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Study of energy consumption of a hybrid vehicle in real-world conditions

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Highlights

- The energy consumption of the vehicle is strongly dependent on the ambient temperature.
- The IC engine significantly increases the total energy expenditure of test cycles.
- CO_2 emissions from the PHEV's average fuel consumption are below the allowable limit.
- The use of a electric motor in vehicles significantly reduces the vehicle operation costs.

Abstract

The paper presents an analysis of energy consumption in a Plug-in Hybrid Electric Vehicle (PHEV) used in actual road conditions. Therefore, the paper features a comparison of the consumption of energy obtained from fuel and from energy taken from the vehicle's batteries for each travel with a total distance of 5000 km. The instantaneous energy consumption per travelling kilometre in actual operating conditions for a combustion engine mode are within the range of 233 to 1170 Wh/km and for an electric motor mode are within the range of 135 to 420 Wh/km. The average values amount to 894 Wh/km for the combustion engine and 208 Wh/km for the electric motor. The experimental data was used to develop curves for the total energy consumption per 100km of road section travelled divided into particular engine types (combustion/electric), demonstrating a close correlation to actual operating conditions. These values were referred to the tested passenger vehicle's approval data in a WLTP test, with the average values of 303 Wh/km and CO_2 emission of 23 g/km.

Keywords

energy consumption, hybrid vehicle, road tests, energy share analysis.

Definitions/Abbreviations

$\bar{a}$ - mean acceleration [m/s^2],
a_D - acceleration in the deceleration phase [m/s^2],
a - acceleration [m/s^2],
AT - Automatic Transmission,
C_F - Fuel consumption in test [kg/s],
C_V - calorific value of fuel [J/kg],
dV - speed change [m/s],
E_M - energy consumption of motion [J],
EM - electric motor,
E_T - total energy consumption [kWh],
E_{Te} - total energy consumption of the electric drive [J],
E_{Tf} - total energy consumption of the combustion engine [J],
EV - Electric Vehicle,
FD - free driving distance,
HEV - Hybrid Electic Vehicle,
ICV - Internal Combustion Vehicle,
L - distance [m],
L_A - distance of the acceleration phase [m],
L_C - distance of the acceleration constant speed phase [m],
MT - Manual Transmission,
NUT - non -urban traffic distance,
P - Power, [W],
PHEV - Plug-in Hybrid Electric Vehicle,
Q_e - distance-based energy consumption of the electric drive [kWh/km],
Q_f - distance-based fuel consumption of the combustion engine [dm^3/100km],
Q_{T_PHEV} - distance-based energy consumption [Wh/km],
Q_{Te} - total distance-based energy consumption of the electric drive [Wh/km],
Q_{Tf} - total distance-based energy consumption contained in the fuel [Wh/km],
SOC - State Of Charge [%],
T_L - time for stop phase or engine idle run [s],
$t_{s,e}$ - start and end time of energy calculation [s],
t_T - time traveled distance [s],
TTW - (Tank-to-wheels),
UT - urban traffic distance,
WLTP - The Worldwide Harmonized Light Vehicles Test Procedure,
$\bar{V}$ - average speed [m/s],

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V_c - speed in uniform motion [m/s],
ΔE_D - energy losses of the internal combustion engine [J],
ΔE_E - energy losses of the electric drive [J],
ΔE_L - energy losses by idle operating conditions of the vehicle [J].

1. Introduction

A passenger vehicle can be analysed in terms of the consequences of specific energy conversions occurring in its engine system. Combustion engines are the dominant engine type in most power train systems. As result of the energy conversions derived from the fuel delivered from the tank, the combustion engine generates heat energy which is then transformed into kinetic energy, transferred to the drive system and ultimately to the vehicle's wheels, thereby setting the vehicle into motion. In the energy balance of a moving vehicle, implementing a selected speed profile, the energy generated from the burnt fuel E_T is expended to drive the vehicle and also lost as result of various energy conversions occurring both in the engine and in the transmission system. Therefore, according to equation (1), it is a sum of the following: energy delivered by the drive system to the wheels and defined as the motion energy consumption (E_M) required for overcoming the vehicle's motion resistance, the drive system's energy losses (ΔE_E) and energy losses of the internal combustion engine – (ΔE_D), as well as losses in energy by idle operating conditions of the vehicle (ΔE_L) including e.g. the vehicle's standstill phase:

$$E_T = E_M + \Delta E_E + \Delta E_D + \Delta E_L. \tag{1}$$

All components of the vehicle's energy balance vary over time and depend on the speed profile parameters and environmental conditions. A vehicle speed profile consist of 4 vehicle motion phases (accelerated motion, constant speed motion - constant speed, delayed motion, and standstill), the energy expenditure is estimated between start and stop of the vehicle and the their kinetic energy is equal to zero at the beginning and end. The description of the speed profile parameters, consist: average speed $\bar{V}$, travel distance L or average acceleration $\bar{a}$, is influenced by the share of particular profile phases i the given road section. The simple speed profile does not occur in practice. Complex speed profiles occur in reality, where the profile's kinematic parameters (speed, acceleration) are averages of many simple profile components (simple modules). The average values can be calculated from equations (3) and (4), where the average speed of a complex profile can be calculated from dependency [29]:

$$\bar{V} = \frac{\sum_i L}{\sum_i \int_{t_s}^{t_e} \frac{dv}{a} + \sum_i \frac{L_c}{V_c} + \sum_i \int_{t_s}^{t_e} \frac{dv}{a_D} + \sum_i T_L}, \tag{2}$$

wherein (i) is the number of simple profiles and the complex profile's average acceleration from dependency (6):

$$\bar{a} = \frac{\Sigma(\Delta V)_i}{2L}, \tag{3}$$

where

$$\Delta V = V_e^2 - V_s^2. \tag{4}$$

Standstill is an undesired motion phase, because the combustion engine's operation results in the generation of energy from burnt fuel, which is not collected by the transmission system. In such a case, the drive system's efficiency is equal to zero. In this context, "Stop&Go" systems started to be used in vehicles [5, 23, 44], which in principle stop the combustion engine during standstill. An additional advantage of this solution is the reduction of emissions of harmful substances and CO_2 contained in exhaust gases into the environment. The share of the standstill phase depends on the speed profile and environmental conditions [37, 42]. In paper [10], the authors put emphasis on the analysis of the share of particular vehicle motion phases in a complex driving cycle in urban and non-urban traffic conditions. The authors demonstrated that over 20% of the acceleration phase is implemented with acceleration in the range of 0 – 1 m/s^2 and over 15% of the acceleration is in the range of 1 – 4 m/s^2 and usually amounts to over 5% of the total vehicle travel duration, i.e. the driving intensity is very important in terms of fuel consumption. In paper [13], Fontaras et al. focused on fuel consumption on the view of the dynamics, demonstrating a slight energy consumption increase of approx. 5% for non-urban driving and nearly 70% for urban driving. These differences mainly derive from two different vehicle speed profiles resulting from the average speed and driving dynamics. In paper [15], the authors dealt with the optimisation of the engine's load selection and the transmission ratio's selection strategies during acceleration of a an ICV (Internal Combustion Vehicle). A change in the driving dynamics by extending the acceleration time by 1s in the case of acceleration in the range of 0 – 30 km/h and by 2 s in the range of 0 – 40 km/h allows for reducing fuel consumption by more than 5%. The authors [6] analysed dynamic parameters of different vehicles. The analysis covered a broad spectrum of vehicles, starting with motorcycles, through passenger vehicles and ending with commercial vehicles, determining the acceleration values of 0.45 – 2.87 m/s^2 and the mean range of 0.2 – 0.82 m/s^2. The high variation in acceleration affects fuel consumption, which is subjective and depends on the road type, driving style and speed profile. In papers [1, 43], the authors noted the variation in driving styles with reference to the implemented driving cycle in actual traffic conditions. The increase in driving dynamics described in the paper causes an increase in fuel demand from 40% in non-urban to 45% in urban traffic. In paper [14], the authors pointed to the varying vehicle energy consumption in real-world conditions depending of its acceleration dynamics. Road tests demonstrated substantial discrepancies in the distance-based fuel consumption fluctuating between 12.44 and 31.8 dm^3/100km on a ¼ mile section, depending on the acceleration dynamics and transmission ratio selection in the transmission system. The selected transmission ratios with lower values resulted in a reduced fuel consumption with an average drive system efficiency fluctuating between 19.38 and 24.6% which are tested on a vehicle with an ICE (Internal Combustion Engine) modern downsized powertrain

On the other hand, the authors of dissertation [12] emphasised the constant speed vehicle motion phase and designated the highest efficiency points for an ICE meeting the Euro 5 standard for specific driving speeds. It was indicated that for the various types of power train systems tested, the optimal speeds in terms of fuel consumption may range from 70 to 75 km/h. In this regard, the authors of a different dissertation [4] analysed the impact of various transmission systems and emphasised the AT and MT transmissions, for which the maximum efficiency point at constant speed of 70 km/h was designated at 24%.

However, in terms of fuel consumption, regardless of the motion phase testing and analysis, it is key to enable kinematic energy recovery in a vehicle accelerated in a delayed motion phase, where in most cases the energy is dispersed into the environment by the braking system. The introduction of the hybrid engine system HEV (Hybrid Electric Vehicle) was aimed at reducing the driving system's energy loss through energy recovery [27, 38, 48] .

In a vehicle with a conventional engine system ICV, only 12–25% of the energy derived from fuel is consumed for motion in urban traffic conditions. Most energy is lost by the combustion engine in the form of emitted heat, own losses deriving from friction, and ineffective combustion in urban driving cycle, hybrid vehicles have 21-40%

of energy derived from fuel and electrochemical battery available for their disposal [11, 45].

In paper [46], the authors compared the combustion engine systems ICV with hybrid powertrain system (HEV) in terms of the driving style and demonstrated that the driving dynamics substantially affects the fuel consumption. In the ICV, the difference is as high as 74%, while in the HEV – 105%. In paper [24], the authors simulated various distance of a cycle consisting of the acceleration phase and the subsequent run-down phase in terms of reduction in fuel consumption in a hybrid electric vehicle. The results obtained demonstrate the potential to reduce fuel consumption depending on the speed range from 5 to 11% when applying an adequate acceleration intensity.

However, regardless of the engine type used, i.e. combustion or electric, or the interoperability of both as a hybrid powertrain system, the aforementioned environmental components affect the fuel consumption in actual operating conditions. In this paper, the authors emphasised the energy expenditure converted to the vehicle weight and distance for a modern PHE) used in various operating and traffic conditions. It is an modern powertrain with two energy storage units (fuel and batteries) and two drive units (ICE and EM) which drive the vehicle together. The drive system's energy consumption is analysed in terms of the TTW (Tank-to-Wheels), understood as the total expenditure of energy obtained from energy storage units referred to the distance travelled. The results were compared to the data obtained from the WLTP (The Worldwide Harmonised Light Vehicles Test Procedure) approval test.

2. Research on and development of hybrid electric vehicles

In the world around us, in which carbon dioxide emissions and environmental pollution are the main problem, electric vehicles are becoming increasingly popular. When compared to vehicles powered with petroleum derivatives, electric vehicles emit substantially less greenhouse gases and air pollutants. Thanks to technological progress, the operation of electric cars has become more user-friendly (e.g., increased mobility), mainly due to the improvement of energy storage parameters and optimization of energy consumption management by individual vehicle systems. Nearly all global car manufacturers are currently starting the development of entirely electrical models. On the other hand, customers are also attracted by the concept of using electric vehicles. The Allied Market Research (AMR) report [39], which provides a thorough analysis of the automotive market, reveals that technological advances and proactive government initiatives have led to an exponentially growing demand for fuel-efficient, low-performance, low-emission vehicles. The report also states that the increase in demand is fostered by strict exhaust gas emission regulations imposed in many countries. On the other hand, technological progress and proactive governmental initiatives ensure an exponential growth of the automotive market.

It is expected that in the next 30 years, the global production of new vehicles will increase by nearly 30% [14], resulting in the presence of over $2 \cdot 10^9$ vehicles on the Earth in several dozen years [3, 8, 17]. Due to the imperfections of currently produced vehicles, there is a need for continuous improvement of modern drives. Therefore, innovative solutions are implemented for the individual components of the vehicle, which will, on the one hand, increase mobility, and, on the other hand, contribute to the protection of the natural environment. New vehicles will be equipped with advanced drive systems with uniform or hybrid engines due to the introduction of increasingly strict standards on exhaust gases and carbon dioxide emissions [32]. It was announced that in 2025, the European Union will introduce a new exhaust fume emission standard named EURO 7, due to which meeting the new emission limits in uniform combustion engine systems will be very difficult or even impossible while maintaining high vehicle traction parameters related to the dynamics and average travel speeds [26]. However, regardless of the engine system used, battery electric engines will be commonly used. The ion-lithium batteries used currently are quickly discharged and require frequent charging. The most novel changes in terms of battery weight reduction and performance improvement are lithium sulphur cells. They are fully compostable and biodegradable organic batteries that will not only be a good eco-friendly option, but also allow for rapid charging. They are also substantially lighter [16]. To allow batteries to easily meet the presented requirements, ultra-capacitors characterised with excellent parameters, especially at low temperatures, are added to vehicles. The ultra-capacitor's and lithium-ion battery's interoperability management requires using a hybrid energy storage system (HESS) with a suitably developed management strategy [47]. Currently, research is being carried out on the optimization of electric power supply systems, which include fuel cells [9, 25].

From the driver's point of view, the energy sources used are of no significant importance. In light of the requirements for a vehicle as an energy system, it is important to ensure adequate traction parameters capable of moving it in a satisfactorily short time on a given road section. In the current state of automotive development, the variety of hybrid or electric engine systems offered by manufacturers is broad, but their market share is insignificant. In the next 10 years, the dominant drive systems will most probably be the PHEV (Plug-in Hybrid Electro Vehicle). This is due to the fact that they combine the advantages of an electric motor with the energy autonomy derived from the limited range of EV (Electric Vehicles). Hybrid engine systems became dominated by such units as the combustion and electric engines, combined in parallel. This results from the greater universality of such an engine system solution in every-day use in urban and non-urban traffic [2, 6, 21, 34, 35]. The testing of hybrid engine systems powered with fuels are conducted with reference to the harmful component emission limits [18, 22, 28, 33, 35, 41, 42]. However, many authors are conducting tests of energy consumption in normal operating conditions [19, 20, 35, 36, 40] or solely with reference to the electric engine system [7, 35]. The real test constituting verification of such hybrid engine systems in terms of energy consumption are road measurements conducted in actual operating conditions. Therefore, this paper features an analysis of the impact of road conditions on the energy consumption in a hybrid engine system. For this purpose, a vehicle was tested on a distance of 5000 km, in three groups, with selected three travel distances:

I – urban traffic (**UT**) with distance up to 20 km,
II – non -urban traffic (**NUT**) with distance up to 70 km C,
III – free driving (**FD**) with distance travels above 70 km D.

All road test was occurred for randomly selected drivers. All above mentioned speed profile parameters were recorded for each travel distance separately.

3. Research topic motivation

The difference in the energy value of energy carriers stored in passenger cars with hybrid drive systems means that a direct comparison of the mileage consumption for an internal combustion engine with the mileage consumption for an electric motor is not adequate in terms of unit. The use of the distance-based energy consumption in the standardized energy unit Wh/km for both drive units within the hybrid drive system allows to increase the possibility of their comparison. The comparative parameters may be the time of use of both drive units, energy expenditure and the possibility of relating the values obtained in operational tests to the values obtained in the approval test. The unit Wh/km adopted in this study is not compatible with the SI system, but it is used in the automotive industry and approval tests. Despite the similarity in the drive train for both drive units, the drive unit decides about the energy expenditure from energy storage. Thus, the motivation to undertake the research was the analysis of the energy parameters of the hybrid drive system for a given car trip, taking into account the drive unit used in real-world conditions. At the same time, it was decided to examine the share of individual drive units in the vehicle's mileage consumption. Additionally, the analysis covered the influence of the ambient temperature on the electricity consumption and, as a result, the vehicle range.

4. Methodology

4.1. Distance-based energy consumption

The distance-based energy consumption is understood as the energy demand from the vehicle's energy storage units to its engine per travelled kilometre. In the case of the ICE, the total energy (E_{Tf}) can be formulated as a product of the fuel consumption (C_F) and the fuel calorific value (C_V):

$$E_{Tf} = C_V \cdot \int_{t_s}^{t_e} C_F \, dt, \tag{5}$$

where:

C_F – fuel consumption [kg/s];
C_V – fuel calorific value depending on the fuel's type [J/kg];
$t_{s,e}$ – energy calculation start and end time [s].

For the electric motor unit, the total energy (E_{Te}) expended by the drive depends on the electric engine's structure, whether it is powered with direct or alternating current, and on the instantaneous output supplied from the batteries to the electric engine unit. In the case of the alternating current, the total energy can be calculated from equation (6):

$$E_{Te} = \int_{t_s}^{t_e} \mathrm{U}(\mathrm{t})\mathrm{I}(\mathrm{t})\cos\varphi(\mathrm{t})\, dt, \tag{6}$$

where:

U - voltage over time,
I - current amperage rating over time,
cosφ - power factor (for direct current cosφ=1),
$t_{s,e}$ - start and end time of power take.

The total energy supplied to the vehicle's drive system in the case of a PHEV is the sum of the energy collected from various energy storage:

$$E_T = E_{Tf} + E_{Te} \, . \tag{7}$$

Energy recovery of the tested vehicle is not the subject of analysis in terms of operation, because it replenishes the energy storage unit by charging up batteries and thereby increasing the vehicle's travel range.

The total energy consumed by the vehicle per distance travelled represents the distance-based energy consumption, which can be compared to the values obtained in the WLTP test, expressed in Wh/km, following dependency:

$$Q_{T\_PHEV} = \frac{E_T}{L} \, . \tag{8}$$

The obtained values vary and depend on the type of engine unit used and on the traction parameters: average travel speed, travel distance, and time.

4.2. Research program

The research concerned the analysis of the distance energy consumption in a selected passenger vehicle equipped with the Plug-in type hybrid engine system with consideration of the following:

1. analysis of the operating time of particular engine units in the hybrid engine system,
2. analysis of the total energy expenditure in instantaneous and incremental terms
3. analysis of the total distance-based energy consumption for the PHEV and consumption broken down into particular engine units,
4. analysis of the vehicle's range in different environmental conditions (temperature).

The traction and energy parameters were monitored using the Mercedes software for mobile devices and the TEXA diagnostic system, which allowed the recording of the following data: total vehicle range, divided into particular engine/motor, capacity of energy storage, total distance, distance for each drive units, travel time, mean speed and energy expenditure as the distance-based fuel consumption and distance-based energy consumption.

Fig. 1. Measurement system diagram

The aforementioned data was systematically recorded in the database and then analysed. The analysis of the distance-based energy consumption was conducted for the vehicle's actual operating conditions deriving from every-day travels divided into three groups. The travels were characterised by freedom in route selection and random selection of drivers with a standard hybrid engine system control mode. All tests were carried out with the battery fully charged (SOC = 100%).

4.3. Test and analysis of energy consumption

The distance-based energy consumption testing of an PHEV vehicle in actual operating conditions of the analysed vehicles was conducted using the Mercedes-Benz A 250e vehicle. It is a passenger vehicle manufactured in 2021 with a full hybrid engine system, wherein two engine units (electric and combustion) are installed on the front drive axis. The engine units interoperate with the 8 F-DCT transmission (Front –Double Clutch Transmission), wherein the drive is transmitted to the front wheels.

The tested vehicle's technical and structural parameters are presented in Table 1. Table 1 presents the average energy consumption for the electric engine system and the average CO_2 emission according to the WLTP test, which was taken from the approval certificate [31].

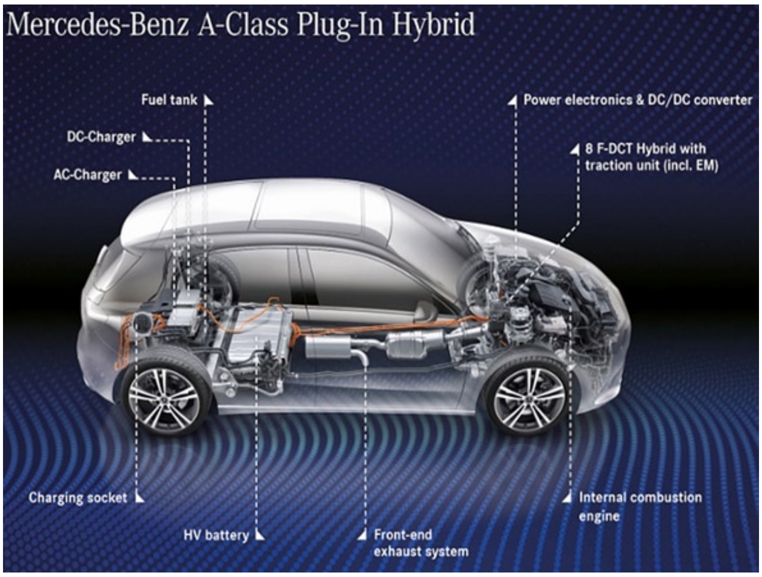

Fig. 2. Mercedes-Benz A-Class Plug-In Hybrid components [30]

Table 1. Tested vehicle parameters [31]

Manufacturer	Mrecedes - Benz
Type	A250e / V177
Combustion engine's displacement	1332 cm^3
Combustion engine's performance	118 kW @ 5500 rpm
Combustion engine's max. torque	210 Nm @ 1750 rpm
Electric engine's power	75 kW
Long-term electric engine's power	55 kW
Electric engine's max. torque	300 Nm @ 0 - 5000 rpm
Engine assembly	Front, transverse
Combustion engine's supercharging	Supercharger
Engine system type	PHEV
Transmission system	Automatic - 8 gears
Battery capacity	15.6 kWh
Vehicle weight	1817 kg
Emission standard	Euro 6 (AP)
Travel range for petrol	450 km
Travel range for batteries	75 km
Average CO_2 emission acc. to WLTP	23 g/km (1.0 dm^3/100km)
Energy consumption for the EV system	209 Wh/km

It is necessary to note the increase in the tested vehicle's weight in comparison to the internal combustion vehicle by nearly 300 kg due to using additional electric engine components (energy storage unit, electric engine, inverter and control system).

5. Test results

According to the adopted methodology, the study of the distance-based energy consumption in real-world cycles was conducted for the vehicle's actual operating conditions derived from the vehicle's every-day operation. The analysis of the hybrid engine system was conducted by using every-day vehicle travels in various atmospheric and road conditions, i.e. urban and non-urban traffic, in Opole and surrounding areas. The driver was free to use any driving technique. The travel distance was divided to three groups according to the methodology. Table 2 presents the traction and energy parameters for the analysed travel groups.

Groups I and II were dominated by the vehicle's electric engine system (EV), in which the combustion engine unit was activated temporarily to increase the instantaneous speed or support the vehicle's intense acceleration on the road. In such situations, both units interoperated as a whole powertrain system. Figure 3 presents the percentage share of particular engine units in the tested vehicle.

In terms of particular percentage shares, the combustion engine unit's share was increasing from 6% in group I in 22% in group III, with an average value of 14% for all travels. The average values of distances in particular travel groups varied, as presented in Table 2. The highest differences can be observed in the energy expenditure expressed in Wh/km, which is presented in Figure 4.

The presented dependencies of the share of the distance-based energy expenditure per kilometre travelled for particular travel groups vary and depend on the time particular engine units were used. In all travel groups, despite the dominance of the electric engine unit powered from batteries, it is the combustion engine unit's use that substantially increases the total energy expenditure in particular travels. When drawing the attention to the average values of the distance-based energy consumption Q_{T_PHEV} for all engine units in particular groups, it is possible to see that the values are higher than those deriving from the approval tests, which amount to 303.1 Wh/km for the tested vehicle. The travels in group II come closest to the above value, because the average distance-based energy consumption amounted to 356.2 Wh/km, which is 17.5% higher than the value achieved during the approval test. However, some travels carried out in groups I and II solely featured the use of the vehicle's electric engine system, the parameters of which are presented below:

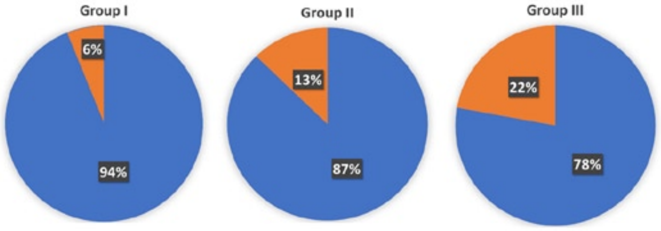

Fig. 3. Percentage shares of engine units for particular travels: a) group I, b) group II, c) group III (orange – combustion engine, blue – electric motor)

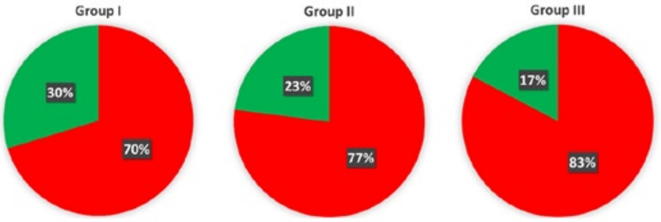

Fig. 4. Percentage share of particular engine units in the distance-based energy expenditure (green – combustion engine, red – electric motor)

In these terms, the average distance-based energy consumption achieved was lower than that achieved during the test. All mileages in the particular groups (Table 2) tested in the vehicle's actual operating conditions demonstrated substantial differences derived from driving the vehicle using particular engine units as well as substantial varia-

Table 2. *Average engine system operating parameters during travels carried out in the hybrid engine system's standard operating mode*

Group	L_T [km]	L_e [km]	t_T [s]	V [km/h]	Q_f [dm^3/100km]	Q_e [kWh/100km]	Q_{Tf} [Wh/km]	Q_{Te} [Wh/km]	Q_{T_PHEV} [Wh/km]
I	9.1	7.7	1086	28.7	1.26	28.3	828.6	350.4	401.2
II	54.1	45.2	3935	51.8	1.10	18.2	740.6	216.4	285.2
III	121.9	83.8	8880	52	2.78	12.1	828.9	173.6	381.7
Average	51.4	41.7	3784.5	47.7	1.22	19.6	760.6	234.9	310.4

Table 3. *Mean engine system operating parameters during travels carried out using solely electric engine unit*

Group	L_T [km]	L_e [km]	t_T [s]	V [km/h]	Q_f [l/100km]	Q_e [kWh/100km]	Q_{Tf} [Wh/km)]	Q_{Te} [Wh/km]	Q_{T_PHEV} [Wh/km]	L_T [km]
I	7.1	7.1	960	25.2	0	33.35	0	333.5	333.5	7.1
II	46.1	46.1	2994	56.14	0	20.56	0	205.6	205.6	46.1

tion in the energy expenditure or distance-based energy consumption. It is difficult to directly compare the average distance-based fuel or energy consumption presented in Tables 2 and 3 in aspect to energy densities of the energy carriers in the storage units (Fig. 4a-c). Figure 6 presents the distance-based energy consumption for an approval test travel with reference to all travels for the PHEV hybrid system. When converted to energy expenditure derived from the used test vehicle, it is 25% higher than that achieved in the WLTP cycle at an mean speed of 13.25 m/s and mean distance of 51400 m (Table 2). This average parameter resulted from the actual road conditions correspond to the distance travelled by the test vehicle. This value was about 200% higher than that travelled in the WLTP test, wherein the traffic test amounts to 23266 m. It must be noted that the average vehicle speed was similar in the WLTP test and in actual operating conditions 12.92 m/s. The observed excessive distance-based energy demand for all travels (Fig. 5) exceeds the values recorded during particular travels above 140 km, which substantially exceeds the electric system's storage unit range. Therefore, in the case of travels in group II, which feature almost identical mean speeds and the distance was lower then energy storage unit's range. The distance-based energy consumption amounts to 285.2 Wh/km for the hybrid engine system and 205.6 Wh/km for the electric engine system and is 6% below the WLTP test value. The research result presented in Figure 5 were compared to WLTP homologation value, wherein the vehicle's average unit energy consumption were superimposed on particular travel groups. The travels carried out up to the energy storage unit's range do not exceed the distance-based energy consumption achieved in the WLTP test. The distance-based energy consumption in the case of the tests drives made from the electric energy storage does not exceed the values obtained during the WLTP approval tests (Fig. 5). In group III, there does not exceed the WLTP cycle value. However, this derives from a fast charging of the batteries during the test travel.

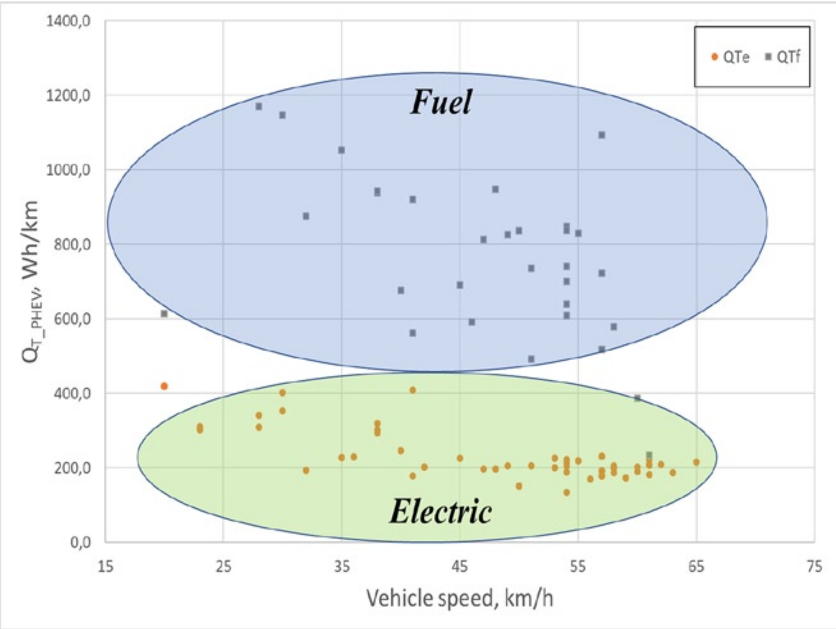

Fig. 6. *Average speed and distance-based energy consumption broken down into particular engine units*

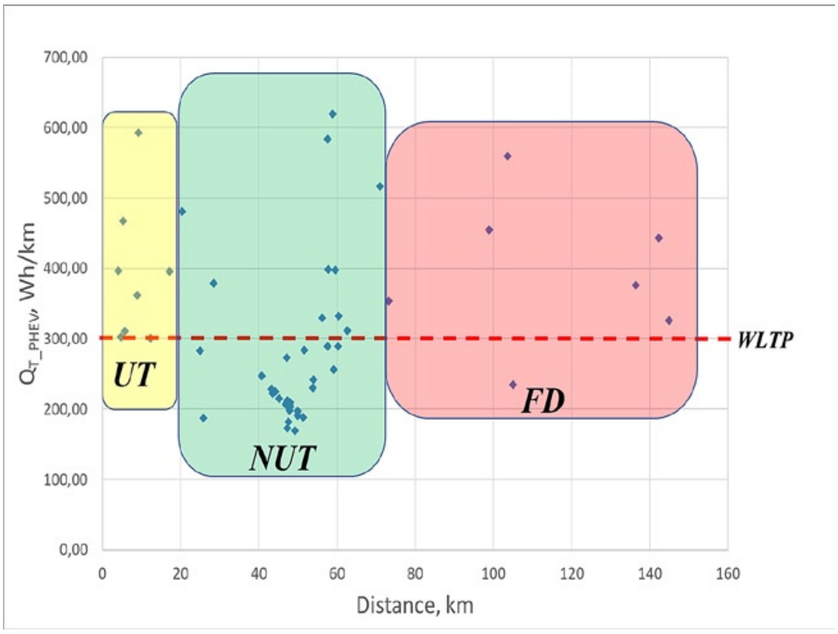

Fig. 5. Distance-based energy consumption refers to the distance travelled

When drawing attention to the vehicle travel groups, the highest distance-based energy consumption was achieved in travels, during which the combustion engine system was used. The average instantaneous energy expenditure amounts to 760.6 Wh/km for the combustion engine system, i.e., approx. 2.86 MJ per kilometre travelled (Fig. 7). These values are 320% greater as the average energy expenditure for the electric motor. The

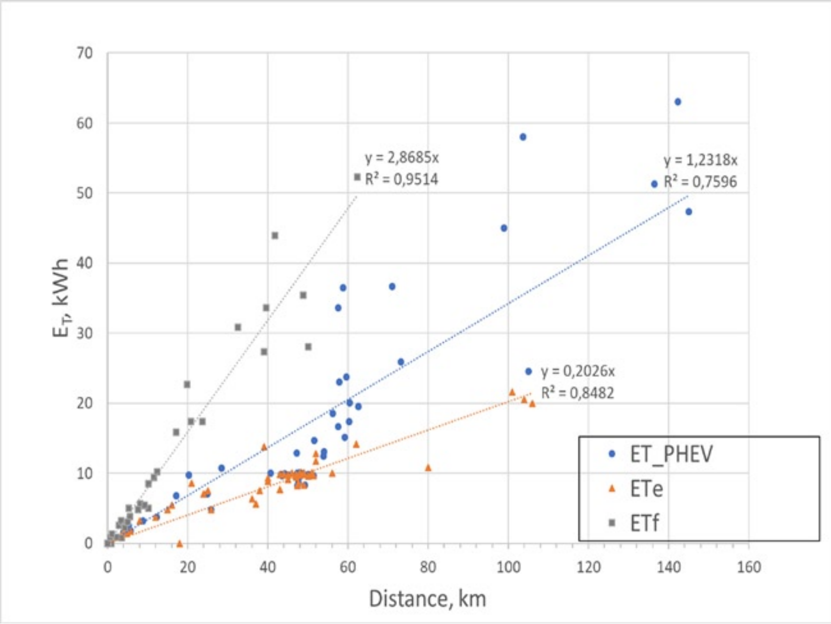

Fig. 7. Total energy expenditure to cover the given distance using various engine unit types with reference to the total distance travelled [29]

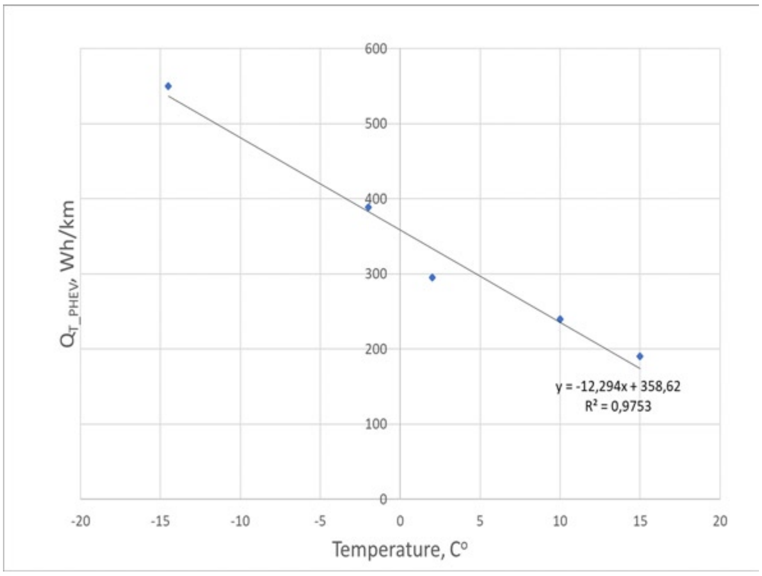

Fig. 8. Changes in the vehicle's total unitary energy consumption in different environmental conditions

average energy expenditure per kilometre travelled of which amounts to 234.9 Wh/km, which is equal to 0.72 MJ/km. This difference results mainly from the efficiency of the power units used [29].

In the case of city and highway driving, it can be expected as a significant increase in energy demand due to high dynamics or significant aerodynamic resistance. The value's decrease is more important when using the combustion engine unit, which results in more than a double reduction in the unit energy expenditure (from approx. 1500 Wh/km at an average speed of approx. 30 km/h to below 600 Wh/km at an average speed exceeding 60 km/h). In these terms, Figure 7 presents the total energy consumption for covering the given distance in terms of the total distance travelled and broken down into particular engine units used to drive the vehicle.

The research was based on the relation between the energy storage unit's capacity and ambient temperature. The issue of battery capacity reduction related to ambient temperature described in the literature was observed. Figure 8 presents an increase in average distance-based energy demand in the temperature range of −15 to 15°C. This constitutes another factor that results in the vehicle's reduced range. An increase in energy demand at low temperatures derives mainly from the additional energy expenditure to heat the interior and the battery assembly, but also from the increased motion energy consumption due to increased motion resistance.

It is necessary to note the vehicle's total unit energy consumption when using the electric engine, wherein the energy consumption at a negative temperature −15°C is over twice as high as at a positive temperature +15°C. In this case, the vehicle's range was reduced by 21 km.

The designated straight line's regression coefficients for the vehicle's powertrain (Fig. 7) can be used for estimating the vehicle's operating indexes during the selected travel and road section. When calculating the energy expenditure, is it then possible to calculate the operating costs and the CO_2 emission different powertrain system. The mean energy consumption for a distance of 50000 m is presented in Table 5.

Attention must be drawn to the energy storage unit's capacity, which for the tested vehicle theoretically allows for covering a 75 km distance at the temperature of 18°C, after which the driver can only use the combustion engine. The tested hybrid vehicle allows for achieving the assumed data deriving from the conducted WLTP test for travel group II (Fig. 6). The PHEV powertrain is a very good solution not only in terms of energy expenditure, but also in terms of the CO_2 emission reduction. On longer routes, it is necessary to remember to replenish the energy storage unit, which lasts for the time depending on the available power grid. The tested vehicle's average charging time from 0 to 100% SOC are:

- for 220V charger (2.2 kW) – approx. 5.5 hours;
- for 380V charger (7.8kW) – approx. 1.5 hours;
- for CCS charger (22kW) – approx. 0.5 hours.

Table 5. Mean parameters during 50 km test distance carried out using the available hybrid system's operating modes [29]

Type	L_T [km]	E_T [MJ]	Q_{T_PHEV} [MJ/km]	Q_f [dm^3/100km]	Q_e [kWh/100km]	Price [Euro/100km]	CO_2 for TTW [g/km]
EV	50	36.3	0.72	0	20.2	2.87	0
PHEV	50	61.6	1.23	1.67	18.5	4.74	18.2
ICV	50	152.5	3.05	9.0	0	10.6	207

Table 6. Mean engine system operating parameters during travels carried out on a total distance of 5,200 km

Distance [km]	dL_T [km]	L_e [km]	t_T [s]	V [km/h]	Q_f [dm^3/100km]	Q_e [kWh/100km]	Q_{Tf} [Wh/km]	Q_{Te} [Wh/km]	Q_{T_PHEV} [Wh/km]
5200	93.9	66.7	7692	41.7	2.78	14.75	893.7	208.6	410.1

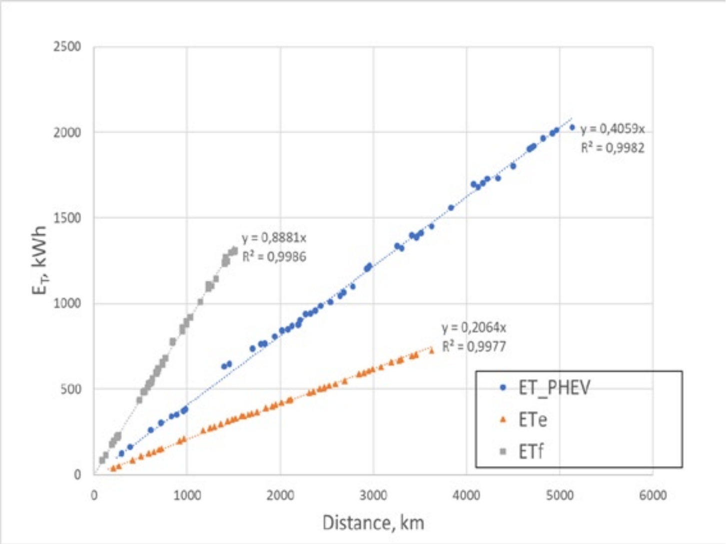

Fig. 9. Accumulated energy expenditure for particular hybrid system components

Using the manufacturer's data regarding the charging time, average energy price, and the obtained results of energy demand, it is possible to calculate the mileage costs. Assuming the average price of 1kWh of energy when using the power grid is 0.142 EUR/kWh and the unit price of energy in fuel (gasoline) is 1.18 EUR/dm^3 (0.129 EUR/kWh), taking into account the energy/fuel consumption from individual storage tanks (battery, fuel tank) during the test driving's being the subject of the analysis (driving with the use of only electric drive, or driving only with the use of an ICE) causes a significant differentiation of operating costs (as energy costs) between the electric drive and the internal combustion engine. In this approach, the cost of energy consumed over a distance of 100 km for an internal combustion engine is approximately 3.7 times higher than for an electric motor (Table 5). The parameters of the drive system in terms of 5200 km the test cycle (Table 6).

The car total unitary energy demand over the distance of 5200 km (including trips using only the ICE) is greater compared to the results obtained only for the PHEV. It is related to the increase of ICE operating time up to 63.9%. These parameters were summed from the start of each distance of the test and counted from travel to travel as mean values. Despite to the greater PHEV vehicle's weight average fuel consumption amounts to 2.78 dm^3/100km on a distance of over 5 thousand km. It means that the standards specified in the new regulations on CO$_2$ emission limit of 95 g/km from 2021 were met. When converted, the analysed vehicle's road emission amounts to 63.9 g/km and is below the acceptable limit.

An analysis of the distance-based energy consumption for urban and non-urban driving (travel groups I and II) demonstrate a double increase in energy consumption on short road sections (Fig. 5). When analysing the distance-based-energy consumption in increments presented in Figure 9, the parameter demonstrates a strong correlation of the energy expenditure to the distance travelled for particular engine systems. The obtained determination coefficient R^2 is equal to one and the straight lines' direction coefficients changed slightly up to 4% in relation to the instantaneous values for particular travels.

6. Summary

The distance-based energy consumption of a passenger vehicle equipped with the Plug-in type hybrid powertrain in actual operating conditions presented in the paper presents a varied energy expenditure that depends on the engine unit used at the given time and driving cycle. The presented energy expenditure calculations based on standardised data for the tested vehicle allow for the formulation of conclusions in terms of the following:

1. Operating time of the hybrid drive system for individual drive units - in all groups of driving cycles, indicates the dominant electric drive unit (Fig. 3),
2. The energy expenditure per kilometre in instantaneous and increasing terms, shows a crucial increase in energy on the ICE (Fig. 4) and, divided by, generates more than a 4-times increase in the distance-based energy demand for the ICE compared to the electric motor in the TTW system,
3. The costs of energy consumption in real-world traffic conditions for the ICE are 3.6 times higher than for the electric drive (Table 5),
4. The range of a passenger car is consistent with the data given in Table 1, but under the condition of an appropriate ambient temperature of 18°C, in the conditions of an outside temperature of $-15°^{\circ}$C, the range has decreased almost four times.

The hybrid powertrain distance-based energy consumption in actual operating conditions for the analysed travel groups from I to III depends slightly on the average speed and driving style. The reference to the three groups of trips presented in the article, differing in terms of the traction parameters of the speed profile from the WLTP homologation test, enables their comparison after conversion to a standard unit of Wh/km. For driving in shorter distances than those resulting from the range of energy storage, the distance-based energy consumption is below the value obtained for the WLTP homologation test. This situation also applies to CO$_2$ emissions, which were recorded under operating conditions at the level of 38 g / km.

The indicators of the distance-based energy consumption of a passenger vehicle over a distance of 5200 km presented in the paper, in terms of average fuel consumption and estimated carbon dioxide emissions, are at a low level. The obtained value of road carbon dioxide emissions from average fuel consumption is 32.6% lower as the current standard in force from 2021.

In addition, the introduction of modern driver assistance systems in the test vehicle was also equipped, which makes a significant contribution to reducing fuel consumption and thus CO$_2$ emissions into the environment. An example is the navigation system, which affects the performance characteristics of the powertrain system, causing the drive system control algorithm to manage the energy consumption to the maximum extent to use the energy stored in the batteries on the route planned for navigation.

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