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THE RESEARCH AND IMPACT EVALUATION OF ECO-DRIVING STRATEGY ON SPECIFIC ENERGY CONSUMPTION IN A PASSENGER VEHICLES

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Resume

The article presents the results of an assessment of the impact of Eco-driving on the achieved emission parameters and performance characteristics of vehicles, with a particular focus on energy efficiency. The first part of the article presents the main principles of Eco-driving and then presents the results of experimental tests carried out on two vehicles powered by conventional fuel in the form of gasoline and substitute (unconventional) fuel in the form of LPG. The vehicles were operated under different traffic conditions. Based on the analysis of the experimental results, final conclusions were formulated. The analysis of the test results made it possible to demonstrate differences in the on-road energy consumption of the vehicles depending on the driving technique used and, in addition, the results obtained were compared to the energy intensity of electric vehicles as reported by their manufacturers.

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1 Introduction

Currently one can observe an over the world trend for changing of energy sources for vehicle powertrain system [1-2]. The main direction of these changes is an electric power system [3], however, now and in the closest future, still are and will be used vehicles with conventional power systems equipped with internal combustion engines [4]. Most of combustion engines, which have been applied for transportation vehicles are the four stroke engines. These engines can be divided in two types, like compression ignition engines (CI - mostly used in commercial vehicles) and spark ignition engines (SI). Presently, both of these engines can be powered by conventional (as technological results of crude oil distillation) or unconventional (for example; biogas, biodiesel, hydrogen, ethanol, etc.) fuels. Besides the vehicles with internal combustion engines (ICE) now automotive manufacturers offer their products equipped with alternative power systems like; battery electric vehicles (BEVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs) and fuel cell vehicles (FCVs). So, nowadays, the automotive's clients have a wide scope of vehicles to choose at local and world

markets, but when they have to make a decision - to buy a new car, they have to calculate summary investment costs and administration requirements connected with the areas where the vehicles will be used. It is a result of critical use of the conventional powered vehicles in the cities and overall "decarbonisation" of all the transport sections.

The presented data in Figure 1 show that the most of nowadays vehicle buyers and users of passenger cars are choosing vehicles, which are equipped with SI engine. Vehicles with diesel engines (CI) have only 20% where SI engines have almost 42% share of a new vehicle market in the second quarter of 2021. The main reason of these decisions can be connected with increase in environmental awareness or administration limits connected with "clean" zones located in the cities. Sometimes consumers decisions result from the overall economical balance between all the investment and maintenance costs and predicted exploitation period. They make a calculation, how much time, or how much mileage have to be done to lose a gap of investment cost between vehicles equipped with CI and SI engine, where vehicle with CI engine is mostly about 10÷15% more expensive than SI. This lets one to state that predicted

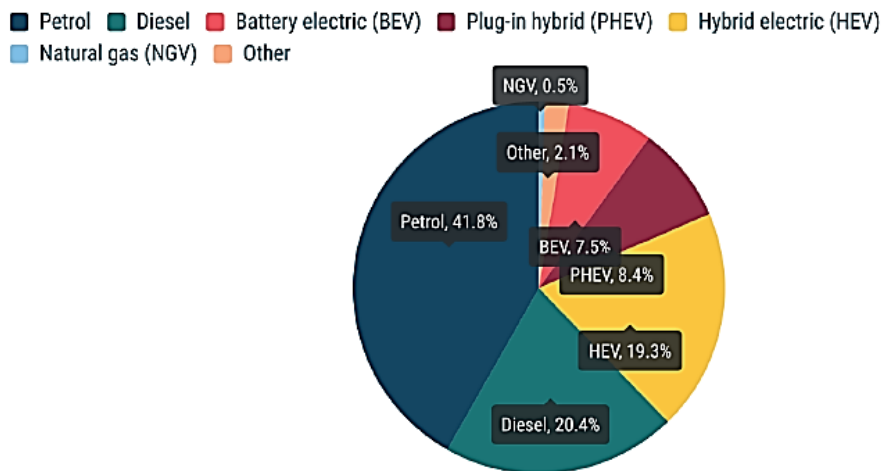


Figure 1 Percentage share of registrations of the new passenger cars for Europe in the 2nd quarter of 2021 by the type of powertrain systems [5]: BEV - battery electric vehicles, HEV - hybrid electric vehicles, PHEV - plug-in hybrid electric vehicles, NGV - Natural gas vehicles

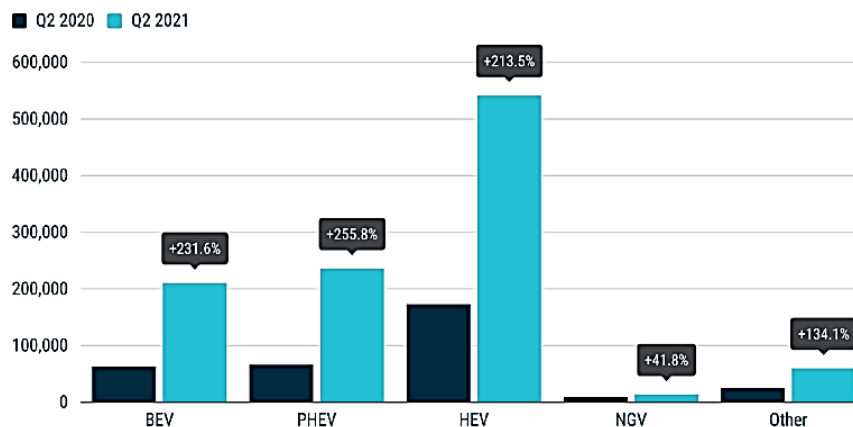


Figure 2 Amount and dynamics of increase in registration of the new passenger cars for EU in the 2nd quarter of 2021, powered alternatively by oil-related fuels [5]; BEV - battery electric vehicles, PHEV - plug-in hybrid electric vehicles, HEV - hybrid electric vehicles, NGV - natural gas vehicles, other - mainly LPG vehicles

exploitation time of vehicles with CI engine will be much longer than that of the SI engines, i.e. the CI vehicles will be used much more intensive - yearly mileage will mostly be more than 50 000 km. Moreover, the users of vehicles with the SI engines sometimes decide to install an LPG/CNG fuel system to convert their vehicle to a cheaper fuel for reducing the operation costs.

Nowadays, increasingly appear vehicles that are powered by electricity, but they do have a share on European market over 10% (all together BEVs, HEVs and PHEVs) - Figure 2. It seems to be expected that in a next 20 years this share should be much more significant. It could be caused by climate change and policy of decrease in GHG emission dedicated to all the mean of transport - for commercial and private usage. Some troubles, related to the electric vehicles' implementation were presented in [6-9]. based on these publications one can conclude that these troubles are strongly related to the user's economic status and availability of electric grid infrastructure equipped with the charger stations. The usage of a gaseous type of fuels (like LPG) for engine feeding, besides reducing the

operating costs, has the significant impact on decrease of the exhaust fumes' toxic ingredients emission, as well, what, on the other hand causes significant impact on environmental destruction related to the conventional fuels [10-12].

The market for vehicles with conventional internal combustion engines is also subject to change due to emissions and powertrain efficiency requirements. Currently, internal combustion engines are fuelled with gas in the form of natural gas or a mixture of propane and butane (LPG). In addition to the economic effects, such measures also improve the environmental balance by reducing exhaust emissions.

The work by Chapman and Patil [13] presents the results of a study of the parameters of an internal combustion engine fuelled with a mixture of gases in the form of hydrogen and methane (in a volume proportion of 0 to 20% H₂). The researchers showed that under full-load conditions, increasing the hydrogen content to 20% allows a reduction in CO₂ emissions by about 20% compared to an engine fuelled with methane. At the same time, they observed a decrease in engine torque

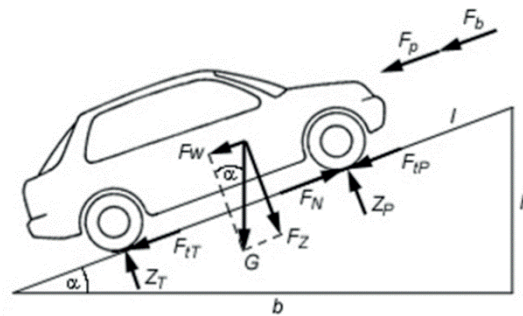


Figure 3 The scheme for a forces impact on moving vehicle on a hill; α - inclination of the road-upward, l - length of the road-upward, h - hill height, Z_r - surface reaction for the rear axle wheels, F_{rr} - rolling resistance forces of the rear axle wheels, F_N - driving force, Z_p - surface reaction of the front axle wheels, F_{rp} - rolling resistance forces of the front axle wheels, F_p - air resistance force, F_b - inertia resistance force, F_w - road-upward resistance force, F_z - normal component of the vehicle's gravity force

values (above 10 % H_2), which resulted from a change in the energy density of the fuel mixture supplied. Hence, in addition to use of unconventional fuels, actions are also necessary to adapt and modernise contemporary and future vehicle propulsion systems to the requirements of increasing the generally understood efficiency.

In the work of Wang et al. [14], a detailed energy and exergetic analysis of a compression ignition internal combustion engine used in trucks was carried out. One of the main conclusions of the presented research was demonstration of significance of influence of parameters controlling the process of creating a combustible mixture on exergy losses, where the injection advance angle and thermodynamic parameters of the supplied working agents (fuel and air) were indicated as the key factor and the appropriate selection and control of these parameters for the engine load made it possible to obtain the value of the thermal efficiency index at the level of almost 48%. Therefore, it can be concluded that the elements of the energy efficiency assessment are often the basis for the already mentioned modernisation of the propulsion systems of vehicles and their engines. Such a detailed analysis of possible changes and trends in these systems is presented in the work by Friedla et al. [15]. The authors of this study indicate that the tendency to increase the requirements regarding reduction of combustion engine emissions, obtained as a result of the type-approval tests, will make the test results more realistic in relation to the actual emission parameters obtained by vehicle users. In addition, the authors point out that electrification and synergy in the retrofitting of many vehicle assemblies will, in the near future, make it possible to achieve near-zero environmental impact of internal combustion engines and they will be able to complement the range of powertrains available on the market.

The work by Leach et al. [16] provides an overview of currently available methods for retrofitting internal combustion engines to achieve an increase in efficiency ratings while reducing exhaust emissions, especially harmful and toxic components. Apart from elements of the engine construction technology and fuel

combustion system analysis, the article also points to some limitations in development of contemporary competitive electric drives, where the problems related to electricity generation, distribution and storage, as well as administrative regulations uniform in various countries, have been pointed out as crucial. In turn, the work by Tsiakmakis et al. [17] presents an analysis of the emission performance of vehicles powered from various energy sources (from conventional combustion engines to electric drives). Their conclusions make it possible to state that the coexistence of multiple propulsion sources is of key importance for the diversification of energy consumption from various sources. The authors also point out that the use of a specific propulsion system, adapted to the conditions of use, makes it possible to achieve the lowest possible values of environmental impact and, at the same time, to obtain relatively high values of indicators corresponding to efficiency of the energy conversion processes. At the same time, the paper points out that, apart from technological issues, which are important from the point of view of vehicle design, the nature of the load variability and its value are of the key importance for the obtained values of emissions and energy consumption, which directly translates into the obtained profile of driving speed.

2 Vehicle movement resistances

When the vehicle is moving, then there are forces, which result in different kinds of resistance. The main of these forces are [18-19];

- rolling resistance (F_r),
- air resistance (F_p),
- hill resistance (F_w),
- inertia forces for mass at translation and circular motion (F_b),
- trailer drag force (F_u).

The scheme of chosen forces, which have been impacted on moving vehicle was presented in Figure 3.

The forces balance for determined and fixed vehicle velocity could be described as

a difference of the driving force (F_N) and the overall resistance forces (ΣF_o) and can be expressed by:

$$F_N - \Sigma F_o = 0, \quad (1)$$

where, based on Figure 3, overall movement resistance forces are:

$$\Sigma F_o = F_t + F_p + F_b + F_w. \quad (2)$$

So, for this forces' balance for vehicle moving with fixed velocity one can express the balance of power as:

$$N_e - \Sigma F_o \cdot \frac{ds}{dt} = 0, \quad (3)$$

where:

N_e - engine effective power,

s - length of route travelled in time (t).

In the case of a lack in power balance in Equation (3), the vehicle is going to change its velocity (if the engine power has overcome an overall resistance power, then the velocity will increase and decrease otherwise).

3 Energetic movement balance

For an analysis of vehicle movement from the energetic point of view, a situation was taken into account where only the engine torque is responsible for a vehicle motion. In this case, an engine torque directly depends on in-cylinder mean effective pressure (MEP), which depends on efficiency of the fuel heat conversion to mechanical energy. Amount of input energy mainly results from the effectiveness of combustion process, mass of fuel and its calorific value. The energy obtained by the fuel combustion can be used for a change of vehicle movement parameters (increase in velocity, acceleration, etc.) and are dissipated as loses of energy (effect of natural dissipation of a vehicle movement energy) and imperfection of mechanical energy conversions by the powertrain system. This energy scheme can be described as a ratio of specific energy consumption (SEC) or overall energy consumption. Currently, it is called as tank-to-wheel (TTW) coefficient [10, 20]. The energy balance can be described as:

$$G_s \cdot W_d = E + \Delta E_s + \Delta E_p, \quad (4)$$

where:

G_s - mean mass of the road fuel consumption [kg/km],

W_d - fuel's energetic value [J/kg],

E - kinetic energy of vehicle movement [J],

ΔE_s - change of energy loses for engines conversion processes [J],

ΔE_p - change of energy loses for vehicles powertrain energy conversion processes [J].

Further considering that the energy required to overcome the resistance of deceleration motion comes

from the mechanical work during (at time T_n) driving the vehicle wheels by the vehicle engine. Then, the energy consumption of a vehicle moving along the road (s), with a known length of its section (L_n), can be defined as:

$$E = \int_0^{L_n} F_n ds, \quad (5)$$

and further, taking into account the dependence of time and path, it can be written that:

$$E = \int_0^{T_n} F_n v dt. \quad (6)$$

It should also be remembered that the components of the balance in Equation (4), such as hill resistance and inertia resistance, can take both positive and negative signs (when this component of the balance causes a decrease in velocity or an increase in velocity).

Taking into account the equivalence of work and energy, the main components included in the sum of the factors describing the energy consumption of the vehicle motion and referring to the quantity that characterizes the road (s), their individual components can be written as:

- energy necessary to overcome the rolling resistance (E_t),
- energy necessary to overcome the air resistance (E_p),
- the energy necessary to overcome the resistance to ascent (E_w),
- the kinetic energy of the vehicle (E_k) or its change.

Hence, taking into account the balance of forces acting on the vehicle in Equation (1) and based on the assumption of some of its components' variability, the general form of the energy balance for a specific road section can be written as:

$$G_s W_d = E_t + E_p \pm E_w \pm E_k + \Delta E_s + \Delta E_p \quad (7)$$

where:

ΔE_s - change of energy due to the gravity force (change of the potential energy),

ΔE_p - change of energy due to the air resistance force.

Then, the energy balance equation for a single phase of motion (for each elementary road profile) can be described in the form:

$$E = mg \int_0^{L_n} f_t ds + c_x A \rho \int_0^{L_n} v^2 ds + m \int_0^{L_n} a ds, \quad (8)$$

where:

f_t - rolling resistance coefficient on the n -th road section,

c_x - air resistance coefficient on the n -th road section,

a - acceleration on the n -th road section.

Taking into account the components, which are describing the energy consumption of the vehicle motion, recommendations can be made as to what kind of actions to control the vehicle should be performed in order to obtain the lowest possible energy demand to cover the

road section as;

- in terms of reducing the value of the rolling resistance forces;
- choosing a road with the least possible deformable surface,
- choosing tires with the minimum possible width for the vehicle,
- keeping of the highest possible pressure in the tires,
- choosing the shape of the tire tread pattern (smooth and full),
- selection of the tyre stiffness and tread hardness,
- reducing the value of the air resistance forces;
- selection of the vehicle speed to the engine load characteristics and torque characteristics,
- the use of aerodynamic spoilers to obtain laminar airflow,
- reduction of inertia resistances by:
 - avoiding the sudden accelerations,
 - using the engine also for the braking process, appropriately anticipating road events,
 - keeping the actual vehicle weight as low as possible (without unnecessary load).

Such formulated recommendations can be called the main assumptions of the ecological and economic operation of a vehicle, which is nowadays referred to as Eco-driving.

An important aspect of the Eco-driving is keeping the car in a proper technical condition, where vehicle manufacturers, in addition to determining the principles of organizing maintenance and repair of vehicles, indicate the vehicle's operational features that can significantly change the value of fuel consumption [21-24]. The first comprehensive representative study on ecological and economic driving in Poland, conducted by TNS OBOP, shows that 90% of drivers in Poland declared their willingness to move in accordance with the principles

of the Eco-driving [22]. The skills and knowledge of the respondents regarding Eco-driving were assessed highly and over 79% of the respondents say that they would be driving vehicles in accordance with these principles.

4 Vehicle traffic energy consumption studies

The aim of the research was to estimate the energy consumption of the vehicle traffic in given real operating conditions and to relate the obtained results to the energy consumption of currently promoted electric vehicles (EVs). The energy consumption of the traffic of the tested vehicles was determined indirectly based on the fuel consumption measurements, both for vehicles operating in the real urban and outside of urban traffic conditions - the so-called mixed cycle.

4.1 Research objects

The subjects of the research were two passenger cars of different design and functional types. These vehicles were designed to transport no more than 5 passengers, while at the time of measurements, only drivers were in the vehicles. The vehicles were equipped with standard tires, typical for each model. The technical and operational characteristics of the tested objects are presented in Table 1.

The characteristics of the power of air resistance as a function of changes in the velocity of vehicle movement for the tested vehicles are shown in Figure 4.

Taking into account the change in the value of the air resistance force, as an effect of the influence of geometric features and the shape of the body structure, it can be concluded that despite the completely different

Table 1 Technical data of the tested vehicles - according to the manufacturers' data.

No.	Property	Vehicle No. 1	Vehicle No. 2
1.	Vehicle frontal area	2.48 m ²	2.26 m ²
2.	Vehicle body air resistance coefficient c_x	0.32	0.31
3.	Engine volume	1870 cm ³ .	2461 cm ³
4.	Body shape and type	single-body / MPV	two-box / station wagon
5.	Engine maximum power at rotation	75 kW @ 4000 rpm	103 kW @ 4000 rpm
6.	Engine maximum torque at rotation	200 Nm @ 1500 rpm	290 Nm @ 1900 rpm
7.	Engine type/ Type of Charger	CI engine, DI, CR I fuel system/turbo	CI engine, DI, CR I fuel system/ turbo
8.	Arrangement and number of cylinders / valves	R4/8V	R5/10V
9.	Type of tyres	195/65 R15 Barum Bravuris 5HM/ energy class C	205/65 R16 Hankook Ventus Prime3 K125/ energy class C
10.	The main gear ratio/ gear box ratio for 5th	4.35/0.947	4.77/1.02
11.	Average fuel consumption - mixed cycle [NEDC]	5.9 dm ³ /100km	6.6 dm ³ /100km
12.	Net weight of the vehicle	1365 kg	1555 kg

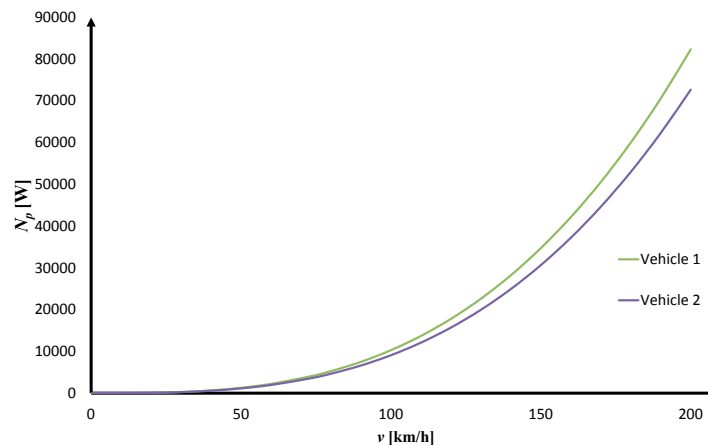


Figure 4 Computational characteristics of the air resistance power (N_p) in relation to the movement velocity for the tested vehicles

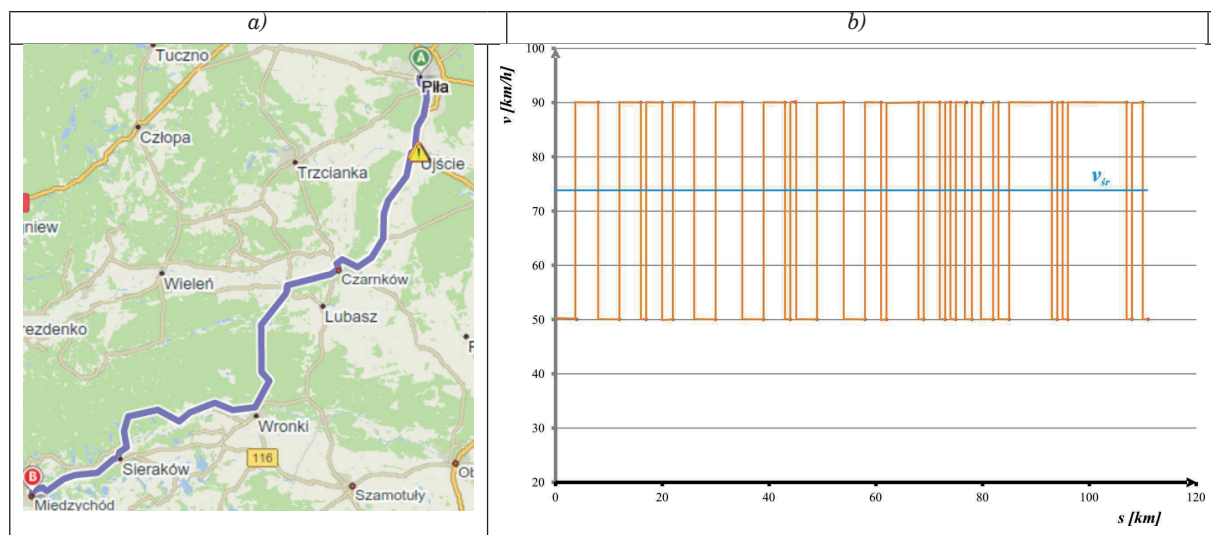


Figure 5 The course and parameters of the measuring section of the route: a) - map of the route [25], b) possible maximum speeds on elementary sections of the route

market segment of these vehicles, the characteristics of air resistance, in terms of the speed of movement covered by the test, do not differ in relative values by no more than 12% and that results mainly from the different values of the air resistance coefficient and the frontal area of the tested vehicles.

4.2 The research methodology

The research was carried out for the two adopted driving strategies. The first test was carried out in terms of real traffic conditions, where the driver steered the vehicle in such a way as to adjust the traffic parameters (speed, acceleration and braking) to the road conditions enabling the shortest possible travel time, while maintaining the local speed limits. It was supposed to reflect the typical behavior of the driver on the road. The second attempt was similar to the first type, with the difference that the driver used the principles of Eco-driving as far as it was possible.

Based on the measurement of the fuel consumption available on board the tested vehicles using the system of automatic acquisition of data about the vehicle motion parameters, with which the tested vehicles were equipped - i.e. the reading of the average road fuel consumption recorded by the vehicle diagnostic and control system. Based on the obtained data on fuel consumption, conversions were made into the value of the waveform energy consumption (unit energy consumption). The value of estimation error was determined by the standardized method, where, based on t analysis of the measurement systems' components, it was determined that the maximum value of the measurement error should not exceed $\pm 5\%$ of the measured value. The route was carried out three times (back and forth) for each of the vehicles and each trial version. The route covered a 111 km section of the country road no 11 and voivodship road no 182 road between the towns of Pila and Miedzzychod (Figure 5a). The total distance of each vehicle was 1332 km and the specific data are presented in Table 2.

Table 2 Route-specific data

	Road property	Value
1.	Length of the AB section of the route	111 km
2.	Maximum speed for sections of the route outside the populated areas	90 km/h
3.	Maximum speed for sections of the route in the populated areas	50 km/h
4.	The computational average velocity of the movement of vehicles on the route	73 km/h
5.	Computational travel time of AB section for average velocity	95 min
6.	The share of the sum of the route sections for the traffic with a speed limit of up to 50 km/h	35.1%
7.	The share of the sum of the route sections for the traffic with a speed limit of up to 90 km/h	64.9%
8.	The difference in altitude of the beginning and end of the route	20 m

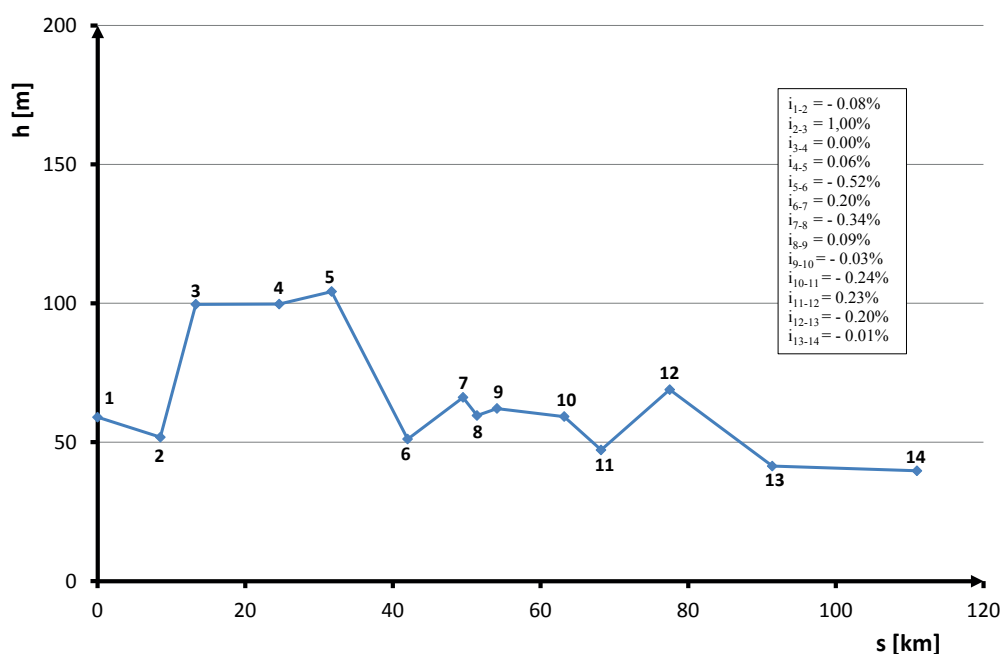


Figure 6 Scheme of the configuration simplified to the critical points of the longitudinal profile of the measurement path from the starting point (1) to the end point (14) together with determination of the longitudinal slopes of the road (i); h - height of the path's points location relative to sea level, s - distance from the starting point A of the route

During the road tests, there were no significant disruptions to the vehicle traffic. There were stable weather conditions, i.e. wind speed below 4 m/s, ambient temperature 20 °C, pressure 101.5 kPa and no renovation or cleaning works were carried out on the road that could significantly change the achieved velocity profile. The route covered both populated, field and forest areas, where there were few local speed limits. On the other hand, the longitudinal profile of the control route for the travel direction from A to B, simplified to reference points and the determination of longitudinal slopes, is shown in Figure 6.

For analysis of the obtained measurement data values, the value of the arithmetic mean obtained for the trip in both directions for all tests was taken. When analyzing the nature of the traffic, it was noticed that between the individual elementary sections of the route there was a cyclical change in speed caused by a change in the value of the ascent resistance force (F_w), which could have influenced the obtained values of the

measured parameters. Hence, the analysis also took into account the features related to the route. Then, using the relationship describing the strength of resistance to ascent in the form:

$$F_w = m \cdot g \cdot \sin \alpha, \quad (9)$$

the total value of the hill resistance force for the entire length of the control route can be determined and written in the form of the equation:

$$\sum F_w = \sum_{j=1}^k F_n = \sum_{j=1}^k m \cdot g \cdot \sin \alpha_j \quad (10)$$

where:

k - number of the last leg of the route,

j - number of the next section of the route,

α_j - longitudinal slope angle of the next section of the route.

Then, taking into account that for small values of the rise/fall angle of the road section, it is close to the

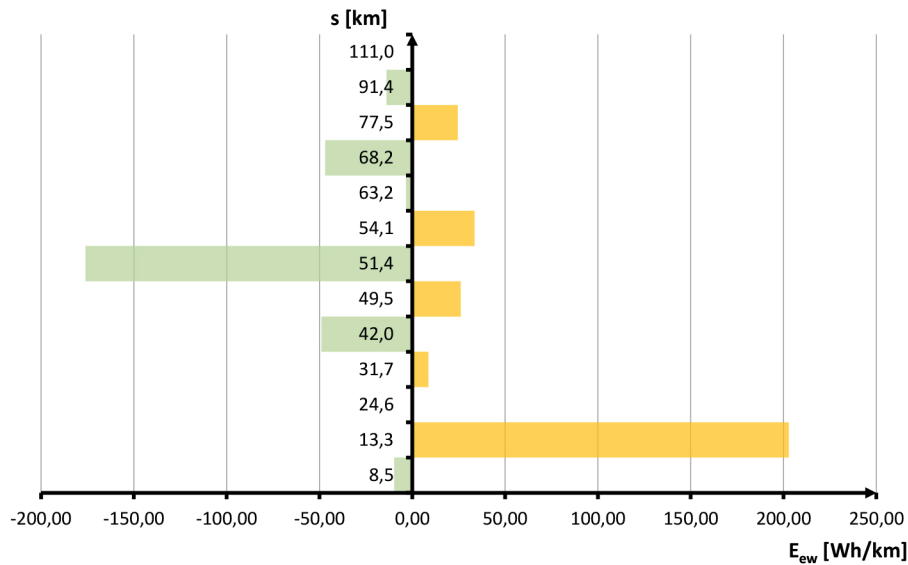


Figure 7 The results of calculations of the specific energy demand for overcoming the sections of ascents and descents for the average speed of forward motion (73 km/h) - based on experimental data; vehicle weight 1365 kg, slopes according to the longitudinal profile of the route

longitudinal gradient of the road that:

$$\sin \alpha_j \cong i_j,$$

where, i_j is the longitudinal slope of the j -th road section defined as the change of height above sea level at the beginning and end of the section (Δh) along its length (l):

$$i_j = \frac{\Delta h}{l} \cdot 100\%.$$

Equation (10) can then be written in its final form as:

$$\sum F_w = \sum_{j=1}^k m \cdot g \cdot i_j. \tag{11}$$

Hence, the total value of energy (E_{ew}), necessary to perform the mechanical work in order to overcome the segmental resistance to motion of a vehicle caused by longitudinal road inclinations (potential energy increase) can be presented as:

$$E_{ew} = \sum_{j=1}^k m \cdot g \cdot i_j \cdot l_j. \tag{12}$$

In the case of assuming a constant value of the average speed of movement of the tested vehicle along the length of the test route, the power of the ascent resistance forces will be; on sections of slopes - reduction of energy demand by the vehicle engine, while in the case of the road slopes - an increase in energy demand.

Thus, in the case of the conducted experimental tests, the power supplied by the engine, necessary to overcome the total power of the ascent resistance (N_{ew}), can be described by the relation:

$$\sum N_{ew} = \frac{\sum E_{ew}}{t} = \frac{\sum_{j=1}^k m g i_j l_j}{t}. \tag{13}$$

or taking into account the speed of movement of the vehicle on each section of the road (V_j):

$$\sum N_{ew} = \sum_{j=1}^k F_{wj} \cdot V_j. \tag{14}$$

Then, taking into account the nature of the traffic (speed variability, speed of movement) and the load of the vehicle, it can be concluded that the power of the resistances to the uphill (road longitudinal inclination) has a significant impact on the energy balance of traffic and at the same time on the energy consumption necessary for the vehicle's movement. Taking into account the travel time of individual sections of ascents / descents, the angle of longitudinal slope and their length, it is possible to estimate the unit value of the energy necessary to overcome the hill due to the difference in height (change of potential energy E_p).

The results of calculations of the road distribution of the demand for unit energy necessary to overcome the slopes (E_{ew}) for the control section and the assumed constant speed of the vehicle movement are shown in Figure 7.

When analyzing the distribution of the specific energy demand for overcoming the resistance of slopes along the length of the control sections of the route (Figure 7), it can be noticed that the values of the demand are closely related to the value of the longitudinal slope of individual road sections. The obtained distribution refers to the value of the average speed of forward motion for the entire length of the route. This means that in the event of an increase in the demand for traffic energy (also supplied to the engine), the driver reduced the vehicle velocity - increasing the value of the gear ratio so much that it was possible to climb this hill. In addition, it should also be noted that the negative values of the specific energy consumption refer to cases where

Table 3 Basic properties of the fuel [26]

Fuel property/parameter	Value of parameter for fuel	
	ON1	ON2
1. Density w 15°C [g/m ³]	822	832
2. Self-ignition temperature [°C]	> 260	>255
3. Kinematic viscosity @ 40°C [mm ² /s]	1.5÷4.5	2.0÷4.5
4. Calorific value [MJ/m ³]	34.77	35.94
5. Vapour pressure @ 40°C [kPa]	0.4	0.4

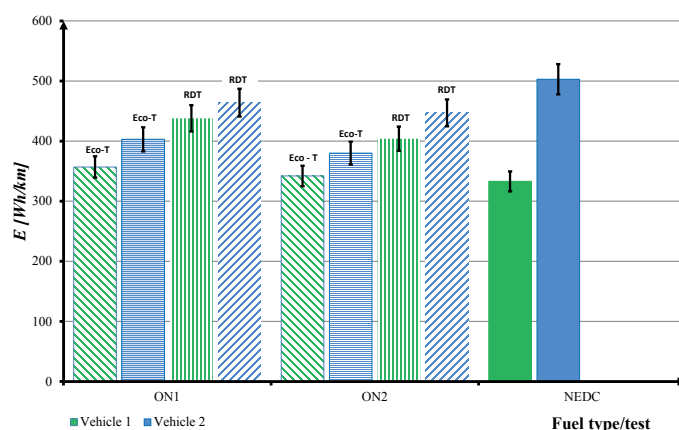


Figure 8 Average specific energy consumption on the control path depending on the type of fuel and the driving method of vehicle control: Eco-T - Eco-driving mode, RDT - driving mode according to road conditions, ON1 - standard diesel oil, ON2 - enhanced diesel oil, NEDC - energy consumption data based on the vehicle manufacturer's data

the longitudinal road slope causes the conversion of the tangent component of the gravity force, i.e. the drag force is converted into a driving force. This ultimately means that the driver can significantly reduce the energy consumption of the engine and at the same time can start using the resistance of the vehicle powertrain to generate braking force.

This is particularly important when planning one-way travel routes and when changing the actual weight of the vehicle or the volume and parameters of road traffic. On the other hand, when the mass of the vehicle is unchanged (electric vehicles) or only to a small extent (mass change due to fuel consumption) and the journey is to be carried out in both directions, the impact of the power of slopes on the energy balance can be considered negligible. The reason for this is that during the travel in both directions (back and forth), the vectors of the resistance forces of the elevations change for each pass, which results in the mutual cancellation of the impact of these forces on the vehicle motion.

Due to the fact that the research was carried out for two directions of traffic, a balanced system of hill resistance forces was adopted in the further part of the study. Moreover, for the purposes of analyzing the energy consumption of the traffic of the tested vehicles, it was assumed that vehicle engines were used for braking, which in the overall balance will allow to partially

compensate for the increase in fuel consumption in the acceleration phase.

The fuel in the form of standard diesel oil (ON1) and enhanced oil (ON2) was used to power the engines of the tested vehicles. The enriching additives were to directly affect the engine cleaning process and result in the improvement of the quality of the created combustible mixture and reduction of the harmful and toxic exhaust components' emission. The basic properties of these fuels are presented in Table 3.

4.3 Research results

The results of experimental studies of the average road energy consumption are presented in Figures 8 and 9. The analysis of the results of the average specific road energy consumption tests presented in Figure 8 allows to conclude that both in the case of Vehicle 1 and Vehicle 2, the lower energy consumption (fuel) was obtained when the driver was using recommendations resulting from the principles of Eco-driving. It should be noted, however, that the obtained values relate to the test performed in determined traffic and environmental conditions. However, the presented data of vehicle manufacturers were for reference only and are intended only for reference purposes. In addition, it should also be noted that the shape of the road may significantly

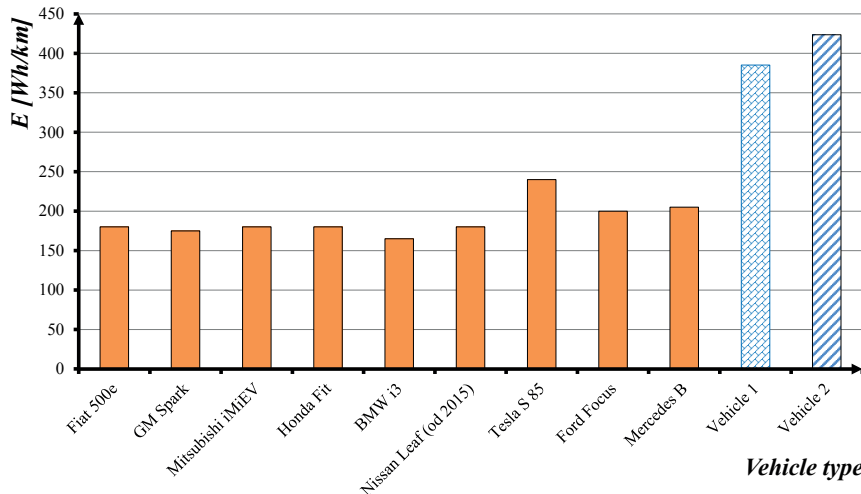


Figure 9 Comparison of the average value for the test of specific energy consumption (E) of the traffic of passenger cars subjected to road tests and cars with electric drive based on manufacturers' data (by the product of battery capacity and range according to the EPA test)

affect the increase in energy consumption, which in the analyzed case may constitute almost a double increase in relation to the specific energy consumption value.

The demonstrated reduction in energy consumption by about 10% in Eco mode (Figure 8) seems to be obvious due to the reduction of idling times of engines, as well as more effective use of the available torque and power of the engines in terms of achieving and maintaining the assumed velocity of movement. Moreover, it can be noticed that in the analyzed case, the use of enriched diesel oil did not significantly affect the result of the average specific energy consumption and the obtained differences are within the scope of measurement errors. Hence, it can be concluded that in the case of diesel fuels, the essence of reducing the energy consumption concerns driving techniques and road conditions. Enriched fuel significant advantage, related to the effects of cleaning the fuel supply system and the combustion chamber, could rather be observed in the perspective of vehicle mileage greater than that achieved in the study.

In the comparison presented in Figure 8, it should be noted that the calculated average specific energy consumption (based on the manufacturer's data on road fuel consumption) for the vehicle No. 1 indicates the comparability of the factory data and the obtained results of energy consumption under "economic" driving conditions. In the case of the car of vehicle no. 2, the manufacturer's data on energy consumption is similar to the results obtained from tests carried out in the real traffic conditions (without the key application of Eco-driving principles). This may indicate that during the road tests for these cases, traffic conditions similar to the NEDC test conditions occurred. Moreover, it can also be concluded that in the remaining cases the main reasons for the discrepancies in the obtained measurement results are the road factors forcing non-standard vehicle traffic conditions during the test. At the same time, it can be concluded that in the daily operation of the

vehicle, the specific energy (fuel) consumption will be up to about 20% higher than the values obtained in the NEDC tests. At the same time, as a result of the research, it was observed that it is also possible to obtain lower unit energy consumption - vehicle No. 2.

A comparison of the average road energy consumption of the tested passenger cars in relation to those powered by electricity (Figure 9) calculated based on the test data on the electric battery capacity and range determined according to the EPA test for a combined cycle (EPA-Environmental Protection Agency of United State of America).

Taking into account the results of research and analysis (Figure 9), it can be concluded that compared to the tested cars, all the presented electric cars are almost twice more effective than ICE vehicles. This situation results from the fact that the energy consumption resulting from the consumption of energy supplied (Q_d) to perform the work and to generate the torque necessary to obtain the driving force on the wheels of the vehicle driving axle, where taking into account the internal resistances and losses of the drive train (η) for a specific road section, which can be written in the following form:

$$E = \frac{Q_d \cdot \eta}{s} \quad (15)$$

In the case of electric vehicles, due to the relatively high efficiency of the electricity conversion process (over 90%), it can be shown that the overall efficiency of the energy conversion processes is greater than the energy conversion processes in the case of vehicles with engines powered by conventional fuels (less than 50%). The main reason for this difference is the efficiency of chemical into mechanical energy conversion processes taking place in internal combustion engines. In this case, taking into account the delivered energy conversion efficiency index, it is possible to record the dependence

on the energy consumption of traffic for vehicles with conventional drive:

$$E = \frac{Q_d \cdot \eta_e \cdot \eta}{s} \quad (16)$$

and an energetic efficiency can be expressed as:

$$\eta_e = \frac{1}{g_e \cdot W_u}, \quad (17)$$

where:

g_e - specific fuel consumption, kg/kWs ,

W_u - calorific value of fuel, kJ/kg .

Hence, the relationship in Equation (16) describes the relation of the energy consumption of the vehicle motion, taking into account the properties of the fuel (energy supplied), the efficiency of its conversion by the engine and the generation of the driving force on the vehicle wheels. At the same time, this relationship allows to understand the essence of differences in values of the average road energy consumption for the selected and tested vehicles (Figure 9), where the key processes seem to be the processes occurring during the conversion of energy supplied to mechanical energy transmitted to the wheels of the driving axle. Taking this into account, it can also be stated that, regardless of the type and features of the vehicle propulsion system, it is important to minimize the energy consumption to use it efficiently for the purposes and processes serving the user.

On the other hand, in the case of electrically powered cars, Equation (16) should take into account, apart from the efficiency of the engine and losses in the powertrain, the losses arising in the process of charging the battery and losses resulting from the self-discharge of the battery, as well. Only this approach and taking them into account will make it possible to realistically compare the energy consumption of electric

and conventional vehicles, which basically refers to resistance to motion. These, in turn, result mainly from the geometric and mechanical properties of the vehicle, therefore they should not constitute significant differences in the analysis of the energy consumption of the vehicle movement.

5 Summary

Taking into account the theoretical analysis and the obtained research results of fuel consumption measurements and based on that calculated a specific energy consumption of vehicle traffic, it can be concluded that:

The application of the principles of Eco-driving allows for the reduction of energy consumption and this change may reach even 10% of the average SEC value and at the same time contribute to reduction of the exhaust gas emissions.

The longitudinal profile of the road significantly influences the change in the average specific energy consumption and the intensity of this change depends directly on the longitudinal gradient of the road and the actual weight of the vehicle.

Even a simplified form of analysis of the longitudinal profile of the route allows to effectively influence the route planning process and the appropriate planning of routes for laden vehicles to shape the longitudinal profile (use of slopes) allows to significantly reduce energy consumption and thus transport operation costs.

Showing the higher energy consumption of the traffic of vehicles with conventional propulsion is burdened with losses on the side of energy conversion, while the specific energy consumption of the traffic itself depends directly on the resistance to motion of a vehicle and not on the method of its propulsion.

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