vehicle is 1.5–2.0 L/100 km in hybrid mode. The tested vehicle was equipped with active cruise control type DISTRONIC, an intelligent active safety system. This system maintains the speed set by the driver and automatically adjusts it to the speed of road traffic. The tests were carried out on a 200 km section of a straight expressway. The vehicle moved at speeds of 80, 90, 100, 110, 120, 130 and 140 km/h. The analysis was carried out in several modes: hybrid, E-mode, E-save and charging. It should be emphasized that the drive system in hybrid mode operates with both the combustion engine and the electric motor. In the E-mode only the electric engine operates in the drive system. In this mode, the vehicle can travel 36 km on electricity. In E-save mode, the vehicle is driven by the combustion engine and saves electricity. Therefore, the process of charging the battery while driving is minimized. On the other hand, the battery charges during braking thanks to energy recovery. In charging mode, the vehicle is driven only by the combustion engine, which also charges the battery. Fig. 1 shows the route the vehicle covered during road tests. A section of an expressway was selected for the tests.

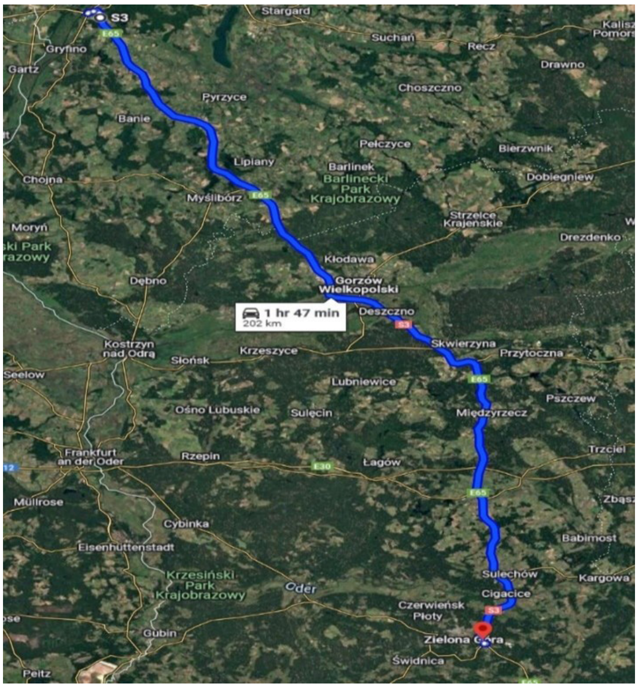

Fig. 1 Projection of the measuring section of the road on which the experiment was performed

Fig. 2 shows the energy transfer in the E-mode and hybrid modes. In these modes, the drive system draws energy from the battery and the combustion engine. In the hybrid mode, the energy consumption depends on the vehicle load conditions.

Fig. 3 shows the energy transfer in E-save and charging modes. In this configuration, energy is drawn from the combustion engine. The task of E-save mode is to save the battery's electrical energy. The combustion engine does

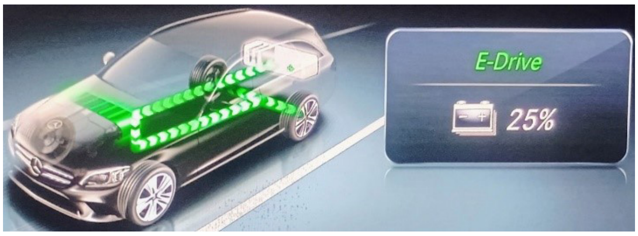

Fig. 2 Energy consumption in hybrid and electric modes (Groupa Mojsiuk, online)

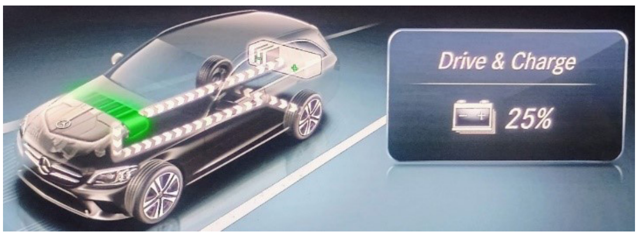

Fig. 3 Power consumption in E-save and charging modes (Groupa Mojsiuk, online)

not charge the battery, while in charging mode the combustion engine additionally charges the battery.

Fig. 4 shows how energy flows in charging mode. The vehicle was idling at an engine speed of 1,000 [rpm].

The aim of the analyses was to assess how the use of the DISTRONIC system while driving may affect the energy consumption of a given vehicle. Its main purpose is to increase comfort and active safety while driving by automatically adjusting the vehicle speed to the road conditions. The system allows the driver to set a preferred distance from the vehicle in front. The system monitors traffic on the road and automatically adjusts the speed to maintain this distance, which eliminates the need to manually brake or accelerate in heavy traffic. Additionally, the system uses radar sensors and cameras to constantly analyze the distance to vehicles in front. This system can detect changes in traffic, which allows for a quick response to sudden decelerations or accelerations of other drivers. It should be emphasized that this system has been adopted by most car manufacturers as basic equipment for hybrid vehicles.

3 Research results

The use of DISTRONIC cruise control, an active safety tool, enabled measurements to be taken in real road conditions in three modes: hybrid, E-save and charging. The results of the research on fuel and energy consumption for individual speeds are presented in Figs. 5 and 6.

Fig. 5 shows the results of fuel consumption measurements in the following modes: hybrid, E-save and charging. It should be noted that in the E-save and charging modes the drive system was powered only by the combustion engine. Fig. 6 shows average energy consumption during the tests.

At this stage of the study, energy consumption was calculated for hybrid, E-save and E-mode drive modes. In order to maintain the logical correctness of the study, in accordance with the vehicle manufacturer's information, it was assumed that 1 L is 10 kWh. In hybrid mode, fuel and electricity consumption were considered.

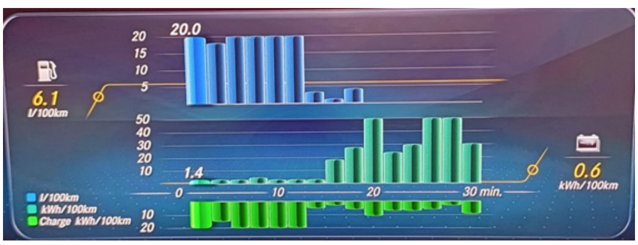

Fig. 4 Power consumption in E-save and charging modes (Groupa Mojsiuk, online)

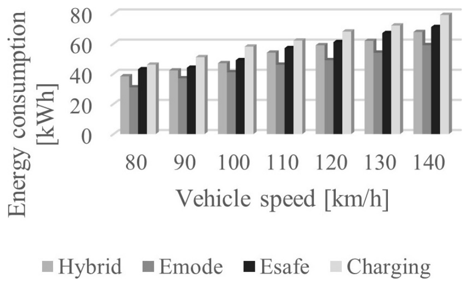

Fig. 5 Fuel consumption in hybrid, E-save and charging modes

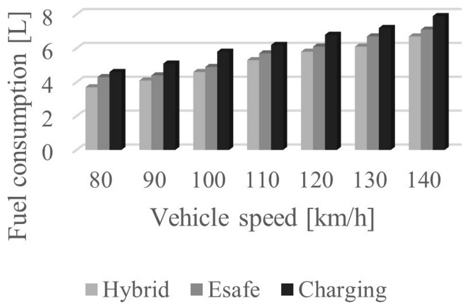

Fig. 6 Power consumption in E-save and charging modes

4 Discussion

It is currently emphasized that owning a low-emission car, which is undoubtedly true for a hybrid vehicle, is associated with many benefits widely described in the literature on the subject (Cai et al., 2022; Husain et al., 2021). One of the arguments cited is the possibility of achieving optimization in terms of energy and fuel consumption (Ganesan et al., 2025). For the demand side, this is one of the key parameters that can determine the choice of a given drive unit; considering that conventionally powered vehicles are still available on the market.

Few articles present tests of a plug-in hybrid vehicle with a compression-ignition engine in real road conditions, while maintaining the permitted speed using active cruise control – one of the most popular solutions in the area of intelligent transport systems and active safety. During the tests, the mentioned drive system was analyzed in four modes. The test results were presented as a function of vehicle speed. In E-save and charging modes, the drive system was operated only by the combustion engine, in hybrid mode, the combustion engine worked in parallel with the electric engine, and in E-mode, only the electric engine was used.

The results of the experiment were based on the assessment of energy consumption in kWh, which are presented in Fig. 6. The experiment showed that the most economical mode in terms of total energy consumption is the E-mode. The vehicle in this configuration can travel about 36 km. It should be noted that the tests were carried out at a maximum speed of 140 km/h. This is the maximum speed that the vehicle can reach using an electric engine. On the other hand, the most economical mode using the internal combustion engine is the hybrid mode. However, this configuration leads to the consumption of energy stored in the traction battery. When the battery is depleted, part of the energy from the conventional engine is redirected to charging it, which leads to a minimal increase in fuel consumption. The charging mode analyzed can therefore be used to charge the battery. It will be most effectively used on expressways, where there are slopes. Then it is possible to achieve lower fuel consumption. Considering the fact that the battery unit is charged from the energy from the braking process, the authors postulate that this mode should be used before entering urban agglomerations, because the obtained energy can be used in urban traffic in the e-mode configuration. However, the analyzed E-save mode is mainly used to save energy contained in the traction battery and, in the authors' opinion, is not recommended for use on expressways.

To sum up, the analysis of the presented measurement results showed that the most beneficial mode on expressways is the hybrid mode. On longer sections, energy from the battery can be managed in this mode, and the electric motor supports the operation of the combustion engine, which leads to reduced fuel consumption.

This document analyzes a selected plug-in hybrid drive unit from one of the leading manufacturers of passenger cars in Europe. Much broader analyses will certainly be needed soon, in terms of new technological solutions in the field of underlying active safety systems and other systems based on the idea of an intelligent vehicle. An important element of further research in this matter should also be the assessment of the impact of the use of the analyzed operating modes not only on the service life of the drive system itself, but also on other components of a given vehicle.

To sum up, the presented research on the assessment of the operation of a plug-in hybrid drive system in a diesel-powered vehicle in terms of optimizing energy consumption does not fully exhaust the essence of the issue. It is only an incentive for further research into this matter. To identify the possibilities of using the phenomenon of synergy around using other systems currently offered on the market from the area of intelligent vehicles and the benefits related to the further process of energy optimization of plug-in hybrid vehicles.

5 Conclusion

The most economical driving mode in terms of energy savings is the E-save function. In urban areas, the vehicle uses the least energy using the E-save function and E-mode. This is a driving mode on battery power alone, while outside the city on motorways, the E-save function and Hybrid mode with the autopilot on are the most economical. Hybrid mode optimizes energy consumption, automatically turns off the combustion engine in traffic jams and uses the electric engine when starting off and recovers energy through recuperation. The least economical mode is Charge, during which the battery is charged. E-save mode allows you to save the battery. It is recommended when driving on the road and then moving in an urban area.

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