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Analysis of Energy Efficiency Parameters of a Hybrid Vehicle Powered by Fuel with a Liquid Catalyst

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Abstract: A notable trend in the modern automotive market is the increased interest in hybrid cars. Hybrid cars combine a standard internal combustion engine with an electric motor solution. Research into increasing the energy efficiency of a conventional unit while meeting increasingly stringent exhaust emission standards is becoming a key postulate in this matter. This article discusses an analysis of modifying the fuel used by hybrid vehicles using the example of a selected drive unit equipped with a spark-ignition engine. This effect was tested after the Eco Fuel Shot liquid catalyst was added to the fuel. The research process was carried out in two stages, as follows: in road conditions using the Dynomet road dynamometer; and on the V-tech VT4/B2 chassis dynamometer. Tests were carried out to replicate road tests with a catalytic additive in the fuel. A mathematical model was created and the following energy efficiency parameters of the hybrid vehicle were calculated: the torque of the internal combustion engine, electric motor, and generator; the rotational speeds of the internal combustion engine, electric motor, and generator; the power of the internal combustion engine, electric motor, and generator; the equivalent fuel consumption of the electric motor and generator; the fuel consumption of the internal combustion engine, electric motor, and generator; and the mileage fuel consumption of the internal combustion engine, electric motor, and generator. The results of the tests made it possible to identify the benefits of using the tested liquid catalyst on the operation of the drive system of the analyzed hybrid vehicle. This research will be of benefit to both the demand side in the form of users of this category of vehicles, and the supply side represented by the manufacturers of power units.

Keywords: hybrid vehicle; internal combustion engine; fuel consumption minimization and economy; drive cycle analysis; simulation and comparison

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1. Introduction

Undoubtedly, the constant expansion of the market for new models of hybrid vehicles is related to the pursuit of zero emissions in road transport. As studies in the literature indicate, a hybrid car is a vehicle that has two sources of propulsion. The most common are hybrid cars powered by a "tandem", consisting of an internal combustion engine (petrol or diesel) and an electric unit [1–3]. However, not all combustion–electric drives are the same and can be divided into the following three main groups: the plug-in hybrid (PHEV), where the car has an additional, large, high-voltage battery with the possibility of charging from a socket; the mild hybrid (mHEV) in which the electric motor usually combines the functions of a starter motor and an alternator. It is not able to power the car on its own, but it can recover energy when decelerating and use it later to power the on-board electrical equipment and to support the internal combustion engine while driving; and full hybrid (HEV), where an additional electric motor supports the combustion engine during acceleration and can even drive the car on its own over short distances at low speeds [4–6]. A common feature of these drives, apart from the pro-ecological approach, is energy efficiency, as noted by supporters of this category of vehicles [7,8]. It is important to note that a number of researchers are currently investigating the potential for hybrid vehicles to evolve into FCHEVs [9,10]. In their research, the authors have indicated that a fuel cell–battery–motor coupling system utilizing optimal predictive control can reduce the consumption of hydrogen while extending the lifespan of the energy sources. Moreover, in comparison to pure electric vehicles, FCHEVs possess the benefits of an extended range, high conversion efficiency, and zero emissions. At present, the FCHEV is available on the passenger vehicle market and produced by German and Japanese manufacturers in the form of the GLC F-Cell model and the Japanese Crown model. It is the view of automotive market experts that the hydrogen–electric hybrid, in terms of the passenger car market, is an incidental project rather than the harbinger of a new wave of products. It is also important to note that, as highlighted by other researchers, the production of hydrogen remains relatively expensive and the infrastructure for filling up with this gas remains underdeveloped. Furthermore, if the electricity in this type of hybrid is not obtained from renewable sources, it is the electric component that puts a strain on the environment, which is the opposite of the way in which petrol hybrids operate.

A vehicle's energy efficiency parameters determine its ability to use energy in an optimal way. This variable has an impact on the vehicle's performance such as its power, torque, degree of pollutant emissions, and vehicle range. An analysis of the literature indicates that issues related to the improvement of performance parameters are of interest to many researchers [11,12]; this research concerns both combustion, hybrid, and fully electric drives. Currently, research is being carried out on the use of hydrogen as a fuel in both internal combustion and electric vehicles. For example, in papers [13,14], based on a computer analysis, a simulation of the influence of the injection starting time on the operation of the combustion cylinder of a hydrogen-powered engine was performed. The aim of the research was to improve the efficiency strategy for the use of hydrogen as a fuel. Another researcher also pointed out that hydrogen fuels can also be used as an additive to liquid fuels [15]. One researcher concluded that enriching coal or vegetable fuels with hydrogen improved the combustion process and reduced the emissions of internal combustion engines. Spark-ignition engines were mainly used to power hydrogen in the study [16]. In another study, the effects of 5% and 10% hydrogen additions to gasoline on the emission of toxic substances into the atmosphere were examined. The study showed that under the influence of hydrogen, CO and HC emissions decreased, while NO_x increased. This phenomenon is caused by the properties of hydrogen, which burns very quickly, increasing the temperature in the engine's combustion chamber. It should be emphasized that this test was carried out on a spark-ignition engine. Similar studies were presented in another paper [17]. Gaseous fuels, such as hydrogen, methane, and natural gas were used for the analysis. They were mixed with conventional fuel in a proportion of 50–50. A platinum–aluminum catalyst was installed in the engine. The studies showed that the catalytic converter reduced nitrogen oxides. In addition, the fuel–hydrogen mixture increased the pressure in the cylinder and caused nitrogen oxides and hydrocarbon emissions and reduced smoke. On the other hand, the use of natural gas and methane reduced nitrogen oxide emissions. In addition, the studies showed that the use of an additional catalyst reduced smoke for these fuels. The experiment was carried out on a compression ignition engine. In another study [18], a two-stroke internal combustion engine powered by hydrogen, oxygen and water with direct injection was designed. The presented design solution was innovative, and preliminary tests showed that the prototype had zero emissions. Another study [19] investigated the use of a selective exhaust gas catalyst in an engine powered by pure hydrogen. Hydrogen engines have zero CO_2 emissions, but their disadvantage is high NOx emissions. The solution described in the paper resulted in a reduction in nitrogen oxides during hydrogen combustion in the engine compartment. In one study [20], an analysis of the use of sodium borohydride as a fuel additive was carried out in order to investigate the efficiency coefficients of an engine powered by gasoline at different rotational speeds. Tests showed that as a result of the fuel additive, the engine power increased by about 33 kW. The energy efficiency of hydrogen cells in relation to combustion engines operating on alternative fuels and an electric vehicle was investigated in another study [21]. The internal combustion engines were powered by natural gas and methanol. The results of the experiment showed that a hydrogen vehicle in which fuel was extracted from green energy through electrolysis showed the highest energy efficiency of all the test subjects. In Ref. [22], a hybrid vehicle with hydrogen cells was proposed. The vehicle was made using digital twin technology. The advantage of this type of solution is the use of smaller cells, which will reduce their degradation. Simulation tests showed an increase in the range of 30 km with less battery power.

As previously discussed, a major focus in research for internal combustion engine vehicles is reducing the levels of harmful substances in exhaust gases, particularly nitrogen oxides, sulfur dioxide, and carbon monoxide. One approach to addressing this issue involves using various fuel additives. For instance, a study referenced in [23] examined the use of a water-in-oil (W/O) emulsion as fuel for compression ignition engines. The findings indicated that adding water to the fuel decreased nitrogen oxide emissions by 19.6% and reduced smoke emissions by 66.3%. Researchers attributed this effect to water's ability to lower combustion temperatures, as heat is absorbed during evaporation and micro-explosions occur due to rapid evaporation of water droplets. This process enables a simultaneous reduction in nitrogen oxides and smoke in the exhaust.

Additionally, it has been demonstrated that emulsion fuels can be produced from non-biodegradable plastic bags used for PGB purchases [24], with studies showing that a water-oil emulsion made from PGB reduces smoke and nitrogen oxide emissions. An exergetic analysis of a compression ignition engine operating on biofuel derived from cottonseed oil, enhanced with titanium dioxide and silver oxide nanoparticles, was conducted in [25]. The results showed that fuels containing nanoparticles had lower exergy losses.

Another study [26] used cerium oxide nanoparticles as an additive to diesel fuel, finding that this type of catalyst reduced soot and hydrocarbon emissions by 30% at partial engine loads, while a minor reduction of around 5% in nitrogen oxide emissions was observed at maximum engine load. Importantly, no change in fuel consumption was detected at either average or maximum engine loads.

Further research [27] explored the effects of blending diesel fuel with methanol, ethanol, n-butanol, methanol/n-butanol, and ethanol/n-butanol. Compared to pure diesel, these mixtures led to a shorter ignition delay period and an improvement in the combustion process, with the best results achieved using a blend of 80% diesel, 10% methanol, and 10% n-butanol. Another investigation [28] proposed an effective control strategy for a hybrid vehicle.

The aims of this measure were to optimize energy management when travelling in a hybrid vehicle and to save fuel. According to the authors of the study, thanks to the use of optimization, it was possible to reduce fuel consumption by 2.6% in the urban cycle. To improve energy efficiency, a strategy to optimize energy management was applied in one study [29]. The simulation showed that programming the controller to the vehicle's operating conditions improved energy management efficiency in urban cycles by 40%. Subsequent work [30,31] used the Deep Q-Network artificial intelligence algorithm as an energy management strategy to reduce the operating costs of a hybrid vehicle. The authors put forward the thesis that the biggest problems associated with these vehicles are their limited range and high degree of traditional fuel consumption. The innovative method proposed by the authors reduced the cost of vehicle operation by 3.1%. In this case, the authors of the study proposed the use of a neural network to diagnose modern fuel injectors [32].

However, none of the studies cited focuses on the assessment of the energy parameters of an HEV powered by the traditional Eco Fuel Shot catalyst. Therefore, when analyzing the literature, it is possible to formulate an existing research gap and at the same time a research problem. What is the impact of the catalytic converter as a fuel additive on the efficiency parameters of a hybrid vehicle?

The purpose of this publication is to investigate how the catalytic fuel additive, Eco Fuel Shot, affects the energy efficiency parameters of a hybrid vehicle. A model was created to analyze the following parameters: the torque of the internal combustion engine, electric motor, and generator; the rotational speeds of the internal combustion engine, electric motor and generator; the power of the internal combustion engine, electric motor and generator; the equivalent fuel consumption of the electric motor and generator; the fuel consumption of the internal combustion engine; the total fuel consumption of the internal combustion engine, electric motor, and generator; and the mileage fuel consumption of the internal combustion engine and generator. The implementation of the presented tasks will allow us to identify the possible benefits associated with the use of the Eco Fuel Shot additive for conventional fuel.

To our knowledge, this is the first research approach to this topic involving the analysis of energy efficiency parameters of a hybrid vehicle powered by fuel with the addition of a liquid catalyst. Therefore, it fills a gap in the literature on the subject, while making a practical contribution to research in the area of reducing exhaust emissions in the internal combustion engines used in hybrid drives. In addition, it can help to set new fuel consumption and pollutant emission standards for newly developed hybrid powertrains.

In short, this article brings new perspectives to the current literature and research in the following areas: (I) hybrid drives; (II) internal combustion engines; (III) energy efficiency; (IV) fuel additives; and (V) drive cycle analysis simulation and comparison.

The article is organized as follows. Section 1 provides an introduction and rationale for the research topic. Section 2 contains a detailed description of the methodological assumptions, including the choice of drive unit, type of route, and measurement method. Section 3 presents the results of the research. Section 4 presents a discussion in relation to the experiment. Section 5 contains the final conclusions of the research, indicating its limitations and practical applications, as well as future directions for research in this area.

2. Material and Methods

2.1. Subject of Research

A vehicle from one of the leading manufacturers was selected at the test facility, in which an HEV unit was installed. The reason for choosing this drive is its considerable popularity among users of hybrid vehicles, with a total sales volume exceeding five million units. It can therefore be considered the most representative powertrain in terms of hybrid vehicles. The vehicle was equipped with a 1.8 HSD unit with Hybrid Synergy Drive technology. It connects the 2ZR-FXE internal combustion engine with a generator (MG1), an electric motor (MG2), and a high-voltage battery. The individual parameters of the analyzed power unit are as follows.

2ZRFXE—1800CC 16-VALVE DOHC EFI (Drive Unit Made in Japan Manufacturer by Toyota, Japan) internal combustion engine:

- capacity—1798 cm^3;
- maximum power—73 kW/5200 rpm;
- maximum torque—142 Nm/3500 rpm;

Generator (MG1)

- AC motor-generator with permanent magnet rotor;
- It generates electrical voltage and serves as the starter motor for the internal combustion engine;

Electric motor (MG2):

- AC motor-generator with permanent magnet rotor;
- acts as the main electric motor with high torque;
- maximum power—60 kW/13,500 rpm;
- maximum torque—207 Nm [28].

2.2. Construction and Procedure

The tests were carried out in road conditions on the selected route for a vehicle powered by standard fuel, and then repeated while maintaining the selected conditions of vehicle movement on the chassis dynamometer. The vehicle on the dyno was powered by fuel with the Eco Fuel Shot catalytic additive. The liquid catalytic converter Eco Fuel Shot is a hygroscopic substance that is dosed directly into the fuel tank. The additive ensures the homogeneity and indivisibility of the fuel, which leads to its complete combustion in the engine compartment. The task of the active substance is to reduce the amount of activation energy by forming a transition compound with the reactants.

On the chassis dynamometer, the loads and speed of the vehicle were mapped.

The test stand was a dry, even, flat, and straight road with a good asphalt surface, located in a non-urban area, characterized by low vehicle traffic (the length of the measurement section was about 1000 m). The test equipment was a portable road dynamometer device by Dynomet (Store Merløse, Denmark) (Figure 1) mounted on a selected rear wheel of the vehicle. The device was equipped with company software installed in the measuring computer.

Figure 1. Portable road dynamometer type Dynomet.

The Dynomet chassis dynamometer software uses the relation to calculate the torque, rotational speed, and useful power of the engine. The acceleration, deceleration and speed of the vehicle were measured on the basis of the rotational speed according to the following formula:

$$a = \frac{v}{t} = \frac{s}{t^2} = \frac{2\pi r n}{t^2} = \frac{\pi d_z n}{t^2} \quad (1)$$

where a is the acceleration or deceleration of the car [m/s^2], v is the speed of the car [m/s], t is the measurement time [s], s is the distance traveled by the vehicle [m], r is the radius of the wheel [m], n is the number of revolutions of the wheel, and d_z is the outer diameter of the wheel [m].

The methodology of the empirical research assumed the use of a research object, research stands, and research equipment to measure, as follows:

- the torque and useful power of the engine;

- the torque and power at the wheels of the vehicle;
- vehicle resistance and losses in the drive system;
- acceleration of the vehicle;
- braking distances.

Prior to the above road test, the following steps were performed:

- the pressure in the tires was replenished to the value specified by the manufacturer;
- the tested vehicle was driven a distance of about 20 km in order to bring the operating oils (in the drive system) to the normal operating temperature, but also to the normal operating temperature of the brakes and tires;
- side windows were closed;
- the car was loaded in accordance with the factory instructions;
- the test was carried out in windless weather.

Before the road measurement, the device (road dynamometer) was mounted on the rear wheel of the vehicle, cables were connected to a laptop computer, and preliminary data of the measurement conditions and the test object were entered into the program.

Specific parameters of the environment and the vehicle were adopted on the basis of the barometer, thermometer and car manufacturer's data, and were entered into the Dynomet software 4.11 (http://www.dynomet.dk/, 14 July 2024). The speed of the vehicle was read using the diagnostic interface. The methodology for the tests in real road conditions using a portable road dynamometer is presented in Figure 2.

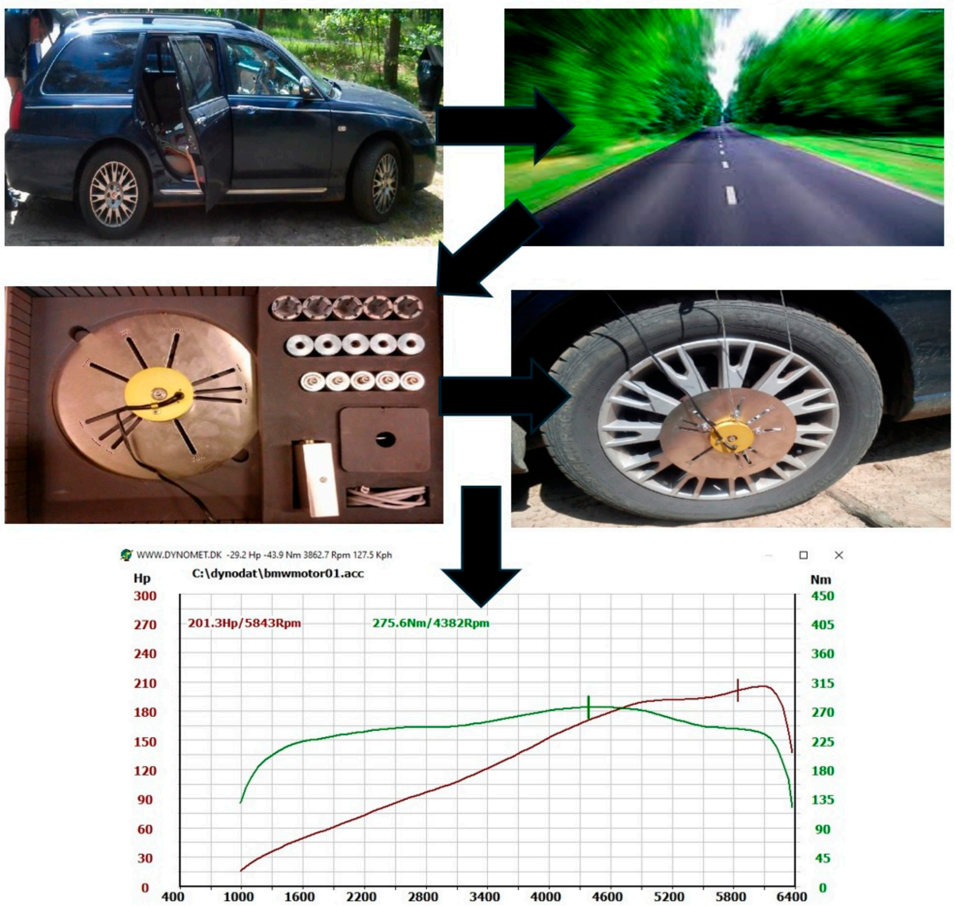

Figure 2. Methodology of measurement for the Dynomet road dynamometer.

The tests were carried out in road conditions on the selected route, and then repeated, maintaining the selected vehicle movement conditions (load and speed) on the V-Tech VT4/B2 chassis dynamometer (Vtech Dynamometers, Braunschweig, Germany). This type of chassis dynamometer is used in practice by vehicle manufacturers, authorized workshops, and diagnostic stations to measure the performance of the engine and other components (Figure 3).

Figure 3. Tested vehicle on V-tech VT4/B2 chassis dynamometer.

2.3. Purpose of the Research

During the research, the following selected parameters of the hybrid power unit were analyzed: torque; power; rotational speeds of the internal combustion engine, electric motor and generator; equivalent fuel consumption of the electric motor and generator; total fuel consumption of the internal combustion engine, electric motor and generator; and fuel consumption of the internal combustion engine.

3. Results

Based on the data collected from the road tests and on the chassis dynamometer, a mathematical model of the energy efficiency parameters of the tested vehicle was made. The model is presented in Figure 4.

The model applied to the study object is characterized by the following relationships. The system's mass moments of inertia and torques are specified as follows [33]:

$$J_E \cdot \dot{\omega}_E = T_E \cdot \eta_{C_1/R} - F_1(R_1 + S_1) \quad (2)$$

$$J_G \cdot \dot{\omega}_G = T_G \cdot \eta_{S_1/C_1} + F_1 S_1 \quad (3)$$

$$J_M \cdot \dot{\omega}_M = T_M \cdot \eta_{R_2/R} - F_2 S_2 \quad (4)$$

$$J_R \cdot \dot{\omega}_R = F_1 R_1 + F_2 R_2 - T_R = \frac{R_1}{R_1 + S_1} T_E \cdot \eta_{\frac{C_1}{R}} \frac{R_2}{S_2} T_M \cdot \eta_{R_2/R} - T_R \quad (5)$$

J_E represents the mass moment of inertia of the internal combustion engine (ICE), J_G denotes the mass moment of inertia of MG_1, J_M is the mass moment of inertia of MG_2, and J_R corresponds to the mass moment of inertia of the planetary ring gear. The angular velocities are given as follows: ω_E is the angular velocity of the ICE, ω_G is the angular velocity of MG_1, ω_M is the angular velocity of MG_2, and ω_R is the angular velocity of the planetary ring gear.

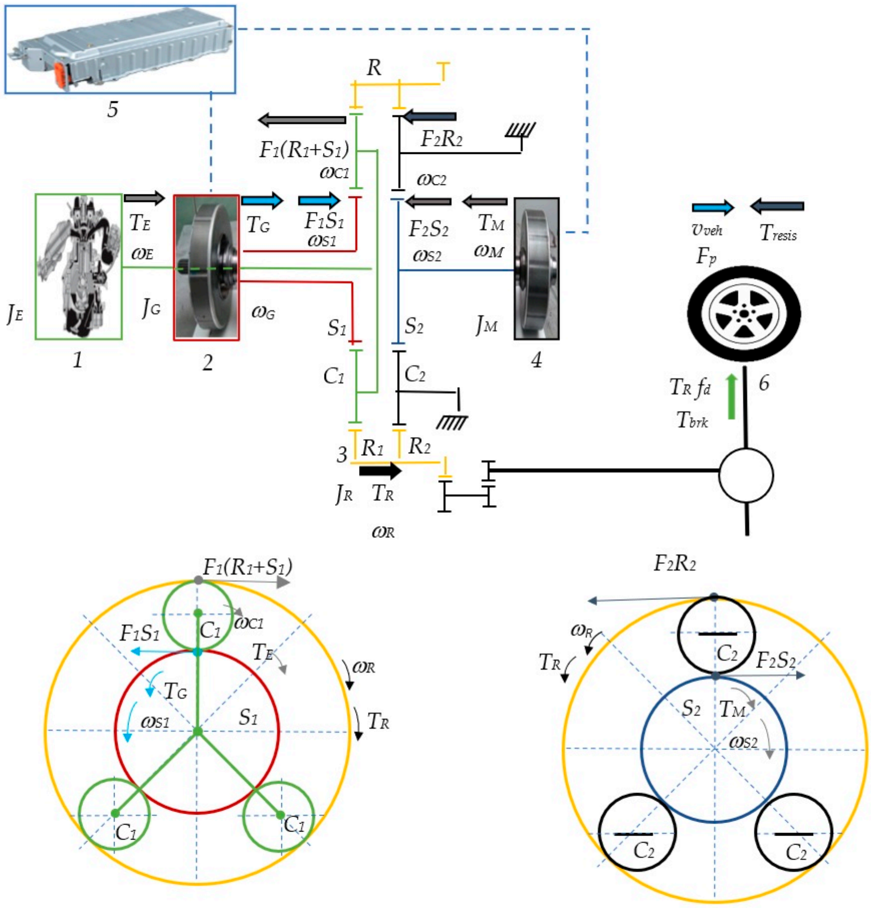

Figure 4. Base physical model of the powertrain of a hybrid vehicle.

The torques in the system are defined as follows: T_{ET} is the torque of the exhaust system, T_G is the torque of MG_1, T_M is the torque of MG2, and T_R is the torque of the planetary ring gear. The efficiency between the first set of planetary gears and the ring gear is represented by R_1C_1, while S_1C_1 indicates the efficiency between the first sun gear and the first planetary gear set. Additionally, R_2 describes the efficiency between the teeth of the second ring gear and the planetary ring gear. The internal forces between the gear teeth are denoted as F_1 for the first gear and F_2 for the second gear.

The number of teeth is given as follows: R_1 is the number of teeth on the ring gear, R_2 is the number of teeth on the ring gear adjacent to the electric motor, S_1 is the number of teeth on the first sun gear, and S_2 is the number of teeth on the second sun gear.

The inertia of the vehicle is described as follows [33]:

$$M \cdot \dot{v}_{veh} = \frac{(T_R f_d + T_{brk}) \cdot \eta_{f_d}}{r_d} - \frac{1}{2} \rho_A \cdot C_d A_f v_{veh}^2 - mg(f_r cos\alpha + sin\alpha) \quad (6)$$

In this context, M refers to the vehicle's total weight, v_{veh} the vehicle's speed, f_d stands for the overall gear ratio, T_{brk} indicates the braking torque, ηf_d is the final drive efficiency, and r_d is the dynamic radius of the wheel. Moreover, ρ_A denotes the air density, C_d is the aerodynamic drag coefficient, A_f is the frontal area of the vehicle, g represents the gravitational acceleration, and f_r is the coefficient of rolling resistance. The terms $cos\alpha$ and $sin\alpha$ describe the road slope.

The equation for vehicle speed is given by:

$$v_{veh} = \frac{\omega_R \cdot r_d}{f_d} \tag{7}$$

Applying the relationships from Equations (1) to (6) and considering the model assumptions (with $J_R \approx 0$), a simplified version of the model is presented as follows:

$$\left[J_E + J_G\left(\frac{R_1 + S_1}{S_1}\right)^2\right]\cdot\dot{\omega}_E - \left[J_G\frac{R_1\cdot S_2\cdot(R_1+S_1)}{R_2\cdot S_1^2}\right]\cdot\dot{\omega}_M = T_E\eta_{C_1/R}T_G\frac{(R_1+S_1)}{S_1}\eta_{S_1/C_1} \tag{8}$$

$$\left[J_E\cdot\frac{R_1}{R_1+S_1}\right]\dot{\omega}_E + \left[J_M\frac{R_2}{S_2} - m\cdot\left(\frac{r_d}{f_d}\right)^2\cdot\frac{S_2}{R_2}\right]\cdot\dot{\omega}_M = T_E\cdot\frac{R_1}{R_1+S_1}\eta_{C_1/R} + T_M\cdot\frac{R_2}{S_2}\eta_{R_2/R} + \frac{T_{brk}\cdot\eta_{f_d}}{f_d} + \frac{1}{2}\cdot\rho_A\cdot C_d\cdot A_f\cdot \frac{S_2{}^2\cdot\omega_M{}^2\cdot r_d^3}{R_2{}^2\cdot f_d^3} - mg\cdot\frac{r_d}{f_d}(f_r cos\alpha + sin\alpha) \tag{9}$$

The relationships that describe the cooperation between the working components of a series-parallel HEV in different driving modes—normal, eco, and power—are as follows. In electric drive mode, the internal combustion engine is inactive, resulting in the angular velocity of the ICE, motor torque T_E = 0, and mass moment of inertia J_E = 0. Consequently, Equations (7) and (8) will take on a slightly modified final form, with ω_{C1} = 0.

Another significant aspect of the energy model for the system is related to the operation of the electrochemical energy storage system.

3.1. Electrochemical Energy Accumulation System

A fully functional HEV electric drive system relies on the efficient utilization of the electrical energy source. The state of the available electrical energy is indicated by the battery's state of charge (*SOC*) which depends on the charging and discharging current of the battery [33], as described below:

$$\dot{SOC} = -\frac{V_{OC} - \sqrt{V_{OC}^2 - 4r_{bat}P_{bat}}}{2r_{bat}Q_{max}} \tag{10}$$

SOC represents the state of charge, V_{OC} is the open-circuit voltage of the battery, r_{bat} denotes the internal resistance of the battery, P_{bat} is the battery power, and Q_{max} is the maximum capacity of the traction battery.

The power from the P_{bat} storage system is utilized across all driving modes, for both propulsion and energy recovery, to meet the power requirements of the generator and/or electric motor, as described by the following equation [33]:

$$P_{bat} = T_G\cdot\omega_G\cdot\eta_G^k\cdot\eta_{C1}^k + T_M\cdot\omega_M\cdot\eta_M^k\cdot\eta_{C2}^k = T_{des}\omega_M - T_E\cdot\omega_E \tag{11}$$

^{k} is a value of -1 for charging or 1 for discharging, η_{C1}^k represents the efficiency of the generator, η_{C2}^k denotes the efficiency of the motor, and T_{des} is the torque anticipated when the accelerator or brake pedal is engaged.

The power of the energy storage system becomes positive when discharging or negative when charging.

3.2. Decision Variable

The decision variable of the system in the MPC-based energy model is the position of the accelerator pedal. It ranges from 0, indicating no pressure on the pedal, to 100%, representing the pedal being fully depressed.

3.3. System Limitations

The applied energy management strategy—the MPC—has certain limitations, as follows [33]:

ICE Torque:

$$T_E^{min} \leq T_E \leq T_E^{max} \tag{12}$$

Angular velocity ICE:

$$\omega_E^{min} \leq \omega_E \leq \omega_E^{max} \tag{13}$$

MG_1 torque:

$$T_G^{min} \leq T_G \leq T_G^{max} \tag{14}$$

Angular velocity of MG_1:

$$\omega_G^{min} \leq \omega_G \leq \omega_G^{max} \tag{15}$$

MG_2 torque:

$$T_M^{min} \leq T_M \leq T_M^{max} \tag{16}$$

MG_2 rotational speed:

$$\omega_M^{min} \leq \omega_M \leq \omega_M^{max} \tag{17}$$

Traction battery power:

$$P_{bat}^{min} \leq P_{bat} \leq P_{bat}^{max} \tag{18}$$

SOC traction battery:

$$SOC^{min} \leq SOC \leq SOC^{max} \tag{19}$$

The mathematical model has been linearized to certain conditions. The linear form of MPC is represented by the following matrices:

$$\begin{bmatrix} E_{11} & -E_{12} \\ E_{21} & E_{22} - \rho_A \cdot C_d \cdot A_f \cdot \frac{S_2^2 \cdot r_d^3}{R_2^2 \cdot f_d^3} \end{bmatrix} \cdot \begin{bmatrix} \dot{\omega}_E \\ \dot{\omega}_M \end{bmatrix} = \begin{bmatrix} \eta_{C_1/R} & \frac{R_1}{R_1+S_1} \cdot \eta_{S_1/C_1} & 0 \\ \frac{R_1}{R_1+S_1} \eta_{C_1/R} & 0 & \frac{R_2}{S_2} \eta_{R_2/R} \end{bmatrix} \begin{bmatrix} T_E \\ T_G \\ T_M \end{bmatrix} \tag{20}$$

where

$$E_{11} = J_E + J_G \left(\frac{R_1 + S_1}{S_1} \right)^2 \tag{21}$$

$$E_{12} = \left[J_G \frac{R_1 \cdot S_2 \cdot (R_1 + S_1)}{R_2 \cdot S_1^2} \right] \tag{22}$$

$$E_{21} = \left[J_E \cdot \frac{R_1}{R_1 + S_1} \right] \tag{23}$$

$$E_{22} = \left[J_M \frac{R_2}{S_2} - m \cdot \left(\frac{r_d}{f_d} \right)^2 \cdot \frac{S_2}{R_2} \right] \tag{24}$$

$$E_D = E_{11} (E_{22} - \rho \cdot C_d \cdot A_f \cdot \frac{S_2^2 \cdot r_d^3}{R_2^2 \cdot f_d}) + E_{12} \cdot E_{21} \tag{25}$$

For the electric driving mode, (ELECTRIC) $T_E = 0$, $\theta_E = 0$.

The relationship between the required values of torque for the ICE and MG_2 is outlined below. The system outputs are also taken into account, with the fuel consumption by the ICE represented by the following equations [33]:

$$b = \frac{\dot{m}}{P_E} \tag{26}$$

$$\dot{m} = b \cdot P_E = b \cdot T_{Edes} \cdot \omega_E = \frac{T_{Edes} \cdot \omega_E}{\eta_E \cdot W_u} \tag{27}$$

b represents the specific fuel consumption, mmm denotes the actual fuel consumption, P_E is the power of the internal combustion engine, T_{Edes} is the desired torque of the internal combustion engine, η_E indicates the overall efficiency of the engine, and W_u refers to the calorific value of the fuel (assumed to be 44×10^6 J/kg for gasoline).

The equivalent fuel consumption, calculated based on the energy used from the traction battery, is determined by the following formula [33]. The parameters of the adopted model are detailed in Table 1:

$$\dot{m}_{eq} = \frac{P_{bat}}{W_u} \tag{28}$$

where $\dot{m}_{eq}$: is equivalent to fuel consumption.

Table 1. Known parameters of the adopted model [33].

Ratio f_d	3.27
Number of teeth ring wheel R_1	78
Number of teeth sun wheel S_1	30
Number of teeth sun wheel S_2	22
Number of teeth ring gear R_2	58
efficiency pg—main gearbox	0.82
Efficiency C_1/R	0.98
Efficiency S_1/R	0.96
efficiency R_2/R	0.99
efficiency R	0.9702
power correction factor	0.93
NiMH charging efficiency bat	0.85
unladen vehicle mass m	1470 kg
dynamic wheel radius r_d	0.291823 m
air density	1.253 kg/m^3
Drag coefficient C_d	0.25
Vehicle frontal area A_f	2.6 m^2
Coefficient of rolling resistance f_r	0.0084
Calorific value of petrol	42.6 MJ/kg
Calorific value of petrol + catalyst	43 MJ/kg
Fuel density (petrol)	0.7 kg/dm^3
Fuel density (petrol + catalyst)	0.71 kg/dm^3
Reference conditions—temperature	25 °C *
Reference conditions—pressure	100 kPa
Traction battery voltage (no load)—V_{OC}	201.6 V
Traction battery current (no load)—I_{OC}	6.5 A
Maximum electrical capacity of the traction battery—Q_{max}	1310.4 Wh

* The choice of this temperature was dictated by previous discussions with the vehicle manufacturer and the catalyst manufacturer.

The model parameters measured included:

- vehicle speed;
- time;
- distance;

- torques: generator, electric motor, combustion engine;
- rotational speeds: generator, electric motor, combustion engine;
- fuel consumption by mass: combustion engine, equivalent, total;
- traction battery power and level of charge (*SOC*);
- mileage fuel consumption: internal combustion engine, total.

Model limitations:

$$0 \leq T_E \leq 142 \text{ Nm} \tag{29}$$

$$0 \leq \omega_E \leq 544 \text{ 1/s} \tag{30}$$

$$-45.56 \text{ Nm} \leq T_G \leq 45.56 \text{ Nm} \tag{31}$$

$$-1077.74 \text{ 1/s} \leq \omega_G \leq 1077.74 \text{ 1/s} \tag{32}$$

$$-207 \text{ Nm} \leq T_M \leq 207 \text{ Nm} \tag{33}$$

$$-1413.68\frac{1}{\text{s}} \leq \omega_M \leq 1413.68\frac{1}{\text{s}} \tag{34}$$

$$-34.46 \text{ kW} \leq P_{bat} \leq 34.46 \text{ kW} \tag{35}$$

$$49.91\% \leq SOC \leq 63.3\% \tag{36}$$

The results of the field tests and the chassis dynamometer are presented in Figures 5–11.

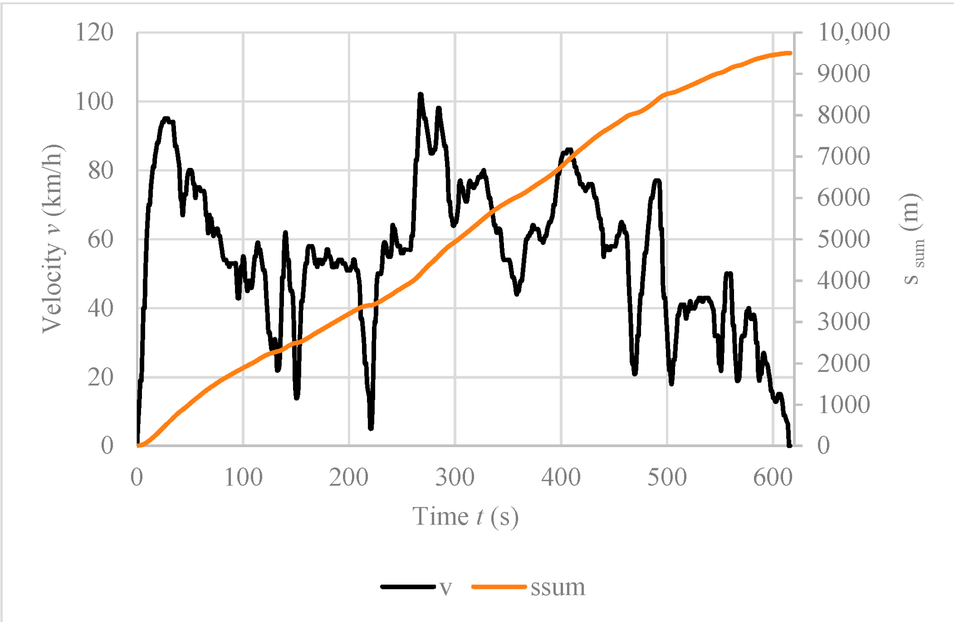

Figure 5. Speed and distance traveled by vehicle under test without the catalyst.

Field tests were carried out under urban and non-urban traffic conditions. They served to collect relevant performance parameters. Tests of energy efficiency parameters with the addition of a liquid catalytic reactor were carried out under stationary conditions. The time-dependent vehicle speed profile was mapped (as shown in Figure 5). The results of the on-road and stationary tests were normalized in accordance with DIN EN 13108-20 [34].

The vehicle speed varied intermittently from 0 to 102 km/h. It depended on the traffic conditions. During urban driving, it did not exceed 50 km/h, while in non-urban areas it was a maximum of 102 km/h (motorway). The vehicle covered a distance of 9498.56 m while driving. This was completed in 616 s. Moments where the power machine was in use were among the important operating parameters examined during the tests.

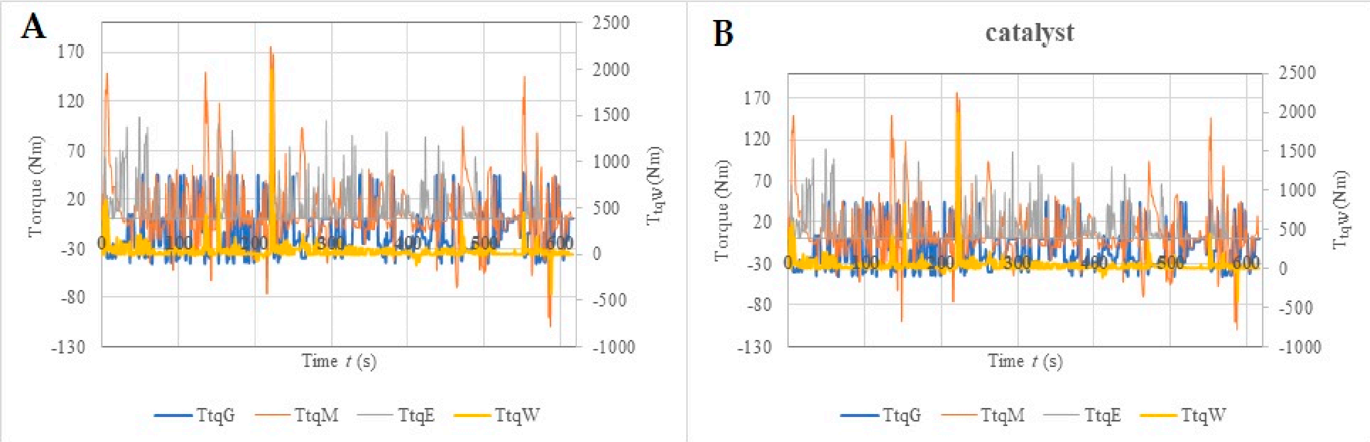

Figure 6. Torques: generator, electric motor, internal combustion engine, on wheels: (**A**) standard fuel; and (**B**) fuel with catalytic converter Eco Fuel Shot.

In road tests (without fluid catalytic converter), the generator torque values varied between −45.56 Nm. . .45.25 Nm; the electric motor torque values varied between −109.57 Nm to 175.34 Nm; and the internal combustion engine torque values varied between 0 Nm to 110 Nm.

In stationary tests (using a fluid catalytic reactor), the generator torque values varied from −45.56 Nm to 45.25 Nm; the electric motor torque values varied from −109.57 Nm to 175.34 Nm; and the internal combustion engine torque values varied from 0 Nm to 113.3 Nm.

Thus, a slight increase in engine torque after the catalytic reactor (from 110 Nm to 113.3 Nm) was noticeable.

The next parameters considered were the speeds of the electric machines.

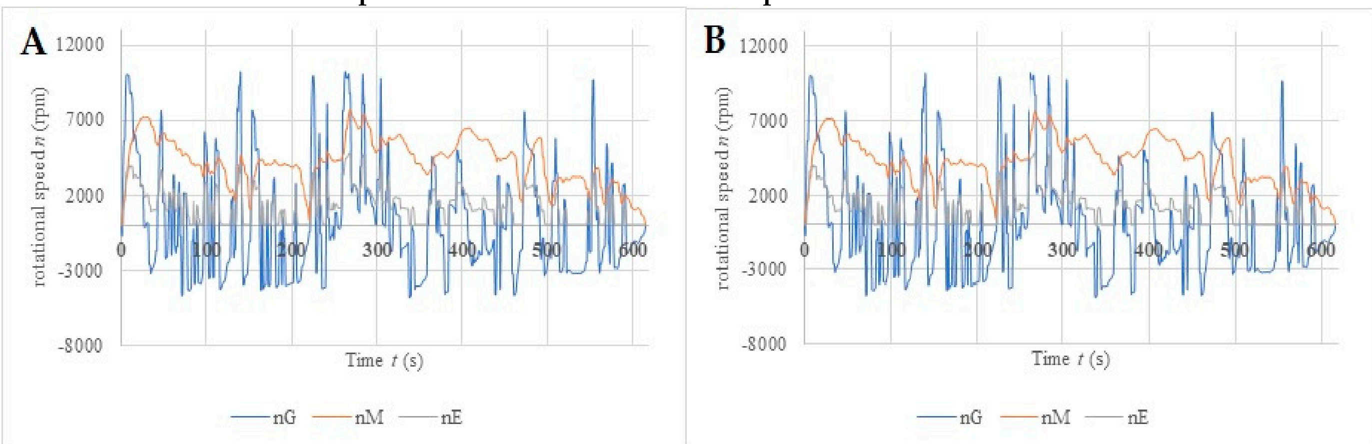

Figure 7. Rotational speeds: generator, electric motor, internal combustion engine: (**A**) standard fuel; and (**B**) fuel with catalytic converter Eco Fuel Shot.

In this case, the use of the catalytic reactor had no effect on the variations in the speed of the power machines (generator, electric motor, and internal combustion engine). The speed of the generator varied from −4769 to 10,292 rpm, the speed of the electric motor varied from 0 to 7630 rpm, and the speed of the internal combustion engine varied from 0 to 4800 rpm.

Energy efficiency was presented in the form of the following three parameters: mass fuel consumption; equivalent fuel consumption; and total fuel consumption.

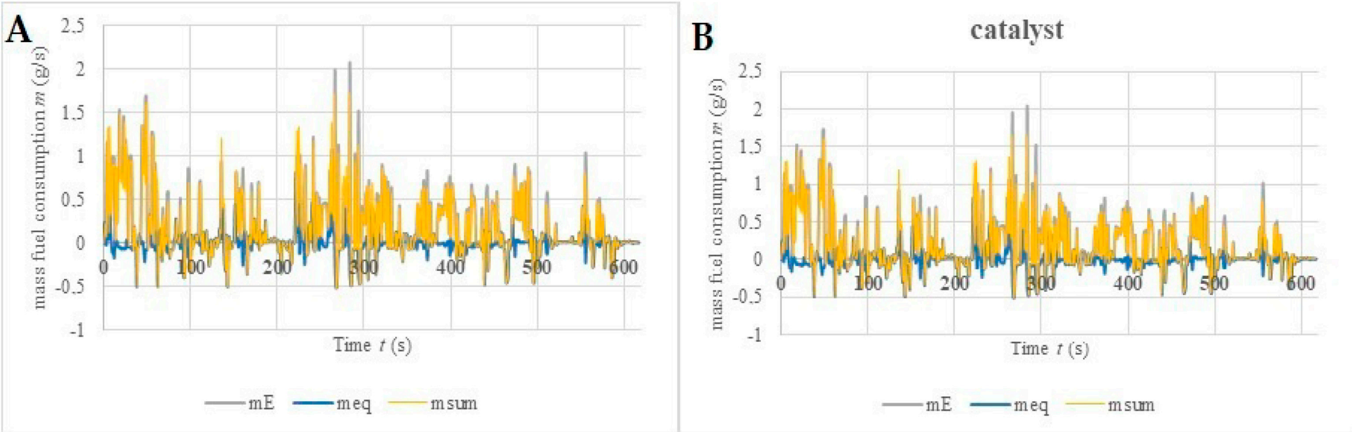

Figure 8. Mass fuel consumption: internal combustion engine, equivalent electric machines, total: (**A**) standard fuel; and (**B**) fuel with catalytic converter Eco Fuel Shot.

During the road tests (without catalytic converter), the mass consumption varied from 0 to 2.07 g/s, the equivalent fuel consumption varied from −0.51 to 0.81 g/s, and the total fuel consumption ranged from −0.51 to 1.72 g/s.

During stationary tests (with catalytic converter), the mass fuel consumption varied from 0 to 2.04 g/s, the equivalent fuel consumption varied from −0.51 to 0.80 g/s, and the total fuel consumption ranged from −0.51 to 1.64 g/s.

Also related to energy efficiency was the power of the traction battery and its degree of charge.

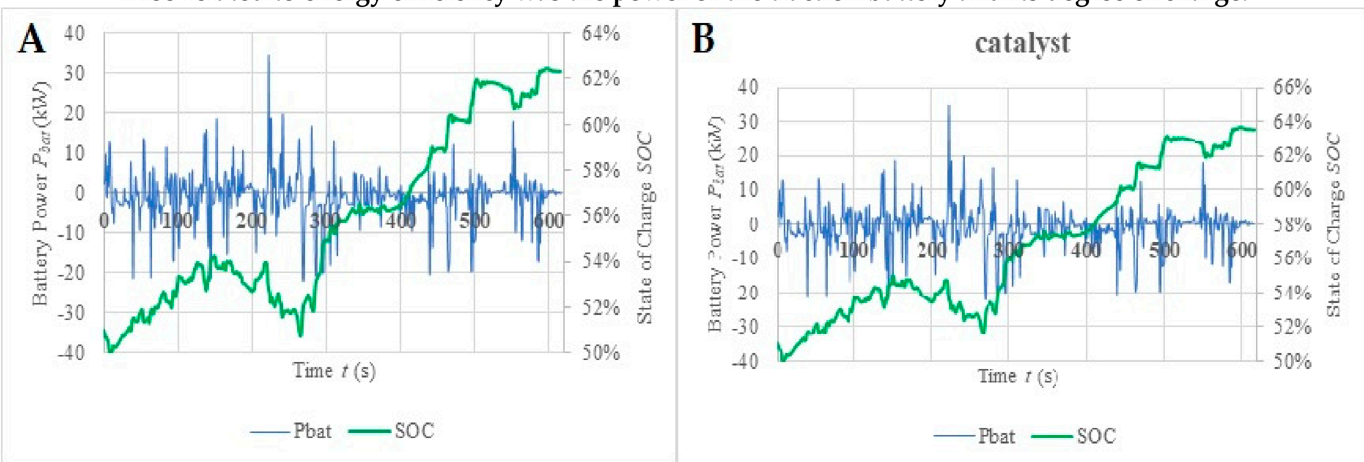

Figure 9. Power and degree of charge of the traction battery: (**A**) standard fuel; and (**B**) fuel with catalytic converter Eco Fuel Shot.

During the road tests (without catalytic converter), the traction battery power varied from −21.82 to 34.46 kW and its degree of charge (SOC) ranged from 49.91 to 62.42%.

During stationary tests (with catalytic converter), the traction battery power varied from −21.82 to 34.46 kW and its degree of charge (SOC) ranged from 49.91 to 63.71%.

The presented discussion related to the reduction in fuel consumption after the application of the catalytic converter can be observed in Figures 10 and 11.

The fuel consumption of the internal combustion engine was measured under on-road test conditions (without catalytic converter) and under stationary test conditions (with catalytic converter) every 100 s. The fuel consumption was taken into account after driving the first 100 s, then after driving the next 100 s (200 s), the next 100 s (300 s), and so on. The mileage fuel consumption after driving a complete distance over 616 s was also taken into taccount.

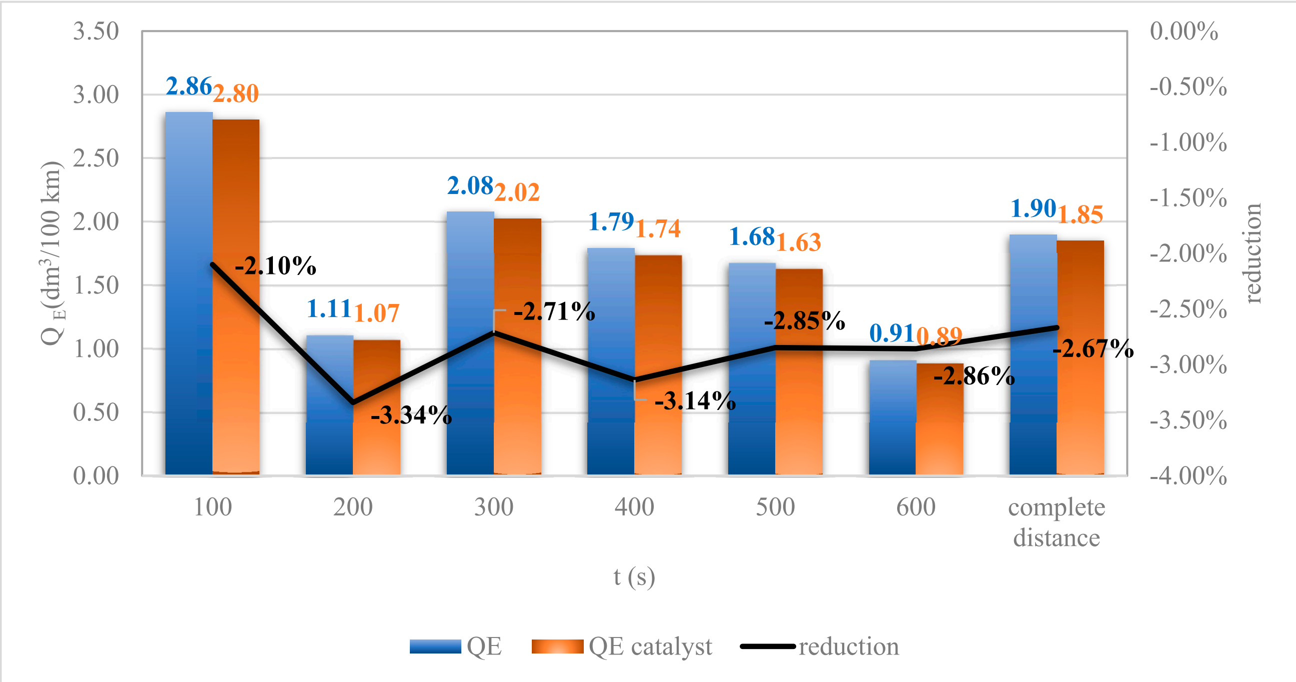

Figure 10. Mileage fuel consumption (internal combustion engine only).

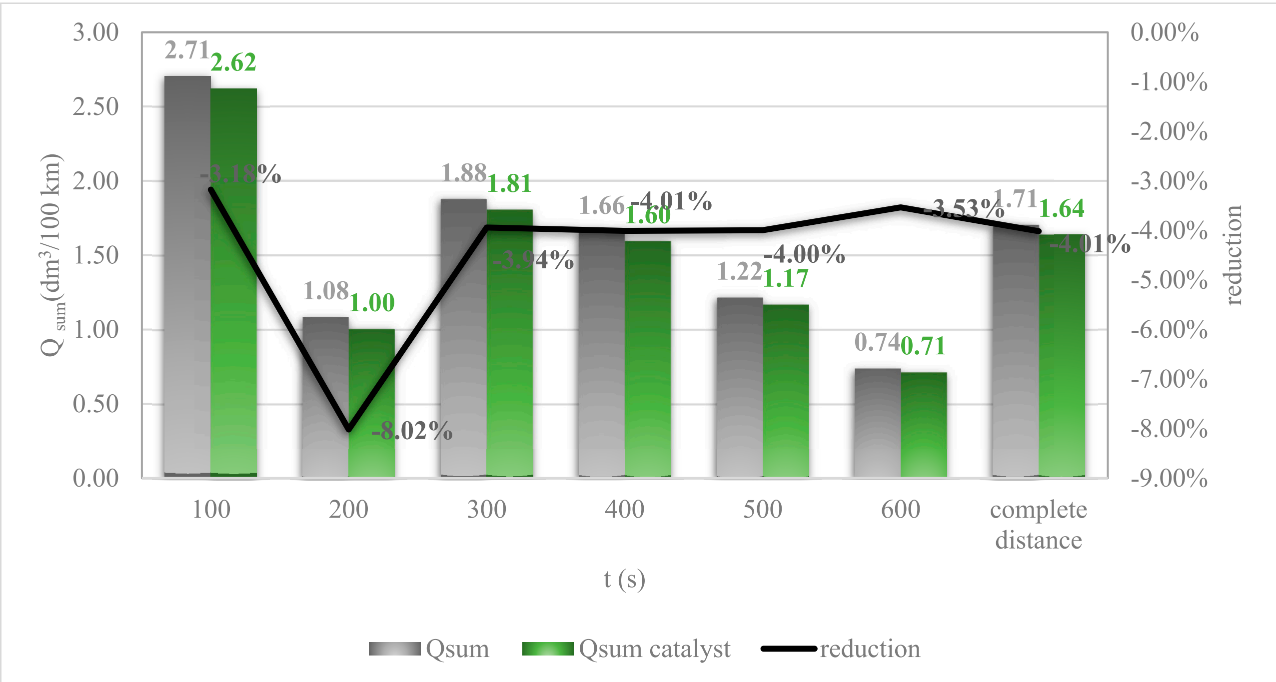

Figure 11. Total fuel consumption of an internal combustion engine with an electric motor.

The use of a catalytic reactor enabled a reduction in the mileage fuel consumption of the internal combustion engine of between 2.10 to 3.34%. A reduction of 2.67% in the fuel consumption of the internal combustion engine was observed over the entire distance travelled.

The total mileage fuel consumption was measured under road test conditions (without catalytic converter) and stationary test conditions (with catalytic converter) every 100 s. The cumulative mileage fuel consumption was taken into account after the first 100 s, after a further 100 s (200 s), then after a further 100 s (300 s), and so on. The cumulative fuel consumption after driving a complete distance over 616 s was also taken into account.

The use of a catalytic reactor reduced the fuel consumption in the total distance travelled of the internal combustion engine by between 3.18 to 8.02%. Over the entire distance travelled, a reduction of 4.01% in total mileage fuel consumption was observed.

4. Discussion

In most cases, spark-ignition engines are used in HEVs. In these engines, fuel and air are mixed with each other, either in the intake system or in the cylinder, where they are mixed with residual gases and then compressed. The combustion process begins in the final compression phase at the spark plug by an electrical discharge between its electrodes. After ignition of the combustible mixture, the flame spreads in a turbulent manner until it reaches the walls of the combustion chamber, and then it goes out.

Eco Fuel Shot is a liquid catalyst designed to reduce and oxidize harmful substances, primarily nitrogen oxides (NOx) and hydrocarbons (HC), in exhaust gases during the combustion process. The active component in Eco Fuel Shot decreases the surface tension of carbon, ensuring the complete combustion of soot and naphthalene and preventing the buildup of deposits. The catalyst influences the combustion chain reaction rate by altering the activation energy of chemically inert particles, facilitating their interaction. This selective catalyst reduces the levels of nitrogen oxides and hydrocarbons by oxidizing them during combustion without altering the process parameters. During combustion, the catalyst initiates redox reactions that involve the oxidation and reduction of various chemical compounds, including nitrogen oxides, hydrocarbons, carbon monoxide, and carbon dioxide. The combustion process within an engine is a rapid chemical reaction involving the combination of substances with oxygen, releasing significant heat. This reaction occurs when colliding molecules possess enough energy to exceed a specific threshold value, breaking existing molecular bonds and forming new ones. The energy required for these molecules to react is known as activation energy. In internal combustion engines, activation energy plays a crucial role in the reaction's progression. Although collisions between molecules are necessary to start a reaction, not all collisions result in a reaction. If every collision did, reactions would happen almost instantaneously. Instead, only a fraction of collisions, those with energy slightly above the average at a given temperature, are effective. Activation energy represents the excess energy that molecules need at the time of collision for a chemical reaction to occur, determining the reaction rate. Lower activation energy increases the reaction rate constant, accelerating the reaction. For hydrocarbon fuels, defined as polyatomic systems, activation energy is the minimum kinetic energy required for a chemical reaction to proceed. The activation energy varies depending on the molecular structure and bond strength, with C–H bonds in paraffinic hydrocarbons (CnH2n+2) having a higher breaking energy than C–C bonds. Surfactants, substances that reduce interfacial tension between two phases, influence the activation energy of reacting substrates. Eco Fuel Shot serves as a low-energy activation catalyst, reacting with substrates to form products more easily, resulting in improved combustion and energy efficiency in hybrid vehicles. The chemical composition of the Eco Fuel Shot catalyst is detailed in Table 2.

Table 2. Chemical composition of the catalyst.

No.	Identification	Concentration [%]
1	3–Metylobutan–1–ol (Isoamyl alcohol)	50
2	Isopropyl alcohol (2–Propanol)	28
3	1–Butanol	12
4	Acetic acid	10

In the analysis of the combustion process, one of the identified stages is the auto-ignition delay period. In spark-ignition engines, this is the interval between the discharge between the electrodes of the spark plug and the ignition of the combustible mixture. The release of a hydrogen molecule allows for the alteration of the fuel's chemical properties, thereby enhancing the combustion process. Due to its properties, hydrogen exerts an influence on the activation energy, reducing it. The physical meaning of activation energy in relation to reciprocating internal combustion engines can be elucidated as follows. For a reaction to commence, it is essential that the reacting particles collide. In practice, not all collisions result in a reaction between the colliding particles. If each collision resulted in a reaction, then all reactions would occur almost instantaneously. Conversely, all reactions are subject to a finite velocity, indicating that only a specific number of collisions result in a reaction. An effective collision is defined as one in which the energy at the moment of impact is slightly higher than the average energy determined for a given temperature. The activation energy is the energy that the molecules must possess at the moment of collision in order to react chemically. It is the fundamental factor that determines the course of a chemical reaction [3,14]. The lower the activation energy, the higher the reaction rate constant and the faster the reaction. To facilitate the overcoming of the energy barrier associated with the activation energy, two potential avenues exist: the provision of additional energy to the reaction medium (e.g., through heating) or the utilization of a substance that readily reacts with the substrate (low-activation energy) and the resulting compound that transitions easily into the final product (also low-activation energy). A substance that facilitates the transition from substrate to product in this way is called a catalyst. Once the substrates have been transformed into products, the catalyst completely reconstitutes itself, which is why one sometimes comes across the expression that a catalyst is a substance that does not take part in the reaction, but only facilitates it.

5. Conclusions

There is no doubt that hybrid vehicles are the next step on the road to zero emissions, and research in this area is becoming crucial for the future of the entire automotive market. The importance of the topic raised by the authors has been justified by the European PHOENICE project, in which representatives of eight global companies that are leaders in the automotive industry from France, Germany, Italy and the United Kingdom participate; one of the goals is to improve the energy efficiency of hybrid units by developing innovative solutions for this category of drives [35].

The aim of this study was to assess selected parameters concerning the energy efficiency of a hybrid vehicle powered by traditional fuel with the addition of the liquid catalyst Eco Fuel Shot. In their earlier research, the authors analyzed the properties of the catalyst in the fuel in the case of a compression ignition engine [36], pointing out that use of the Eco Fuel Shot liquid catalyst can reduce the emissions of selected toxic substances in exhaust gases.

The current presented research focused on assessing the use of a catalytic additive in the combustion process of a spark-ignition engine used in hybrid vehicles. The research has shown that the mentioned catalytic converter can lead to an average reduction in the fuel consumption of an internal combustion engine of 2.67%. In addition, calculations based on the proposed mathematical model showed that there is a measurable increase in the efficiency of the powertrain, which reduces the equivalent energy consumption of the electric motor and the battery energy system in the hybrid vehicle. This postulate is particularly interesting given the ongoing research on additives to traditional fuels.

It should be emphasized that the presented research focused on the assessment of selected parameters in the operation of a hybrid unit in a real and simulated environment. Both in practice and in theory, it is crucial to answer the question as to whether the conclusions of the tests can be directly implicated in the case of other hybrid units used in other vehicles. The authors postulate that a full assessment of the possible benefits of using the Eco Fuel Shot additive in the case of hybrid power units where the main role is played by a compression ignition unit should be individual. Given that the direct implications are influenced by many determinants, including the varying degrees of complexity in the construction of individual drive units, variable operating characteristics, technical condition, ambient temperatures, etc., it should therefore be remembered that a possible comprehensive assessment of all the consequences resulting from the use of a fuel additive will only be possible through thorough and in-depth research covering the entire spectrum of consequences of its use in the long term. However, the use of fuel additives, such as Eco Fuel Shot, can be an extremely important step towards achieving the goal of extending the life of spark-ignition units in the era of increasing requirements for exhaust emission standards such as EURO 7 [37].

This article presents an analysis of the energy efficiency parameters of a hybrid vehicle powered by fuel with a liquid catalyst. The research process was presented. The selection of the drive unit for the research was explained and a description of selected variables for analysis was included. However, due to limitations, the focus was on one of the most popular types of HEV power unit. Thus, like any test, this one also has its limitations. In the authors' opinion, further research on this topic should be comprehensive. Therefore, it should include a larger number of drive units. Further directions should concern operational aspects, including the impact of using fuel additives on the service life of individual elements of the drive unit. Research should focus on the economic impact in connection with the constantly rising prices of energy resources and changes in the field of car repairs, including the introduction of a circular cycle in terms of individual parts and components of the vehicle.

To sum up, the presented considerations do not exhaust the entire topic of Eco Fuel Shot fuel additives in relation to HEVs, which are gaining popularity. This study certainly provides a basis for polemics and encouragement for further research on this topic. According to the authors, further work in the research area may determine the future of this category of vehicles in today's competitive market.

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Conflicts of Interest: The authors declare no conflict of interest.

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