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Research of energy efficiency indicators of a hybrid electric automotive power unit based on a spark ignition engine

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Abstract. The article examined the results of an experimental study on the energy-efficiency indicators of a hybrid electric automotive power unit based on a spark-ignition engine. The purpose of the study was to conduct a comprehensive assessment of the energy efficiency of a hybrid electric automotive power unit based on a spark-ignition engine. The research method involved experimental bench tests of a hybrid electric automotive power unit in defined operating modes to determine the regularities of changes in control parameters of the internal combustion engine, electrical subsystems, fuel economy, and environmental indicators. The experimental study of the hybrid electric automotive power unit identified regularities in energy-efficiency indicators and working-process characteristics depending on the output shaft rotational speed and power. Changes were observed in the speed and load modes of the internal combustion engine, motor generator 1, and motor generator 2, as well as in fuel consumption, the air-fuel equivalence ratio, and the ignition timing of the internal combustion engine. The state of charge of the traction battery, thermal-regime parameters of the air supply, lubrication, cooling, and exhaust systems of the internal combustion engine, motor generator 1, motor generator 2, inverter, and battery, and exhaust pollutant concentrations and their neutralisation efficiency were also analysed. Notably, a nearly direct relationship was found between the rotational speed and load of the internal combustion engine and the overall load mode of the power unit. Controlling the air-fuel mixture composition and ignition timing in all modes ensured high fuel efficiency and low emissions of harmful substances. High energy-efficiency indicators under various operating conditions were achieved due to the electric subsystem of the power unit, which provided optimal control of the speed and load mode of the internal combustion engine

Keywords: torque; hybrid transmission; operating mode; traction battery state of charge; fuel economy; environmental indicators

Introduction

The most common sources of energy in transport, particularly in the automotive sector, remain internal combustion engines (ICEs). Consequently, motor vehicles are significant consumers of fuel resources and major contributors to environmental pollution through harmful substances emitted with engine exhaust gases. The performance indicators of automotive engines depend on the nature and characteristics of their energy conversion

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processes, the fuels used, parameter regulation, and their technical condition. At the same time, these features of the working processes largely determine the level of pollutant emissions. Therefore, fuel economy indicators, as well as the energy and environmental performance of engines, can be combined into a general group of energy-efficiency indicators. Modern requirements for automotive vehicles, particularly Regulation (EU) 2019/631 (2019), emphasise substantial reductions in carbon dioxide emissions, primarily achieved through improvements in fuel economy. For this reason, continuous efforts are made to improve the working processes of automotive engines to achieve higher fuel-efficiency levels, as noted by P. Kumbar (2020) and D. Rimpas *et al.* (2025). One of the approaches to such improvement is enhancing engine efficiency under the most common operational modes. According to Y. Pan *et al.* (2025), a relevant direction in the development of automotive engines is the adjustment of their operating modes toward those that ensure high efficiency through the use of a hybrid electric drivetrain. Among such hybrid electric automotive power units, spark-ignition engines have become the most widely used. A significant number of recent studies have been devoted to determining the performance indicators of hybrid electric automotive power units. N. Sergienko *et al.* (2023) presented simulation models of the control and monitoring system and provides an investigation of the dynamic behaviour of parameters of elements of a hybrid vehicle with a series-parallel drivetrain using simulation modelling in the Matlab/Simulink environment. The analysis by O.V. Bazhynov & M.M. Kravtsov (2023) is devoted to theoretical research on methods for assessing the performance indicators of electric and hybrid vehicles during operation, with particular regard to the vehicle's average speed. The work by B. Šarkan *et al.* (2019) highlighted the significance of hybrid vehicles in urban traffic from an environmental perspective. Results obtained using an exhaust gas analyser, together with emission calculations based on engine control unit data, indicate that during urban operation the hybrid vehicle functioned in electric-drive mode for up to 75.40% of the time, while CO_2, HC, and NOx emissions were substantially lower than those of conventional vehicles of a comparable class. C. Saju *et al.* (2022) examined the issue of optimal control of hybrid vehicle drivetrain components and determined vehicle characteristics through modelling in Matlab/Simulink using the EPA HWFET (United States Environmental Protection Agency Highway Fuel Economy Test) highway driving cycle (United States) to evaluate fuel economy.

N.N. Mustafi (2021) provided an overview of modern hybrid electric vehicle technologies, including an analysis of the main configurations combining different energy sources, characteristics of hybrid system components, methods of energy storage and conversion, hybrid powertrain control strategies, environmental indicators, and the critical problems and challenges faced by contemporary hybrid power units. Among the most significant issues identified are: the efficiency, availability, and reliability of electrical energy storage systems; effective management of energy flows from various sources; efficient system architecture based on power-demand and cost considerations; efficiency and reliability of power electronics; characteristics of primary electric machines; and effective control of key hybrid power unit components. The work by Y. Wang *et al.* (2021) presented a novel hybrid power unit based on a linear free-piston engine intended for hybrid light commercial urban vehicles. The study analysed the efficiency of the proposed hybrid power unit as well as the various factors influencing its performance. M. Tomita *et al.* (2024) described new Toyota technologies aimed at enhancing Toyota Prius hybrid vehicles to increase their efficiency and reduce CO_2 emissions globally. In particular, improvements were made to traction battery capacity, transmission efficiency, internal combustion engine energy efficiency, and power-electronics performance. These advancements led to an increase in the electric-drive range to 72 km while simultaneously enhancing overall energy efficiency. The work by A.N.F. Abdelbaky *et al.* (2025) investigated the efficiency of implementing a series-parallel hybrid electric powertrain in a commercial VW (Volkswagen) Crafter vehicle equipped with a diesel engine, with respect to fuel consumption, CO_2 emissions, and driving range under standard driving cycles (New European Driving Cycle, Worldwide Harmonised Light Vehicles Test Procedure, Federal Test Procedure-75, and HWFET). The results of Matlab/Simulink modelling indicate that the average fuel consumption and CO_2 emissions are reduced by about 29%, while the driving range increases by nearly 41% when using a hybrid powertrain compared with a conventional one, provided that the nominal power and torque are similar. At the same time, the study by E.V. Rojas-Reinoso *et al.* (2024) showed that despite the declared high fuel efficiency and low CO_2 emissions, vehicles with hybrid electric powertrains may exhibit reduced fuel economy under conditions of extremely dense traffic with severe congestion. Based on the results of this study, the dependence of fuel consumption for vehicles with gasoline engines of various displacements and for a vehicle with a hybrid powertrain was analysed under conditions of overloaded urban highways in high-altitude areas. The highest fuel efficiency was demonstrated by the vehicle with the smallest analysed engine displacement of 1.2 L, whereas the hybrid vehicle showed relatively high fuel consumption under the specified driving conditions.

The analysis of these and other recent studies in the field of hybrid electric automotive power units demonstrates the significant interest of researchers and automotive developers in such transport energy-supply technologies. Leading global automotive companies have already developed and continue to refine hybrid vehicle components. However, substantial unresolved critical issues remain concerning the efficiency, reliability, and cost of hybrid electric power units. In Ukraine, the development of hybrid electric vehicle technologies is at an early stage, prompting further research in this direction, particularly the study of existing technologies, their efficiency, and features of implementation. This will enable the introduction and development of such power units in the domestic automotive sector to enhance energy efficiency and environmental safety. A primary step in studying existing hybrid power units is experimental laboratory research, which makes it possible to determine the main operational characteristics of these units and the regularities of controlling their operating modes. The aim of the work was a comprehensive assessment of the energy efficiency of a hybrid electric automotive power unit featuring a spark-ignition engine. To achieve this objective, the following tasks were carried out:

1. Development of a structural and functional diagram of an experimental setup and justification of the technical characteristics of the equipment necessary for conducting experimental research on a hybrid electric motor unit for a vehicle.

2. Conducting experimental bench tests to determine energy efficiency indicators and study the features of the working processes of a hybrid electric motor unit of a car based on an internal combustion engine.

3. Conducting a comprehensive analysis and scientific discussion of the results of experimental studies of the energy efficiency indicators of a hybrid electric motor unit for a car, with an assessment of their practical and theoretical significance.

Materials and Methods

The object of the experimental research was the hybrid electric power unit of a Toyota Prius vehicle equipped with a 1NZ-FXE spark-ignition engine (4FS 7.5/8.47) with a rated power of 57 kW, featuring electronically controlled fuel injection, variable valve timing, and an exhaust-gas (EG) aftertreatment system with a three-way catalytic converter (Fig. 1). The setup was installed in the Engine Testing Laboratory of the Department of "Engines and Heating Engineering" at the National Transport University (Ukraine). The subject of the study was the influence of operating modes on the energy efficiency indicators of a hybrid electric automotive power unit based on a spark-ignition engine.

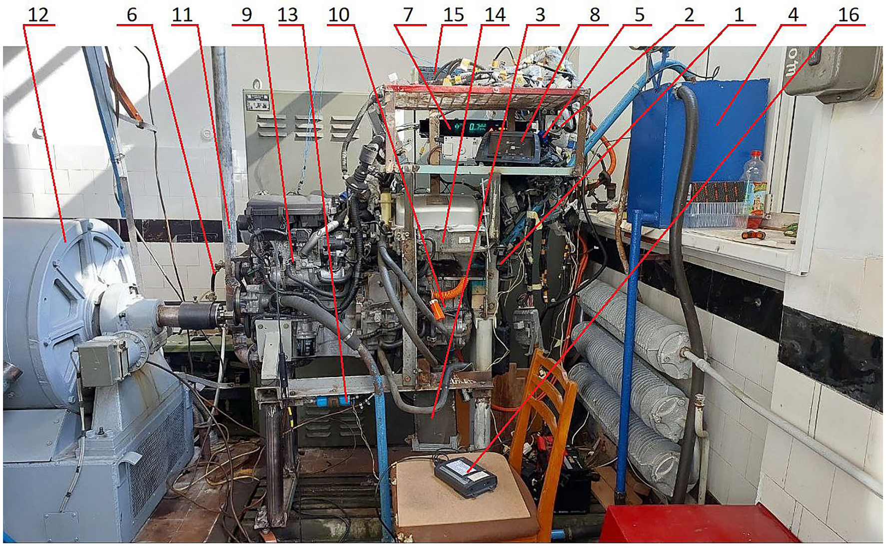

Figure 1. A hybrid electric power unit equipped with a Toyota 1NZ-FXE engine

Note: 1 – accelerator pedal with a device for fixing its position; 2 – transmission mode selector; 3 – inverter and transmission cooling system; 4 – ICE cooling system; 5 – diagnostic device for connection to the OBD (on-board diagnostics) data-reading system; 6 – exhaust gas sampling system; 7 – instrument panel; 8 – energy flow monitor; 9 – ICE; 10 – hybrid transmission; 11 – exhaust and exhaust-gas aftertreatment system; 12 – electric load machine; 13 – fuel supply system; 14 – inverter; 15 – high-voltage traction battery; 16 – oil temperature measurement device

Source: authors' photo

Figure 1 depicts a hybrid electric power unit featuring an engine, highlighting key components like energy monitoring, cooling systems, and diagnostic tools. It demonstrates the integration of traditional ICE technology with hybrid systems, ensuring optimised performance, fuel efficiency, and emissions control. The experimental setup also includes other components not shown in Figure 1, in particular: a brake pedal, a control panel for the load machine, a power unit control system, a device for displaying OBD system parameters, and gas analysis equipment for determining the composition of the exhaust gases. A brief technical specification of the power unit is provided in Table 1.

Table 1. Brief technical specifications of the experimental research object

No.	Parameter name	Parameter value
1	Engine model	1NZ-FXE
2	Number of cylinders	4
3	Firing order	1-3-4-2

Table 1, Continued

No.	Parameter name	Parameter value
4	Cylinder arrangement	inline
5	Displacement, L	1.497
6	Cylinder bore and stroke, mm	75/84.7
7	Compression ratio	13
8	Number of intake/exhaust valves per cylinder, pcs	2/2
9	Rated power, kW	57 at 5,000 min^{-1}
10	Maximum torque, Nm	111 at 4,200 min^{-1}
11	Fuel type	gasoline A-95
12	Fuel injection system	port fuel injection
13	Variable valve timing system	hydraulically controlled camshaft drive clutch
14	Ignition system	electronic, with individual ignition coils and knock control
15	Exhaust gas aftertreatment system	three-way catalytic converter
16	Hybrid system type	series-parallel
17	Traction battery type	nickel-metal hydride (NiMH)
18	Battery voltage, V	201.6
19	Traction battery capacity, kWh	1.31
20	Battery mass, kg	40.3
21	Battery power, kW	21
22	Inverter voltage range, V	200…500
23	Type of MG1 and MG2 motor-generators	AC motors with permanent-magnet rotors
24	Rated power of MG1, kW	33
25	Rated power of MG2, kW	50 at 1,200…1,540 min^{-1}
26	Maximum torque of MG2, Nm	400 at 0…1,200 min^{-1}
27	Hybrid transmission	single planetary gearset for power-split
28	Planetary gearset ratio	-2.6
29	Final drive ratio	4.113
30	Maximum system power, kW	82 at ≥ 85 km/h
31	Maximum system torque, Nm	478 at ≤ 22 km/h

Note: MG – motor generator
Source: developed by the authors based on Toyota Motor Sales (2004), R.H. Staunton *et al.* (2006), Toyota Motor Europe (n.d.)

The power unit consists of two main parts: the ICE and its associated systems, and the electrical subsystem. The ICE is an inline four-cylinder gasoline engine with a four-valve valve train, spark ignition, and a relatively high geometric compression ratio, operating on an Atkinson cycle with a high expansion ratio. The electrical subsystem of the hybrid power unit is based on a series-parallel configuration with a nickel-metal hydride high-voltage battery, two synchronous alternating current electric machines (MG1, and MG2), and a planetary gear set for power splitting. The schematic diagram of the experimental setup is shown in Figure 2.

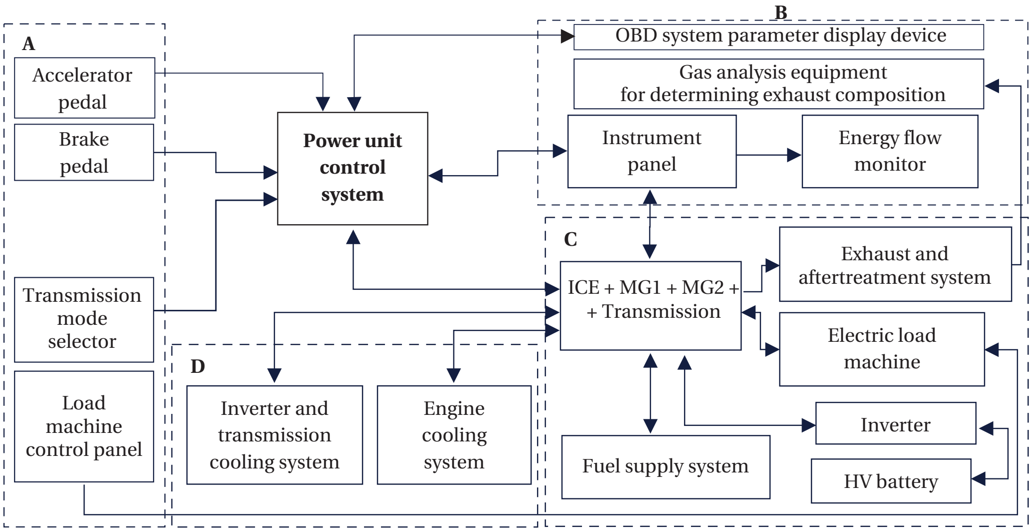

Figure 2. Diagram of the experimental setup

Source: developed by the authors

The structure of the experimental setup comprises four subsystems: the test control subsystem (A), the information subsystem (B), the power subsystem (C), and the thermal management subsystem (D). The test control subsystem (A) consists of the accelerator and brake pedals, the transmission mode selector, and the control panel of the load unit. The information subsystem (B) includes devices for data display and acquisition, namely the OBD system parameters interface, gas analysis equipment for determining exhaust gas composition, the instrument panel, and the energy flow monitor. The power subsystem (C) comprises the ICE, the hybrid transmission with MG1 and MG2, the fuel supply system of the ICE, the high-voltage battery, the inverter, the exhaust and exhaust-gas aftertreatment system, and the electric load machine. The operating modes of the power unit components are controlled by the control system. Measurement accuracy was evaluated based on the absolute or relative errors of the respective instruments and sensors listed in Table 2.

Table 2. Specifications of the instruments and equipment used during the experiment

No.	Measured parameter	Unit	Measuring instruments	Error
Brake test bench parameters				
1	Brake test bench	–	SAK-670 with electric brake machine GPF a17h, 250 kW, max 3200 min^{-1}	–
2	Rotor speed	min^{-1}	Pulse device for measuring rotational speed	±1
3	Torque	N·m	Dynamometric link with strain-gauge sensor	0.01%
Fuel consumption measurement system parameters				
4	Fuel mass	kg	Electronic scales MERA VM–2/3	±0.0005
5	Time	s	Stopwatch	±0.01
Power unit control system parameters				
6	Power unit control parameters	–	Device for connection to engine control system (OBDII), laptop	–
7	Crankshaft speed	min^{-1}	Hall-effect rod sensor	±0.25
8	Mass air flow	g/s	Hot-wire air flow meter	±0.01
9	Intake manifold air temperature	°C	Temperature sensor with thermistor	±1
10	Ignition timing advance	°CA	Individual ignition coil	±0.5
11	Coolant temperature	°C	Temperature sensor with thermistor	±1
12	Throttle valve opening angle	deg	Potentiometric throttle position sensor	±0.1
13	Oil pressure in lubrication system	kgf/cm^2	Low-pressure warning sensor	±0.01
14	Exhaust gas temperature	°C	Thermistor in wideband λ-sensor housing	±1
15	Excess air ratio	–	Wideband λ-sensor before catalytic converter	±0.001
16	Vehicle speed	km/h	Half-shaft rotation speed sensor	±1
17	Inverter temperature MG1/MG2	°C	Thermistor in MG1/MG2 inverter housing	±1
18	MG1/MG2 speed	min^{-1}	Inductive sensors	±1
19	MG1/MG2 torque	N·m	Equivalent electric current meter	±0.125
20	Traction battery state of charge	%	Battery current and voltage meters	±1
21	MG1/MG2 temperatures	°C	Thermistor in MG1/MG2 housing	±1
22	Traction battery temperature (1,2,3)	°C	Thermistors 1, 2, 3 in battery housing	±1
Lubrication system condition parameters				
23	Engine oil temperature in oil pan	°C	Bosch BEA 030 temperature meter	±1
Exhaust gas composition				
24	O_2 concentration in exhaust gases	vol.%		±0.010
25	*CO* concentration in exhaust gases	vol.%		±0.001
26	CO_2 concentration in exhaust gases	vol.%	Multicomponent gas analyser Bosch BEA 060	±0.010
27	C_mH_n concentration in exhaust gases	ppm		±1.0
28	NO_x concentration in exhaust gases	ppm		±1.0
29	Excess air ratio (λ) from exhaust gas composition	–		±0.001
Ambient conditions				
30	Atmospheric pressure	Pa	Barometric aneroid ND-49-A	±100
31	Air temperature	°C	Mercury thermometer	±0.1%
32	Relative humidity	%	Hair hygrometer	±2.5

Source: developed by the authors

Table 2 presented brief specifications of the instruments and equipment used in the study. The measuring equipment includes instruments for measuring the rotational speed and torque at the output shaft of the power unit using the SAK-670 test bench with the GPF a17h electric brake machine; fuel consumption by the weight method; parameters of the power unit control system by means of the corresponding built-in sensors and by reading the obtained values from the onboard OBD system using an appropriate adapter and a laptop; oil temperature in the ICE lubrication system using a Bosch BEA 030 sensor; exhaust gas composition using a Bosch BEA 060 multicomponent gas analyser; and ambient environmental parameters. During the experimental studies, the following parameters were measured using the specified equipment: output shaft rotational speed n; torque on the output shaft of the power unit M; engine crankshaft rotational speed n_e; throttle opening degree φ_{thr}; hourly fuel consumption G_{fuel}; hourly air consumption G_{air}; intake manifold air temperature t_{in}; excess air ratio α; ignition timing advance θ; engine coolant temperature t_{cool}; oil temperature t_{oil}; exhaust gas temperature t_{EG}; traction battery state of charge S_{ch}; rotational speed of MG1 n_{MG1}; torque of MG1 M_{MG1}; rotational speed of MG2 n_{MG2}; torque of MG2 M_{MG2}; MG1 temperature t_{MG1}; MG2 temperature t_{MG2}; MG1 inverter temperature $t_{inv.MG1}$; MG2 inverter temperature $t_{inv.MG2}$; traction battery temperatures t_{B1}, t_{B2}, t_{B3}; exhaust gas concentrations of O_2 (C_{O2}), CO (C_{CO}), CO_2 (C_{CO2}), C_mH_n (C_{CmHn}), and NO_x (C_{NOx}); and the equivalent vehicle speed V_a. The parameters of the power unit control system, determined by reading them from the onboard OBD system during measurements at each test point, were accumulated in the corresponding data file with a time interval of approximately 1 s. For further analysis, the arithmetic mean values of these parameters over the time interval corresponding to each test mode were used. The experimental research programme included determining a series of load characteristics of the hybrid power unit at output shaft rotational speeds of 250 min^{-1}, 500 min^{-1}, and 750 min^{-1}. The load characteristics were determined by measuring the specified parameters under steady-state conditions with selected loads ranging from minimum to maximum at a given rotational speed, such that the number of test points made it possible to establish the nature of the dependence of the corresponding parameter on the load, as specified in ISO 15550:2016 (2016).

The rotational speeds of the power unit output shaft were selected so as to uniformly cover the range of variation of this parameter under operating conditions, which are determined by the vehicle speed. The equivalent vehicle speed V_a, km/h, during bench testing of the power unit can be determined from relationship:

$$V_a = \frac{3.6 \cdot \pi \cdot n \cdot r_w}{30}, \quad (1)$$

where n is the rotational speed of the output shaft, min^{-1}; r_w is the rolling radius of the wheel, m.

The rolling radius of the wheel can be approximately determined from the geometric dimensions of the tire using relationship:

$$r_w = \frac{d}{2} + \lambda_t \cdot \frac{h}{B} \cdot B, \quad (2)$$

where d is the rim diameter, m; $\frac{h}{B}$ is the ratio of the tire profile height to its width; B is the tire section width, m; λ_t is the radial deformation of the tire profile, which can be assumed as $\lambda_t = 0.9$ (Sakhno *et al.*, 2004).

For the Toyota Prius 2004 vehicle, on which the investigated power unit is installed, the parameters of the standard P185/65R15 tires specified in relationship (2) are as follows: $d = 15$ inches or 0.381 m; $\frac{h}{B} = 0.65$; B = 0.185 m (Toyota Motor Sales, 2004). Therefore, the rolling radius is $r_w = 0.299$ m. For the specified rotational speeds of the power unit output shaft, the corresponding equivalent vehicle speeds of 28.2 km/h, 56.3 km/h, and 84.5 km/h were determined using relationship (1). These speeds practically divide the speed range of 0…120 km/h uniformly, which is defined for M1 category vehicles during compliance testing with environmental standards in accordance with Regulation No 83 of the Economic Commission for Europe of the United Nations (UNECE) (2015). This allows the performance indicators of the power unit to be evaluated under these Regulations in further studies. Fuel consumption was determined by the weight method using the electronic scales and the stopwatch (Table 2). The measurement procedure involved determining the time required for the power unit to consume a specified mass of fuel (the fuel dose mass was selected to ensure a minimum measurement time of at least 30 s) under steady-state operating conditions at each test point.

The value of the hourly fuel consumption G_{fuel}, kg/h, is determined from relationship:

$$G_{fuel} = \frac{\Delta G_{fuel}}{\tau_{fuel}} \cdot 3.6, \quad (3)$$

where ΔG_{fuel} is the mass of the fuel dose whose consumption time is measured, g; τ_{fuel} is the time required to consume the measured fuel dose, s.

All measuring equipment was verified for accuracy prior to testing using reference instruments in order to achieve the required measurement accuracy in accordance with ISO 15550:2016 (2016). At this stage of the research, all the above-mentioned energy efficiency indicators were measured directly using the equipment specified in Table 2. The measured parameters of the power unit constitute the basis for further analysis and modelling of the vehicle's energy efficiency performance under driving cycle conditions. Within the scope of this study, it is intended to evaluate the patterns of variation of the measured power unit parameters as a function of its effective power. The effective power N at the output shaft of the power unit, kW, is determined by relationship:

$$N = \frac{M \cdot n}{9550}, \quad (4)$$

where M is the torque at the output shaft, N·m; n is the rotational speed of the power unit output shaft, min^{-1}.

The errors of direct measurements are specified in Table 2. The errors of indirect measurements were determined in accordance with generally accepted calculation formulas. In this case, the relative errors in measuring the hourly fuel consumption and the power of the power unit are equal to the sums of the relative errors of the directly measured parameters included in equations (3) and (4), as determined from Table 2. According to the results of the evaluation, all errors of direct and indirect measurements are within the permissible limits for engine testing as specified in ISO 15550:2016 (2016).

Results and Discussion

The energy-efficiency indicators of an automotive power unit include fuel-economy indicators, as well as energy and environmental indicators, which are described by fuel consumption and emissions of harmful substances with exhaust gases under the main operating modes. In modern engines, these indicators substantially depend on the engine's air consumption, the concentrations of pollutants in combustion products, and the efficiency of the exhaust-gas aftertreatment system. Therefore, the experimental bench studies of the energy-efficiency indicators of the hybrid electric automotive power unit are aimed at determining the mass flow rates of fuel and air, the concentrations of harmful substances in the exhaust gases, and establishing the operating parameters of the electrical components in different operational modes, which define the speed parameters and load levels of the energy-source components. The results of the study of the ICE parameters under the above-mentioned operating modes of the hybrid power unit are presented in Figure 3.

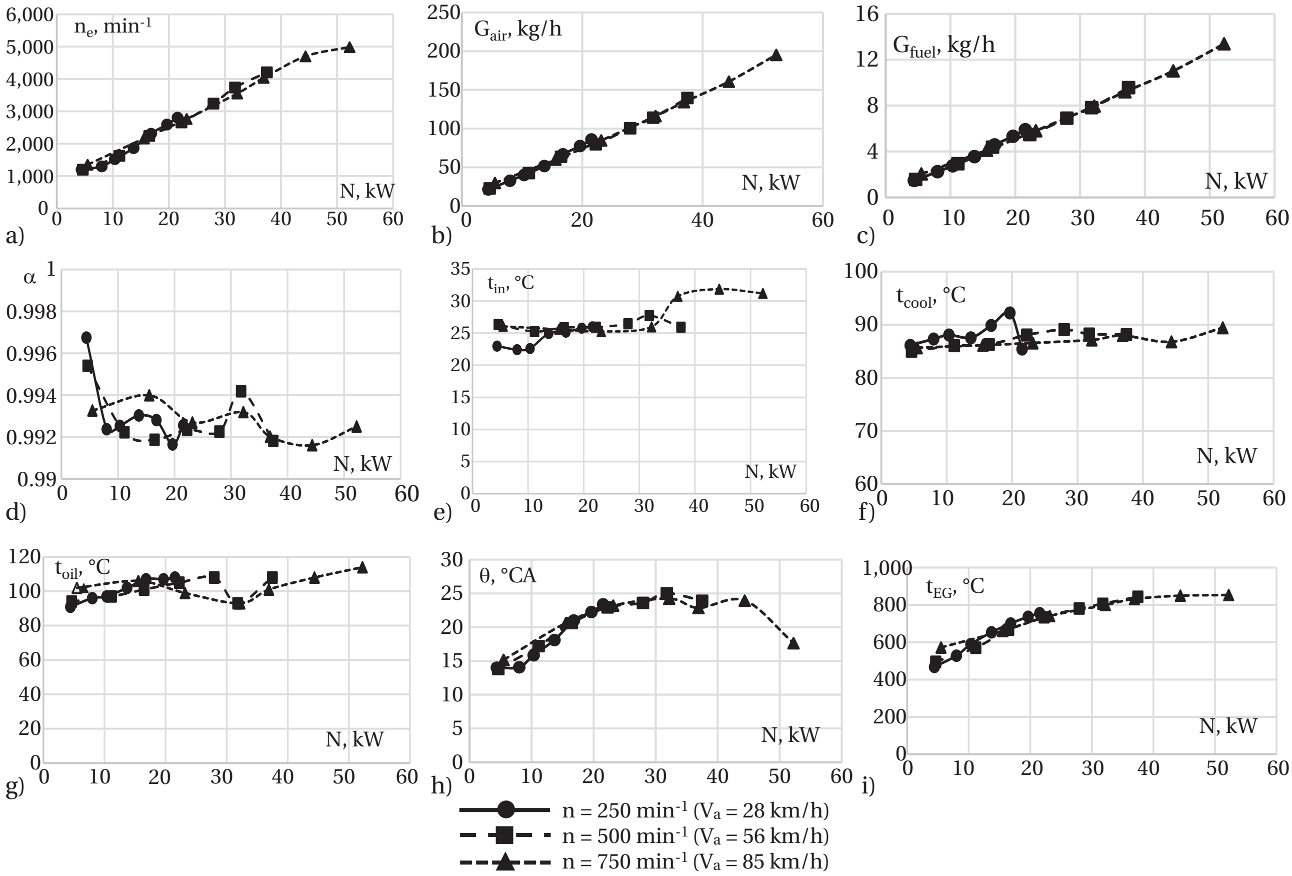

Figure 3. Load characteristics of the hybrid power unit with a Toyota 1NZ-FXE engine (measured ICE parameters)

Note: a – crankshaft rotational speed; b – hourly air consumption; c – hourly fuel consumption; d – excess air ratio; e – intake air temperature; f – coolant temperature; g – oil temperature; h – ignition timing advance; i – exhaust gas temperature

Source: developed by the authors

As can be seen from the dependencies of the engine crankshaft rotational speed n_e, there is an almost linear relationship between n_e and the power of the power unit N (Fig. 3a). In higher-speed operating modes of the power unit, a higher engine rotational speed is achieved at correspondingly higher output power. In low-load modes, the curves of n_e for different output shaft rotational speeds n overlap. Thus, there is a direct relationship between the load mode of the power unit and the engine rotational speed n_e. The influence of the power unit load on the ICE load is also confirmed by the dependencies of hourly air consumption G_{air} (Fig. 3b) and the associated hourly fuel consumption G_{fuel} (Fig. 3c). A nearly linear effect of load on G_{air} and G_{fuel} is observed; the curves of G_{air} and G_{fuel} for different n overlap. Therefore, the dependence of the ICE load mode on the hybrid power unit load is also practically linear. The measured values of the excess air ratio α (Fig. 3d) indicate that the control system maintains a stoichiometric air-fuel mixture across all operating modes of the power unit. The thermal operating conditions of the ICE systems are characterised by the intake manifold air temperature t_{in} (Fig. 3e), engine coolant temperature t_{cool} (Fig. 3f), oil temperature t_{oil} (Fig. 3g), and exhaust gas temperature t_{EG} (Fig. 3i). These dependencies confirm that the thermal operating conditions of these systems remained within acceptable limits during the tests. The ignition timing advance θ dependencies (Fig. 3h) characterise the engine control unit (ECU) algorithm for controlling this parameter. Up to an external load of 20 kW and, correspondingly, $n_e \leq 2{,}500$ min⁻¹, θ increases significantly from 14° CA to 23° CA with increasing N. This corresponds to θ adjustment to compensate for combustion duration in crank-angle degrees under rising n_e, ensuring the highest cycle efficiency. At loads of $N \approx 20 \ldots 45$ kW and at corresponding n_e values in the range of 2,500…4,700 min⁻¹, θ remains within 23…25° CA. This reflects θ correction under medium-load conditions to ensure optimal cycle efficiency and to minimise NO_X emissions. At loads above 45 kW and with increasing rotational speed up to the nominal 5,000 min⁻¹, θ sharply decreases to 17° CA. This corresponds to θ correction at high load conditions to prevent knock combustion. The results of the study of the electrical component parameters under the investigated operating modes of the hybrid power unit are presented in Figure 4.

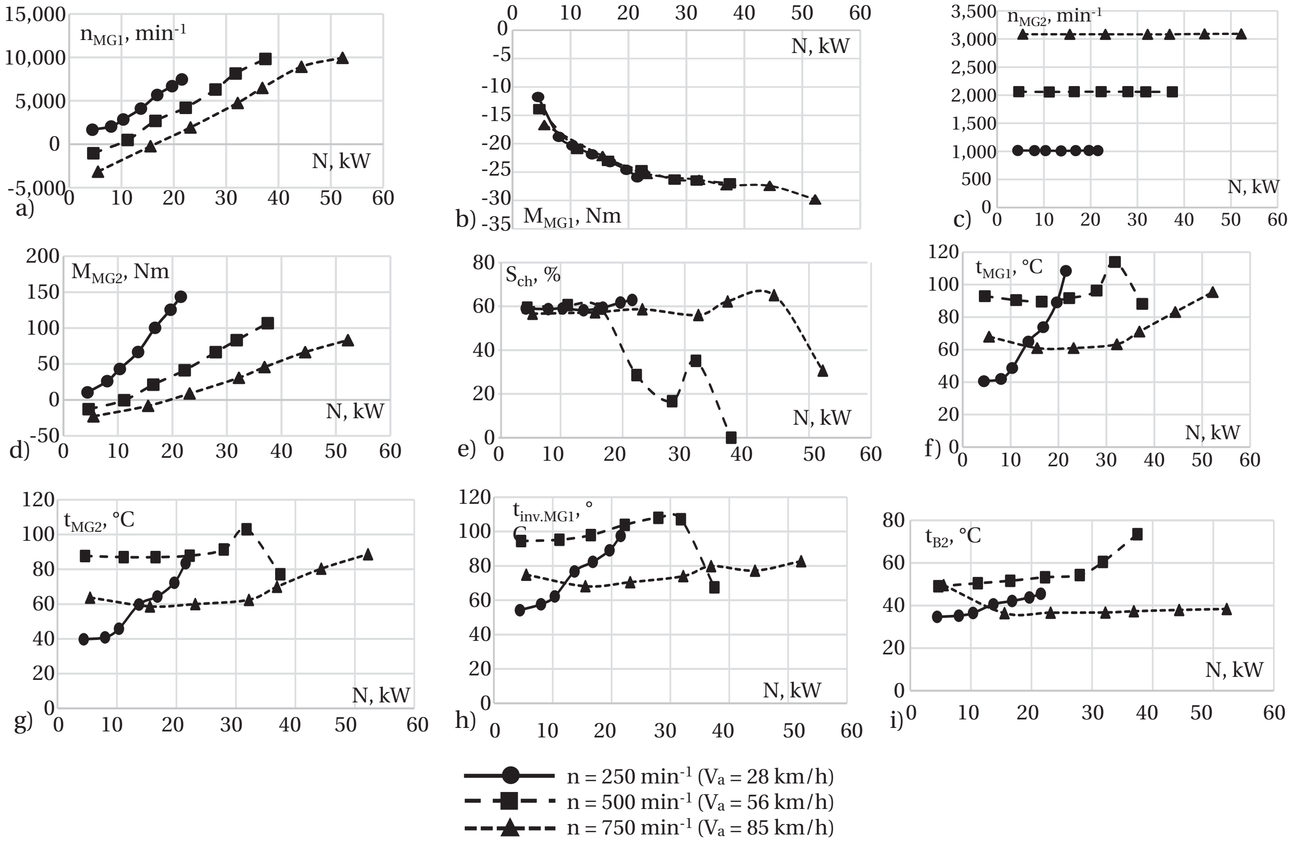

Figure 4. Load characteristics of the hybrid power unit with a Toyota 1NZ-FXE engine (measured parameters of the electrical components)

Note: a – MG1 rotor speed; b – MG1 torque; c – MG2 rotor speed; d – MG2 torque; e – traction battery state of charge; f – MG1 temperature; g – MG2 temperature; h – MG1 inverter temperature; i – traction battery temperature

Source: developed by the authors

The rotational speed of MG1, n_{MG1} (Fig. 4a), varies according to nearly linear dependencies similar to those of n_e, because MG1 is kinematically linked to the ICE through the planetary gearset and serves as the regulator of the ICE crankshaft speed. The maximum n_{MG1} value is 10,000 min⁻¹. At the same time, the rotational speed of MG2, n_{MG2} (Fig. 4c), does not depend on the external load, since MG2 is connected to the output shaft of the hybrid power unit through a fixed gear ratio; therefore, n_{MG2} is determined exclusively by the vehicle speed. The MG1 torque M_{MG1} (Fig. 4b) depends on the rotational speed and direction of rotation n_{MG1}, which in turn are determined by the required gear ratio of the hybrid transmission depending on vehicle speed (MG2 rotational speed n_{MG2}) and external load. If the required n_{MG1}, determined by the planetary gearset relationships, is opposite to the ICE direction of rotation ($n_{MG1} < 0$), as observed at loads up to 10 kW for n = 500 min⁻¹ and up to 15 kW for n = 750 min⁻¹, then MG1 operates in motor mode. The mechanical energy generated by MG1 is added to the ICE energy, and as the absolute value of n_{MG1} decreases, the absolute value of M_{MG1} increases, since in this case M_{MG1} is the driving torque. If the required $n_{MG1} > 0$, then MG1 operates in generator mode, consuming mechanical energy, and with increasing n_{MG1}, the absolute value of M_{MG1} increases, because M_{MG1} in this case represents resisting torque. To maintain the energy balance of the hybrid power unit (supplying mechanical energy and consuming generated electrical energy during generator operation) under operating modes without involving the traction battery, both motor-generators MG1 and MG2 must operate cooperatively: one in motor mode, the other in generator mode. Therefore, in modes with $N < 10$ kW at

$n = 500$ min^{-1} and $N < 15$ kW at $n = 750$ min^{-1}, when MG1 operates in motor mode, MG2 operates in generator mode. The resisting torque of MG2 (Fig. 4d) in generator mode is related to the torque of MG1 in motor mode (and vice versa) in such a way that when reduced to the same shaft (MG1 or MG2), the torques satisfy the conditions:

$$\left|M_{MG1}^{red(G)}\right| > \left|M_{MG2}^{red(M)}\right|, \quad \left|M_{MG2}^{red(G)}\right| > \left|M_{MG1}^{red(M)}\right|. \tag{5}$$

The difference between these torques is related to the efficiency of converting mechanical energy into electrical energy in the generator and electrical energy into mechanical energy in the motor, and it determines the overall efficiency of the hybrid transmission. The traction battery state of charge S_{ch} (Fig. 4e) remains at approximately 60% in most of the investigated modes and decreases under high-load conditions. This is associated with prolonged operation of the power unit at sustained high loads, where charging the battery becomes impossible (due to high mechanical power demand, thermal condition of the battery), as well as with potential loss of battery capacity as a result of long-term use. The temperature modes of MG1 (Fig. 4f), MG2 (Fig. 4g), the inverter (Fig. 4h), and the traction battery (Fig. 4i) remain within permissible limits. A battery temperature above 50°C (Fig. 4i) leads to a reduction in charging-discharging efficiency, as can be seen in Figure 4e. The environmental performance of the power unit is described by the measured concentrations of pollutants and other substances in the exhaust gases before and after the catalytic converter (Fig. 5).

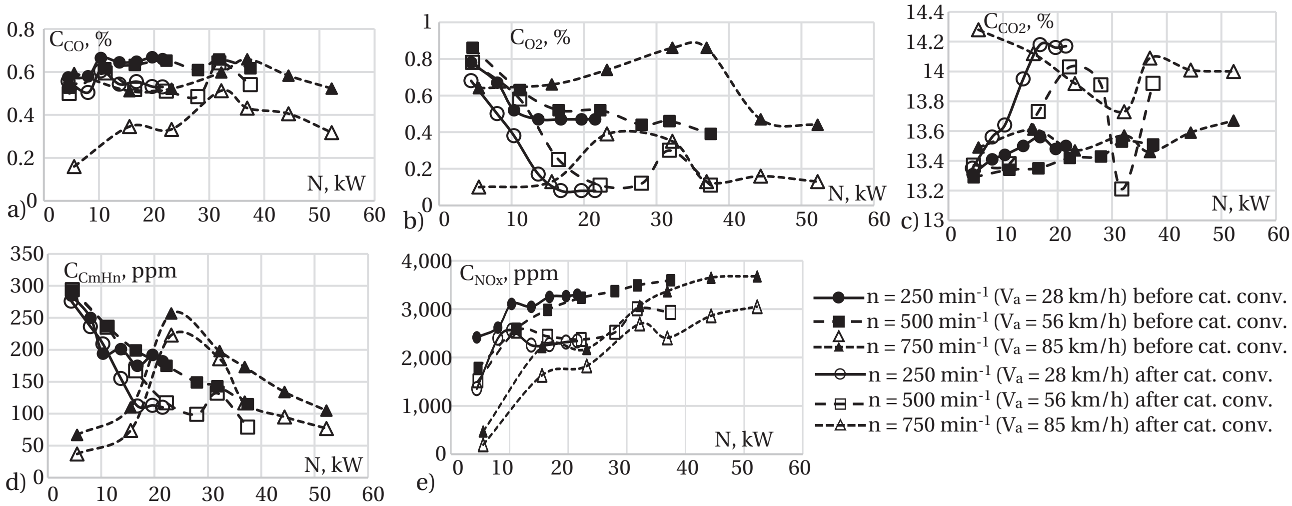

Figure 5. Load characteristics of the hybrid power unit with a Toyota 1NZ-FXE engine (measured environmental indicators)

Note: a – CO concentrations in the exhaust gases; b – O_2 concentrations in the exhaust gases; c – CO_2 concentrations in the exhaust gases; d – C_mH_n concentrations in the exhaust gases; e – NO_x concentrations in the exhaust gases

Source: developed by the authors

The variation in concentrations of different substances in the exhaust gases for this engine is determined primarily by the air-fuel mixture composition, described by α (Fig. 3d), and by the load. Since, according to Figure 3d, the air-fuel mixture composition in all investigated modes is nearly stoichiometric ($\alpha \approx 1$), the concentrations of O_2 in the exhaust gases before the catalytic converter (Fig. 5b) vary only slightly and remain within the range of 0.4…0.9%. This, in turn, results in changes in the pre-catalyst concentrations of CO (Fig. 5a) within 0.5…0.7% and CO_2 within 13.3…13.7% (Fig. 5c). Concentrations of C_mH_n in the exhaust gases (Fig. 5d) before the catalytic converter change from 300 to 100 ppm as α decreases from 0.997 to 0.992. The concentrations of NO_X in the exhaust gases (Fig. 5e) before the catalytic converter at low loads strongly depend on α: when the mixture is leaned from $\alpha = 0.993$ to $\alpha = 0.997$, C_{NOx} increases from 500 to 2,400 ppm. With a further increase in load, C_{NOx} increases from 2,500 to 3,600 ppm. After treatment by the catalytic converter, the concentrations of O_2, CO, C_mH_n, and NO_X in the exhaust gases decrease significantly, while the concentration of CO_2 increases. The degree of concentration change is determined by the neutralisation reactions, the efficiency of which depends on the size and placement of the catalytic converter. The obtained relatively low neutralisation efficiencies for CO, C_mH_n, and NO_X are explained by the non-standard design of the exhaust aftertreatment system. Based on the measured parameters of the hybrid power unit, it becomes possible to determine the following: MG1 power, MG2 power, ICE torque, ICE power, specific effective fuel consumption, cycle air consumption, volumetric efficiency of the ICE cylinders, ICE efficiency, hybrid transmission efficiency, hybrid power unit efficiency, and the transmission ratios of the hybrid transmission from MG1 and from the engine. According to the results of the experimental study of the energy efficiency indicators and the features of the operating processes of the hybrid electric automotive power unit based on a spark-ignition engine, the following dependencies were established as functions of the output shaft speed and the power of the power unit: speed and load modes of the ICE, MG1, and MG2; fuel consumption, air-fuel ratio, ignition timing of the ICE; traction battery state of charge; temperature regime parameters of the air supply, lubrication, cooling, and exhaust systems of the ICE, MG1, MG2, the inverter, and the traction battery; pollutant concentrations in the exhaust gases and the efficiency of their neutralisation.

The obtained results have formed the basis for further determination of the efficiency of individual components of the power unit and refinement of the mathematical model of the hybrid vehicle's motion in order to study the influence of individual parameters of its power unit on fuel economy and environmental performance. These results can also be compared with related studies by other authors. A theoretical generalisation and a new solution to an important applied scientific problem – enhancing the operational efficiency of hybrid vehicles through the rational use of the ICE and electric motors – is presented by O.P. Smyrnov (2016). According to the obtained research results (Fig. 3c), at a power unit output of 5.3 kW (which, under the conditions of this study, corresponds to the power at the driving wheels), the fuel consumption is about 1.7 kg/h. This correlates fairly well with the results reported in the study by O.P. Smyrnov (2016) and, at the same time, differs due to the apparently more efficient design configuration of the power unit and the different experimental conditions. The study by V. Dvadnenko *et al.* (2022) considered an improved control algorithm for the traction induction motor of a mild hybrid vehicle by increasing the efficiency of regenerative braking in order to improve economic and environmental parameters. O.V. Bazhynov *et al.* (2018) focused on substantiating the efficient use of electric and hybrid vehicles to support their widespread introduction into production and to minimise the environmental hazards posed by existing ICEs. A mathematical model for evaluating vehicle quality based on the key consumer indicators is presented, and the influence of electric components in electric and hybrid vehicles on overall and environmental safety indicators is analysed. According to the results of this study, relationships between environmental safety criteria and the vehicle speed of conventional and hybrid vehicles have been established. For example, at the above-considered speed of 55 km/h, the environmental safety criterion for the Toyota Prius hybrid vehicle was about 0.5. In the present study, the NO_X concentration, which is proposed by O.V. Bazhynov *et al.* (2018) as a basis for determining the environmental safety criterion, is about 200 ppm (Fig. 5e), which corresponds to 0.15 g/km at the given speed and, according to the calculation methodology, yields an environmental safety criterion of approximately 2.5. Such a discrepancy between the results of this study and those reported by O.V. Bazhynov *et al.* (2018) is primarily explained by the efficiency of the exhaust aftertreatment system, which exhibits low efficiency under the conditions of the present study, as discussed above. The study by Kh. Maush (2017) focused on developing a concept for converting a vehicle equipped with an ICE and a manual transmission into a hybrid vehicle. Experimental research was conducted to select a suitable traction electric motor for the conversion, complemented by mathematical modelling and experimental evaluation of the economic characteristics of the converted hybrid vehicle under urban driving conditions. Based on the results of the mathematical modelling of fuel economy and emissions for both conventional and hybrid vehicles operating under driving-cycle conditions, it was determined that the hybrid vehicle's fuel consumption is 28% lower, while emissions of regulated pollutants are reduced by 48%. Experimental studies have further indicated a reduction in fuel consumption by a factor of 2 to 3 compared with the baseline vehicle. According to the results, it is not possible to assess how the type of power unit (hybrid electric or conventional) affects fuel consumption or pollutant emissions in a driving cycle or under real urban driving conditions. At the same time, it is possible to compare the hourly fuel consumption obtained at the same power output of the power unit in hybrid and conventional configurations. As has been determined above, at a power output of 5.3 kW, the hourly gasoline consumption of the considered hybrid power unit is 1.7 kg/h. For the compared conventional gasoline power unit, as reported by S.V. Sosida (2023), at a power output of 5.3 kW and an engine speed of 2,400 min-1, the gasoline consumption was 2.2 kg/h. Thus, it can be concluded that the fuel consumption of the hybrid electric power unit under steady-state driving conditions is reduced by 23% compared to the conventional gasoline power unit. This result correlates well with that obtained in Kh. Maush (2017). Mathematical modelling of fuel economy indicators and CO_2 emissions under transient operating conditions was performed by I. Taymaz & M. Benli (2014) for a conventional commercial vehicle and a hybrid vehicle designed on its basis. The results showed that, at the same performance level, the hybrid vehicle emits nearly 30% less CO_2. A comparison of the obtained result on the effect of using a hybrid power unit on CO_2 emissions with the results of this study can be carried out in a manner analogous to the comparison of the effect on fuel consumption described above. The measured CO_2 concentrations for a load of 5.3 kW of the hybrid power unit are about 13.4% (Fig. 5c), whereas for the conventional gasoline power unit they are about 13% (Sosida, 2023). Since the CO_2 concentration for the hybrid power unit is higher by approximately 3% compared to the conventional one, while the fuel consumption, as indicated above, is lower by 23%, the CO_2 emissions are reduced by about 20% when using the hybrid power unit under steady-state driving conditions at a vehicle speed of 55 km/h. This also correlates fairly well with the results reported in (Taymaz & Benli, 2014). The differences in the obtained effects on CO_2 emissions are explained by different emission determination conditions, different types of vehicles, and other factors. R.H. Staunton *et al.* (2006)

focused on determining the energy-efficiency indicators of elements of the Toyota Prius II hybrid transmission – specifically the electric motor, inverter, and mechanical gear – based on experimental bench tests of the components. Based on the results of study of R.H. Staunton and this research, the efficiency of energy transfer from the ICE to the output shaft through the electric hybrid transmission can be determined for a given power unit load, for example, 16.5 kW at a vehicle speed of 56 km/h. In this operating mode, MG1 produces a resisting torque of about 23 N·m (Fig. 4b) at 2,700 min^{-1} (Fig. 4a), corresponding to 6.5 kW, to generate electrical energy, which in MG2 produces a torque of 22 N·m (Fig. 4d) at 2000 min^{-1} (Fig. 4c), corresponding to 4.6 kW. Thus, in order to obtain an output shaft power of 16.5 kW, the ICE produces 18.4 kW, and the transmission efficiency is 0.89. At the same time, according to the authors, the efficiency for the specified operating mode was 0.87, which correlated with the results of this study.

Conclusions

The study provided a comprehensive assessment of the energy efficiency of a hybrid electric automotive power unit based on a spark-ignition engine. The assessed indicators include component operating parameters, fuel consumption, and exhaust gas pollutant concentrations under specific control system settings and thermal conditions. Following this methodology, an experimental setup was created at the Engine Testing Laboratory of the Department of Engines and Heating Engineering, National Transport University, using a Toyota Prius hybrid power unit with a 1NZ-FXE engine. The test bench setup with an electric brake machine simulated various speed and load conditions and measured OBD parameters, fuel consumption, temperatures, and exhaust gas composition. Bench tests showed a nearly direct relationship between the power unit load and the ICE speed and load modes. As the power unit's speed and load varied, the control system maintained a stoichiometric air-fuel mixture and engine thermal conditions within permissible limits. The ignition timing was adjusted to maximise cycle efficiency at low and medium loads, reduce NO_x emissions at medium loads, and prevent knock at high loads. MG1 speed varied almost linearly with vehicle speed and load, while MG2 speed depended solely on power unit speed. MG1 and MG2 torques adjusted to maintain the energy balance in modes without traction battery involvement, with one machine operating as a motor and the other as a generator depending on MG1 rotation. In this case, the resisting torque in generator mode is always greater than the driving torque in motor mode, and their difference determines the efficiency of the hybrid transmission. The state of charge of the traction battery is about 60% and decreases under high-load conditions due to the influence of the thermal regime and capacity degradation. The composition of the exhaust gases under various operating modes of the power unit is determined primarily by the air-fuel mixture composition of the ICE and the load. However, due to the use of a non-standard exhaust aftertreatment system design, its efficiency is reduced. The research results align with related studies on the impact of power unit type on fuel consumption, CO_2 emissions, and hybrid transmission efficiency. Compared with a conventional power unit, the hybrid unit reduces fuel consumption by approximately 23%, CO_2 emissions by approximately 20%, and achieves a transmission efficiency of 0.89. However, the low efficiency of the non-standard exhaust aftertreatment system used in the experiments led to lower environmental performance than reported by other authors. Future work will focus on developing a mathematical model of the hybrid vehicle to evaluate energy efficiency under driving-cycle conditions.

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Conflict of Interest

None.

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Дослідження показників енергоефективності гібридної електричної автомобільної силової установки на базі двигуна з іскровим запалюванням

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Анотація. У статті наведено результати експериментального дослідження показників енергоефективності гібридної електричної автомобільної силової установки на базі двигуна з іскровим запалюванням. Метою роботи було здійснення комплексної оцінки енергоефективності гібридної електричної автомобільної силової установки на базі двигуна з іскровим запалюванням. Методика дослідження передбачала проведення експериментальних стендових випробувань гібридної електричної автомобільної силової установки у визначених режимах роботи для встановлення закономірностей зміни керувальних параметрів двигуна внутрішнього згоряння, електричних підсистем, показників паливної економічності та екологічних характеристик. У ході експериментального дослідження встановлено закономірності зміни показників енергоефективності та характеристик робочого процесу залежно від частоти обертання та потужності вихідного вала. Виявлено зміни швидкісних і навантажувальних режимів двигуна внутрішнього згоряння, мотор-генератора 1 і мотор-генератора 2, а також витрати палива, коефіцієнта надлишку повітря та кута випередження запалювання двигуна внутрішнього згоряння. Проаналізовано ступінь заряду тягової акумуляторної батареї, параметри теплового режиму систем впуску повітря, змащування, охолодження та випуску двигуна внутрішнього згоряння, мотор-генератора 1, мотор-генератора 2, інвертора й акумуляторної батареї, а також концентрації шкідливих речовин у відпрацьованих газах і ефективність їх нейтралізації. Встановлено майже прямий зв'язок між частотою обертання та навантаженням двигуна внутрішнього згоряння і загальним навантажувальним режимом силової установки. Керування складом паливно-повітряної суміші та кутом випередження запалювання в усіх режимах забезпечило високу паливну економічність і низький рівень викидів шкідливих речовин. Високі показники енергоефективності за різних умов експлуатації досягнуті завдяки електричній підсистемі силової установки, яка забезпечувала оптимальне керування швидкісним і навантажувальним режимами двигуна внутрішнього згоряння

Ключові слова: потужність; крутний момент; гібридна трансмісія; режим роботи; ступінь заряду тягової акумуляторної батареї; паливна економічність; екологічні показники