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Analysis of energy efficiency and dynamics during car acceleration

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Highlights

- The authors assessed the dynamic index for the dynamics of a passenger car movement.
- The proposed dynamic index combines the energy (from fuel) and acceleration intensity.
- The index enables an objective quantification of the vehicle acceleration process.
- The obtained results can be applied to electric passenger cars due to their universal nature.

Abstract

In this work, the authors focused on analyzing the energy efficiency and dynamics during car acceleration, featuring investigation of acceleration dynamics under various acceleration intensities. The tests were performed in the speed range between 45 km/h and 120 km/h, at a constant gear ratio. This enabled obtaining variable dynamic parameters of the acceleration process, ranging from about 0.1 to 1.4 m/s^2, and recording variation in fuel consumption from 6.28 to 27.03 dm^3/100km. The study focused on determining the relation between fuel consumption, energy efficiency and vehicle acceleration depending on the available drivetrain power. The relation between fuel consumption and vehicle acceleration was described by using the dynamic index. The proposed dynamic index takes into account the energy (from burned fuel) and vehicle acceleration intensity to obtain an objective metric for characterizing the acceleration process. The aforementioned index takes the form of the passenger car movement energy quality index and can be related to widely known physical properties, thus ensuring its universality. The index expresses the energy expenditure within the time needed to accelerate a vehicle weighing 1kg by a 1m distance. As opposed to other criteria that are applied to the assessment of passenger cars dynamics, the index shows a high determination coefficient R2 in excess of 0.99, and can be used as a universal metric to test other vehicle types.

Keywords

acceleration, fuel and energy consumption, vehicle dynamics, acceleration dynamic index

1. Introduction

1.1. Drivetrain operating conditions and its energy demand

In terms of safety, the ability to accelerate is of particular importance among a vehicle's traction properties. The common real-world traffic situations in which the ability to accelerate plays a significant role include the overtaking maneuver, as it often involves temporary occupation of the traffic lane dedicated for vehicles moving in the opposite direction. Other maneuvers where the ability to accelerate is crucial include entering traffic or merging. The aforementioned maneuvers require the vehicle to be dynamically accelerated.

It needs to be noted that all of the mentioned maneuvers are potentially dangerous. However, due to the particularly adverse effects of road accidents, such as frontal collisions during an overtaking maneuver, it is especially important to attain proper

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acceleration. The maneuver begins at a known initial speed and the increase of this speed throughout the acceleration process is determined by the drivetrain's available power, and the prevailing traffic conditions, as they also affect the vehicle's dynamic and energy parameters. It is often the case that such acceleration is performed in a single gear, which essentially constitutes a classic flexibility test. In particular, in urban driving conditions, which often involve vehicle speed variations, the vehicle's dynamic and energy parameters vary to a large extent. In the work of Mamala et al. [22], the authors have focused on the variation in the vehicle's energy demand, resulting from transient traffic conditions and the drivetrain type: hybrid, electric or internal combustion, demonstrating that the use of an internal combustion engine-based drivetrain generates approx. 3.7 times higher energy cost compared to an electric drivetrain, and approx. 2.2 times higher than in a PHEV drivetrain, when investigated over a distance of 50 km in real-world driving conditions. The publication [27] shows a non-linear increase in a hybrid electric vehicle's (HEV) fuel consumption over larger mileages. The average cumulative fuel consumption, in relation to the dozen or so tested vehicles, increased with the distance traveled, however this relationship is non-linear. In paper [11], a method was developed to describe the energy efficiency by using fuel consumption in a road test, depending on the road surface's inclination. This enabled the determination of the energy efficiency of a car that overcomes a hill. In [17], the authors presented a method of utilizing a high accuracy position measurement system to estimate the energy consumption of an EV. In the work [29], the authors also discussed the use of actual data from a GPS system to estimate an EV's electrical energy consumption. The electricity demand during every-day driving is estimated on the basis of the GPS coordinates and a model that takes into account the data derived from these coordinates. The study [13] used the results of extensive dynamometric tests conducted on several electric vehicles. The conducted research allowed for the development of a multidimensional model with regression coefficients of about 0.97 in order to map the power and energy demand for all test conditions, thereby facilitating the interpretation of the aforementioned indicators. Similar studies have also been carried out in [4] to investigate the acceleration and deceleration behavior of drivers for different vehicle types using modern instruments, such as the Global Positioning System (GPS). As the analysis of the cited works shows, a substantial number of research papers deal with the issue of total energy demand in real-word conditions.

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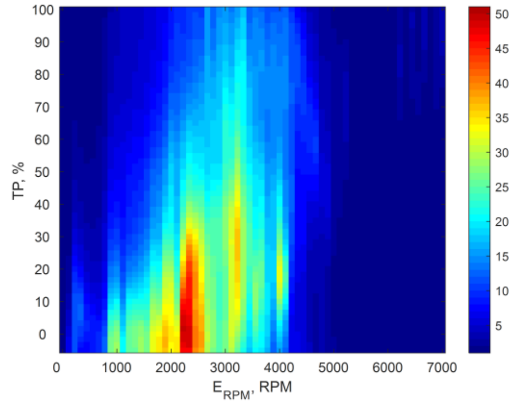

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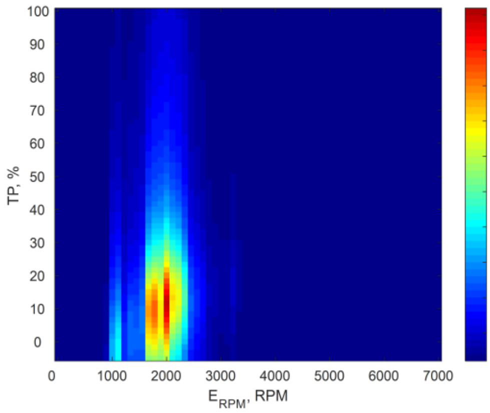


Fig. 1. Variations in throttle position during a road test in urban conditions for the adopted driving styles: a) dynamic, b) economical [23]

The paper [23] investigated throttle position variations in a real urban driving cycle, recorded during a drive test performed in a small town, and resulting from the driver's assumed driving style (Fig. 1). In that research, the authors were searching for engine power ranges most commonly used in urban traffic by adopting different driving strategies. Under all investigated traffic conditions, the vehicle's engine was generally operating at low power (and low efficiency) conditions.

The presented characteristics demonstrate the combustion engine's varied use in the drivetrain, specifically in conditions marked as the dynamic driving style, where the throttle positions range from 0 to 100% for about 5% of the total driving time. The throttle dynamics variations mean that the power in the drive system needs to vary substantially to enable adaptation to the road conditions. Regardless of the operator's driving style, the characteristics are dominated by the most frequently used operating field for partial engine power, resulting from the crankshaft's low rotational speed and small throttle position angles. Particularly noteworthy are the points in the engine operating field, which correspond to the throttle position of 20% and 30%, and the rotational speed (E_{RPM}) ranging from 1000 to 2000 rpm, as the acceleration process in the aforementioned overtaking maneuver is most often performed under such conditions when characterized in terms of the drivetrain components' energy consumption.

Another study [9] explored the issue of low vehicle mean speeds and accelerations in urban cycles. It was found that the vehicle's average acceleration ranged from 0.2 m/s^2 to 1.6 m/s^2, depending on the traffic conditions, where the instantaneous maximum acceleration reached the peak value of 4.5 m/s^2. In [32], the authors presented the real-world energy consumption of an EV. According to the study's results, the calculated energy consumption increased from 40% to 60% each time the vehicle mass was doubled, but only by 5% whenever the electric motor power was doubled. This research encompassed passenger cars with fuel consumption tending to increase about 0.1 dm^3/100 km with each 100 kg of vehicle mass. The outcomes of the studies reported in [12] focused on driver behaviors and their reaction to changing traffic conditions. Analysis of the test results shows that aggressive driving causes a greater variation in fuel consumption for HEV when compared to similar vehicles with ICE drivetrains. At the same time, the work [28] presented the correlation between fuel consumption and energy consumption per vehicle mileage, but was primarily related to particular design features of specific cars. The energy expenditure from fuel demand while the vehicle is in motion is also affected by many other parameters, aside from design parameters, which increase petrol consumption and, in the case of internal combustion engines, also result in increased CO_2 emissions. Numerous publications explored the parameters affecting the vehicle's so-called dynamic fuel consumption:

- the vehicle's design parameters, such as mass, aerodynamic parameters [5, 32],
- drivetrain and suspension parameters [8],
- parameters of operating fluids and materials used in the vehicle, such as oils, lubricants, and tires [7, 34],
- operating parameters of auxiliary systems, such as air conditioning, power steering, and comfort systems [2, 24].
- the vehicle's exterior parameters: road characteristics [31], traffic conditions [33] or weather conditions [28, 30].

In [33], which focused on passenger car speed variations in urban driving cycles, attention was paid to the energy aspects of the energy consumption ratio, which was compared to the determined time density of vehicle speeds expressed in 7 classes, each in the velocity range of 15 km/h. The determined energy consumption ratio was described by an exponential equation with the equation's coefficients resulting from the analyzed motion's dynamic parameters. The obtained determination coefficients R^2 amount to 0.9975 on average. In [28], the investigation focused on determining the effect of acceleration intensity and vehicle speed on fuel consumption in an ICE drivetrain. A change in acceleration intensity was obtained by referencing scales that describe the selected passenger car acceleration processes, and the obtained results have shown an increase in the drivetrain's energy demand from 5 – 65% to 25 – 65% in an urban cycle. In the case of highly dynamic driving styles, the increase in energy demand was 100% higher.

The authors of the study [16] proposed an individually tailored driving speed resulting from the driving style to evaluate the dynamic vehicle parameters. Logic trees were applied to classify the dynamics, and the obtained results indicated a significant difference in acceleration and fuel consumption on the test route in relation to the adopted driving speed's statistical model. Cited studies from various research centers provide an overview of the subject and an insight into various research methodologies. A variety of studies [6] refer to subjective indicators in an assessment of dynamic parameters of vehicle movements with the most frequently used being acceleration, often characterized by its mean acceleration value. However, the mileage-based fuel consumption is most often used as an energy demand parameter. The indicated parameters are commonly used and enable comparing the design parameters of two identical vehicles, and the comparison of two different passenger cars can only be considered in subjective terms.

In order to elaborate on the latest knowledge in the field, the authors of this publication conducted an analysis of the acceleration phase based on energy indicators of a passenger car's drivability, derived from fuel consumption, distance traveled, average speed and acceleration.

1.2. Vehicle movement dynamics

Passenger car movement varies in terms of speed, hence the driver's input and the drivetrain control techniques significantly affect the vehicle's driving speed during a cycle. Among some studies in this area, [19] is particularly noteworthy, as different acceleration and deceleration phase tests were simulated in terms of an HEV's fuel consumption reduction. The obtained results have shown the potential reduction in the total fuel energy consumption ranging from 5 to 11% thanks to the application of an optimal acceleration intensity. At the same time, the most optimal fuel demand was achieved at high acceleration intensity, but the value was much lower than the maximum drivetrain performance. The study [20] analyzed a different way of controlling the drive system by simulating the energy demand when accelerating with different intensities. The simulation results obtained using the Dynamic Program demonstrated the use of the mean acceleration value of around 0.55 m/s^2 as the optimal value obtained at about 60% of the accelerator pedal position. Study [10] highlighted an analysis of the share of individual vehicle movement phases throughout various driving tests. It was found that the acceleration range of 0 – 1 m/s^2 covers over 20% of the acceleration phase, while 1 – 4 m/s^2 covers 15% and these phases usually correspond to more than 5% of the driving cycle's entire duration. Hence, the authors in [15] focused on control strategy optimization during the acceleration process to reduce the energy demand. The experimental results confirmed that an extension of the acceleration time by 1 second in the range from 0 to 30 km/h and by 2 seconds in the range from 0 to 40 km/h, enabled a reduction in energy demand of over 5%. The publication [13] contains an account of tests which involved several vehicles and modeled the energy demand described by high-order polynomial vehicle speed function, and taking into account the driving style classified as fast & hard, mid high, mid low, and sedate. The obtained results have shown the minimum values of specific energy consumption, depending on the vehicle, in the range of target speeds from approx. 50 – 65 km/h. At the same time, the energy consumptions in aggressive, fast, and hard driving styles was almost 218% of the value obtained for the sedate style. Further research in this area, shown in [4], focused on acceleration and braking intensity for vehicle types ranging from motorcycles to trucks, establishing the maximum acceleration range of 0.45 – 2.87 m/s^2 and the mean acceleration values of 0.2 – 0.82 m/s^2. Subsequently, it was proposed to model the acceleration intensity for different types of vehicles depending on vehicle speed to obtain consistent results. The paper [1] has described three different acceleration profiles since the vehicle's start. The comparison of profiles was based on the assumption of a constant time to achieve various constant speeds, and the comparison of the differences in acceleration intensity during the acceleration cycles. At the same time, the authors presented the fuel consumption related to these profiles and stated that differences in fuel consumption ranging from 10 to 30% were found. In addition, the study [3] took on the impact of vehicle acceleration intensity on fuel consumption, directly defined in terms of an aggressiveness factor. The tests demonstrated a linear increase in fuel consumption related to mean acceleration. It is the most commonly used method of assessing a vehicle's acceleration ability, but is effective for a limited number of vehicles. In a broader sense, as well as in relation to the conducted literature review, there are no objective indicators that would provide a way to compare the dynamics with the vehicle movement's energy demand. The parameters characterized by mean acceleration and the time needed to achieve the target speed, and the traveled distance to reach the earlier assumed speed, are irrelevant and depend on the vehicle's design parameters and the drivetrain's parameters. However, an analysis of the vehicle acceleration process (regardless of whether the initial speed was 0 or from a certain initial speed to the target speed), has shown that acceleration is the most energy-consuming movement phase, as demonstrated by the detailed analysis presented in the following portion of this work.

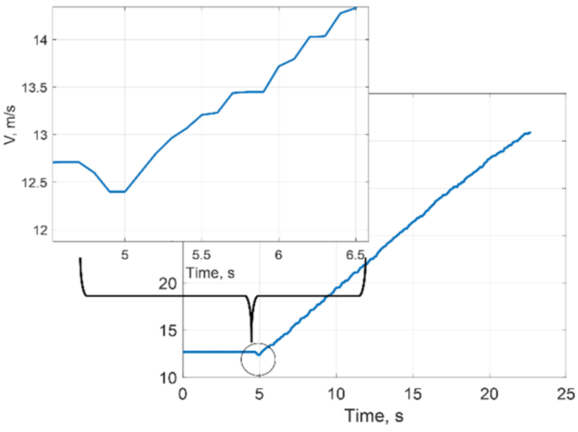
When driving on a sufficiently long road section, the acceleration process' vehicle speed determines the vehicle's dynamics, which are not only related to the drivetrain' design, but also depend on external factors that affect vehicle performance (such as energy loss due to rolling resistance, air and inertial forces). In the acceleration process, the inertial energy is particularly variable, as it decreases with the increase in vehicle speed due to the driving force reserve's reduction. The specified acceleration results were derived from the apparent inertial force acting on the vehicle at a given acceleration value. The acceleration determined by equation (1) can be related to the instantaneous and mean values.

$$a = \frac{\sum(V_e^2 - V_s^2)}{2L}, \qquad (1)$$

The mean vehicle acceleration in the acceleration phase, from initial to target speed, depends solely on the executed acceleration profile. However, in the first phase of acceleration with constant transmission ratio, the dynamics of the process vary as a result of applying additional energy to the drivetrain, thereby leading to a rapid increase in acceleration in the first phase and causing the so-called jerk, and is only followed by a physical increase in speed. The initial stage of the acceleration process often features temporary reduction in vehicle speed and acceleration, as described in the studies reported in [14] .

Preliminary research conducted by the authors shows the area characterized by a change in the initial acceleration phase, which is related to a sudden increase in drivetrain energy to its maximum value, with control over 100% of the output power. The waveforms recorded at that time indicate that the increase in acceleration is related to the increase in the output power, and thus the driving force (Fig. 2).

a)



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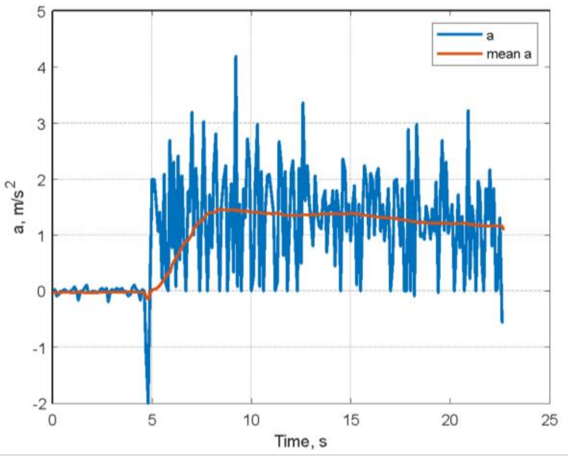
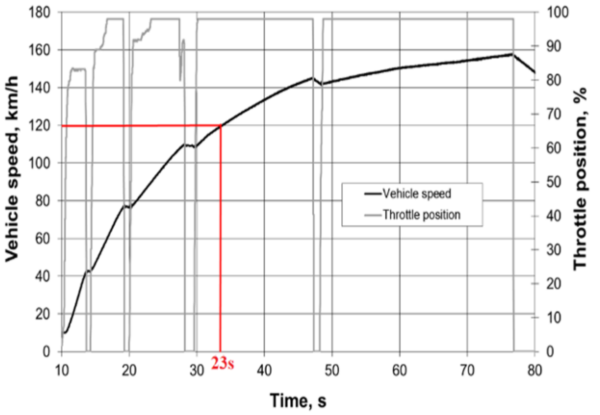


Fig. 2. Variations in kinematic parameters for the acceleration process performed at full intensity (TP =100%): a) for linear speed, b) for acceleration

The total energy demand is directly related to the driving force during the acceleration phase. Hence, the use of this parameter alone in acceleration assessment may lead to inconclusive statements. It is therefore difficult to unambiguously assess the dynamic properties of two different vehicles with the same drive unit power, but with differently configured drivetrains (e.g. different total gear ratios).

a)



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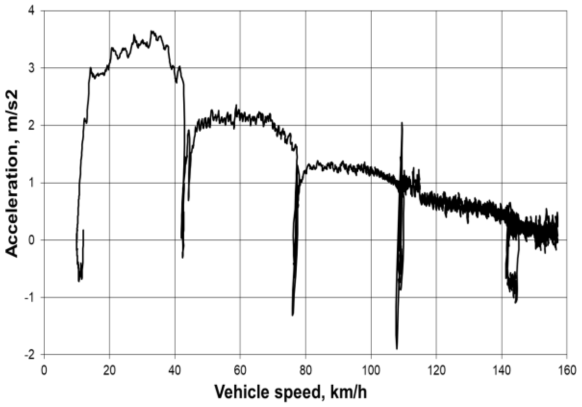


Fig. 3. Variations in parameters during the vehicle's acceleration process (engine maximum power – 60 kW, maximum engine torque – 130 Nm, mass – 1170 kg, maximum speed – 180 km/h) with 6-speed manual transmission: a) change in linear speed and TP vs. time, b) change in longitudinal acceleration [21].

This may lead to incorrect conclusions if these vehicles are evaluated, e.g. on the basis of the speed achieved in the assumed time (e.g. 30s). The issue of choosing the drivetrain's ratio is decisive when the vehicle's target speed is at its maximum value that should be reached over a limited distance. At the same time, vehicle acceleration from a standstill with a fully pressed accelerator pedal is an extreme case of movement in which the transmission ratio control is of great importance as it involves gear shifts (Figs. 3 and 4).

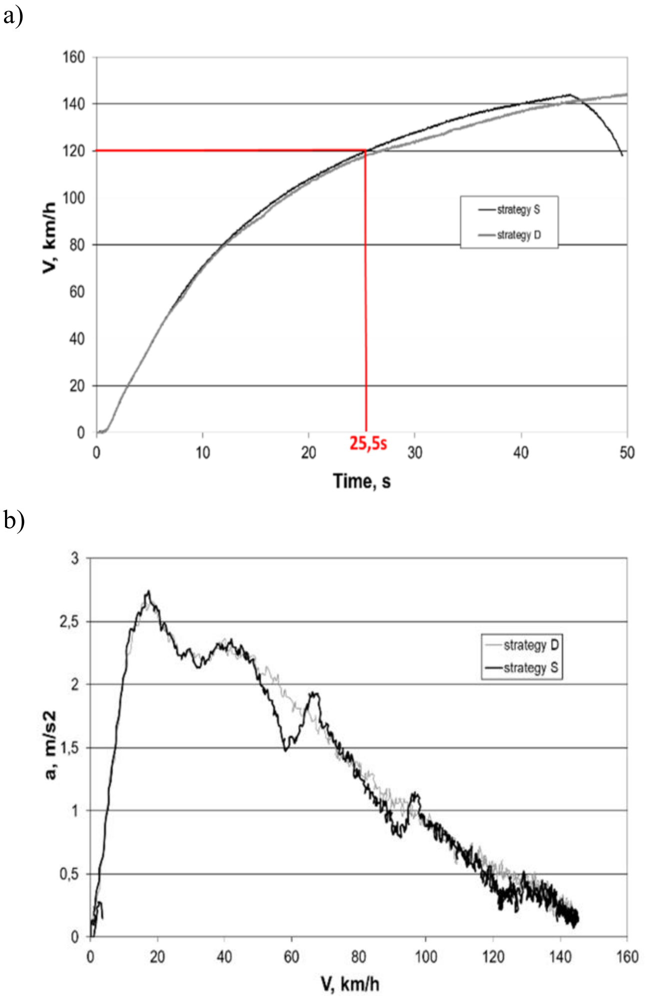


Fig. 4. Variations in parameters during the vehicle's acceleration process (engine maximum power – 59 kW, maximum torque – 119 Nm, mass – 1010 kg, maximum speed – 165 km/h) with Continuous Variable Transmission (CVT): a) change in linear speed and throttle opening vs. time, b) change in longitudinal acceleration [21].

The waveforms of speed and acceleration observed for the acceleration process of two completely different drivetrains from vehicle standstill to the maximum speed, presented in Figures 3 and 4, following abrupt pressing of the accelerator pedal, demonstrate significant differences during the acceleration process. Despite similar ICE power maximum values, these vehicles recorded different times of acceleration to the speed of 120 km/h from a standstill. Despite the lower maximum torque available on the crankshaft (119 Nm), as well as lower mass, the manual transmission vehicle accelerated 2.5 seconds faster, and the average acceleration in the analyzed process was 1.28 m/s^2 and 0.98 m/s^2, respectively. The instantaneous longitudinal acceleration of both vehicles decreases along with an increase in the vehicle's longitudinal speed. In the acceleration process taken into account in the performed tests, drivetrain flexibility becomes more important than the vehicle design features, such as weight, drag coefficient, tire type, and engine output. This is particularly true when the test is performed at a constant drivetrain transmission ratio.

1.3. Fuel consumption and energy efficiency during vehicle movement

Regardless of the power source, the outcome of specific energy transformations in the drivetrain is the energy supply to the drive system, required for the passenger car's movement. This energy can be used to accelerate the vehicle, climb a hill or to maintain a constant speed. For energy reasons, the acceleration phase evaluation is essential for determining the passenger car's total energy consumption. The reason for this is that an increase in fuel consumption or energy demand results in a reduction in the vehicle's range. In the study reported in [30] an algorithm was developed to predict the energy demand, taking into account the energy correction, among others, resulting from driving style identification based on the vehicle's mean acceleration, considered both in the short and long term time horizons. The results demonstrated that the application of a predictive algorithm, taking into account various corrections, enables reducing the discrepancy between the predicted results and the actual observed energy demand to less than 10%. The subject of prediction is even more important in the case of electric vehicles, where attempts are made to monitor the demand based on the driving style. Some researchers [2] propose a driving style classification, describing styles as aggressive, ordinary, or economic. In this context, referring also to Fig. 1, they examined the impact of driving style on the energy demand during various driving cycles, and reported variations in the range of 0.9 – 4.5 dm^3/km, leading to an increase in energy demand of 4.5 times, regardless of the type of investigated drivetrain (ICE, EV). The study found an increase in energy consumption of around 40% at lower speeds and a significant acceleration rate when comparing aggressive and economic styles. The driving style is often directly related to the acceleration profile, which also indirectly affects other movement phases, i.e. maintaining a constant speed and deceleration phases. High instantaneous and mean accelerations characterize an aggressive driving style and directly affect energy parameters. Acceleration with moderate intensity resulting from the drivetrain's low energy demand is balanced by an increase in inertial energy which is directly proportional to the square of the vehicle's acceleration. In terms of physical quantity, the energy delivered to the drivetrain, mostly resulting from fuel demand, far exceeds the energy consumption needed to overcome rolling and drag resistances [18].

Hence, the driving style, which affects the acceleration process, is characterized by different dynamics and different total energy consumption, including energy derived from fuel. The study [26] described the impact of mileage on specific energy consumption parameters. The distance-related specific energy demand E_{TU} is described as the ratio of the energy delivered to the wheels, considering only the driving phase (the energy consumption of all drive units (E_T)), to the total traveled distance (L) and vehicle mass (m), as expressed by the following equation [25]:

$$E_{TU} = \frac{E_T}{m \cdot L} \tag{2}$$

In the case of a flexible acceleration process on a flat road and with a certain intensity, the energy intensity of the movement needed to accelerate the vehicle is balanced by the total energy consumption *(E_T)* expedited to overcome losses resulting from resistances (rolling (E_R), air drag (E_A), vehicle inertial force (E_I), drivetrain efficiency (Δ), energy loss without transmitting to drive *(D),* taking the form expressed in equation (3).

$$E_T = \underbrace{(E_R + E_A \pm E_I \pm E_H \pm E_P)}_{E_M} + \underbrace{\Delta E_{ICE} + \Delta E_{PT}}_{\Delta} + \underbrace{\Delta E_L}_{D} \tag{3}$$

In this equation, components such as energy recovered from the deceleration phase do not exist. Total energy from all energy sources is converted into the driving force in the vehicle's wheels.

$$E_T = \int_{t_s}^{t_e} F_D \, v \, dt, \tag{4}$$

where: F_D – propulsion phase driving force [N], $t_{s,e}$ – beginning and end of the acceleration phase [s], v –constant speed [m/s], hence the energy consumption related to movement is expressed in the energy unit [J].

$$F_D = m \cdot g \cdot (f_t \cdot cos\alpha + sin\alpha) + \frac{\rho}{2} \cdot C_w \cdot A \cdot v^2 + m_r \cdot a \tag{5}$$

where: m- vehicle mass [kg], g – gravitational acceleration, f_t – rolling resistance index, α – road inclination [°], ρ – air density[kg/m^3], C_w – air drag coefficient, A – vehicle frontal area [m^2], m_r – reduced vehicle mass [kg], a – vehicle acceleration [m/s^2]

$$m_r = \delta \cdot m \tag{6}$$

$$\delta = 1.03 + 0.24 \cdot i_b^2$$

where: δ – rotating mass factor, i_b – gear ratio, [29]

As presented above, various subjective measures are used to evaluate vehicle movement and dynamics, including the determination of acceleration parameters, as well as the acceleration time from standstill to the target speed. Vehicle acceleration time is one of most commonly used performance indicators in the automotive industry. In addition, other methods are used in the assessment of the vehicle's acceleration parameters, such as the distance traveled from standstill to the assumed relative speed. Another metric is the distance traveled in a specific time from standstill to the speed achieved in the assumed time, e.g. 30s. Yet another index is used to describe the time required to reach half of the vehicle's maximum speed. A commonly used measure of the vehicle's acceleration parameters, particularly common in sports cars, is the time required to cover a ¼ mile road section. Three parameters are mentioned in the above examples: time, distance and speed. It is necessary to note, however, that the above measures are objective for vehicles with identical design features in terms of mass, force and inertial resistance coefficients. This is due to the fact that when using the acceleration process' kinematic parameters, e.g. time, as a measure of the acceleration ability, the decisive characteristic is associated with the energy volume transferred to the drivetrain in a sufficiently short time. Assuming a constant vehicle weight and varying drivetrain power, total vehicle energy consumption in the acceleration process can vary substantially depending on the applied model.

1.4. Research topic motivation

As shown in the literature analysis, fuel consumption and energy efficiency depend on many parameters, including the vehicle movement dynamics. The subject literature lacks a single objective parameter that would enable robust evaluation of vehicle acceleration in terms of its drivability. In this work, the authors aimed to develop such an objective index to facilitate the aforementioned assessment. According to the authors' intentions, the indicator would enable vehicle drivability analysis across different groups and drivetrain types. According to the authors, the flexibility measurement seems to be the most reliable method of those analyzed above to assess the vehicle's drivability.

For this reason, the study is focused on the analysis of the relationship between energy efficiency and the vehicle acceleration dynamics. The analysis based on the total energy demand during the acceleration process was conducted at a fixed total transmission ratio, taking into account the vehicle's weight and distance traveled. The research presented in the following portion of the article mainly concerns a passenger car. The tests presented below, in chapter 4, allowed for proposing the dynamic index ID, characterized by the unit (kg⋅m)/s. The universality of the proposed index will enable the assessment of various types of combustion, hybrid or electric drives, as it is based on parameters independent of the drivetrain type and takes into account the total energy demand, regardless of its type (energy contained in the fuel tank or electricity stored in batteries).

2. Research on the passenger car's acceleration intensity

2.1 Research methodology

Tests with various acceleration intensities were conducted in order to obtain data describing the relationship between the passenger car's fuel consumption, energy efficiency and dynamics. It was possible to achieve repeatability of subsequent tests by performing them on a chassis dynamometer (MAHA MSR 500). Different acceleration intensities used in the tests made it possible to determine the impact of acceleration intensity on the drivetrain's operating parameters. This will enable finding dependencies between fuel consumption, energy efficiency and acceleration dynamics. The tests involved vehicle acceleration from the speed of 45 km/h in the fourth gear over a quarter-mile distance, based on the assumption that the distance is deemed as critical when overtaking or merging with traffic. The tests were carried out at different intensities, resulting in a number of predefined permanent throttle positions. All acceleration dynamics measurements were preceded by the power unit operation's stabilization at the speed of 45 km/h for at least 10 seconds, with the assumed measurement points, including throttle positions, shown in Table 2. Data collection for parameter comparison was carried out at 50 m intervals over a ¼ mile section (Table 2). Ideally, both parameters would correlate for all variable dynamics measurements. At the same time, the assumption of a ¼ mile distance enabled analyzing the acceleration process around the greatest energy variations, while minimizing the drive system's jerk effect.

The advanced method of active identification by recording of drivetrain parameters under dynamic operating conditions was applied during subsequent analysis. The concept of vehicle acceleration intensity testing (flexibility test) compares the energy contained in fuel consumption and conversion energy efficiency to the dynamic parameters recorded on the road.

2.2. Test object

The test object was a passenger car equipped with a spark-ignition ICE with a turbocharging system, including performance-oriented modifications. The summary of the test vehicle's ICE parameters is presented in Table 1.

Table 1. Parameters of the investigated vehicle.

Manufacturer	Volkswagen
Engine type	AWT
Engine displacement	1781 cm^3
Max. Power	110 kW at 5700 rpm
Max. Torque	210 Nm at 1750 rpm
Engine layout	Front, transverse
Supercharging	Compressor
Camshaft	DOHC
Cylinders	R4
Valves	20
Compression ratio	9.5 : 1
Cylinder bore × piston stroke	81 × 86.4 mm
Injection system	Multipoint (MPI)
Vehicle mass	1286 kg
Gross vehicle weight	1615 kg
4th gear ratio	0.971
Air drag coefficient	0.27
Vehicle body frontal area	2.18 m^2

The measurement system was developed in the LabView environment to allow measuring the vehicle's energy and dynamic indicators and saving the outcomes in a single file. The file stores data from the OBDII on-board diagnostics system and the CAN BUS data transmission, as well as independent traction data from the MSR 500 and Corrsys Datron L-350 dynamometers. The entire measurement system was created in the Department of Vehicles of the Opole University of Technology and was described in greater detail in [22]. Fuel consumption was estimated based on a direct measurement of injection time and injector flow parameters. The fuel consumption estimation was calibrated with the use of the Flowtronic 215 measurement system.

3. Research on the passenger car's acceleration intensity

3.1. Identification of drivetrain operating parameters in flexibility tests - results

The acceleration process flexibility was tested over a ¼ mile distance and analyzed in 50 meter intervals (Table 2).

Table 2. Specific distance travel time with selected flexibility test throttle positions in 4th gear during experimental testing.

	Acceleration pedal positon, %								
Distance, m	20	25	30	35	40	45	50	70	100
0-50	3.7s	3.6s	3.5s	3.5s	3.5s	3.4s	3.5s	3.4s	3.3s
50-100	3.4s	3.2s	3.0s	2.9s	2.8s	2.7s	2.7s	2.6s	2.6s
100-150	3.3s	3.0s	2.8s	2.6s	2.4s	2.3s	2.3s	2.3s	2.2s
150-200	3.2s	2.8s	2.6s	2.4s	2.2s	2.2s	2.1s	2.0s	2.0s
200-250	3.1s	2.8s	2.4s	2.2s	2.1s	1.9s	1.9s	1.8s	1.8s
250-300	3.0s	2.7s	2.4s	2.2s	1.9s	1.8s	1.8s	1.7s	1.6s
300-350	3.0s	2.6s	2.2s	2.0s	1.8s	1.7s	1.7s	1.5s	1.6s
350-400	3.0s	2.6s	2.2s	1.9s	1.7s	1.6s	1.6s	1.5s	1.4s

Ultimately, it was possible to determine the average values of kinematic and energy parameters at 8 intervals (Fig. 5b). For the throttle positions above 45%, it is possible to use linear approximation with a high determination coefficient R^2, where the approximation curve represents the mean constant acceleration in the acceleration flexibility test (Fig. 5).

a)

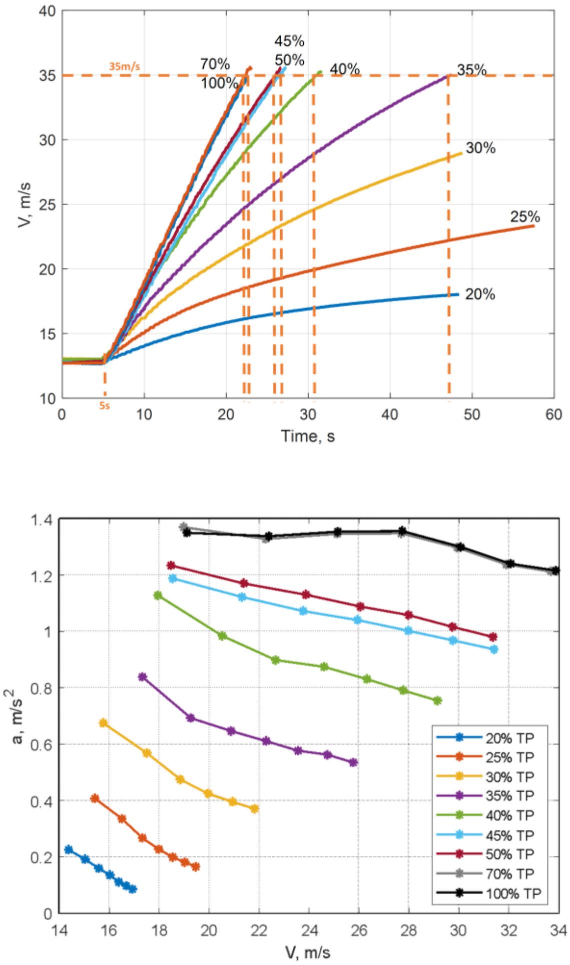


Fig. 5. Traction parameters in the flexibility test conducted on a chassis dynamometer for specific throttle positions *(TP)*: a) variations in linear speed, b) variations in longitudinal acceleration in time

As shown in Figure 1, low intake manifold throttle positions of up to 30% are specific to smooth driving, with slight excess in drivetrain power. The small throttle angles were maintained until the end of the vehicle's acceleration process over the ¼ mile distance. As a result, the vehicle was unable to accelerate to the target speed of 125 km/h (35 m/s) on this road section, as shown in Figure 5a.

The proposed test method is related to a different range of obtained speeds. The proposed dynamic index values take into account the energy required to overcome inertia and the remaining resistances. The share of inertia-related forces / powers (mass + rotation) in this case is substantial, especially in the case of high acceleration values. The energy required to compensate for the air resistance resulting from the driving speed is decreasing along with the increase in acceleration intensity. For example, at the speed of 17 m/s (speed achieved in all tests – Figure 5) and acceleration intensity of 1.4 m/s, the energy required to overcome air resistance is slightly above 4%. The percentage share is higher for smaller acceleration values or higher speeds. It is therefore evident that the driving force required to overcome the inertia resistance is significant and can often account for more than 90% of the vehicle's total resistance.

The obtained results of flexibility tests for all throttle positions are summarized in Table 3.

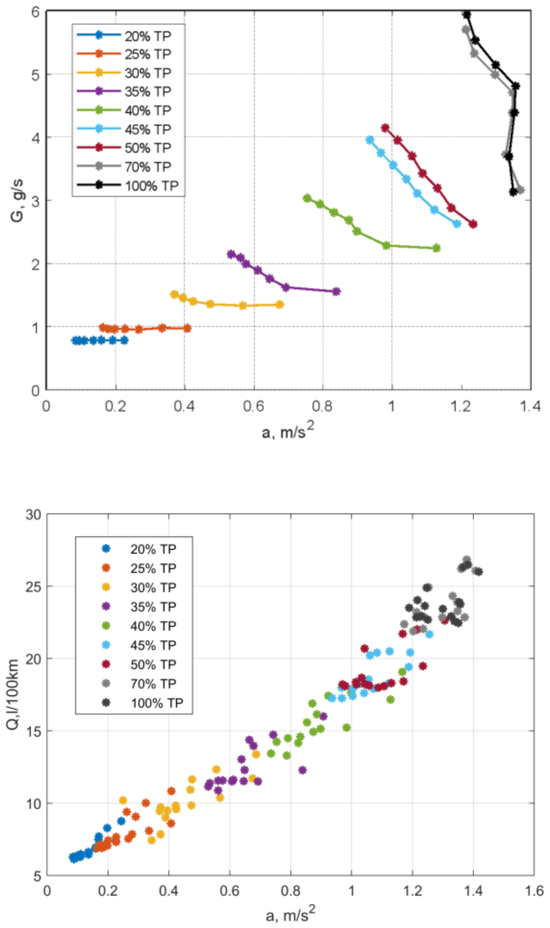
Table 3. Dynamic and energetic indices obtained in acceleration flexibility tests at a ¼ mile distance

TP [%]	a_{sf}	*Time* [s]	*L* [m]	a_{max} [m/s^2]	P_{mean} [kW]	Ge_{mean} [g/s]	E_{TF} [MJ]	E_{TU} [J/(kg·m)]
20	0.11	25.9	401.2	0.25	4.53	0.78	0.441	0.355
25	0.17	23.5	401.5	0.41	7.73	0.97	0.496	0.519
30	0.34	23.5	401.8	0.67	10.34	1.22	0.550	0.688
35	0.51	19.7	400.8	0.83	18.99	1.79	0.720	1.061
40	0.85	18.4	401.4	1.13	26.32	2.45	0.888	1.404
45	1.06	17.6	402.8	1.18	32.67	3.02	1.024	1.664
50	1.08	17.6	401.4	1.23	33.13	3.09	1.033	1.691
70	1.30	16.8	400.5	1.36	40.57	4.00	1.232	2.003
100	1.31	16.7	400.8	1.37	40.96	4.05	1.224	2.008

The increase in acceleration also affects fuel consumption which slightly deviates from the mean value for throttle positions above 45% due to the adopted 50 m data collection intervals.

3.3. Energy consumption indices during vehicle acceleration

The fuel consumption values obtained in the acceleration flexibility tests, taken at various throttle positions, were compared with the mean acceleration values. Subsequently, those values were compared with noted fuel consumption (Fig. 6). For relatively low acceleration values, fuel consumption is almost constant and is not affected by the acceleration value. On the contrary, for maximum accelerations, fuel consumption varies in a relatively wide range. By analyzing the obtained results, it is possible to distinguish the range of average acceleration values from 0 to 0.8m/s^2, which does not substantially affect fuel consumption. However, when analyzing higher mean acceleration values, it is possible to notice the rapidly increasing fuel consumption. However, in the relation of fuel consumption and vehicle acceleration, the values can be approximated by using a linear function and demonstrate a close relationship, as demonstrated in Fig. 6a.


a)

b)

Fig. 6. Variations in traction parameters in the acceleration flexibility test conducted using a test bench for a vehicle equipped with manual transmission for set throttle positions: a) fuel consumption, b) mileage fuel consumption.

The relations between energy and dynamic parameters observed in the vehicle acceleration flexibility tests are presented in Table 4.

Table 4. List of energy parameters obtained in acceleration tests conducted at a ¼ mile distance

TP [%]	Ge_{mean} [g/s]	Ge_{min} [g/s]	Ge_{max} [g/s]	Q_{mean} [dm^3/100km]	Q_{min} [dm^3/100km]	Q_{max} [dm^3/100km]	E_{TFmean} [MJ]	E_{TFmin} [MJ]	E_{TFmax} [MJ]
20	0.780	0.773	0.787	6.93	6.28	7.96	0.441	0.064	0.829
25	0.967	0.954	0.981	7.86	6.89	9.63	0.496	0.077	0.934
30	1.219	0.705	1.507	9.71	7.41	11.71	0.550	0.055	1.173
35	1.795	1.551	2.142	12.29	11.38	15.20	0.721	0.119	1.451
40	2.446	1.822	3.031	15.58	14.24	17.16	0.888	0.126	1.850
45	3.017	2.124	3.956	18.26	17.25	19.41	1.024	0.149	2.174
50	3.088	2.133	4.143	18.66	17.98	19.62	1.033	0.143	2.222
70	4.005	2.427	5.704	22.88	22.04	25.89	1.232	0.163	2.743
100	4.056	2.391	5.945	22.92	21.48	27.03	1.224	0.161	2.768

The mean values of acceleration are directly proportional to both fuel consumption and distance-related fuel consumption, with high determination coefficients R^2 (Fig. 7).

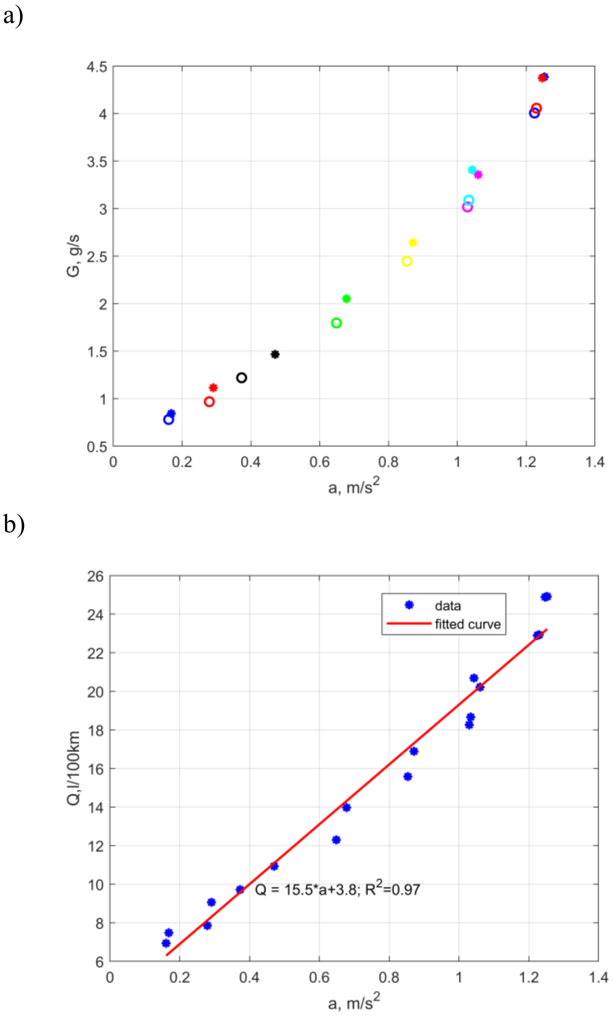


Fig. 7. Variations in mean parameters in the acceleration flexibility test conducted using a dynamometer for a vehicle with step-gear transmission for set throttle positions: a) fuel consumption, b) mileage fuel consumption

The obtained results confirm the overall dependence between vehicle acceleration reduction with reduced fuel and energy consumption, while the linearity of this function is maintained with respect to acceleration. It is ultimately difficult to absolutely assess the values due to the variations in vehicle dynamics resulting from changes in the available drivetrain energy, as presented in Table 4.

3.4. Cumulative specific energy consumption in vehicle acceleration

In order to obtain a factor that enables a more accurate analysis of the entire acceleration process, it is proposed to correlate the vehicle's total energy consumption with its weight and travel distance. Hence, according to the definition derived from formula (5), the cumulative energy consumption during the entire acceleration process, which is related to the vehicle's mass and distance traveled, can be expressed in m/s^2. On the other hand, in the physical sense, the unit is used to express the average accelerations during the acceleration phase. The relationship between the specific energy consumption and the average acceleration is directly proportional.

The resulting correlation between the vehicle's specific energy consumption and acceleration presented in Fig. 8b demonstrates an approximation error of 0.001%. The approximation function coefficient specifies the dynamics of energy consumption accompanying the vehicle's acceleration process and is determined as the energy required to accelerate a vehicle with the mass of 1 kg at a one meter distance [*J/(kg·m)*]. The specific and cumulative energy consumption increases long with increasing acceleration intensity, which follows the common principles of acceleration. The cumulative specific energy consumption accounts for fuel consumption and is related to the vehicle's design parameters. This, in turn, affects the results of ¼ mile road tests. The cumulative energy consumption is not directly proportional to the drivetrain's power output.

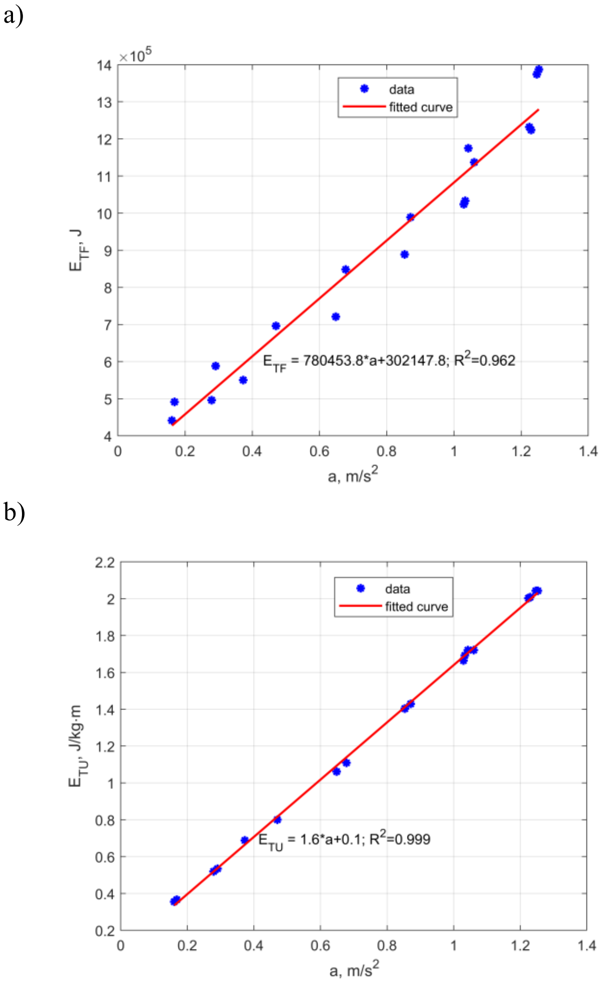


Fig. 8. Variations in mean parameters in the acceleration flexibility test conducted using a test bench and an acceleration function for a vehicle with manual transmission for set throttle positions: a) total movement-related energy consumption, b) cumulative specific energy consumption

4. Passenger car movement indicators - energy quality dynamic index

The presented plots of total energy consumption related to the acceleration process depend on energy consumption and vehicle dynamics. The plots are not necessarily related to the drivetrain's power output. Therefore, in reference to specific energy consumption based on the drivetrain's power output, it is possible to obtain the vehicle's movement dynamics parameter for use as a new qualitative indicator of the car movement energy consumption, as per equation 7. The vehicle dynamic index is an objective measure which combines energy indices resulting from energy consumption and dynamic indices resulting from vehicle dynamics.

$$I_D = \frac{P_e}{E_{TU}} \tag{7}$$

The proposed index describes the energy required to accelerate a vehicle with the mass of 1kg over a 1m distance in 1 second.

4.1. Validation of the dynamic index

To verify the sensibility of the proposed dynamic index relative to changes in drivetrain power, resulting from acceleration dynamics, additional tests were conducted with the use of a chassis dynamometer. The increases in the total vehicle energy consumption in a time domain for variable acceleration intensities are presented in Figure 9. The increased engine power affects the acceleration time, however these changes are insignificant for the introduced acceleration dynamics' index. In the case of $I_{D20\%}$ for small throttle position angles, the differences are small and amount to 2.71 kg·m/s, combined with the fuel demand of 6.94 dm^3/100km for full throttle position. The differences at peak $I_{D100\%}$ are equal to 7.94 kg·m/s and involve a sharp increase in fuel consumption of up to 22.93 dm^3/100km.

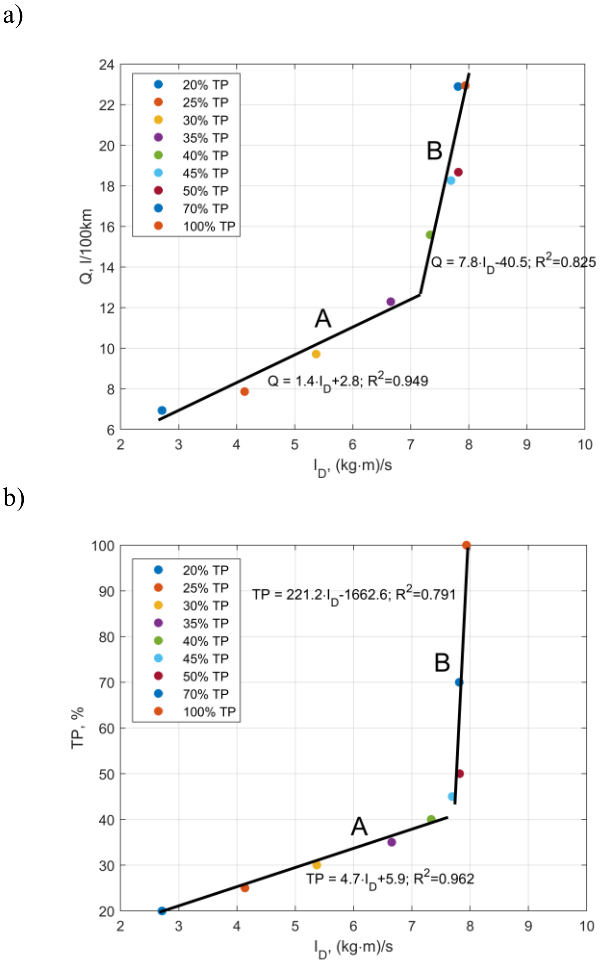


Fig. 9. Fuel consumption (a) and throttle positions (b) as the dynamic index function

The quality-based vehicle movement indicator corresponds to the vehicle's kinematic parameters. For the developed index (I_D), the assigned value corresponds to the achieved speed and the fuel consumption curve. At higher longitudinal speeds, the dynamic index (I_D) increases, which is consistent with the fundamental laws of physics, as such conditions necessitate a higher energy expenditure (Fig. 10a). The same holds true for fuel consumption (Fig. 10b).

Table 6. Mean parameters for the ¼ mile distance

TP	V_{max}, m/s	P_e, kW	I_D, (kg·m)/s	Q, dm^3/100km	$a_{sf,}$
20%	16.94	4.45	2.71	6.94	0.11
25%	19.47	7.79	4.14	7.86	0.17
30%	21.82	13.23	5.37	9.72	0.34
35%	25.78	19.33	6.66	12.3	0.51
40%	29.15	27.27	7.33	15.58	0.85
45%	31.4	32.95	7.69	18.26	1.06
50%	31.36	34.35	7.82	18.67	1.08
70%	33.68	41.33	7.81	22.89	1.30
100%	33.88	41.73	7.94	22.93	1.31

4.2. Discussion of results

Figure 9 shows the areas corresponding to economic and dynamic driving styles, which are related to the authors' former research presented in [14]. Hence, it is possible to relate the traffic dynamic index to complex vehicle speeds indicative of the driving style. The absolute parameters of the analyzed acceleration tests are summarized in Table 6. The effects of vehicle dynamics and energies on the recorded acceleration parameters are essential to understand the entire process. As a result of the approach that involved the development of a uniform index capable of defining the driving style, it is possible to infer environmentally significant conclusions, regardless of the investigated drivetrain configuration. Identification of the acceleration process' impact on the energy and dynamic indices allowed for an objective driving style and energy demand recognition. The transition from line A to B in Figure 9 is the throttle opening corresponds to 40-45%, which largely covers an ICE's operating conditions. In terms of the throttle position plots presented in Figure 1, the values presented are the maximum values for an economical driving style and the ultimate significant values for a dynamic driving style. However, an increase in acceleration dynamics entails a substantial increase in fuel consumption, consequently resulting in increased carbon dioxide emissions. This confirms the acceleration profile's impact, which depends on the driving style, on the dynamic and energy parameters during driving cycles.

The study contains a comparison of dynamic and energy parameters obtained during a passenger car's acceleration process in flexibility tests. The comparison involved an assumption that the acceleration process is defined as one of the decisive phases of movement in terms of the drivetrain's energy demand according to the TTW scheme - (Tank To Wheels). The energy quality parameters were assumed as the total distance-related specific energy consumption parameters. The relation between fuel demand and average acceleration was compared to other drivetrain parameters. Mean acceleration, dependent on the vehicle's speed in the acceleration process (Fig. 5), for small throttle position angles, led to a noticeable reduction in the vehicle's dynamics. This is in contrast to full-intensity acceleration, where the power generated by the engine and the available energy density in the drive system are of great importance. Therefore, when taking into account mean acceleration as a qualitative parameter, the analysis becomes subjective and one-dimensional. Making a comparison between mean acceleration and energy parameters (Fig. 8) allows to retain the correlation between these parameters, but it does not account for other important process parameters, such as road conditions or drivetrain energy consumption. For this reason, the acceleration process' movement energy quality index in the form of the total specific energy consumption demonstrated a high correlation in terms of the determination coefficient R^2, which amounted to 0.999 for both parameters. It involves very little variation and the relation is directly proportional. In the physical dimension, both parameters have the same values expressed in m/s^2. However, each of the parameters has different properties. Mean acceleration depends on vehicle speed achieved in a cycle, while the total specific energy consumption depends on the drivetrain's energy consumption and is not related to engine power. Hence, the authors point out that referring the drivetrain's power to the vehicle movement's quality index, i.e. total energy consumption, can offer a new two-dimensional perspective and allow for an objective assessment of the acceleration process. The presented validation of this index (Figure 9) shows two intensities, including one in which the dynamic index increase is smaller (line A) and the mean acceleration achieved lower values of up to 0.8 m/s^2. In light of the literature review, the values are deemed dominant in the acceleration process and define a moderate driving style. The presented acceleration values are also characterized by a moderate increase in fuel consumption. In the same plot, line B demonstrates a different dynamic index dependence, which becomes clearly visible, and is highlighted by a significant increase in fuel consumption. Such an interpretation of the dynamic index is consistent with the physical properties of the vehicle acceleration process.

5. Conclusions

The lack of a universal index that would enable an assessment of the acceleration ability prompted the authors to search for and then propose a parameter referred to as the dynamic index. An important criterion of this work is therefore the use of a complementary universal parameter to assess the acceleration ability. The universality of the proposed index enables a comparative assessment of the dynamic capabilities of vehicles differing in terms of weight and drivetrain power. The index combines energy demand and dynamic parameters (as acceleration intensity) that determine the acceleration process. In the physical sense, the index expresses the time required to accelerate a vehicle with specific mass at a specific distance. The analysis of the obtained results allows for a clear determination of the ranges of the dynamic index, corresponding to the reduced and increased energy demand values. The results can be used to determine acceleration values optimal in terms of energy expenditure. In the case of the tested vehicle, excess mean acceleration of approx. 0.8 m/s^2 or excess pedal position above 40% results in non-optimal operation in terms of energy expenditure. At the same time, the dynamic index should not exceed the value of 7 kg·m/s. The universality of the proposed index also makes it possible to objectively quantify the acceleration process of electric vehicles. However, it is necessary to perform further research to determine the sensitivity of various factors, such as vehicle speed, drivetrain torque characteristics and other factors, to changes in the dynamic index.

Definitions/Abbreviations

$\underline{a}$ – mean acceleration in the speed increase phase [m/s^2]
ΔE_{ICE} – ICE energy loss [kJ]
ΔE_L – transmission energy loss [kJ]
ΔE_{PT} – engine-to-wheels energy loss [kJ]
a – acceleration [m/s^2]
a_{sf} – inclination factor
CE – compression ignition engine
E_A – air resistance energy [kJ]
E_H – gradient resistance energy [kJ]
E_I – inertia energy [kJ]
E_M – movement energy demand [kJ]
E_P – pull energy [kJ]
E_R – rolling resistance energy [kJ]
E_{RPM} – engine rotational speed, [RPM]
E_T – total energy demand [MJ]
E_{TF} – total energy consumption [MJ]
E_{TU} – specific energy consumption [MJ/(kg·m)]
EV – electric vehicle
F_D – driving force in the phase when power is supplied to the wheels [N],
F_{PT} – driving force [N]
g – gravitational acceleration [m/s^2]
G_e - fuel consumption [g/s]
i – number of movement phases,

ICE – internal combustion engine,
I_D – dynamic index [kg·m/s]
L – traveled distance [m]
L^* – drive phase distance and total distance traveled ratio
m – mass [kg]
P_e – mean engine power during test [kW]
Q_F – total fuel consumption [dm^3]
Q – distance-related fuel consumption [dm^3/100km]
R^2 – correlation coefficient
t_e – end time [s]
TP – throttle position [%]
t_s – start time [s]
v – instantaneous vehicle speed [m/s]
V – vehicle speed in cycle [m/s]
V_e – end speed [m/s]
V_{max} – highest vehicle speed [m/s]
V_s – start speed [m/s]
$*_{mean}$ – mean parameter value
$*_{max}$ – maximum parameter value
$*_{min}$ – minimum parameter value

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