ARCHIVES OF TRANSPORT
Volume 72, Issue 4, 2024

ISSN (print): *0866-9546*
e-ISSN (online): *2300-8830*
DOI: *10.61089/aot2024.gb7qdr81*

EFFECT OF VEHICLE OPERATING PARAMETERS ON FUEL CONSUMPTION AND THE OVERALL ENERGY EFFICIENCY OF THE DRIVE SYSTEM

Jarosław GONERA[1], Michał JANULIN[2], Oleksandr VRUBLEVSKYI[3]

[1,2,3] Department of Construction, Operation of Vehicles and Machinery, Faculty of Technical Sciences, University of Warmia and Mazury in Olsztyn , Olsztyn, Poland

Abstract:

This article presents a research methodology that supplements known studies to solve the problem of a correct complementary analysis of vehicles with different drive units. This method can be used at the stage of selecting a car for specific tasks, as well as for in-service technical condition checks. A new method is proposed for analysing the impact of operating conditions on the mileage fuel consumption, unit fuel consumption and overall energy efficiency of vehicles. In the study, it was possible to determine the effect of changing the vehicle speed, road gradient angle and vehicle weight. Tests identifying fuel consumption and efficiency characteristics as a function of vehicle load were carried out using passenger cars with different drive designs. Carrying out tests under laboratory conditions on a chassis dynamometer bench enabled the precise determination of the change in operating conditions. The criteria adopted for the evaluation included fuel consumption and overall vehicle energy efficiency. The variable parameters included speed, vehicle weight, and the road gradient angle. The data for criteria calculation were acquired using a diagnostic tester with a functional parameter recording function. The application of the presented method enabled a comparison of the overall energy efficiency of two vehicles equipped with spark-ignition combustion engines, according to the criteria listed. The experiment showed that in a three-cylinder engine, unit fuel consumption is more sensitive to parameter changes under identical conditions (speed, vehicle weight, road gradient angle) than in a four-cylinder engine. To evaluate the drive units of the test vehicles, characteristics of changes in the overall energy efficiency were used as well. It was observed that in all testing variants, the value increased with increasing road gradient values, with the intensity of η increase not being constant. A car with a four-cylinder engine has a higher energy efficiency at low loads. The proposed methodology is relevant for evaluating vehicles with different drive systems (including hybrid) and adapting drive characteristics to the operating conditions. Partially the presented methodology can also be transferred to EV vehicles - in terms of energy efficiency.

Keywords: *conventional car, chassis dynamometer, vehicle load, fuel consumption, vehicle energy efficiency*

To cite this article:

Gonera, J., Janulin, M., Vrublevskyi, O., (2024). Effect of vehicle operating parameters on fuel consumption and the overall energy efficiency of the drive system. Archives of Transport, 72(4), 109-128. https://doi.org/10.61089/aot2024.gb7qdr81

Contact:
1) jaroslaw.gonera@uwm.edu.pl [https://orcid.org/0000-0001-7758-2684] – corresponding author; 2) michal.janulin@uwm.edu.pl [https://orcid.org/0000-0003-3436-9079]; 3) aleksander.wroblewski@uwm.edu.pl [https://orcid.org/0000-0002-5871-6381]

1. Introduction

Over recent decades of automotive sector development, the main emphasis has been placed on environmental aspects, manifested mainly in reducing harmful substance emissions into the atmosphere. Fuel consumption measurements are most often performed during standardized operating cycles, which should be additionally supplemented by, among others, traffic mode, road conditions, load weight and weather conditions (Ismadiyorov and Sotvoldiyev, 2021). One of the methods for reducing emissions is to reduce vehicle fuel consumption. For many years, this issue has been at the center of the attention of researchers worldwide. Huo et al. (Huo et al., 2012) analysed the fuel consumption index values for individual categories of vehicles sold and used in China. This analysis assessed the effectiveness of the traffic fuel consumption reduction policy that has been implemented in China since 2004.

However, Wang et al. (wang et al., 2008) carried out measurements of the effect of the driving style on fuel consumption using a portable exhaust emission measurement system. They found that the optimal fuel consumption of passenger cars per distance unit occurs between 50-70 km/h. Similarly, a study by Gonzalez et al. (Gonzalez et al., 2010) also investigated the effect of the driving style on fuel consumption. The study found that an environmentally friendly driving style reduces the fuel consumption of cars with a compression ignition engine by approximately 14%, whereas an aggressive driving style can increase fuel consumption by up to 40%. The effect of the driver's driving style on fuel consumption was also addressed in a study by Yao et al. (Yao et al., 2020), which additionally proposed a method for collecting information and building a database based on mobile phone data and an onboard diagnostics (OBD) system. The authors developed fuel consumption prediction models with a less than 10% relative error. The issue of using an onboard diagnostics system to determine fuel consumption was also referred to by Pavlovic et al. (Pavlovic et al., 2021), who assessed the accuracy of onboard fuel consumption monitoring instruments in light- and heavy-duty vans. The tests described in the article confirmed the accuracy of monitoring systems at the required level of ± 5% for laboratory tests or road drives. However, statistical analyses showed that the accuracy of the onboard diagnostics system could be affected by the average vehicle speed, acceleration, and overall driving dynamics. A similar topic was taken up in their work by Abediasl et al. (Abediasl et al., 2024), who conducted similar studies on fleet vehicles. Their research aimed to develop practical and accurate models for estimating instantaneous fuel consumption based on on-board diagnostics (OBD) data.

Saboohi and Farzaneh (Saboohi and Farzaneh, 2008) focused on developing an optimal driving strategy, particularly considering the intensified traffic conditions. They developed an optimal driving strategy model that was then used to identify the optimal driving strategy for a vehicle under varying traffic conditions. Similarly, Mysłowski (Mysłowski, 2014) highlighted the discrepancies in fuel consumption measurements provided by vehicle manufacturers compared to real-life operation data, in which traffic intensity plays a considerable role. Lee et al. (Lee et al., 2011) presented a method for estimating fuel consumption based on information acquired via the onboard diagnostics (OBD) system. The measurement results indicate that the developed method enables a precise fuel consumption estimation. Kuo and Wang (Kuo and Wang, 2011) developed a route-planning method taking into account fuel consumption minimisation based on three main factors, i.e. the distance, driving speed and the weight of the cargo being transported. Other factors affecting fuel consumption were also indicated following a 2008 U.S. Department of Energy report. Similarly, the issue of vehicle route planning was addressed by Zhang et al. (Zhang et al., 2015), in which the authors used the RS-TS algorithm, and in another study by (Zeng et al., 2020), which also proposed a routing algorithm characterised by fuel consumption minimisation by the vehicle. However, Wang et al. (Wang et al., 2015), when analysing the results concerning the effect of different factors on fuel consumption of heavy-duty vehicles, determined that the greatest influence is exerted by the weight, aerodynamic resistance coefficient and rolling resistance. In the work (Gkyrtis, 2024) attention was drawn to the influence of road slope on fuel consumption. The authors thus drew attention to the need to take into account the impact of roads on the emission of harmful substances, and consequently, the natural environment, stimulating the ad hoc development of fuel consumption models based on actual measurements, so that local conditions could be properly taken into account and used by road engineers and/or urban planners.

2. Literature review

It should be noted that vehicle weight is indicated in numerous studies as one of the major factors affecting fuel consumption (Fuć et al., 2012). This takes on particular importance nowadays when the weight of many vehicles is increasing with each successive generation of a particular model. Reynolds and Kandlikar (Reynolds and Kandlikar, 2007) highlighted fuel consumption in hybrid vehicles. They observed an increase in the fuel consumption of second-generation HEV vehicles, as compared to the first-generation HEV vehicles. An increase in the vehicle weight was indicated as the reason, with test results showing that a 100 kg change in vehicle weight increases fuel consumption by an average of 0.7 dm^3/100 km in combustion-powered vehicles, whereas this value increases by 0.4 dm^3/100 km in hybrid vehicles. Del Pero et al. (Del Pero et al., 2017) also noted that to reduce fuel consumption, particular attention should be paid to the use of design solutions that contribute to weight reduction. Study results from an article by Koffler and Rohde-Brandenburger (Koffler and Rohde-Brandenburger, 2010) were also cited. In that article, the authors indicated that approximately one-third of a vehicle's total fuel consumption depends directly on its weight. The problem of increasing vehicle weight was also noted by Van den Brink and Van Wee (Van den Brink and Van Wee, 2001). An analysis was carried out to demonstrate that in the Dutch market, in the last decade of the 20th century, despite technological developments and exhaust emission standards being introduced, no reduction was noted in the fuel consumption of the car fleet. The main identified reasons included the increasing engine displacement and, specifically, the weight, which increased successively in each subsequent model generation of the respective cars. The main reasons for the increase in vehicle weight were found to be the increasingly stringent safety requirements and the increasingly richer equipment provided in cars. Study results from an article by Mrozik and Merkisz-Guranowska (Mrozik and Merkisz-Guranowska, 2024) were also cited. In that article, the authors indicated that the mass of BMW 7 Series vehicles increases on average by about 13±2.0 kg each year. The relative changes in mass for different groups of vehicles (segments) in successive production periods are at a similar level. Cheah et al. (Cheah et al., 2009) also pointed out that in the US market, the development of new vehicles is focused on developing larger, heavier and more powerful cars, with the result that the average fuel consumption does not decrease as expected as the technology develops. The authors estimated that when the focus on reducing fuel consumption increases, the average consumption by new cars could be reduced by as much as 40%. Similar conclusions were drawn by Sprei et al. (Sprei et al., 2008), who estimated that only approximately 35% of the effects of technology improvements over the period of 1975-2002 resulted in a reduction in net fuel consumption, whereas the remaining 65% were used to meet consumer expectations for improved vehicle comfort and dynamics. Similarly, the authors of a paper (Romero et al., 2024) pointed out that vehicle weight is a major factor affecting fuel efficiency. They also pointed out that reducing weight not only reduces the need for tractive power (road climbing and acceleration), but also affects the reduction of wheel rolling resistance, which undoubtedly leads to fuel savings (Tao and Quang, 2024). Therefore, at the stage of designing and manufacturing new vehicles, special attention should be given to the use of lightweight components for their construction, which can contribute to a reduction in the weight of the structure and, consequently, to a reduction in fuel consumption (Chirinda and Matope, 2020, Subadra et al., 2020) It should be noted that the use of hybrid and electric drives has grown rapidly in popularity in recent years. What is characteristic is that these vehicles have a greater weight than their conventionally powered counterparts. Hence, in recent years, most of the research on traffic energy intensity has focused on the energy intensity of electric vehicles. The mass of the vehicle as one of the main factors influencing the energy intensity of vehicles was identified in a paper (Weiss et al., 2024). The authors analysed the energy consumption of 342 electric car models and indicated that each additional 100 kg of vehicle mass increases energy consumption by about 0.2 kWh/100km. In contrast, the work (Weiss et al., 2020) showed that each additional 100 kg of passenger car mass increases energy consumption by approximately 0.6 kWh/100km. The authors of paper (Berjoza et al., 2024) also carried out a study of the effect of changing the weight of an electric car on its energy intensity. On the other hand, the authors of the paper (Silva et al., 2024) dealt with the analysis of the selection of an appropriate means of transport in the process of parcel delivery in courier companies. Different means of transport with different propulsion sources were adopted and their energy intensity was analysed. The authors pointed out that terrain is important in the parcel delivery process, so analyses were carried out on the impact of road gradient on parcel delivery operations. On the one hand, the focus was on the energy intensity of the traffic, and on the other hand, on the increase in delivery time due to the slopes of the means of transport. Similarly, in the article (He et al., 2022) the focus was on the comparison of fuel consumption and exhaust emissions of vehicles with different power sources. Attention was also drawn to significant differences in the emission levels during cold and hot engine start-ups. The issue of the influence of road slope and vehicle weight on fuel consumption was also raised in the work (Rosero et al., 2021). The authors conducted tests of the influence of the above factors in city buses, one of which was fuelled with compressed natural gas, while the other one was fuelled with diesel oil. The measurement cycle was carried out in real traffic conditions in Madrid. In the work (Giechaskiel et al., 2021), the authors added the ambient temperature to the factors influencing fuel consumption and emission levels. After conducting the test cycle, it was observed that, about the reference conditions (23 °C), CO_2 emission increases with a drop in temperature significantly below 0 °C (in the range of -10 to -30 °C), as well as with a significant increase in ambient temperature (50 °C) and the use of air conditioning in such conditions. On the other hand, driving uphill in a vehicle towing a trailer caused 2-3 times higher CO_2 emissions. The influence of road slope on fuel consumption was also discussed in (Šarkan et al., 2022), where the authors focused on the issue of terrain in the vicinity of intersections and the need for vehicles to start on a flat road, uphill and downhill. In view of this, the present study aimed to investigate the effect of vehicle weight on the energy intensity of driving under varying operating conditions.

Based on an analysis of the state of affairs, it can be found that there are no comprehensive studies to compare the energy efficiency of vehicles with varying engine designs and varying technical conditions. To this end, the paper proposes a new method for analysing the impact of operating conditions on the mileage fuel consumption, unit fuel consumption and overall energy efficiency of vehicles. This method can be used at the stage of selecting a car for specific tasks, as well as for in-service technical condition checks.

3. Research methodology

3.1. The object of the study

Tests identifying fuel consumption and efficiency characteristics as a function of vehicle load were carried out using two passenger cars with different drive designs. Both cars were classified as B-segment (urban cars) according to the European classification. They were equipped with naturally aspirated spark-ignition engines with indirect fuel injection. Each car had a manual gearbox with five gears. The main parameters characterising these vehicles are provided in Table 1. The vehicles had similar mileage (approximately 60 000 km). They had previously been used by a single owner for a period of three years. The cars differed in engine design. The combustion engines from car A and car B met the EURO 6 exhaust standard.

The tests were carried out using two conventional vehicles (Table 1), which differed, e.g., in the number of cylinders and the mean piston speeds $S \cdot n/30$, where n is the engine crankshaft speed. The three-cylinder engine of car A was characterised by a higher piston stroke value S, which translated into a higher mean piston speed of 17.25 m/s, whereas the four-cylinder engine of car B was characterised by a lower mean piston speed of 13.75 m/s. Values in the range of 17-23 m/s are the limit values for engines used in cars (Heywood, 1988). As noted in a study by Filipi and Assanis (Filipi and Assanis, 2000), engines with a longer piston stroke, achieving an S/B dimension ratio of 1.3, are characterised by a higher thermal efficiency of approximately 3-4%, as compared to engines with a short piston stroke.

Since passenger car engines most often operate at a low or medium load, the improvement in thermal efficiency of long-stroke engines, as described in a study by Filipi and Assanis (Filipi and Assanis, 2000), may manifest itself in fuel consumption. However, a number of other factors, including mechanical efficiency, inertia, wear of the piston or the cylinder bearing surface, and changing valve timing, can eliminate the benefits of extended engine piston stroke at certain load values.

Table 1. Vehicle characteristics

Parameter	Car A	Car B
Engine capacity, dm^3	1.2	1.4
Piston stroke S / piston diameter B, mm	90.5 / 75	75 / 77
Number of cylinders	3	4
Maximum engine power at rpm, kW/rpm	60 / 5750	75 / 5500
Maximum torque at rpm, Nm/rpm	118 / 2750	137 / 4200
Car weight, kg	1150	1170
Permissible load capacity, kg	530	580
Air resistance coefficient c_x	0.29	0.30
Frontal surface A_c, m^2	2.12	2.2
Mileage, km	58 500	61 000

3.2. Testing apparatus

Fuel injection, crankshaft speed, torque and other engine operation parameters were recorded using a Texa TXTs Navigator (Fig. 1c) diagnostic tester and a dedicated version of IDC5 Cars software. In addition to computer diagnostics for many categories of vehicles, the instrument also enables the recording of operating parameters of individual vehicle components. As for the tests performed in the study, it was used to record data from the engine controller. The diagnostic head was connected to the vehicle via a standard OBD2 connector, whereas the laptop computer was connected via Bluetooth Class 1 wireless connection (maximum range of 30 m). This instrument enabled recording at a sampling rate of 2 Hz. The device supported the following communication protocols: blink codes, K, L, ISO9141-2, ISO14230, CAN ISO11898-2, ISO11898-3, SAE J1850 PWM, SAE J1850 VPW, SAE J2534-1. The device was equipped with CORTEX M3 STM32F103ZG 72 MHz hardware, 1024 KBytes FLASH, 96 KBytes SRAM and SRAM memory: 8 Mbit - 512 Kb x 16 bit NAND, flash memory: 1 GBit on an 8-bit bus. The device was equipped with a two-way multiplexer, thirteen-channel. Before the testing began, the device was set up using the Rec&Play function, which is used to record changes in selected engine operation parameters over time. Texa TXTs Navigator diagnostic tester can be used in research to record the operating parameters of individual components (Rymaniak et al., 2020, Vrublevskyi et al. 2023). The Texa TXTs Navigator that the authors used for their research was manufactured in 2020. The device had the latest software version.

The investigation of the effects of speed, vehicle weight, and road gradient angles on the mileage fuel consumption, unit fuel consumption, and energy efficiency of the vehicles was conducted using an MAHA LPS 3000 4x4 (Fig. 1a) two-axle load chassis dynamometer. The chassis dynamometer meets the following standards related to dynamic measurements of vehicles: DIN 70020, EWG 80/1269, ISO 1585, JIS D 1001, and SAE J 1349. Thanks to the use of a chassis dynamometer, it was possible to simulate real vehicle traffic conditions under reproducible laboratory ambient conditions. The chassis dynamometer used enabled the performance of power measurements and load simulations for passenger cars with a maximum output of up to 520 kW (for two-axis drive vehicles) or 260 kW (for single-axis drive vehicles). The main parts of the simulation and measurement station included two eddy current brakes, two integrated sets of rollers (two rollers per axle), sliding plates, exhaust extraction systems, an air circulation-forcing system including a fan, a remote control panel, and a communication panel with a computer on which the control software (Fig. 1b) was installed. The dynamometer roller diameter was 504 mm, and the weight of the entire roller set was 1300 kg. The maximum axle load of the dynamometer is 2500 kg. The dynamometer has the ability to change the wheelbase of the rollers. The dynamometer has a pneumatically adjustable roller threshold. The dynamometer is powered by 400V voltage. The Maha LPS 3000 dynamometer that the authors used for the study was manufactured in 2012. The device had a current approval for testing.

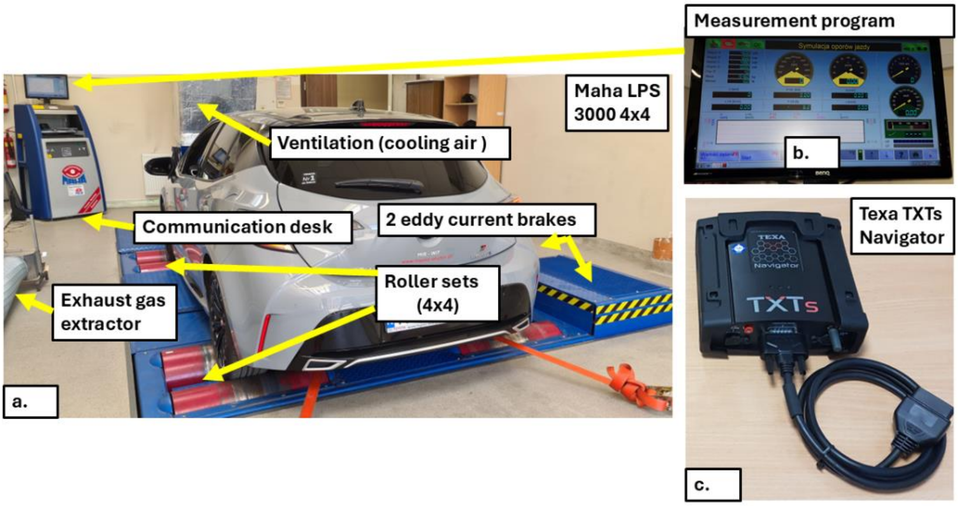


Fig. 1. The research stand and measuring equipment: a. MAHA LPS 3000 4x4 two-axle dynamometer, b. Measurement program, c.Texa TXTs Navigator diagnostic tester

3.3. The course of testing

During the tests, it was necessary to simulate different load variants to identify the effects of the car's weight (including load) and speed on fuel consumption g_e and energy efficiency η (Fig. 2). Measurements were taken for four simulated load variants for each test vehicle. The tests that were performed first were those with a load of only the driver's weight (OW), followed by a simulation with a load of ½ of the permissible load capacity (50% L). The third variant was a load that took a value of ¾ of the permissible load capacity (75% L), whereas the fourth variant simulated the full load of the test car (TM).

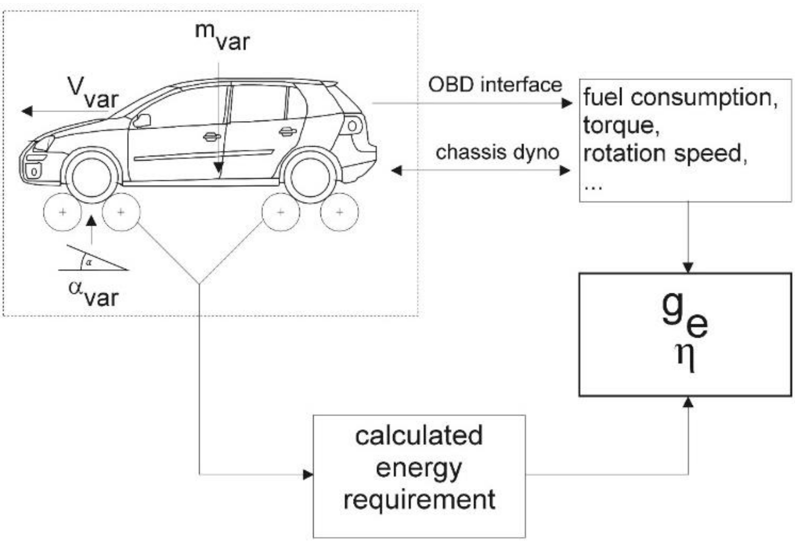


Fig. 2. Diagram for determining the overall efficiency of the test vehicles

Each of the two cars performed four test drives. Each drive was conducted with a fixed simulated load variant (OW, 50% L, 75% L, TM). Moreover, each test drive comprised several stages. The first stage was keeping the vehicle at a standstill with the engine running for 120 seconds (Fig. 3). Three main stages were then distinguished, i.e. driving at a speed of 50 km/h on the third gear ratio of the gearbox, driving at 70 km/h on the fourth gear ratio, and driving at 90 km/h on the fifth gear ratio. Each stage was preceded by an acceleration phase and a deceleration phase, each lasting 30 seconds. In addition, the final stage was a standstill (90 seconds), during which the vehicle engines were running at idle. The essential driving stages lasted 180 seconds each, during which a change in the road gradient was simulated every 30 seconds. The first 30 seconds involved driving at a gradient of 0%, the next 30 seconds at a gradient of 1%, and then at 2%, 3%, 4% and 5%, respectively. The road gradient was determined from the relationship $w = \tan\alpha \cdot 100\%$, where α is the road gradient angle. However, the analysis of fuel consumption values omitted the stages during which the vehicles were not moving due to the fact that the weight of the vehicle did not affect the test results at that time. The tests were carried out at speeds of 50, 70 and 90 km/h, as these are the most common permissible speeds on the roads of the European Union countries. On the other hand, the selection of gear ratio at a given speed was dictated by the fact that, when driving at a particular speed, it was not necessary to reduce the drive system ratio as the gradient of the road increased.

The simulated road gradient value was changed during the test using the chassis dynamometer software. However, before the testing, the values of the A_e and C_e parameters had to be entered for each load variant, in addition to the weight of the vehicles and the road gradient, in order to simulate the traffic conditions. These were, respectively, parameters related to the individual components of resistance to motion:

A_e – equivalent of the power lost to overcome rolling resistance:

$$A_e = f_r \cdot m \cdot g \cdot V, \quad (1)$$

where f_r - rolling resistance coefficient (for calculations, $f_r = 0.012$ is assumed), m – vehicle weight, g – gravitational acceleration, V – vehicle speed (for calculations, $V = 25$ m/s is assumed).

C_e – equivalent of the power lost to overcome aerodynamic resistance:

$$C_e = 0.5 \cdot \rho_a \cdot c_x \cdot A_c \cdot V^3, \quad (2)$$

where ρ_a – air density, A_c – vehicle frontal area, c_x – air resistance coefficient.

Table 2 provides the calculated values of the coefficients taken into account during simulated drives for both cars.

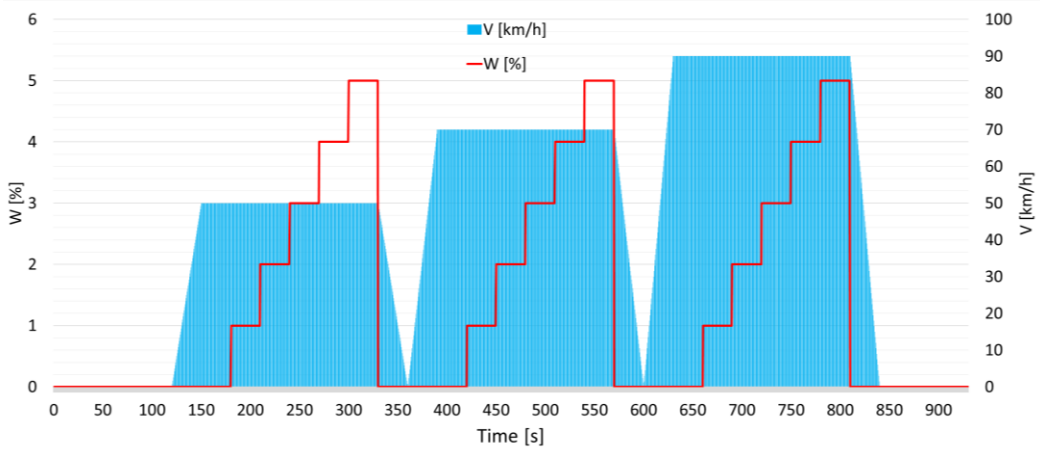


Fig. 3. Speed and gradient profile for one test stage

Table 2. Values of the coefficients taken into account during simulated drives

Load variant	Car A			Car B		
	m, kg	**A_e, kW**	**C_e, kW**	**m, kg**	**A_e, kW**	**C_e, kW**
OW	1150	3.38	5.28	1170	3.44	5.67
50% L	1415	4.16		1460	4.30	
75% L	1547.5	4.55		1605	4.72	
TM	1680	4.94		1750	5.15	

In order to determine the mileage fuel consumption, the following relationships were used:

$$Q_j = 3 \cdot n_j \cdot s_w \cdot V_j^{-1} \cdot \sum_{i=1}^{k} \tau_{ij}, \quad (3)$$

where τ_{ij} - injection time on each cylinder, n_j - engine crankshaft revolutions, V_j - vehicle speed, km/h, i - cylinder number, j - measuring point number, s_w – injection constant for a particular injector type (for car A, $s_w = 0.0028\ l \cdot s^{-1}$, for car B, $s_w = 0.0037\ l \cdot s^{-1}$).
The first criteria - unit fuel consumption g_{ej} was determined from the following relationship:

$$g_{ej} = 9.549 \cdot \rho_f \cdot 30 \cdot s_w \cdot M_j^{-1} \cdot \sum_{i=1}^{k} \tau_{ij}, \quad (4)$$

where M_j - engine torque at a particular moment, ρ_f – fuel density.
During the testing, the focus was on assessing the energy intensity of the movement of the two test vehicles. To this end, energy consumption per unit of distance covered, expressed in kJ/km, was determined. The energy demand of a vehicle in motion (Fig. 4) was determined as (Kropiwnicki, 2011):

$$E = \int_0^{t_c} \left(F_{op} \cdot V(t) \right) dt, \quad (5)$$

where t_c - cycle duration, F_{op} - the sum of motion resistance forces acting on a moving vehicle.
The sum of motion resistance forces acting on a vehicle comprises the rolling resistance force F_f, air resistance force F_{aero}, grade resistance force F_w, inertial resistance force F_b, the sum of internal vehicle resistance force F_{wew}.
Since the focus of this study was on the amount of energy supplied to the system in the form of fuel being consumed, considerations of the energy intensity of vehicle movement were presented. A vehicle in motion has kinetic energy that can be divided into:

$$E_{kp} = \frac{m \cdot V^2}{2} \quad (6)$$

in linear motion, and

$$E_{ko} = \frac{I \cdot \omega^2}{2} \quad (7)$$

in rotational motion, where I is the mass inertial moment of the rotating components of the drive system, and ω is their angular velocity. In addition, the test plan assumed changes in the simulated road gradient value, which allowed the vehicle's engine parameters to be recorded as it was driving up steep roads. Thus, the present considerations must take into account changes in potential energy that are determined according to the equation:

$$E_p = m \cdot g \cdot h, \quad (8)$$

where h is the height at which the vehicle is located. Based on the parameters recorded, the change in height can be expressed as:

$$\Delta h = \Delta s \cdot sin\alpha, \quad (9)$$

where $\Delta h = h_{j+1} - h_j$ and $\Delta s = s_{j+1} - s_j$.
For each of the test vehicles, the energy balance can be presented as follows (Mitschke, 1977, Gillespie, 1992):

$$E = E_f + E_{aero} + E_{ko} + E_{kp} + E_p + E_l \quad (10)$$

$$E = f \cdot Q_i \cdot \int_0^T V(t)dt + 0.5 \cdot c_x \cdot \rho_a \cdot A_c \cdot \int_0^T V(t)^3 dt + 0.5 \cdot I \cdot \int_0^T \varepsilon(t)dt + 0.5 \cdot m \cdot \int_0^T a(t)dt + m \cdot g \cdot \int_o^T sin\alpha \cdot V(t)dt + E_l \quad (11)$$

where E_f – energy consumed to overcome rolling resistance, E_{aero} – energy consumed to overcome aerodynamic resistance, E_l – energy losses, Q_i – ground response force acting on the wheel, I – inertial moment of the rotating components, ε – angular acceleration, T – single test stage duration.

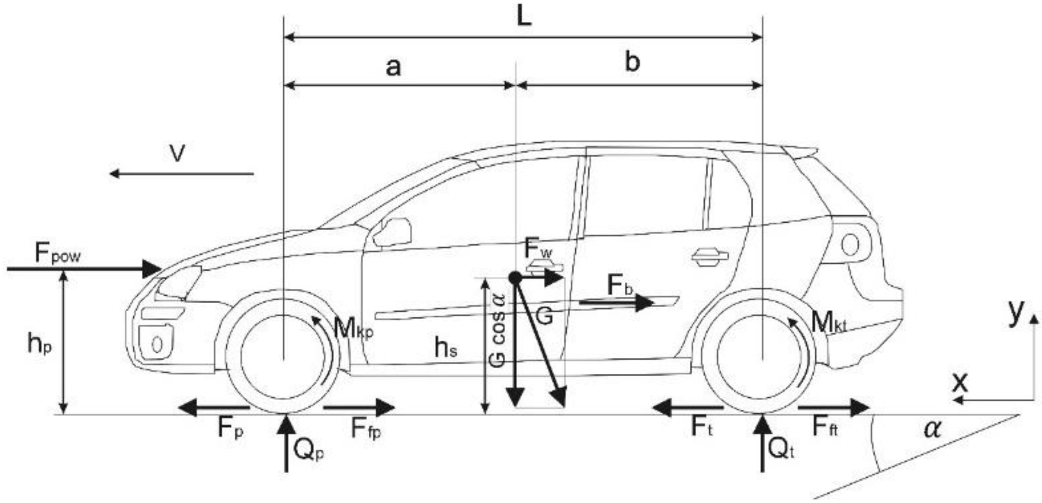


Fig. 4. A system of forces and moments acting on a moving vehicle: Q_t,Q_p – forces of ground response to driving wheels, F_t,F_p – wheel driving forces, F_{ft},F_{fp} – rolling resistance forces, G – vehicle weight, F_w – grade resistance force, F_b – inertial force, F_{aero} – air resistance force, L – distance between driving wheel axles, a,b – distances of the wheel axles from the vehicle centre of mass, h_p – height of the resultant air resistance force application, h_s – height of the vehicle centre of mass position.

Based on the calculations made and the fuel consumption measurements carried out, the value of the overall efficiency of the vehicle's drive system was determined for each of the test variants. To this end, the fuel consumption results calculated according to relationship (3) were converted, and after the conversion, the value of energy per unit of distance was determined according to the following:

$$E_{e=}\frac{Q_{ave}}{100}\cdot Q_w, \quad (12)$$

where Q_{ave} – average mileage fuel consumption, Q_w – fuel calorific value.

After determining the amount of energy per unit of distance according to equation (12), and the amount of energy required due to the vehicle's movement conditions according to relationship (11), the second criterion, namely the overall energy efficiency of the drive system, was determined:

$$\eta = \frac{E}{E_e}\cdot 100, \% \quad (13)$$

The η values obtained were used to analyse and compare the efficiency of the two test vehicles.

4. Test results

4.1. Analysis of operational fuel consumption

The analysis of the test results obtained began with comparing the average mileage fuel consumption Q_{ave} at simulated vehicle loads. While this comparison has a certain utilitarian value, it is not sufficient to analyse all the aspects affecting fuel consumption. Furthermore, it cannot be used to compare electrically powered cars or vehicles with other non-conventional drive sources.

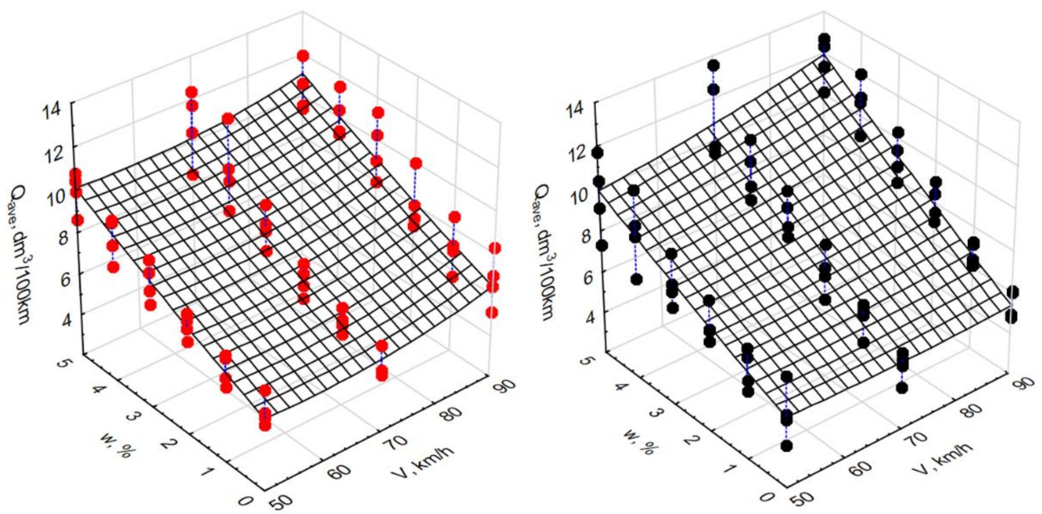
During the tests, each car covered a total distance of 46 km (three simulated speed variants and four simulated weight variants). To cover this distance, the car with the three-cylinder engine consumed 3.91 litres of fuel, whereas the car with the four-cylinder engine consumed 3.97 litres of fuel.

However, such a comparison can be extremely useful at the first stage of analysing the simulation results. A graphical interpretation (Fig. 5) of the relationship $Q_{ave}=f(m, V, w)$ was obtained for 72 experimental points. At the same time, the surfaces in Fig. 5 present the average fuel consumption value Q_{ave} as a function of speed V and road gradient w. The generalised empirical relationship $Q_{ave}=f(m, V, w)$ can be represented by the following equation:

$$Q_{ave} = (a_1 + a_2 V + a_3 w + a_4 V^2 + a_5 V w + a_6 w^2) a_M, \quad (14)$$

where a_1 - a_6 are the coefficients of the quadratic equation describing the surface (Table 3), and a_M is the coefficient taking into account the weight of the car (Table 3).

Under analogous vehicle load conditions, significant differences were noted in mileage fuel consumption between vehicles A and B (Fig. 5). It was found that at a speed of 50 km/h in a car with a three-cylinder engine (A) when driving on a flat road (road gradient equal to 0%), there were relatively small differences in fuel consumption between the three smaller simulated load variants. The average fuel consumption was only noticeably higher, with a load equal to the permissible total weight. With a road gradient of 1%, there was a clear increase in fuel consumption when simulating a load equal to 75% of the permissible total weight. Starting from a road gradient value of 2%, clear differences can be observed between the individual load variants in the values of the average mileage fuel consumption. When comparing the minimum and maximum road gradient values, it can be seen that, with each load variant, there is an increase in the average mileage fuel consumption of around 4 dm^3/100 km. At a speed of 70 km/h, when driving on a flat road, relationships similar to those in the previous case were noted. However, at higher road gradient values, greater differences in the average mileage fuel consumption can be observed between the individual load variants. Particularly large increases in fuel consumption occurred at road gradient values of 4% for a load equal to the permissible total weight and at a 5% road gradient for a load equal to 75% of the permissible total weight. When comparing the minimum and maximum road gradient values, an approximately twofold increase in the average mileage fuel consumption can be observed for each load variant. Compared to the previous driving speeds, at a speed of 90 km/h, it can be found that there are greater differences in the average mileage fuel consumption between the individual simulated load variants. In addition, when simulating a load equal to the vehicle's curb weight, there was a significant increase in the average mileage fuel consumption with an increase in the road gradient. This was particularly evident when comparing the results for road gradients of 0% and 5%. On the other hand, at the maximum simulated load, the increases in the average mileage fuel consumption as a function of the road gradient were no longer as great, especially starting from a road gradient of 3%.



vehicle A vehicle B

Fig. 5. A change in fuel consumption in the space of speed V and road gradient w for cars A and B

able 3. Empirical coefficients of equation (15) for the test vehicles

	a_1	a_2	a_3	a_4	a_5	a_6	a_M			
							OW	**50%**	**75%**	**TM**
vehicle A	8.8439	-0.1183	0.8243	0.001	-8.54E-05	0.0224	0.86	0.96	1.04	1.16
vehicle B	6.8028	-0.0436	0.2944	0.0003	0.0102	0.0188	0.84	0.96	1.06	1.17

As compared with car A with the three-cylinder engine, in car B, equipped with the four-cylinder engine, one can observe that at a speed of 50 km/h, there are clear differences in the average mileage fuel consumption between each simulated load variant. With an increase in load and an increase in road gradient, the average mileage fuel consumption increased significantly. A similar situation occurred when driving at a speed of 70 km/h. Here, an even greater effect of the road gradient on the average mileage fuel consumption can be observed, especially for the test in which a load equal to the total permissible vehicle weight was simulated. In this case, when comparing road gradients of 0% and 5%, the difference in the average mileage fuel consumption was approximately 8 dm^3/100 km. On the other hand, when comparing the average mileage fuel consumption at a road gradient of 5%, the difference between drives with simulated curb weight and simulated permissible total weight was nearly 5 dm^3/100 km. Based on the results of tests carried out on the car with the four-cylinder engine at a speed of 90 km/h, it can be found that, with road gradients of 0% and 1%, the average mileage fuel consumption during tests with a simulated load of 75% of the permissible total weight and with a load of the permissible total weight, remained at a similar level. However, it was considerably larger than the two smaller load variants. At higher road gradient values, the differences between all load variants were already clear. For each load variant, when comparing the average mileage fuel consumption at road gradients of 0% and 5%, a more than twofold increase in the fuel consumption value can be observed.

Figures 6 and 7 summarise the values of changes in the mileage fuel consumption of cars A and B due to the increase in car weight about the results collected for tests with curb weight load. In car A with a three-cylinder engine (Fig. 6), the largest increases in average mileage fuel consumption after loading the vehicle occurred at a driving speed of 70 km/h. When simulating a 100% weight load, as compared to a simulation of a load equal to the vehicle's curb weight, at a speed of 70 km/h, there was an increase in the average mileage fuel consumption of approximately 35%, whereas at a speed of 90 km/h, there was an increase of nearly 30%, and at a speed of 50 km/h, there was an increase of over 25%. When simulating a load equal to 75% of the permissible total weight at driving speeds of 50 and 90 km/h, there was an increase in the average mileage fuel consumption, as compared to the simulation of a load equal to the curb weight, of approximately 15%, whereas at a speed of 70 km/h, there was an increase of over 20%. When simulating a load equal to 50% of the permissible total weight, the increases in the average mileage fuel consumption were, at speeds of 50 and 90 km/h, over 5%, whereas at a speed of 70 km/h, they were over 10%.

In car B with the four-cylinder engine (Fig. 7), the largest increases in the average mileage fuel consumption after loading the vehicle with a simulated weight were observed at a driving speed of 50 km/h. When simulating a full load, as compared to the load value equal to the curb weight, there was an increase in the average mileage fuel consumption of approximately 50%. When simulating a 75% load, the average mileage fuel consumption increased by nearly 30%, whereas when simulating a 50% load, it increased by over 10%. At a speed of 70 km/h, it amounted to nearly 40%, almost 30% and 10%. However, at a speed of 90 km/h, the changes amounted to approximately 30%, 20% and 10%.

4.2. Analysis of unit fuel consumption and changes in vehicle energy efficiency

An analysis of the change in the unit fuel consumption g_e (Fig. 8-10) enables a comparison of the drive units of the cars not in general terms, such as, for example, fuel consumption per unit of distance covered by the car, but also in terms of the adaptation/response of the internal combustion engine to a change in load simulated on the dynamometer. When analysing the results summarised in Fig. 8, it can be found that in the car with a three-cylinder engine with a piston stroke-to-diameter ratio of 1.2, when driving at a speed of 50 km/h, there was a high sensitivity both to an increase in the vehicle load and to an increase in the simulated road gradient, manifested by changes in the unit fuel consumption g_e. As the load on the car increased, there was a reduction in g_e. This indicates more favourable conditions for the course of the operating process in the cylinders due to the greater relative time in the engine with a longer piston stroke (Filipi and Assanis, 2000).

In a four-cylinder engine, at a speed of 50 km/h, g_e changes slightly as the road gradient changes (Fig. 8).

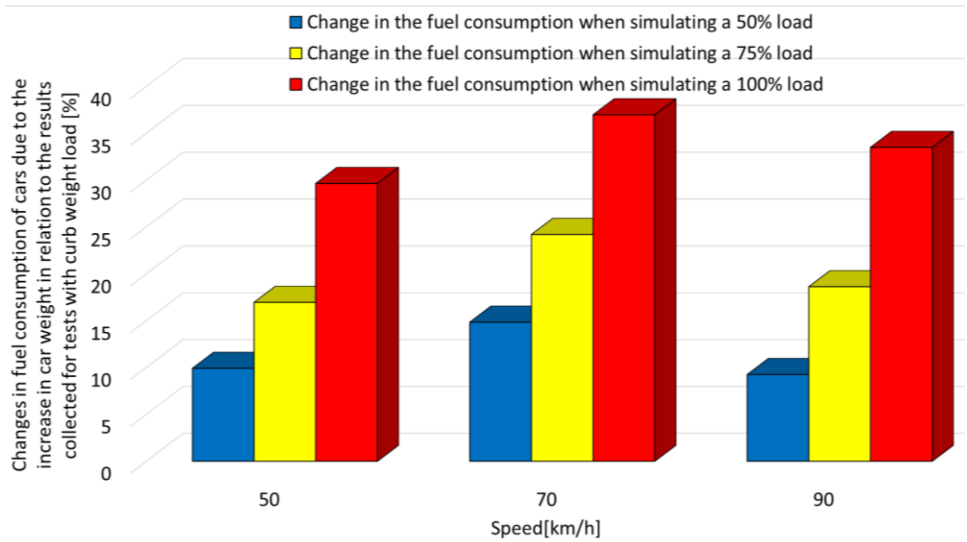


Fig. 6. A comparison of fuel consumption after loading car A with a weight in relation to fuel consumption under the car's curb weight

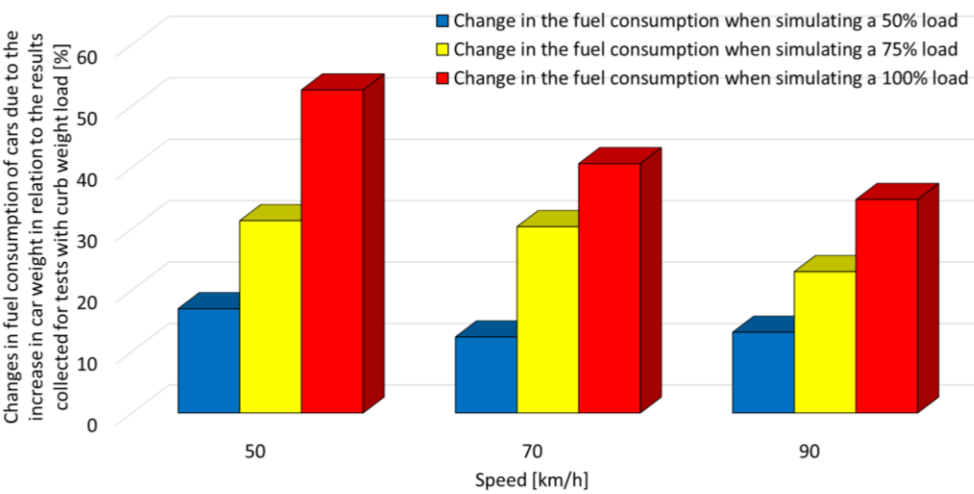


Fig. 7. A comparison of fuel consumption after loading car B with a weight in relation to fuel consumption under the car's curb weight

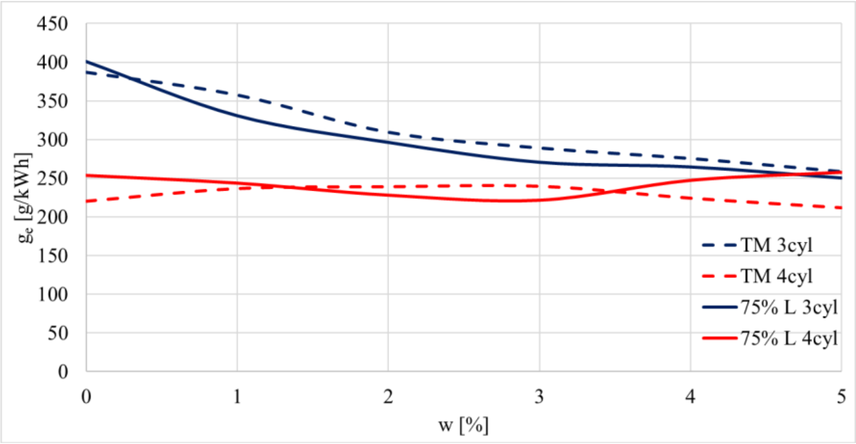


Fig. 8. A pattern of changes in unit fuel consumption in cars A and B during a test at a speed of 50 km/h

At a speed of 70 km/h, the relative change in the unit fuel consumption g_e for the two test engines is almost identical at higher road gradient values. In this case, a greater effect of the load conditions on g_e can be observed for the four-cylinder engine (Fig. 9). For both engines, an increase in the g_e value was observed as the engine load increased. This is due to a reduction in the relative time of mixture preparation and combustion and an increase in mechanical friction losses. Consequently, the three-cylinder engine virtually has characteristics similar to those in Fig. 8, and, at the maximum test loads, it achieves g_e values similar to those of the four-cylinder engine.

When analysing the results of tests carried out at a speed of 90 km/h, it can be found that the nature of changes in unit fuel consumption (Fig. 10) was different. In the four-cylinder engine, changes in g_e for the two presented car weights were almost identical. This indicates that engine performance is more influenced by factors related to achieving a particular speed of 90 km/h. At the same time, the three-cylinder engine shows a greater dependence on the weight of the car. As the weight increases, there is an increase in the unit's fuel consumption, which ranges from 30 to 70 g/kWh. The other relationships, i.e. a decrease in g_e with increasing load for the three-cylinder engine and an increase in g_e for the four-cylinder engine, are similar to those at speeds of 50 and 70 km/h.

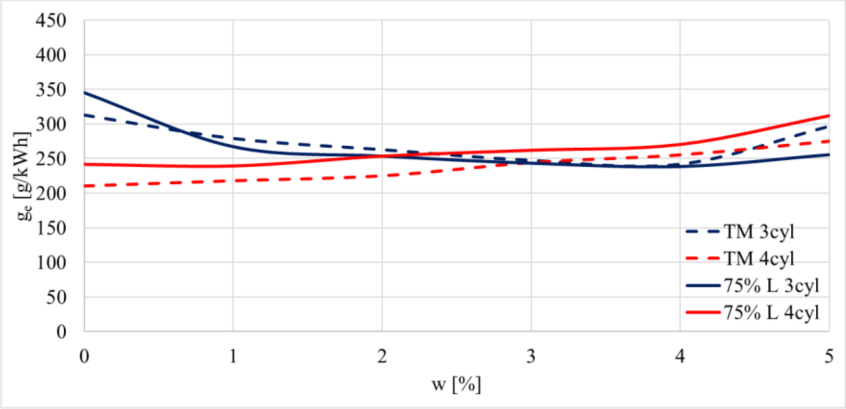


Fig. 9. A pattern of changes in unit fuel consumption in cars A and B during a test at a speed of 70 km/h

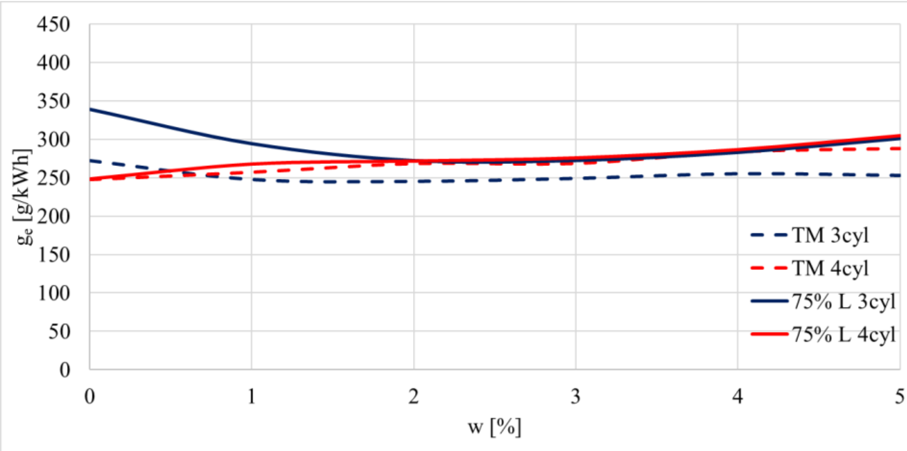


Fig. 10. A pattern of changes in unit fuel consumption in cars A and B during a test at a speed of 90 km/h

A significant amount of information is provided by the characteristics of the change in energy efficiency η. In contrast to the unit fuel consumption, which has a high analytical potential for engine evaluation, η also enables an overall assessment of the performance of both the engine and the gearbox. This includes the efficiency of the selected gearbox ratio and the condition of the engine-transmission-wheels systems. For all the test conditions of the engine-transmission-wheel system load, the η increases with an increase in the road gradient (Figs. 11-13).

At the same time, the intensity of the η value increase is not constant. Within the road gradient range of 3-5%, there is a deceleration in the increase in η. The decelerating moment is not constant for the test vehicles and tends to move towards higher road gradient angle values as the vehicle speed increases.

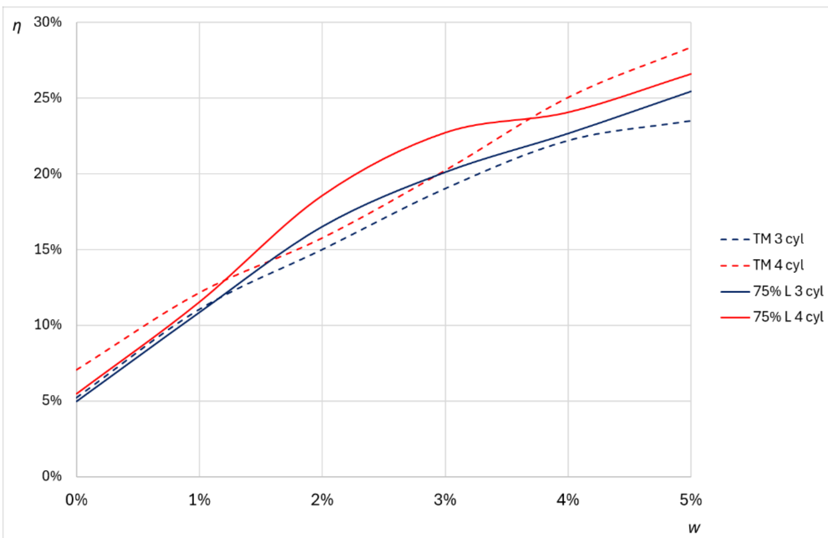


Fig. 11. Changes in the energy efficiency of the test vehicles at a speed of 50 km/h and varying road gradient value

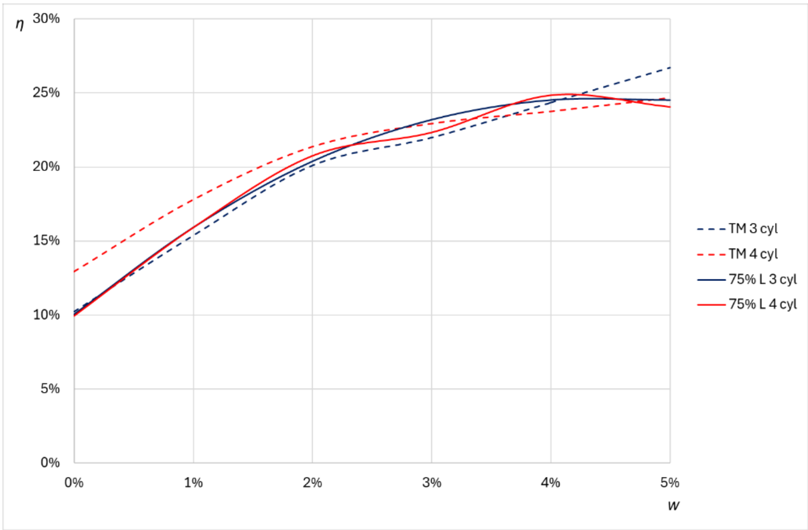


Fig. 12. Changes in the energy efficiency of the test vehicles at a speed of 70 km/h and varying road gradient value

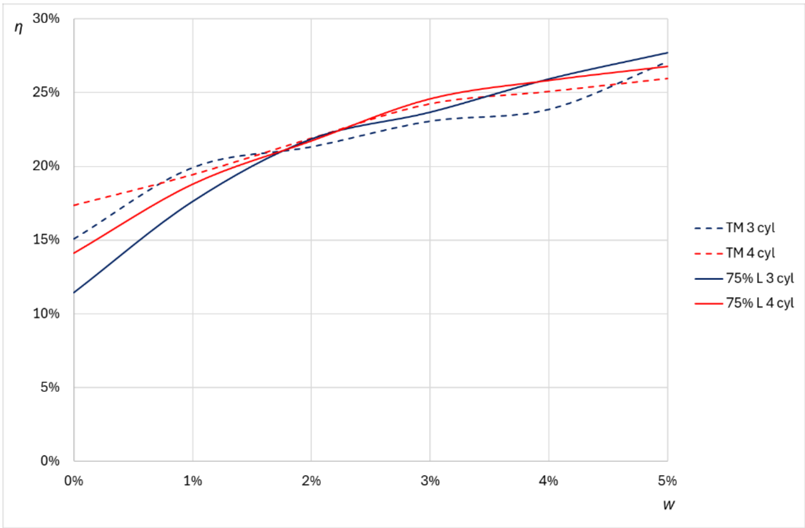


Fig. 13. Changes in the energy efficiency of the test vehicles at a speed of 90 km/h and varying road gradient value

The engine-transmission-wheel system achieves a maximum efficiency of 22-30% at a maximum road gradient of 5%. It can be noted that a reduction in the vehicle weight leads to an increase in η, or maintains efficiency at a level similar to that at a greater load. According to the η criterion, the comparison of engines is not perfect and provides insufficient information. Other systems exert a significant influence, especially the power transmission system. In this aspect, what may be of interest is the generalised characterisation (Fig. 14), where the area of all possible η values is marked in grey for the two cars.

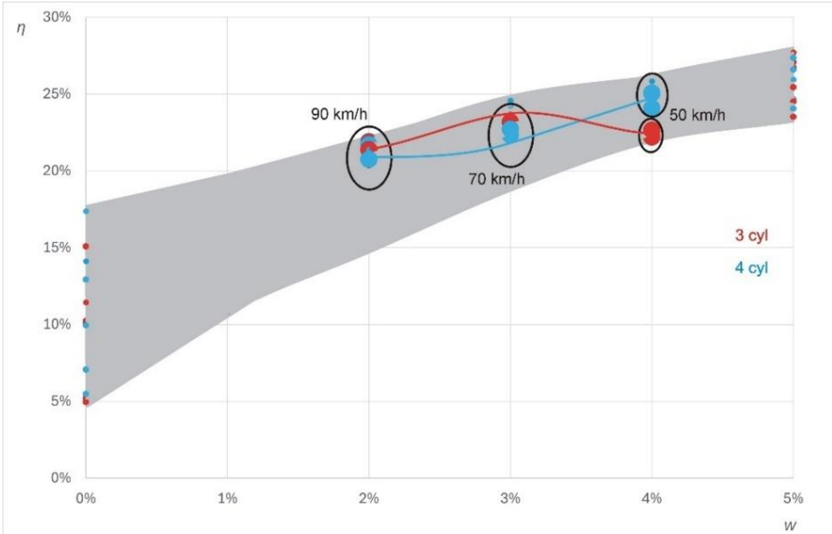


Fig. 14 Area (grey colour) of a change in the energy efficiency of the vehicles

Starting from the road gradient of 1%, the efficiency values for the two cars are convergent. The maximum efficiency values of 17-19% are achieved at a speed of 90 km/h on a road with a 1% gradient and those of 20-22% at a 2% gradient. At a road gradient of 3%, such efficiency concentration can be observed for a speed of 70 km/h. The absolute values of 22-24% are not the maximum values for this vehicle load. For a speed of 50 km/h, no such concentration can be identified for the two cars.
The reasons for the characteristic properties described are interesting. One of the ways to increase efficiency may be to optimise the selection of gearbox ratio under particular conditions. In this case, the overall energy efficiency will be the criterion, and the gearbox ratio will be the decisive parameter.

5. Summary

It can be found that there are no comprehensive studies to compare the energy efficiency of vehicles with varying engine designs and varying technical conditions. To this end, the paper proposes a new method for analysing the impact of operating conditions on the mileage fuel consumption, unit fuel consumption and overall energy efficiency of vehicles. This method can be used at the stage of selecting a car for specific tasks, as well as for in-service technical condition checks. The innovative vehicle testing methodology presented in this paper complements known studies aimed at solving the problem of a correct comparative analysis of vehicles with different drive units. In the study, it was possible to determine the effect of changing the vehicle speed, road gradient angle and vehicle weight. The criteria adopted for the evaluation of the test vehicles included mileage fuel consumption, unit fuel consumption, and overall energy efficiency.

1. Based on the analysis of changes in the unit fuel consumption g_e, it was observed that a three-cylinder engine, when driving at a speed of 50 km/h, was characterised by a high sensitivity to changes in load, manifested by a decrease in the g_e values with an increase in the road gradient. This is due to the more favourable conditions for the course of the operating process in the cylinders, resulting from the longer relative time in the engine with a longer piston stroke. As for a four-cylinder engine, no significant changes in g_e were observed. At a speed of 70 km/h, the two engines were characterised by similar patterns of changes in g_e. However, at the highest speed of 90 km/h for the four-cylinder engine, very similar patterns of changes in g_e were observed for the two vehicle weights presented in the graphs. This was due to the greater load on the engine, resulting from overcoming mainly the aerodynamic resistance force at a pre-set speed of 90 km/h. On the other

hand, for the three-cylinder engine, a greater dependence of g_e on the vehicle weight was observed, manifested by an increase in the g_e value from 30 to up to 70 g/kWh.

2. An analysis of the average mileage fuel consumption shows that the scatter of the absolute values is greater for car B. The highest consumption for the tested car loads was also noted for car B (a speed of 70 km/h, w = 5%, a maximum weight). Car B consumed 1.5% more fuel over the entire test cycle, which indicates the higher efficiency of the three-cylinder engine when operated under urban conditions.
3. In car A with the three-cylinder engine, the largest increases in average mileage fuel consumption after loading the vehicle occurred at a driving speed of 70 km/h. When simulating a total permissible weight load, as compared to a simulation of a load equal to the vehicle's curb weight, at a speed of 70 km/h, there was an increase in the average mileage fuel consumption of approximately 35%, whereas at a speed of 90 km/h, there was an increase of nearly 30%, and at a speed of 50 km/h, there was an increase of over 25%. In car B with the four-cylinder engine, the largest increases in average mileage fuel consumption after loading the vehicle with a simulated weight occurred at a driving speed of 50 km/h (an increase of approximately 50%). At a speed of 70 km/h, it amounted to nearly 40%, whereas at a speed of 90 km/h it was approximately 30%.
4. To evaluate the drive units of the two test vehicles, characteristics of changes in the overall energy efficiency η were used as well. It was observed that in all testing variants, the η value increased with increasing road gradient values, with the intensity of η increase not being constant. For road gradients within the 3-5% range, there was a deceleration in the increase in η, whereas it was noted that for greater speeds, this deceleration tended to shift towards higher road gradient values. The overall energy efficiency of the vehicle drive reached a maximum value of 22-30% at the maximum test road gradient of 5%. It should be noted that reducing the vehicle weight contributed to an increase in η or maintained the value at a level similar to that during tests with a greater vehicle load. Undoubtedly, one way to increase the overall energy efficiency could be to optimise the total gear ratio value in the vehicle drive system under particular conditions, where η would be the criterion, whereas the gear ratio would be the decisive parameter.
5. The experiment showed that in a three-cylinder engine, unit fuel consumption is more sensitive to parameter changes under identical conditions (speed, vehicle weight, road gradient angle) than in a four-cylinder engine. A car with a four-cylinder engine has a higher energy efficiency at low loads.

Similar tests can be continued in numerous scientific studies. The same comparisons and analyses can be carried out on cars with compression ignition engines. In addition, tests can be carried out to identify the effects of individual parameters related to body design, e.g. the aerodynamic coefficient and the frontal area, on the average mileage fuel consumption, unit fuel consumption, and the overall energy efficiency of vehicles. In addition, tests can be performed to identify the effect of the gear ratio in the drive system on these parameters during tests performed on a chassis dynamometer under varying load conditions (speed, road gradient, etc.). Analyses identifying the energy consumption over a distance and the overall energy efficiency of vehicles can also be used to compare cars with electric, hybrid or other non-conventional drive sources, as well as cars powered by LPG, CNG, LNG gases, etc. The application of the comparison of the overall energy efficiency of vehicles enables the performance of analyses of the efficiency of the use of energy supplied in the form of electricity or fuel and, consequently, the identification of the most advantageous source of vehicle drive, depending on the conditions of its planned operation. Such a comprehensive approach related to the selection of drive sources would allow the energy consumed for transport to be used in an optimal manner, regardless of the form in which the energy is supplied.

In the next works, the authors will analyse changes in CO_2 emissions as a function of changes in vehicle design parameters. They will also analyse the effect of changes in the weight and weight distribution of trucks with a maximum permissible weight of 3.5 tonnes on changes in CO, NO_x and CH emissions. These tests will be carried out on a chassis dynamometer and in real traffic conditions.

Abbreviations:

OBD	– On-Board Diagnostics
RS-TS algorithm	– Route Splitting Tabu Search algorithm
HEV	– Hybrid Electric Vehicle
US	– United States
OW	– load of only the driver's weight
TM	– total mass
LPG	– liquefied petroleum gas
CNG	– compressed natural gas
LNG	– liquefied natural gas

References

1. Abediasl, H., Ansari, A., Hosseini, V., Koch, C. R., Shahbakhti, M. (2024). Real-time vehicular fuel consumption estimation using machine learning and on-board diagnostics data. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, 238 (12), 3779-3793. https://doi.org/10.1177/09544070231185609
2. Berjoza, D, Jurgena I, & Millers R. (2024). Effect of electric vehicle mass change on energy consumption and the range. *Agronomy Research, 22*. https://doi.org/10.15159/AR.24.052
3. Cheah L W, Bandivadekar A P, Bodek K M, Kasseris E P, Heywood J B. (2009). The trade-off between automobile acceleration performance, weight, and fuel consumption. *SAE International Journal of Fuels and Lubricants*, 1(1), 771-777. https://doi.org/10.4271/2008-01-1524
4. Chirinda G, Matope S. (2020). The lighter the better: Weight reduction in the automotive industry and its impact on fuel consumption and climate change. *In Proceedings of the 2nd African international conference on industrial engineering and operations management*; Harare, Zimbabwe, 20-22.
5. Del Pero F, Delogu M, Pierini M. (2017). The effect of lightweighting in automotive LCA perspective: Estimation of mass-induced fuel consumption reduction for gasoline turbocharged vehicles. *Journal of Cleaner Production*, 154, 566-577. https://doi.org/10.1016/j.jclepro.2017.04.013
6. Filipi Z S, Assanis D N. (2000). The effect of the stroke-to-bore ratio on combustion, heat transfer and efficiency of a homogeneous charge spark ignition engine of given displacement. *International Journal of Engine Research*, 1(2), 191-208. https://doi.org/10.1243/1468087001545137.
7. Fonseca Gonzalez N E, Casanova Kindelán J, Espinosa Zapata F. (2010). Influence of driving style on fuel consumption and emissions in diesel-powered passenger car. *In Proceddings 18th International Symposium Transport and Air Pollution*, Dübendorf, Suiza, 2010.
8. Fuć P, Merkisz J, Ziółkowski A. (2012). Wpływ masy ładunku na emisję CO2, nox i na zużycie paliwa pojazdu ciężarowego o masie całkowitej powyżej 12 000 kg. *Postępy Nauki i Techniki*, 41-53.
9. Giechaskiel B, Komnos D, & Fontaras G. (2021). Impacts of extreme ambient temperatures and road gradient on energy consumption and CO2 emissions of a euro 6d-temp gasoline vehicle. *Energies*, *14*(19), 6195. https://doi.org/10.3390/en14196195
10. Gillespie T D. (1992). Fundamentals of Vehicle Dynamics. *SAE Technical Paper*, 114. https://doi.org/10.4271/R-114
11. Gkyrtis, K. (2024). Theoretical considerations from the modelling of the interaction between road design and fuel consumption on urban and suburban roadways. *Modelling*, 5(3), 737-751. https://doi.org/10.3390/modelling5030039.
12. He L, You Y, Zheng X, Zhang S, Li Z, Zhang Z, ... & Hao J. (2022). The impacts from cold start and road grade on real-world emissions and fuel consumption of gasoline, diesel and hybrid-electric light-duty passenger vehicles. *Science of The Total Environment*, *851*, 158045. https://doi.org/10.1016/j.scitotenv.2022.158045
13. Heywood J B. (1988). Internal Combustion Engine Fundamentals, International Editions - Automotive Technology Series, McGraw-Hill Book Company.

14. Huo H, He K, Wang M, Yao Z. (2012). Vehicle technologies fuel-economy policies, and fuel-consumption rates of Chinese vehicles. *Energy Policy*, 43, 30-36. https://doi.org/10.1016/j.enpol.2011.09.064.
15. Ismadiyorov, A. A., Sotvoldiyev, O. U. (2021). Model of assessment of fuel consumption in car operation in city conditions. *Academic research in educational sciences*, 2 (11), https://doi.org/1013-1019.0.24412/2181-1385-2021-11-1013-1019.
16. Koffler C, Rohde-Brandenburger K. (2010). On the calculation of fuel savings through lightweight design in automotive life cycle assessments. *The International Journal of Life Cycle Assessment*, 15, 128-135. https://doi.org/10.1007/s11367-009-0127-z
17. Kropiwnicki J. (2011). Ocena efektywności energetycznej pojazdów samochodowych z silnikami spalinowymi. Monografie, 110.
18. Kuo Y, Wang C. (2011). Optimizing the VRP by minimizing fuel consumption, *Management of Environmental Quality*, 22 (4), 440-450. https://doi.org/10.1108/14777831111136054
19. Lee M G, Park Y K, Jung K K, Yoo J J. (2011). Estimation of fuel consumption using in-vehicle parameters. *International Journal of u-and e-Service, Science and Technology*, 4(4), 37-46.
20. Mitschke M. (1977). Teoria samochodu. Dynamika samochodu (Automobile theory. Dynamics of motor vehicles). WKŁ Warszawa: 85-88.
21. Mrozik M, Merkisz-Guranowska A. (2024). Modeling of material and energy inputs in the life cycle of a vehicle. *Archives of Transport*, 70(2), 117-136. https://doi.org/10.61089/aot2024.vzsv6b46.
22. Mysłowski J. (2014). Zużycie paliwa europejskich samochodów osobowych. *Autobusy: technika, eksploatacja, systemy transportowe*, 15(6), 195-198.
23. Pavlovic J, Fontaras G, Broekaert S, Ciuffo B, Ktistakis M A, Grigoratos T. (2021). How accurately can we measure vehicle fuel consumption in real world operation?. *Transportation Research Part D: Transport and Environment*, 90, 102666. https://doi.org/10.1016/j.trd.2020.102666.
24. Reynolds C, Kandlikar M. (2007). How hybrid-electric vehicles are different from conventional vehicles: the effect of weight and power on fuel consumption. *Environmental Research Letters*, 2(1), 014003. https://doi.org/10.1088/1748-9326/2/1/014003
25. Romero C A, Correa P, Ariza Echeverri E A, & Vergara D. (2024). Strategies for reducing automobile fuel consumption. *Applied Sciences*, *14*(2), 910. https://doi.org/10.3390/app14020910
26. Rosero F, Fonseca N, López J M, & Casanova J. (2021). Effects of passenger load, road grade, and congestion level on real-world fuel consumption and emissions from compressed natural gas and diesel urban buses. *Applied Energy*, *282*, 116195. https://doi.org/10.1016/j.apenergy.2020.116195
27. Rymaniak Ł, Lijewski P, Kamińska M, Fuć P, Kurc B, Siedlecki M, Kalociński T, Jagielski A. (2020). The role of real power output from farm tractor engines in determining their environmental performance in actual operating conditions. *Computers and Electronics in Agriculture*, 173, 1-7. https://doi.org/10.1016/j.compag.2020.105405
28. Saboohi Y, Farzaneh H. (2009). Model for developing an eco-driving strategy of a passenger vehicle based on the least fuel consumption. *Applied Energy*, 86(10), 1925-1932. https://doi.org/10.1016/j.apenergy.2008.12.017
29. Šarkan B, Loman M, Synák F, Skrúcaný T, & Hanzl J. (2022). Emissions production by exhaust gases of a road vehicle's starting depending on a road gradient. *Sensors*, *22*(24), 9896. https://doi.org/10.3390/s22249896
30. Silva V, Vidal K, & Fontes T. (2024). Evaluating parcel delivery strategies in different terrain conditions. *Transportation Research Part A: Policy and Practice*, *187*, 104158. https://doi.org/10.1016/j.tra.2024.104158
31. Sprei F, Karlsson S, Holmberg J. (2008). Better performance or lower fuel consumption: Technological development in the Swedish new car fleet 1975-2002. *Transportation Research Part D: Transport and Environment*, 13(2), 75-85. https://doi.org/10.1016/j.trd.2007.11.003
32. Subadra S P, Yousef S, Griskevicius P, & Makarevicius V. (2020). High-performance fiberglass/epoxy reinforced by functionalized CNTs for vehicle applications with less fuel consumption and greenhouse gas emissions. *Polymer testing*, *86*, 106480. https://doi.org/10.1016/j.polymertesting.2020.106480

33. Tao N Q, & Quang N T. (2024). Analysis of effect of rolling resistance coefficient on automobile fuel consumption. *HaUI Journal of Science and Technology,* 60(5), 216-218. http://doi.org/10.57001/huih5804.2024.185
34. Van den Brink R M, Van Wee B. (2001). Why has car-fleet specific fuel consumption not shown any decrease since 1990? Quantitative analysis of Dutch passenger car-fleet specific fuel consumption. *Transportation Research Part D: Transport and Environment*, 6(2), 75-93. https://doi.org/10.1016/S1361-9209(00)00014-6
35. Vrublevskyi O, Gonera J, Napiórkowski J. (2023). Precision diagnostics of a diesel engine under agricultural tractor operating conditions. *Transport Problems Problemy Transportu*, 18 (2), 181-194. https://doi.org/10.20858/tp.2023.18.2.16
36. Wang H, Fu L, Zhou Y, Li H. (2008). Modelling of the fuel consumption for passenger cars regarding driving characteristics. *Transportation Research Part D: Transport and Environment*, 13(7), 479-482. https://doi.org/10.1016/j.trd.2008.09.002.
37. Wang L, Kelly K, Walkowicz K, Duran A. (2015). Quantitative effects of vehicle parameters on fuel consumption for heavy-duty vehicle, *SAE Technical Paper*, 2773. https://doi.org/10.4271/2015-01-2773
38. Weiss M, Cloos K C, & Helmers E. (2020). Energy efficiency trade-offs in small to large electric vehicles. *Environmental Sciences Europe*, *32*, 1-17. https://doi.org/10.1186/s12302-020-00307-8
39. Weiss M, Winbush T, Newman A, & Helmers E. (2024). Energy Consumption of Electric Vehicles in Europe. Preprints. https://doi.org/10.20944/preprints202406.1974.v1
40. Yao Y, Zhao X, Liu C, Rong J, Zhang Y, Dong Z, Su Y. (2020). Vehicle fuel consumption prediction method based on driving behavior data collected from smartphones. *Journal of Advanced Transportation*, 1-11. https://doi.org/10.1155/2020/9263605
41. Zeng W, Miwa T, Morikawa T. (2020). Eco-routing problem considering fuel consumption and probabilistic travel time budget. *Transportation Research Part D: Transport and Environment*, 78, 102219. https://doi.org/10.1016/j.trd.2019.102219
42. Zhang J, Zhao Y, Xue W, Li J. (2015). Vehicle routing problem with fuel consumption and carbon emission. *International Journal of Production Economics*, 170, 234-242. https://doi.org/10.1016/j.ijpe.2015.09.031.