Article citation info:
Depczyński W, Marchenko A, Mishchenko S, Mishchenko M. The effect of hydrogen addition to traditional petrol engine fuel in a hybrid power plant on its environmental performance and fuel efficiency. Combustion Engines. 2025;200(1):87-94. https://doi.org/10.19206/CE-199735

Wojciech DEPCZYŃSKI
Andrii MARCHENKO
Svitlana MISHCHENKO
Mykyta MISHCHENKO

Combustion Engines
Polish Scientific Society of Combustion Engines

The effect of hydrogen addition to traditional petrol engine fuel in a hybrid power plant on its environmental performance and fuel efficiency

ARTICLE INFO

Received: 27 November 2024
Revised: 12 November 2024
Accepted: 2 January 2025
Available online: 4 February 2025

The article is concerned with studying the impact of hydrogen additive on the traditional fuel of a petrol internal combustion engine (ICE) as part of a hybrid power plant on key indicators of its efficiency and environmental friendliness. The main attention is paid to the assessment of fuel consumption and CO_2 emissions within the NEDC driving cycle.

The paper develops a mathematical model of the internal combustion engine's working process, which takes into account the addition of hydrogen to the fuel mixture and creates a model for determining the parameters of a hybrid powertrain in the NEDC cycle modes. The results of the study showed that every 2% addition of hydrogen to petrol reduces the specific effective fuel consumption by 2.8–3.5%, depending on the speed mode. It was found that the hybrid system provides effective energy recovery during braking, which contributes to the overall efficiency of the system.

The study confirms the prospects of using hydrogen as an additive to traditional fuels to improve the environmental friendliness and efficiency of transport, reduce CO_2 emissions and decarbonise the transport sector. The developed calculation methodology can be used for further research and implementation of new technologies in the field of hybrid powertrains.

Key words: *hybrid powertrain, hydrogen addiction, fuel consumption, emission, driving cycle*

This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/)

1. Introduction

Transport is fundamental to the UN's proposed global strategy for the sustainable development of our civilisation. It can be argued that none of the 17 areas of this strategy can be achieved without the use and development of transport and transport technologies. Such a mission of transport in the functioning of national economies and society requires constant improvement. Today, the main global trends in transport improvement are related to improving its performance, reducing the negative impact on the environment, decarbonisation and green technologies. According to the National Transport Strategy of Ukraine for the period up to 2030 [24], global trends in the development of transport systems show the need for a rapid integration of transport technologies and regional mobility projects. Transport is becoming more energy efficient and ‘green’, safe and friendly to the consumer and the environment.

Transport has become more environmentally friendly, but the growth in its production and operation means that it remains among the main artificial sources of noise and environmental pollution. The problem is the need to eliminate the transport system's dependence on oil without compromising efficiency and technical performance.

The White Paper – A Plan for the Development of a Single European Transport Area – Towards a Competitive and Resource Efficient Transport System [26], emphasises that in practice, transport should use less energy, which should be cleaner, make better use of modern infrastructure and reduce its negative impact on the environment and key natural assets such as water, land and ecosystems.

There is a public need to develop tools and implement systemic measures to reduce the energy dependence of the transport sector, improve air quality in cities and fulfil international commitments on climate change, including limiting and inventorying greenhouse gas emissions from road transport [14].

The relevance of this topic corresponds to the world trends in transport development. It is determined by the global need to develop and implement new technologies to comprehensively address the problem of increasing energy efficiency, using non-traditional fuels and, as a result, reducing air pollution by road transport. In this regard, the main areas of reducing the negative impact of transport on the environment include the use of alternative fuels based on renewable energy sources, for example, based on rapeseed oil or by adding alcohol [6, 22, 25], or the use of hydrogen [2, 21].

Hydrogen energy implies determining the potential for transforming the global energy system while addressing important climate change issues.

2. Literature study

Research on decarbonisation in transport, the transition to hybrids and electric vehicles, the abandonment of internal combustion engines, and attempts to introduce alternative fuels, including hydrogen additives to internal combustion engine fuels, are presented in many publications by scientists around the world. At the same time, researchers focus on optimising the processes of fuel supply, mixture formation and combustion.

A comprehensive study [11] assesses the current state of hydrogen energy and examines its potential for transforming the global energy landscape while addressing important climate change issues.

The study [3] focuses on optimising the operation strategy of a serial hybrid powertrain, discussing in detail the analysis and optimisation of the mixture preparation, supported by high-speed Schlieren measurements, 3D modelling and thermodynamic analysis performed on multi-cylinder engines.

Paper [12] discusses the appropriate powertrain topologies for light commercial vehicles (LCVs) and passenger cars (PCs) using future hydrogen engines. It analyses the requirements and challenges for the relevant components as well as subsystems such as fuel injectors and exhaust gas treatment and discusses the requirements for exhaust gas treatment concepts for LCV/PC powertrains using H_2-engines.

In an experimental study [7], ethanol derived from grape pomace was used in fuels produced by blending it in increasing ratios (10, 20 and 30 vol%) with oxygen-free petrol. These ethanol and petrol fuel blends were used to evaluate the emissions and energy consumption of a motorcycle equipped with a large displacement SI four-stroke engine.

Study [20] presents a study of the effect of CO_2 dilution in a hydrogen-enriched SI engine on the performance and combustion characteristics and the hydrogen knock limit of a spark ignition engine running on hydrogen-petrol mixtures. The experiments were conducted on a single-cylinder Ricardo engine with direct petrol injection and hydrogen port induction.

Engine studies to study the characteristics of combustion knock were carried out on hydrogen and petrol fuel in a single-cylinder engine with piston injection and spark ignition to study the compatible fuel use (CFR) presented in [10].

The use of hydrogen as a fuel in vehicles and modern experimental studies in the literature are considered in [1], and the results of using hydrogen as an additional fuel are investigated. The impact of hydrogen use on engine performance and exhaust emissions as an additional fuel to petrol, diesel and liquefied gas internal combustion engines is explained.

A study [23] examined the impact of hydrogen as an additional fuel for spark ignition (SI) and compression ignition (CI) engines on engine performance and gas emissions.

Considering the above studies, it should be noted that the issue of studying and analyzing the impact of adding hydrogen to traditional fuels on fuel efficiency and carbon dioxide emissions during the operation of a hybrid powertrain in the driving cycle is relevant on the path to decarbonization of transport.

The aim of the study is to determine the impact of hydrogen additive on fuel efficiency and carbon dioxide emissions in a sequential hybrid powertrain based on a gasoline engine according to the NEDC driving cycle. This will allow analyzing the results obtained to study changes in fuel consumption and harmful emissions effects and will become the basis for solving the problems of decarbonization in transport, driven by the Sustainable Development Strategy.

3. Methodology of the calculation research

The New European Driving Cycle (NEDC) is a standardised laboratory test designed to evaluate fuel consumption, CO_2 emissions and other vehicle parameters under conditions as close to ideal as possible. It was used in Europe for the certification of passenger cars and light commercial vehicles until the introduction of its successor, WLTP [9]. The NEDC methodology is based on the division into two segments: urban and non-urban cycles.

The main objective of NEDC is to provide standardised conditions for comparing vehicles in the aspects of [9, 17]:

- fuel economy [dm^3/100 km] or [miles per gallon]
- carbon dioxide emissions [g/km]
- other pollutants such as NO_x, HC, and CO.

The tests allow vehicles to be compared against each other based on a single set of parameters, excluding external factors such as weather conditions, driving style, and road topography.

NEDC consists of two segments: the urban driving cycle UDC = (4 × ECE) and Extra-Urban driving cycle (EUDC), together they represent the different driving conditions for evaluating vehicle performance:

- distance: 4 km
- average speed: 14 km/h
- top speed: 50 km/h.

Duration: 195 seconds (3 minutes 15 seconds), repeated 4 times.

The cycle consists of four acceleration and deceleration periods, constant speed and idle periods.

The Extra-Urban Cycle simulates driving conditions on motorways and country roads:

- distance: 7 km
- average speed: 63 km/h
- top speed: 120 km/h
- duration: 400 seconds (6 minutes 40 seconds).

Driving characteristics:

- 50% of the time at constant speed
- variable speeds, with periods of acceleration and braking.

The overall test result, e.g. fuel consumption or CO_2 emissions, is calculated as a weighted average of the urban and non-urban cycles. The weighting of the segments depends on the distance travelled:

- urban cycle: ~37%
- non-urban cycle: ~63%.

Test conducted under controlled laboratory conditions at temperatures between 20°C and 30°C.

Vehicles are tested on a rolling road that simulates aerodynamic drag and vehicle weight.

Additional systems such as air conditioning, headlights and radio are switched off to minimise vibrations.

The cars must be driven at least 3000 km before testing, which provides a ‘running-in’ period.

NEDC has been criticised for its lack of realism, as it does not consider real-world driving conditions such as weather, road gradients, or the use of auxiliary systems.

Fixed acceleration and speed values allow manufacturers to optimise engine settings specifically for this test, known as ‘cycle work-up’.

Real-world fuel consumption and emissions are often significantly higher than NEDC.

Despite these limitations, NEDC has spurred vehicle efficiency and emissions technology advances. However, its replacement, the WLTP, offers a more accurate and dynamic test covering longer distances, a wider range of speeds and additional driving patterns.

The first stage of the computational study is to create a mathematical model of the petrol engine's operating process that takes into account the addition of hydrogen to the petrol mixture.

The calculation of the working process is based on a quasi-stationary thermodynamic model of a spark ignition engine, which allows to set the composition of the fuel mixture. This mathematical model was developed at the Department of Engines and Hybrid Power Plants of the National Technical University ‘Kharkiv Polytechnic Institute’ and confirmed by the results of experimental studies on the VAZ-21081 engine [18]. It is used to determine the parameters of an internal combustion engine as part of a hybrid power plant with the addition of hydrogen to petrol.

The mathematical model is based on the first law of thermodynamics, the law of mass conservation, and the equation of state. The amount of heat energy transferred to the walls is calculated using the Newton-Richman equation, where the heat transfer coefficient is determined by the Voschni formula. The combustion process in the cylinder is modelled by the Wiebe formula, and the mechanical friction losses are determined on the basis of empirical dependencies on the crankshaft rotation frequency, which were refined experimentally at the Department of Engines and Hybrid Power Plants of NTU ‘KhPI’ [16]. The dependencies for establishing and calculating the duration and nature of combustion used in the mathematical model to determine the effect of hydrogen additive on the performance of a petrol engine are described in [13]. The mathematical model allows varying the composition of the fuel mixture and studying the effect of hydrogen additive to petrol on engine performance and carbon dioxide content in exhaust gases. The percentage of hydrogen additive in the mathematical model can be varied by mass from the main fuel.

An experimental study was conducted at the Department of Engines and Hybrid Power Plants of NTU ‘KhPI’ to identify the mathematical model of the automobile engine workflow. As the object of research was used the engine of a passenger car VAZ-21081. The experimental engine is equipped with a camshaft and a receiver from the VAZ-21103 engine, a distributed fuel injection system, a set of sensors for monitoring parameters and an engineering electronic control unit. In the course of the experimental study, a number of measures were developed to remove the indicator diagram.

Figure 1 shows a general view of the experimental stand with the VAZ-21081 engine.

The tests were carried out under the following conditions:

- ambient temperature 298 K
- atmospheric pressure 0.0978 MPa
- coolant temperature at the engine outlet was 80...90°C
- oil temperature – within 80...100°C.

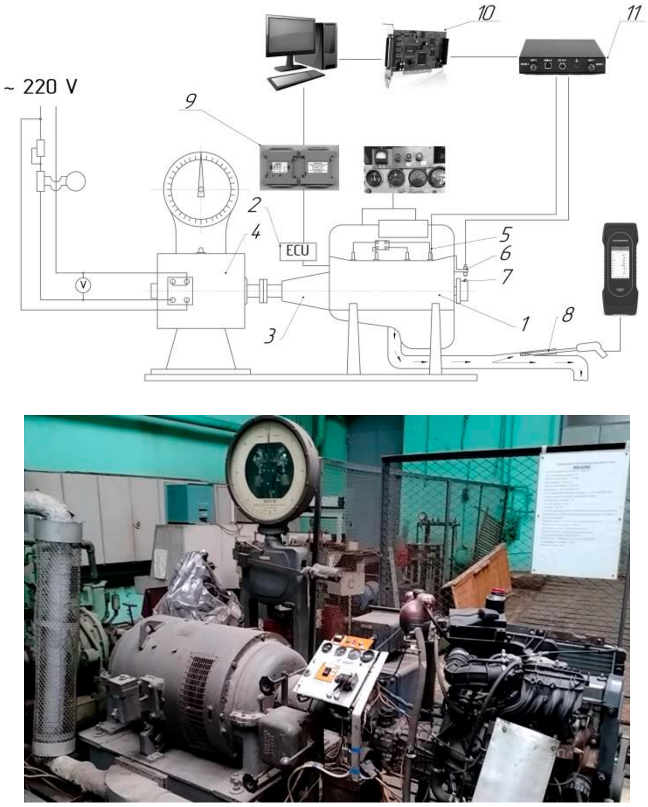

Fig. 1. Scheme of the test bench and general view: 1 – engine equipped with control and measuring devices and devices ensuring its operation; 2 – diagnostic connector; 3 – gearbox; 4 – loader/electric motor for driving the crankshaft during scrolling; 5 – pressure sensor in the engine cylinder AVL; 6 – crankshaft angle sensor; 7 – mark of the VMT; 8 – probe of the Sauermann Si-Ca 230 gas analyser; 9 – K-Line adapter; 10 – PCI L-Card 783-86 ADC board; 11 – amplifier

The VAZ-21083 engine is controlled by the ECU based on Janus 7.2, which is functionally similar to the Bosch M7.9.7. The engineering unit is controlled by the J5 On-Line Tuner software, which allows the air excess ratio, engine crankshaft speed, hourly air flow rate and ignition timing angle to be determined. Mass fuel consumption was determined by the weight method. A chromium-aluminium thermocouple and a galvanometer were used to determine the exhaust gas temperature. A K-Line adapter cable is used to connect to the engineering unit.

The automated engine display complex consists of an AVL GM11D engine cylinder pressure sensor, a crankshaft rotation angle sensor, an amplifier unit, a PCI L-Card 783-86 ADC board, Powergraph 3.3.9 Pro software, and EngineAnalysisPro v1.0 software. The engine cylinder pressure sensor is a piezoelectric quartz sensor manufactured by AVL (Austria). In addition, a signal amplifier was installed specifically for this sensor, and it was calibrated. An electric balancing machine loads the engine.

A Sauermann Si-Ca 230 gas analyser was used to take exhaust gas samples to measure the concentration of carbon dioxide (CO_2).

At the second stage of the study, a mathematical model was created to determine the parameters of a hybrid power plant in the modes of the NEDC test cycle with the addition of hydrogen to traditional fuel.

It is advisable to evaluate the efficiency of a hybrid powertrain in the full range of operating modes. To calculate the operational parameters of a vehicle, test cycles can be used to determine the speed of the vehicle as a function of time. In this paper, the European driving cycle NEDC is used. A mathematical model for determining the parameters of a hybrid powertrain with the addition of hydrogen to traditional fuel has been created, describing the speed of a car at different stages of the cycle by linear empirical time dependencies [15].

To simulate the movement of a car within the NEDC cycle, a time scale is created, discretised in 1 – 1-second increments over the entire cycle interval. The speed profile is calculated based on the standard time coordinates ti and the speed values v_i at each cycle stage. Formula (1) for calculating the vehicle speed at each stage:

$$v(t) = \begin{cases} \frac{v_i(t-t_{i-1})}{t-t_{i-1}} \\ v_i \end{cases} \tag{1}$$

$$t_{i-1} < t < t_i$$

$$t = t_i$$

The electric motor is powered by a battery and/or a generator driven by an internal combustion engine. Its rotational speed depends on the vehicle speed and is calculated using the following formula (2):

$$n_{em} = \frac{v \cdot u_0}{0.377 \cdot r_{st}} \tag{2}$$

where: v – vehicle speed [km/h], u_0 – gear ratio of the final drive, r_{st} – static wheel radius [m].

The power consumed from the battery to operate the electric motor is calculated by the formula (3):

$$N_{eb} = \frac{N_\Sigma}{\eta_{em}} \tag{3}$$

where: N_Σ – total power required to drive the vehicle with the specified cycle parameters [kW], η_{em} – efficiency of the traction electric motor.

The acceleration of the vehicle at each second of the test cycle is calculated as the difference (4) between the current speed and the speed at the previous time point:

$$a(t) = \frac{v(t+1)-v(t)}{3.6} \tag{4}$$

The total power N_Σ is calculated by the equation (5):

$$N_\Sigma = \frac{v}{3600 \cdot \eta_{TR}}$$

$$\left[\frac{k_w \cdot F \cdot V^2}{12.96} + m \cdot 9.81 \cdot \Psi_d + m \cdot a \cdot (1.05 + 0.05 \cdot u_0^2\right] \tag{5}$$

where: v – is the vehicle speed [km/h], η_{TR} – transmission efficiency, k_w – flow coefficient, F – area of frontal resistance [m^2], m – vehicle mass [kg], ψ_d – coefficient of total road resistance, a – vehicle acceleration [m/s^2], u_0 – is the gear ratio of the final drive.

The current capacity of the battery varies according to the following dependence (6):

$$C_{bi} = C_{bi-1} - N_{eb} \cdot \frac{1}{3600} \tag{6}$$

where: C_{bi-1} – battery capacity in the previous calculation step [kWh].

The operating modes of the internal combustion engine depend on the state of the battery. When the battery is fully charged, the ICE is switched off [19]. If the battery charge level falls below the minimum allowable capacity $C_{b\,min}$, the ICE switches to the external speed characteristic mode with the lowest specific fuel consumption $g_{e\,min}$. The power of the engine in this mode can be calculated based on the modelling of its operating process.

When the engine is running, its second fuel consumption is calculated using the formula (7):

$$G_f(t) = \frac{N_{en}(t) \cdot g_e}{3600} \tag{7}$$

where: g_e – specific fuel consumption at the operating speed of the engine [g/kWh].

The fuel consumption of the engine based on the results of the car's movement on the NEDC cycle is determined by the formula (8):

$$G_{f/100km} = \frac{100}{S \cdot \rho_П} \int_0^{t_ц} G_f(t) \cdot \Delta t \tag{8}$$

where: S – the distance travelled by the vehicle during the NEDC cycle test [km], $\rho_П$ – fuel density [kg/m^3], Δt – time calculation step [s], $t_ц$ – duration of the test cycle [s].

If the power of the traction electric motor is lower than the power of the internal combustion engine, the proportion of the internal combustion engine power used to charge the battery is determined by the formula (9):

$$N_{eb} = \frac{N_e}{\eta_g} - \frac{N_\Sigma}{\eta_{em}} \tag{9}$$

where: η_g – efficiency of the current generator.

The current value of the battery capacity varies according to the dependency:

$$C_{bi} = C_{bi-1} + N_{eb} \cdot \frac{1}{3600} \tag{10}$$

Energy is recovered during braking. In this case, the traction electric motor functions as a generator. The power used to charge the battery calculated by the formula (11):

$$N_{eb} = \frac{N_e}{\eta_g} - \frac{N_\Sigma}{\eta_{em\,g}} \tag{11}$$

where: $\eta_{em\,g}$ – efficiency of a traction electric motor when operating in generator mode.

The volume fraction of CO_2 in the combustion products was determined by the formula (12):

$$rCO_2 = \frac{1}{12} \cdot C/M'_{pr.c.} \tag{12}$$

where: $M'_{pr.c.}$ – amount of combustion products per 1 kg of fuel [kmol].

To calculate CO_2 emissions, we used a relationship (13) that takes into account the share of hydrogen in the fuel mixture:

$$E_{CO_2}(t) = G_f(t) \cdot (1 - \psi_{H_2}) \cdot m_{CO_2\,gasoline} \tag{13}$$

where: ψ_{H_2} – volume of hydrogen in the fuel mixture [%], $m_{CO_2\,gasoline}$ – carbon dioxide content during the combustion of 1 litre of gasoline [kg].

The calculation of the NEDC driving cycle based on the above model is implemented in the MATLAB software environment. The initial data for the calculation are shown in Table 1.

Table 1. Initial data for the calculation

Parameters	Value
Vehicle weight m, kg	1600
Static wheel radius r_{st}, m	0.2794
Vehicle height B_r, m	1.445
Vehicle width H_r, m	1.725
Vehicle frontal area filling factor α	0.78
Nominal effective power of the electric motor $N_{d\,n}$, kW	38
Rated speed of the traction electric motor $n_{ed\,n}$, min^{-1}	1200
Maximum traction electric motor speed $n_{ed\,max}$, min^{-1}	5600
Transmission efficiency η_t	0.9
Total gear ratio from electric motor to vehicle wheels u_0	4.13

It is accepted that the specified parameters of the traction electric motor should provide the traditional high enough vehicle dynamics indicators, which are charactersised by the comfort of driving in urban conditions.

4. Research results

4.1. Research on the effect of hydrogen additive on the efficiency of internal combustion engines

Figure 2 shows a comparison of the effective power (N_e) and specific effective fuel consumption (g_e) at the external speed characteristic modes. The effect of hydrogen addition on CO_2 emissions is shown in Fig. 3.

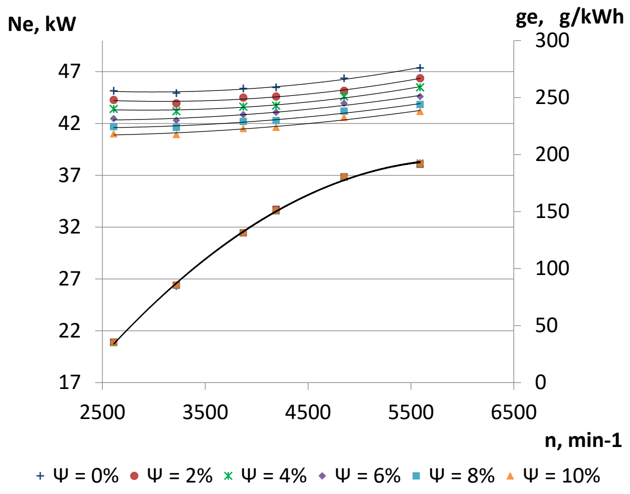

Fig. 2. Comparative characteristics of effective power and specific fuel consumption at external speed characteristic modes

Analysing Fig. 2 shows that the addition of hydrogen contributes to a significant reduction in specific effective fuel consumption. This is due to an increase in the efficiency of the combustion process in the engine cylinders. Hydrogen has a higher specific heating value of fuel and its combustion rate, a wide range of flammability, which allows for a more complete and rapid combustion of the fuel-air mixture. This results in higher thermal efficiency, which leads to a reduction in the amount of fuel consumed per unit of specific power.

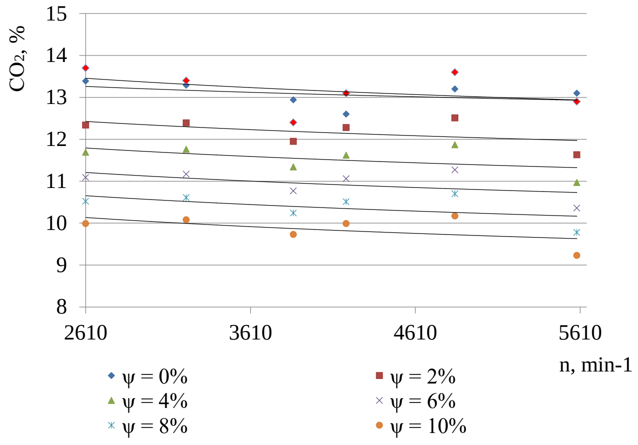

Fig. 3. Effect of hydrogen additive on the CO_2 concentration in the gas mixture at the modes of the external speed characteristic of the VAZ-21081 engine

It is also important to note that the addition of hydrogen has a positive effect on the environmental performance of the engine, reducing the amount of harmful substances emitted, which can also indirectly affect the reduction of specific effective fuel consumption.

It has been determined that each 2% hydrogen additive to petrol by weight reduces specific effective fuel consumption by 2.8–3.5%, depending on the speed regime.

The comparative characteristics of emissions in Fig. 3 shows a significant positive effect of hydrogen addition on CO_2 emissions from the exhaust gases of the VAZ-21081 engine. It was found that with the addition of hydrogen $\psi = 10\%$ by weight of fuel, the volume fraction of CO_2 concentration in the exhaust gas decreases to 30% in each of the modes of the external speed characteristic. This effect of hydrogen addition can be explained by its physicochemical properties since hydrogen ignites within 2 ms of sparking, and because it is under high temperature and pressure, it begins to split into atomic hydrogen. Atomic hydrogen is very reactive and causes a rapid chain reaction that spreads almost instantly throughout the combustion chamber. The almost simultaneous ignition of hydrogen initiates the simultaneous ignition of the main fuel.

Combustion using hydrogen additives has significant advantages over conventional combustion and is considered one of the most promising methods for decarbonising internal combustion engines in transport.

Firstly, hydrogen promotes more complete combustion of petrol, which reduces the amount of unburned hydrocarbons and reduces the formation of harmful substances.

Secondly, hydrogen dilutes the fuel mixture, reducing the carbon concentration and, consequently, the amount of CO_2 produced [4, 8]. However, the addition of hydrogen to petrol does not completely eliminate CO_2 emissions, as petrol still contains carbon.

4.2. Results of calculating the parameters of a hybrid power plant on the NEDC test cycle modes

The results of calculating the parameters of the engine and vehicle in the NEDC test cycle modes with the recommended parameters of the hybrid powertrain elements are shown in Fig. 4.

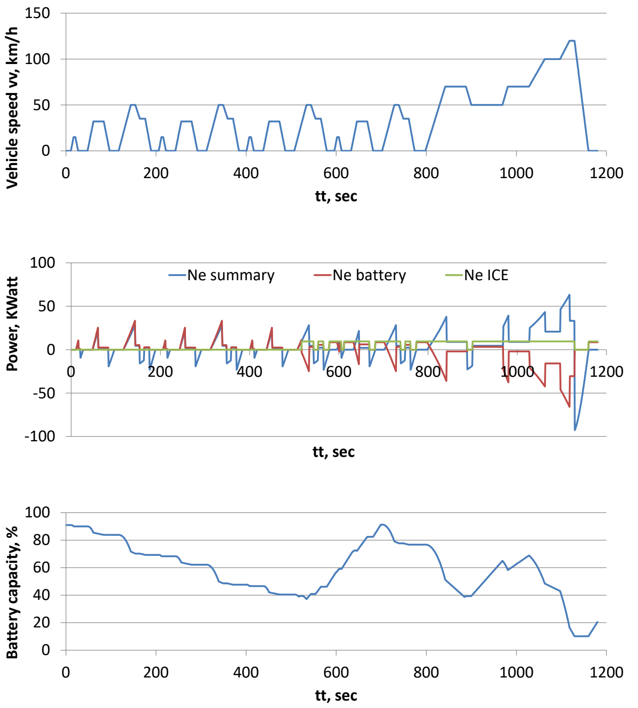

Fig. 4. Results of calculating the parameters of a hybrid car on the NEDC test cycle modes

Analysis of the results shows that braking energy is a reserve for increasing the fuel efficiency of the engine when using the recovery of this energy. The graph of the current battery capacity shows how the charge changes during the test cycle. The battery discharge time from 90% $C_{b\ max}$ to 40% $C_{b\ max}$ lasts 560 s. When reaching 40% of the battery capacity, the charging process begins, which lasts 176 seconds. When switching to the Extra-Urban cycle mode, a significant decrease in capacity is observed, this is explained by the joint operation of the internal combustion engine and the electric motor during intensive acceleration.

4.3. Calculation of fuel consumption and CO_2 emissions according to the NEDC cycle

Adding hydrogen to the fuel mixture leads to a significant reduction in petrol consumption due to the high calorific value of hydrogen and its efficient use in the combustion process. Hydrogen has a higher specific heat of combustion (about 120 MJ/kg) compared to petrol (about 44 MJ/kg), which allows for the use of less fuel to produce the same power.

Figure 5 illustrates the effect of hydrogen additive on fuel consumption in a hybrid drive. Based on the calculation of fuel consumption with increasing hydrogen content in the fuel, it can be seen that already at 5% hydrogen addition, fuel consumption per 100 km is reduced by 5.3% compared to pure petrol. At a 10% hydrogen concentration, fuel consumption is reduced by 11.1%.

The graph shows that the reduction in fuel consumption is linear up to a certain level of hydrogen addition. This shows that hydrogen at low concentrations significantly improves fuel efficiency, especially at partial engine load.

Reducing CO_2 emissions is one of the key effects of adding hydrogen to the petrol fuel mixture. Hydrogen does not contain carbon, which means that it does not produce CO_2 when burned. Thus, the more hydrogen is added to the fuel, the less carbon dioxide is released into the atmosphere.

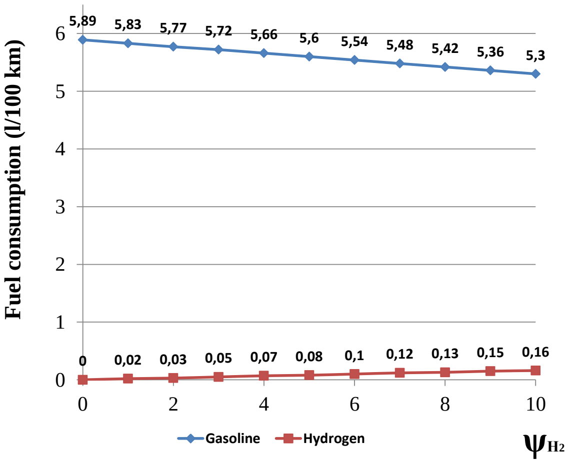

Fig. 5. Effect of hydrogen additive on petrol consumption

According to the calculations presented in Fig. 6, with a 10% hydrogen addition, CO_2 emissions are reduced by 22.1% compared to using pure petrol. This is a significant reduction, especially for hybrid systems, which already demonstrate low emissions due to the efficient use of battery power.

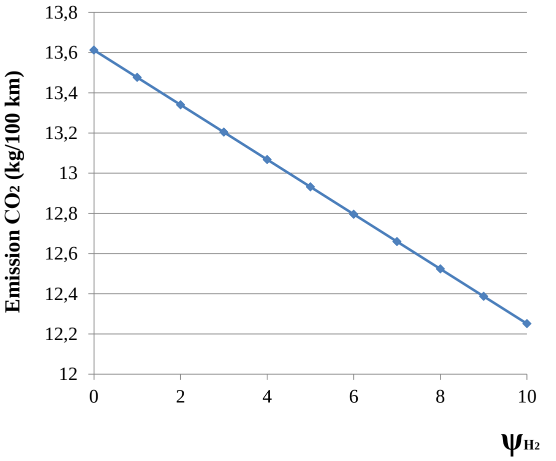

Fig. 6. Impact of hydrogen addition on CO_2 emissions

The graph confirms the theoretical assumptions that CO_2 emissions decrease with increasing hydrogen content. It is important to note that even with small hydrogen fractions, CO_2 emissions are reduced at a significant rate.

5. Conclusions

Based on NEDC's driving cycle model using a hybrid powertrain running on petrol and hydrogen, the following conclusions can be drawn about the impact of hydrogen on key indicators:

Reduced fuel consumption: the addition of hydrogen to the fuel mixture reduces petrol consumption, as hydrogen has a high specific heat of combustion and increases the overall efficiency of the internal combustion engine. Adding 2% hydrogen to petrol reduces fuel consumption by about 2.8% to 3.5%, depending on the speed. By increasing the proportion of hydrogen in the fuel mixture to 10%, petrol consumption decreases from 5.89 dm^3/100 km to 5.3 dm^3/100 km, which corresponds to a reduction of 0.59 dm^3/100 km or 10%. This effect is particularly noticeable in areas with low to medium engine load, where the hybrid system uses mainly energy recovery and optimised fuel combustion.

The corresponding hydrogen consumption with 10% hydrogen is approximately 0.16 kg/100 km. This demonstrates the feasibility of using small amounts of hydrogen to achieve significant reductions in petrol consumption.

Decarbonisation: As hydrogen does not contain carbon, its addition reduces the amount of CO_2 produced during the combustion of the fuel mixture. CO_2 emissions per 100 km decrease in proportion to the increase in hydrogen content in the fuel. Adding 2% hydrogen leads to a 5% reduction in CO_2 emissions. An increase in the hydrogen content to 10% reduces CO_2 emissions from 13.6 kg/100 km to 12.2 kg/100 km, which corresponds to a decrease of 1.4 kg/100 km or 10.3%. This effect confirms the feasibility of using hydrogen to improve the environmental performance of hybrid powertrains on the way to decarbonising transport.

Stabilisation of engine operation at low loads: Hydrogen has a positive effect on engine stability at idle and low loads. This is due to its high flammability, which improves combustion at low temperatures, which is especially important for hybrid systems where the engine often runs at partial load. As a result, efficiency is increased and incomplete combustion is reduced.

The need to optimise the fuel mixture: Despite the positive impact of hydrogen on emissions and fuel economy, too high a concentration of hydrogen may require changes to the engine settings. This is due to the higher combustion rate of hydrogen and its effect on the temperature of the internal combustion engine. For stable operation of the hybrid system, it is recommended to maintain an optimal balance of hydrogen and petrol in the mixture, which is also taken into account in the calculations.

Thus, the addition of hydrogen to the fuel mixture significantly improves both the economic and environmental performance of the hybrid powertrain within the NEDC driving cycle. The use of hydrogen can achieve significant reductions in CO_2 emissions and improve fuel efficiency, making this approach promising for the further development of low-carbon vehicles in accordance with modern European requirements.

The NEDC driving cycle calculation methodology described in this study allows the modelling of a hybrid powertrain with different percentages of hydrogen in the fuel. This model makes it possible to evaluate the efficiency of the powertrain as well as its environmental performance.

Nomenclature

CI	compression ignition
ICE	internal combustion engine
LCV	light commercial vehicle
NEDC	New European Driving Cycle
PC	passenger car

Bibliography

[1] Akal D, Öztuna S, Kemalettin M. A review of hydrogen usage in internal combustion engines (gasoline-Lpg-diesel) from combustion performance aspect. Int J Hydrogen Energ. 2020;45(60):35257-35268. https://doi.org/10.1016/j.ijhydene.2020.02.001

[2] Avramenko A, Lievtierov A, Bhantsev V, Hladkova N, Kirieieva V. Prospects of using hydrogen microaddition to improve diesel engine ecological indicators. Problems of Mechanical Engineering. 2019; 22(2):70-75. https://doi.org/10.15407/pmach2019.02.070

[3] Geiler J, Springer K, Lorenz T, Blomberg M, Achenbach J, Bloch P. H_2 engine hybrid powertrain for future light commercial vehicles. In: Heintzel A. (ed). Internationaler Motorenkongress 2023. Int. Engine Congr. 2024. Springer Vieweg. Wiesbaden 2024;1-15. https://doi.org/10.1007/978-3-658-44982-7_1

[4] Heffel J. NO_x emission reduction in a hydrogen fueled internal combustion engine at 3000 rpm using exhaust gas recirculation. Int J Hydrogen Energ. 2003;28(11):1285-1292. https://doi.org/10.1016/S0360-3199(02)00289-6

[5] Hennek K, Graba M, Mamala J. The influence of the throttle inclination characteristics of a SI engine on fuel consumption in driving cycles. Combustion Engines. 2017;170(3):78-83. https://doi.org/10.19206/CE-2017-312

[6] Iakovenko A, Dunin A, Dushkin P, Savastenko E, Shatrov M. The influence of mass composition of water-fuel emulsion on ecological characteristics of a diesel engine. Energies. 2019;12(14):2689. https://doi.org/10.3390/en12142689

[7] Iodice P, Langella G, Amoresano A. Ethanol in gasoline fuel blends: Effect on fuel consumption and engine out emissions of SI engines in cold operating conditions. Appl Therm Eng. 2018;130:1081-1089. https://doi.org/10.1016/j.applthermaleng.2017.11.090

[8] Ismatov J, Djalilov J, Fayzullayev A. Application of hydrogen as a supplement for car engines. Universum: Technical Sciences. 2021;85. https://doi.org/10.32743/UniTech.2021.85.4-2.22-24

[9] Koszałka G, Szczotka A, Suchecki A. Comparison of fuel consumption and exhaust emissions in WLTP and NEDC procedures. Combustion Engines. 2019;179(4):186-191. https://doi.org/10.19206/CE-2019-431

[10] Le TT, Sharma P, Bora BJ, Tran VD, Truong TH, Le HC et al. Fueling the future: a comprehensive review of hydrogen energy systems and their challenges, Int J Hydrogen Energ. 2024;54:791-816. https://doi.org/10.1016/j.ijhydene.2023.08.044

[11] Lejsek D, Leick P, Jochmann P, Grabner P, Schutting E. Analysis of mixture formation and combustion in H_2 engines for passenger cars and light commercial vehicles. In: Heintzel A. (ed). Internationaler Motorenkongress 2022. Proceedings. Springer Vieweg. 2024;3-16. https://doi.org/10.1007/978-3-658-44740-3_16

[12] Marchenko A, Mishchenko M. Investigation of the parameters of combustion of petrol with the addition of hydrogen in a spark ignition engine in the modes of external speed characteristics. Internal Combustion Engines. 2024;1:52-60. https://doi.org/10.20998/0419-8719.2024.1.07

[13] Mishchenko M. Defining innovative areas and prospects to develop the patenting of technological advances in the automotive power plant industry. Eastern-European Journal of Enterprise Technologies. 2024;13(127):92-102. https://doi.org/10.15587/1729-4061.2024.298643

[14] Osetrov O, Chuchumenko B. Mathematical modelling of the influence of internal combustion engine parameters on the dynamics of car acceleration. Internal Combustion Engines. 2021;2:3-10. https://doi.org/10.20998/0419-8719.2021.2.01

[15] Osetrov O, Chuchumenko B, Polivyanchuk A, Korohodskyi V. Mathematical modeling and computational study of a passenger car dynamics during acceleration. 25th International Scientific Conference "Transport Means". Part I. 2021;284-289. https://transportmeans.ktu.edu

[16] Osetrov A, Kokush V, Alyokhin D. Experimental study and mathematical modeling of mechanical losses in car engine. Bulletin of NTU "KhPI". Series: Transport Engineering. 2017;5(1227):59-63. https://repository.kpi.kharkov.ua/handle/KhPI-Press/33682

[17] Osetrov O, Kravchenko S, Chuchumenko B. Justification of the parameters of the passenger car series hybrid power plan. Internal Combustion Engines. 2022;1:78-85. https://doi.org/10.20998/0419-8719.2022.1.10

[18] Parczewski K, Romaniszyn KM, Wnęk H. A dynamic test of a vehicle in motion and exhaust gas emissions during alternative fuelling with gasoline and compressed natural gas (CNG). Combustion Engines. 2008;134(3):52-60. https://doi.org/10.19206/CE-117239

[19] Purayil S, Al-Omari S, Elnajjar E. Experimental investigation of the effect of CO_2 dilution on the performance and hydrogen knock limit of a hydrogen-gasoline dual fuel spark ignition engine. Int J Hydrogen Energ. 2024;68:410-427. https://doi.org/10.1016/j.ijhydene.2024.04.239

[20] Rusanov A, Solovey V, Zipunnikov M, Shevchenko A. Thermogas dynamics of physical and energy processes in alternative technologies (in Ukrainian). Monograph in 3 vol. 2018;1:336. http://monograph.com.ua/pctc/catalog/view/978-617-7319-18-3/7/29-2\

[21] Samoilenko D, Savchenko A, Kravchenko S. Improving the performance of diesel engines fueled with water-fuel emulsion. Combustion Engines. 2023;194(3):116-122. https://doi.org/10.19206/CE-169139

[22] Shadidi B, Najafi G, Yusaf T. A review of hydrogen as a fuel in internal combustion engines. Energies. 2021;14(19): 6209. https://doi.org/10.3390/en14196209

[23] Szwaja S, Bhandary K, Naber J. Comparisons of hydrogen and gasoline combustion knock in a spark ignition engine. Int J Hydrogen Energ. 2007;32:5076-5087. https://doi.org/10.1016/j.ijhydene.2007.07.063

[24] The Cabinet of Ministers of Ukraine Order of 30 May 2018 No. 430-r Kyiv 'On Approval of the National Transport Strategy of Ukraine for the Period up to 2030' (in Ukrainian). https://zakon.rada.gov.ua/laws/show/430-2018-%D1%80#Text

[25] Tutak W, Jamrozik A, Pyrc M, Sobiepański M. A comparative study of co-combustion process of diesel-ethanol and biodiesel-ethanol blends in the direct injection diesel engine/ Appl Therm Eng. 2017;117:155-163. https://doi.org/10.1016/j.applthermaleng.2017.02.029

[26] White Paper of the European Commission – Plan for the Development of a Single European Transport Area – Towards a competitive and resource-efficient transport system. EU Publishing Centre in Luxembourg. 2011;28. https://brdo.com.ua/wp-content/uploads/2016/01/1_Bila-knyga-transport-plan-rozvytku-yedynogo-yevropey-skogo-transportnogo-prostoru-na-shlyahu-do-konkuretnospromozhnoi-ta-resursoefektyvnoi-.pdf (in Ukrainian).

Wojciech Depczyński, DSc., DEng. – Faculty of Mechatronics and Mechanical Engineering, Kielce University of Technology, Poland.

e-mail: *wdep@tu.kielce.pl*

Svitlana Mishchenko, PhD, Institute of Energy, Electronics and Electromechanics, National Technical University «Kharkiv Polytechnic Institute», Ukraine.

e-mail: *svitlana.mishchenko@khpi.edu.ua*

Prof. Andrii Marchenko, DSc., DEng. – Professor Institute of Energy, Electronics and Electromechanics, National Technical University «Kharkiv Polytechnic Institute», Ukraine.

e-mail: *AndreyMarchenko51@gmail.com*

Mykyta Mishchenko. PhD student – Institute of Energy, Electronics and Electromechanics, National Technical University «Kharkiv Polytechnic Institute», Ukraine.

e-mail: *mykyta.mishchenko@gmail.com*