Article citation info:
Hennek K, Mamala J, Bieniek A, Kołodziej S. Analysis of the acceleration process of a passenger vehicle under variable load conditions. Combustion Engines. 2025;202(3):100-108. https://doi.org/10.19206/CE-205975

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Analysis of the acceleration process of a passenger vehicle under variable load conditions

ARTICLE INFO

Received: 16 April 2025
Revised: 3 June 2025
Accepted: 5 June 2025
Available online: 29 June 2025

The study contains an analysis of the acceleration process of a passenger vehicle equipped with an IC powertrain, aimed at determining a throttle control strategy that minimizes fuel consumption during acceleration while maintaining adequate dynamic performance. The first stage involved measuring traction parameters for a constant assumed engine power. The second stage focused on determining a control trajectory that would ensure minimal fuel consumption during acceleration.
To achieve this the acceleration process was examined during a flexibility test in the speed range from 12.5 to 35 m/s, following an acceleration pedal control line related to the crankshaft rotation speed. Implementing the acceleration process along this control line resulted in a reduction in acceleration dynamics, accompanied by a decrease in fuel consumption per distance traveled by nearly 51%. An analysis of the average acceleration values for a given drivetrain gear ratio revealed that exceeding an acceleration pedal position of 70% yields no significant improvement in vehicle dynamics. The optimal acceleration pedal positions during acceleration were found to be within the range of 25% to 70%.

Key words: *acceleration, variable load, chassis dynamometer, fuel consumption, acceleration elasticity*

1. Introduction

Instantaneous values of indicators determining the dynamics and energy intensity of vehicle motion depend on their design, external conditions, traffic intensity, and driver behavior. Regardless of the energy source used, vehicle powertrains consist of propulsion units cooperating with drivetrain systems. This configuration results in the energetic complexity of powertrain systems, which complicates comparative analysis, especially between internal combustion, electric, and hybrid solutions.

At the same time, vehicle movement is powered by energy supplied to the drivetrain from an energy storage system, which directly contributes to the emission of substances into the atmosphere, including carbon dioxide (CO_2), recognized as a greenhouse gas. This issue affects every vehicle with an internal combustion powertrain, while in the case of BEVs (Battery Electric Vehicles), it depends on the method of electric energy generation. For PHEV (Plug-In Hybrid Vehicle) solutions, the overall CO_2 emission is also influenced by the share of different energy types stored in the energy reservoirs – fuel tank and battery packs – as well as the method of energy replenishment (grid charging, regenerative braking) [17].

The need to reduce the negative environmental impact of the automotive sector has two dimensions. The first is local, directly linked to the emission of toxic components into the atmosphere, and is addressed through successive emission standards. In the European Union, these are defined by successive iterations of the Euro standards, from Euro 1 to Euro 7. Since Euro 4 (implemented in 2006), there have been no significant changes in the permissible limits for nitrogen oxides (NO_x), carbon monoxide (CO), and hydrocarbons (HC).

A significantly greater challenge is reducing the environmental impact caused by emissions of non-toxic exhaust components, such as carbon dioxide (CO_2), and the mass and number of particulate matter emitted from the exhaust system, which unequivocally affects global emissions.

In 2021, the successive iterations of emission standards abandoned synthetic test cycles like NEDC (New European Driving Cycle) in favor of real-world driving measurements, through the implementation of the RDE (Real Driving Emissions) procedure. Numerous scientific studies have since been published describing indicators such as fuel consumption and emissions of harmful substances during RDE tests [4, 11, 12].

The rate at which carbon dioxide emissions are being reduced in passenger vehicle exhaust differs across global regions, as illustrated in Fig. 1. The most effective method for reducing CO_2 emissions in exhaust gases is decreasing the consumption of fossil fuels within the TTW (Tank to Wheels) energy chain.

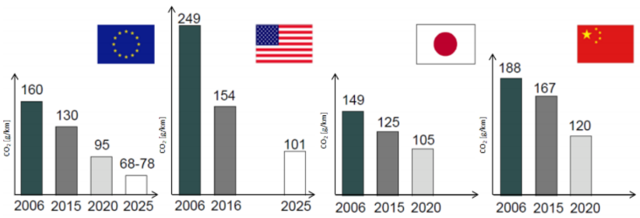

Fig. 1. Trend of carbon dioxide emission reduction in exhaust gases across different regions of the world in g/km [19]

According to report [7], in which global carbon dioxide emissions were presented and was published by scientists from over 90 institutions, the total projected CO_2 emissions for the year 2024 are expected to reach nearly 40 billion tons, indicating a continued upward trend, despite reductions achieved by the EU and the USA (Fig. 2).

The widespread drive to reduce carbon dioxide emissions is the primary motivation behind the continuous efforts of vehicle engineers to improve powertrain systems, including propulsion units. These improvements encompass aspects of design, control strategies, and driver support methods that promote environmentally conscious driving in accordance with the principles of so-called "Eco-Driving."

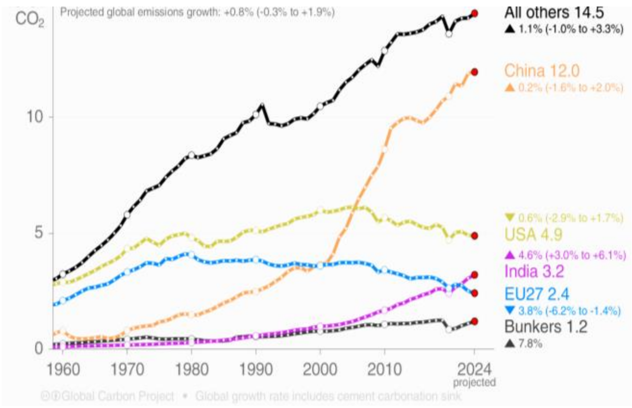

Fig. 2. Annual carbon dioxide (CO_2) emissions forecast for 2024 [7]

In many vehicle brands, driver support for ecological vehicle operation is limited to suggesting optimal instantaneous operating parameters of the powertrain. A common feature is the gear shift indicator displayed on the dashboard, which is mainly used in internal combustion vehicles with manual transmissions. An alternative approach is applied in some vehicles (e.g., Renault), where driving style is evaluated by awarding points on a scale from 0 to 100. This method particularly assesses the driver's behavior regarding the selection of driving speed, driving dynamics, and the use of the brake pedal. Frequent braking and aggressive use of the accelerator may result from high traffic density or a desire to achieve high driving dynamics, thus increasing the load on the powertrain.

Consequently, this leads to high variability in the speed profile, increasing the frequency and intensity of acceleration and braking phases. According to a study [13], eco-driving reduces fuel consumption by 12–37%, with only a minor drop in average driving speed of approximately 3% compared to dynamic driving. In study [14], it was shown that driving style significantly affects energy consumption in electric vehicles, while study [15] demonstrated a considerable impact of driving style, road conditions, and infrastructure on the efficiency of electric vehicles.

Literature source [2] defines moderate vehicle acceleration as acceleration up to approximately 0.85 m/s^2. Achieving higher acceleration rates involves a significant increase in power demand from the powertrain.

The fuel-optimal constant driving speed depends on the specific drivetrain type and vehicle characteristics. According to [6], the optimal speed for minimizing fuel consumption in engines compliant with Euro 5 is 70–75 km/h. On the other hand, publication [16] indicates that minimum fuel consumption occurs while following another vehicle at a speed of approximately 40 mph (65 km/h). Research shows that, for vehicles operating in electric mode or for electric vehicles, the optimal constant speed varies depending on the model and lies within the range of 37 to 60 km/h [18]. Another source [10] confirms an optimal speed of 60 km/h for several different electric vehicles.

Referring to the author's own research on an urban internal combustion vehicle (Fig. 3), the lowest fuel consumption per distance traveled was observed at speeds between 35 and 60 km/h.

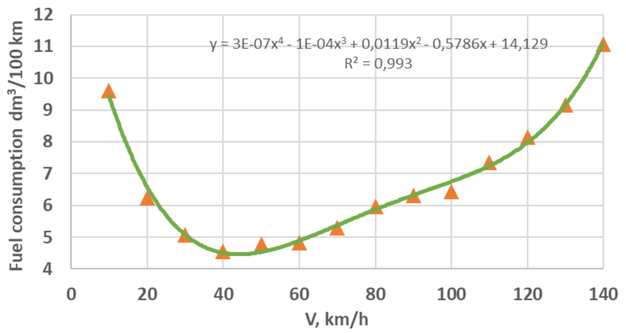

Fig. 3. Distance-specific fuel consumption at constant driving speed for an internal combustion powertrain

Minimizing fuel consumption directly reduces carbon dioxide emissions. By converting the distance-specific fuel consumption of 0.01 dm^3/km (equivalent to 1 $dm^3/100$ km), the corresponding CO_2 emission values are:

- Gasoline: 23.3 g/km
- Diesel: 26.3 g/km.

The impact of vehicle dynamics (acceleration intensity) on fuel consumption has been the subject of numerous scientific studies. In study [3], the authors analyzed the distribution of driving phases within urban and non-urban cycles, noting that over 20% of accelerations fall within the range of 0–1 m/s^2, and over 15% within 1–4 m/s^2. Despite the relatively small share of acceleration phases (approx. 5%) in the total driving cycle, the acceleration intensity significantly influences fuel consumption.

Fontaras et al. [5] demonstrated a 5% increase in fuel consumption in non-urban traffic and up to 70% in urban traffic. Simultaneously, study [9] analyzed the possibility of optimizing engine load and gear ratios, indicating that extending the acceleration time to 2 s in the 0–40 km/h range may reduce fuel consumption by more than 5%.

In study [2], the acceleration values for different vehicle groups were identified in the range of 0.45–2.87 m/s^2, highlighting their effect on fuel usage depending on driving style and road type. Research presented in [1] showed that higher driving dynamics increase fuel consumption by 40% outside urban areas and by 45% in city traffic.

Ultimately, the dynamics of the acceleration process and the energy demand of vehicle motion depend mainly on how the driver controls the powertrain. Regardless of how advanced the powertrain is – including hybrid or electric configurations – the driver can always operate the vehicle in a non-ecological manner. Therefore, the acceleration phase is the primary factor influencing the energy consumption of vehicle motion. This behavior does not always stem from the driver's intention – it can be forced by traffic conditions, e.g., performing maneuvers in public road traffic that require high dynamics to avoid hazards. Hence, the present analysis of the acceleration process is an attempt to establish a compromise between driving dynamics and energy intensity, aiming to enable dynamic acceleration using an economical operation line within the drivetrain system.

2. Identification studies

2.1. Vehicle acceleration under constant power

The first stage of the study involved performing an acceleration test of a passenger car on a chassis dynamometer with a predefined constant power input in the powertrain. The tested vehicle was equipped with a spark-ignition engine featuring port fuel injection and a manual transmission. The technical specifications of the tested vehicle are presented in Table 1.

Table 1. Basic parameters of the tested vehicle

Manufacturer	Volkswagen
Engine designation	AWT
Displacement	1781 cm^3
Maximum power	110 kW
Crankshaft rotational speed at maximum power	5700 rpm
Maximum torque	210 Nm
Crankshaft rotational speed at maximum torque	1750 rpm
Charging method	turbocharger
Compression ratio	9.5:1
Measurement gear number	4
Measurement gear ratio	1.029

In the acceleration test, a flexibility trial of the vehicle acceleration process was conducted for a selected, constant gear ratio in the drivetrain system. The flexibility test was carried out within the speed range from 45 km/h (12.5 m/s) to 120 km/h (35 m/s) using a MAHA MSR500 chassis dynamometer. The acceleration trials were performed under constant excitation conditions, resulting from a fixed power level in the drivetrain, which in turn was determined by a predefined throttle pedal position. The individual throttle pedal positions and the corresponding vehicle speed profiles during the tests are presented in Fig. 4.

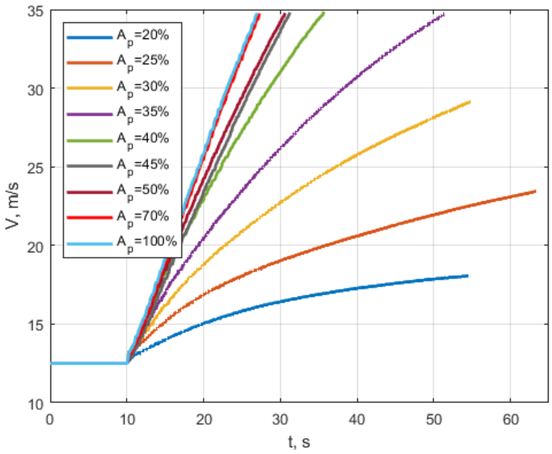

Fig. 4. Time profiles of vehicle speed measured during acceleration tests

Each acceleration test was initiated by reaching and stabilizing the minimum vehicle speed of 12.5 m/s for at least 10 seconds. Subsequently, the accelerator pedal was rapidly depressed to the target position, which was maintained until the vehicle reached the maximum speed or exceeded 35 m/s. In the initial trials, due to low throttle positions, the vehicle did not reach the target maximum speed, as the resistive forces exceeded the available wheel power. This situation occurred at throttle pedal positions (A_p) of 20%, 25%, and 30%, where the intended final speed was not achieved.

In Fig. 5, the vehicle speed profiles obtained from all acceleration trials are presented and indicated as ‘Dane’. These profiles were then subjected to linear interpolation, denoted as V(t). The tolerance field of the interpolated results is also marked in Fig. 5 and reflects the repeatability of measurements at a given power level. A linear equation was selected as the interpolation function. The quality of this approximation was described using the coefficient of determination (R^2), and the standard deviation (σ) was calculated.

The instantaneous vehicle speed as a function of time reveals differences in acceleration dynamics, which increase with engine power. A higher power level also improves measurement repeatability, due to the progressively more stable operation of the powertrain. For maximum power, the correlation coefficients approach 1, and the standard deviation is three times lower than for the lowest throttle positions, amounting to 0.11.

In Table 2, the parameters of the correlation functions for the analyzed vehicle acceleration trials are presented. The argument value of the regression function corresponds directly to the slope coefficient of the linear function and provides information on the average acceleration achieved in a given test. The average acceleration values range from 0.112 m/s^2 to 1.328 m/s^2.

Table 2. Correlation functions and their parameters comparison

A_p, %	V(t)	R^2	σ
20	V(t) = 0.112·t + 13.765	0.9347	0.38
25	V(t) = 0.178·t + 14.871	0.9559	0.58
30	V(t) = 0.347·t + 15.025	0.9722	0.75
35	V(t) = 0.521·t + 14.926	0.9824	0.82
40	V(t) = 0.866·t + 13.900	0.9938	0.49
45	V(t) = 1.080·t + 12.484	0.9992	0.18
50	V(t) = 1.097·t + 12.997	0.9981	0.27
70	V(t) = 1.319·t + 12.409	0.9995	0.13
100	V(t) = 1.328·t + 12.651	0.9997	0.11

In Fig. 6, the average acceleration values during the acceleration process are presented. The average acceleration increases significantly for the initial power levels in the range of A_p from 20% to 45%. Subsequently, the values stabilize and remain similar for 45% and 50% throttle positions, then increase further to reach maximum values at 70% and 100% throttle pedal deflection.

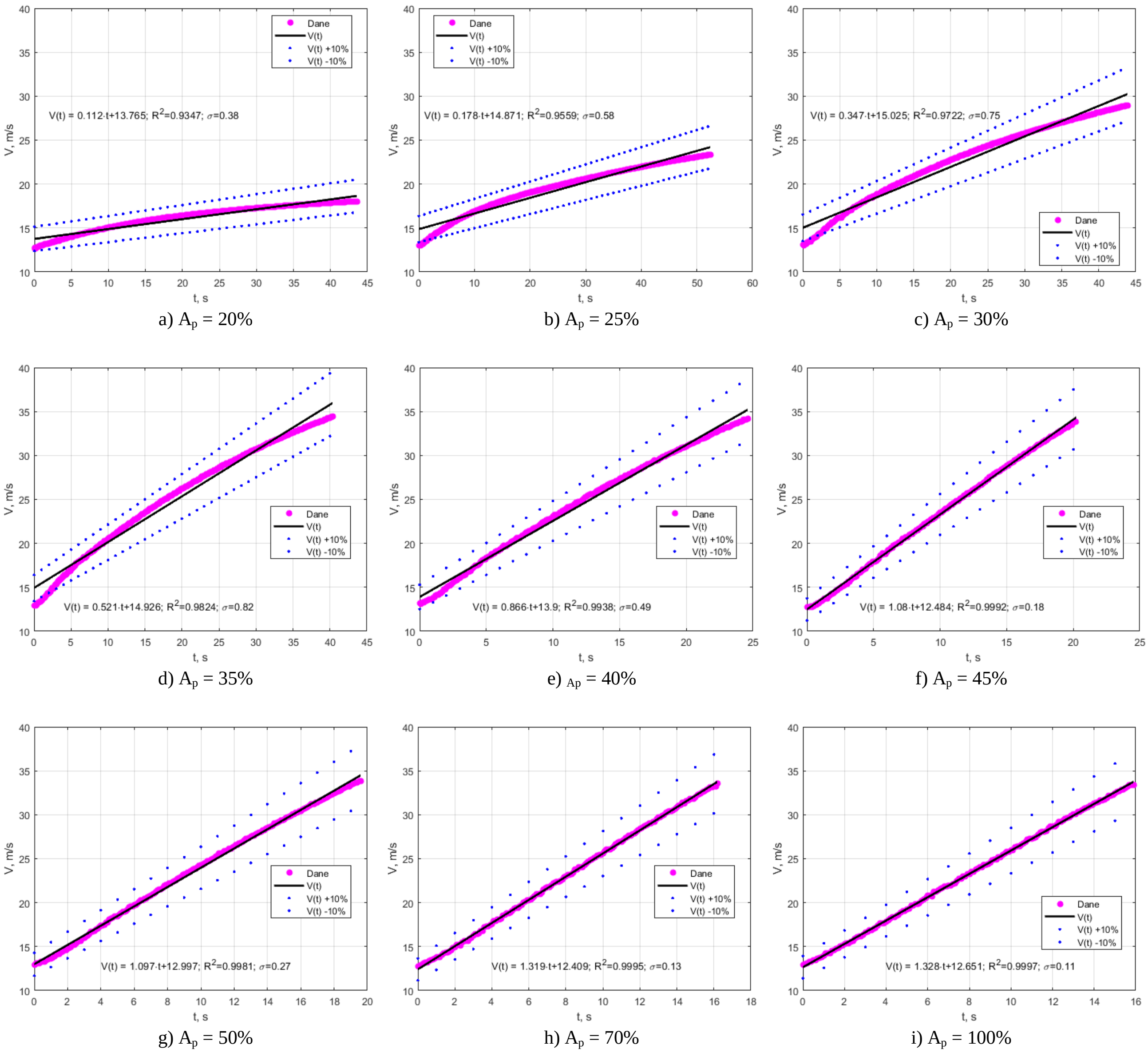

Fig. 5. Velocity profile as a result of constant acceleration pedal position A_p

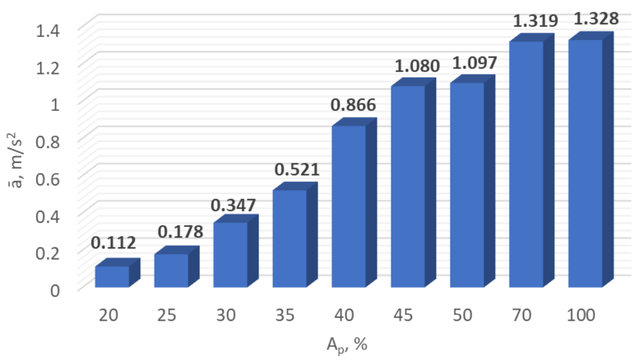

Fig. 6. Mean acceleration interpolation results

The primary factors determining the acceleration dynamics of a vehicle under constant power conditions are the vehicle's motion resistances. To determine their instantaneous and cumulative impact on the acceleration profile on a chassis dynamometer at constant drivetrain power, the percentage contributions of the main resistance components were calculated as a function of linear speed (Fig. 7). The profiles of the contributions from aerodynamic drag, rolling resistance, and inertial resistance, determined for each test, are presented in the left column of Fig. 7.

The profiles of the main components of motion resistance confirm the increasing contribution of inertial resistance to the total resistance force as the acceleration intensity rises. For averaged values, the share of power required to overcome vehicle inertia increases from 39.5% to 83.4%. Under conditions of maximum acceleration dynamics, 83.4% of the drivetrain power is irreversibly dissipated for accelerating the vehicle, thereby reducing the relative impact of rolling resistance and aerodynamic drag.

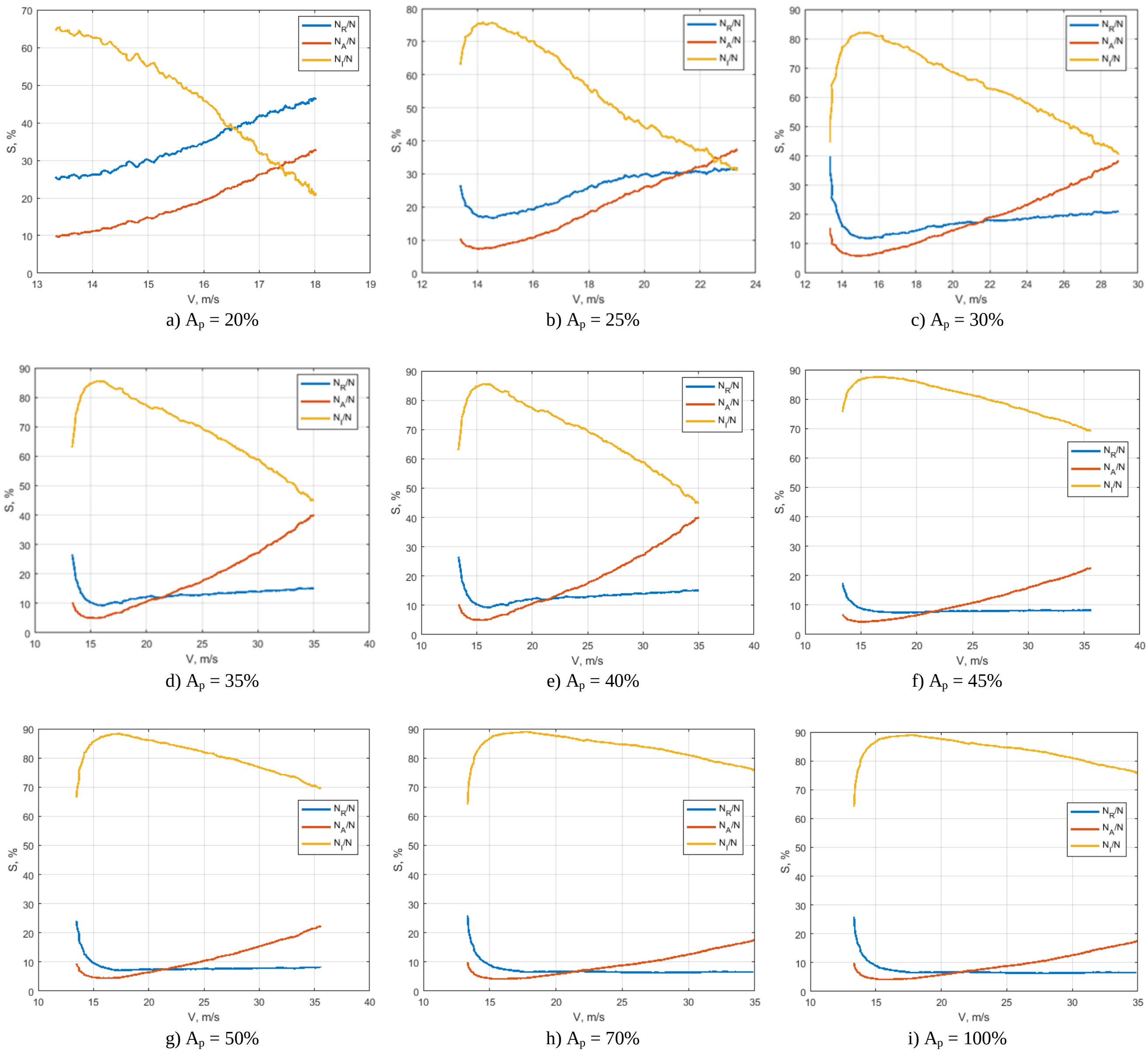

Fig. 7. Percentage contribution (S) of motion resistance components as a function of the linear speed of the test vehicle during the acceleration trial (N_R – rolling resistance, N_A – aerodynamic drag, N_I – inertial resistance, N – wheel power)

When comparing these profiles across individual tests, it can be observed that in the initial speed range (up to approximately 20 m/s), the power share of rolling resistance is greater than that of aerodynamic drag. However, in the speed range between 20 and 25 m/s, the respective curves intersect, and from this point on, the aerodynamic drag power share exceeds that of rolling resistance.

$$N_I = m\delta\bar{a}\int_{t_s}^{t_e}\frac{ds}{dt} \qquad (1)$$

where: N_I – inertial resistance, m – vehicle mass, δ – rotating mass factor, ā – mean acceleration, t_s and t_e – start and end time, t – time, s – distance.

However, in each trial, the highest values are recorded for the average inertial power, which directly depends on the average acceleration and velocity over time, in accordance with Equation (1).

2.2. Fuel consumption during the acceleration process of a vehicle under constant power

Distance-specific fuel consumption (G_e) serves as an indirect indicator of the energy demand required to provide the power during the analyzed acceleration trial at constant drivetrain power (Fig. 8). At the same time, the power output of the drivetrain directly depends on the instantaneous speed and acceleration, under given motion resistance conditions.

In Fig. 9, the aggregate characteristics of specific fuel consumption (g_e) are presented. This parameter is a derivative of distance-specific fuel consumption (G_e) and drivetrain power (N), as defined by Equation (2).

$$g_e = \frac{G_e}{N} \qquad (2)$$

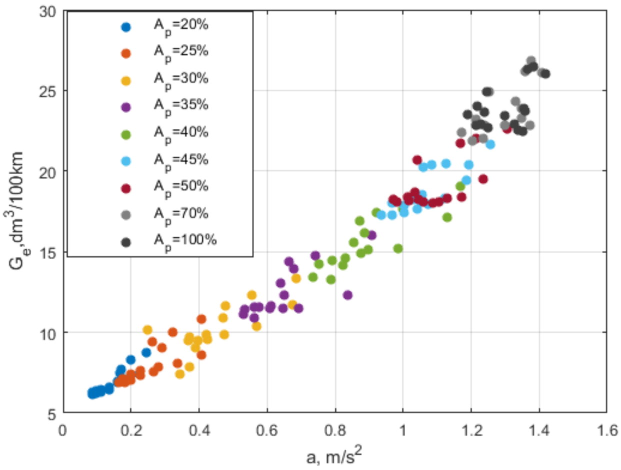

Fig. 8. Total distance-specific energy consumption as a function of mean acceleration in acceleration flexibility tests at constant throttle positions [8]

Taking into account the accuracy of the components that allow the calculation of fuel consumption, that is, the measurements of fuel pressure, the flow performance of injectors from the manufacturer's catalog, and time, the measurement error was calculated by the method of the complete differential, which is 3.3%.

To establish guidelines for the power control process during vehicle acceleration, attention was focused on the profile of the minimum specific fuel consumption line for each power input condition (Fig. 9).

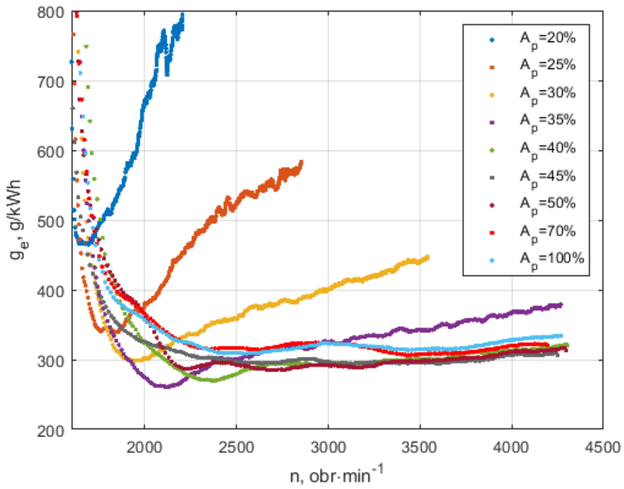

Fig. 9. Specific fuel consumption characteristics of the research passenger vehicle

For each curve, it is possible to determine the points of minimum specific fuel consumption across the full range of crankshaft rotational speed. The points obtained in this manner can be associated with the throttle pedal deflection and the speed range at which maximum drivetrain efficiency is achieved, in accordance with Equation (3).

$$\eta_{UN} = \frac{1}{g_e \cdot W_d} \quad (3)$$

where: η_{UN} – powertrain efficiency, W_d – lower heating value.

The determined points are presented in Table 3.

Since the values for A_p = 70% and 100% overlap above the crankshaft rotational speed of 3500 rpm, and considering the data from Table 3, it was decided to limit the throttle pedal deflection to 70%.

Table 3. Determined power control ranges for the efficient optimal line in the drivetrain system as a function of throttle pedal position and crankshaft rotational speed

Parameter	Value						
n, rpm	from 900 to 1650	from 1651 to 1800	from 1801 to 1900	from 1901 to 2250	from 2251 to 2600	from 2601 to 3320	from 3321 to 6500
A_p, %	20	25	30	35	40	50	45

In this way, it becomes possible to determine the theoretical power control line, referred to as the Efficient Optimal Line (EOL), within the drivetrain system under variable load conditions during the acceleration process.

2.3. Vehicle acceleration under variable power conditions in the flexibility test

For the defined range of variable speeds and throttle pedal positions, flexibility tests were carried out for vehicle acceleration under the same measurement conditions (Fig. 10).

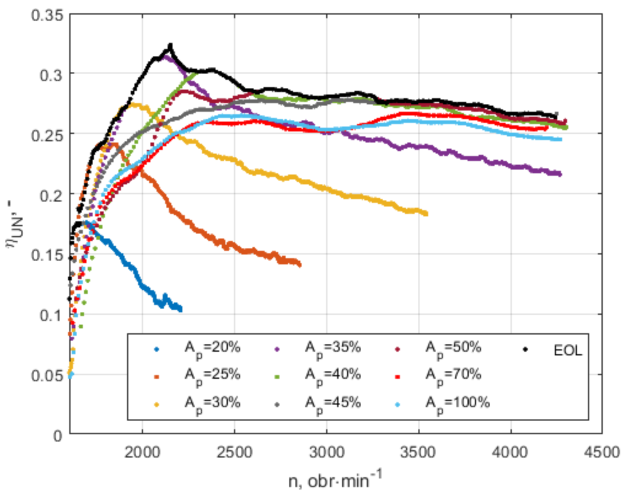

Fig. 10. Powertrain efficiencies for the defined control points

The drivetrain efficiency is a measure of the effectiveness in utilizing the energy contained in a given volume of fuel. The highest efficiency was achieved at A_p = 35% throttle pedal deflection and a crankshaft rotational speed of 2110 rpm. As anticipated, starting the acceleration process with variable and increasing throttle excitation is highly advantageous, closely following the acceleration intensity of A_p = 100%. However, as the crankshaft rotational speed increases, a decline in the overall drivetrain efficiency is observed.

Therefore, it was proposed to develop a physical acceleration trajectory based on the EOL, taking into account the objective of achieving high drivetrain efficiency. The trajectory was constructed by selecting individual points corresponding to the maximum drivetrain efficiency values, which define its course (Fig. 10).

The electrical characteristics of the factory throttle pedal position was determined and saved in a National Instruments (NI) software. The course of the characteristics depended on the engine's crankshaft speed. Using a NI control card and the programmed acceleration pedal position control trajectory made it possible to obtain external and repeatable control of the acceleration pedal.

Direct application of EOL in the process of controlling the throttle position of the test car yielded unsatisfactory results regarding the car's acceleration dynamics. The defined segments represent the highest instantaneous overall drivetrain efficiency, which in the initial phase is identical for $A_p = 20\%$ and $A_p = 25\%$ lines. This resulted in excessively slow initial vehicle acceleration, and therefore, it was decided to initiate the tests from a throttle deflection of 25%. This is related to the method of determining the EOL, which does not take into account the excess power in the drivetrain necessary for the acceleration process, and is only based on the efficiency of the drivetrain. In order to obtain sufficient surplus power, the accelerator pedal override range was increased while maintaining the engine crankshaft speed ranges specified in the EOL. The result was a control line, laboriously named T8. Its characteristics are given in Table 4.

In Fig. 11, a comparison of the results of speed curves during the acceleration flexibility test is presented. It should be noted that the newly defined acceleration trajectory T8 resulted in the vehicle reaching a speed of 120 km/h in a time 0.1 s shorter than that of the EOL, but 7.7 s longer compared to the 100% pedal deflection test. The parameters of the acceleration process are presented in Fig. 12.

Table 4. Determined power control ranges for the T8 strategy as a function of throttle pedal position and crankshaft rotational speed

Parameter	Value						
n, rpm	from 900 to 1650	from 1651 to 1800	from 1801 to 1900	from 1901 to 2250	from 2251 to 2600	from 2601 to 3320	from 3321 to 6500
A_p, %	25	30	35	40	45	50	70

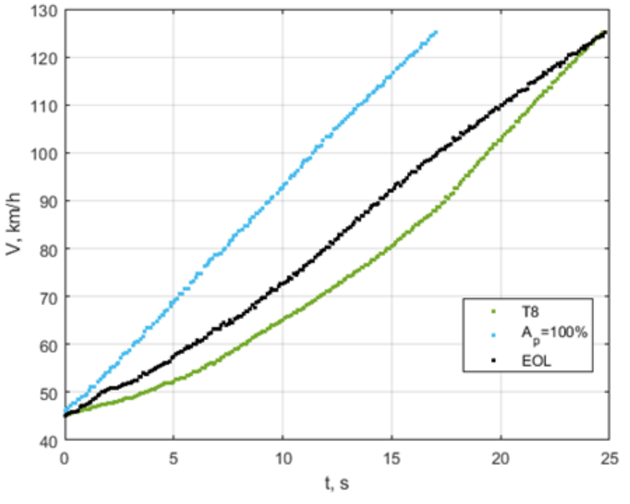

Fig. 11. Powertrain efficiencies for the defined control points according to: • – the theoretical efficient optimal line (EOL), • – full load at 100% throttle pedal deflection, • – the physical implementation of the T8 control strategy

A reduction in vehicle acceleration dynamics resulted in a decrease in mean distance-specific fuel consumption from 21.68 dm^3/100 km to 10.71 dm^3/100 km, representing an almost 51% reduction in fuel usage (Fig. 13). Simultaneously, the acceleration distance increased by approximately 151 m, which corresponds to a 32.9% increase. Such an increase in distance is unacceptable in critical situations that determine the safety of vehicle occupants. On the other hand, under non-critical acceleration conditions, there is a possibility of significantly reducing fuel consumption at the expense of reduced acceleration performance.

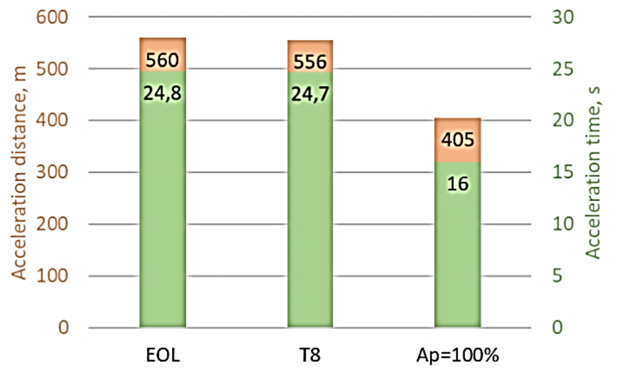

Fig. 12. Comparison of vehicle acceleration dynamics and distance travelled during acceleration from 45 to 120 km/h at 100% power utilization and according to the EOL and T8 control trajectories

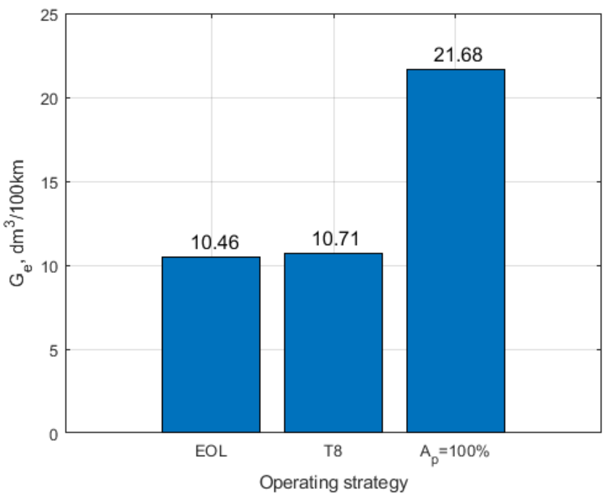

Fig. 13. Comparison of mean distance-related fuel consumption at 100% power utilization and according to the EOL and T8 control trajectories

3. Conclusion

For several years, there has been ongoing discussion regarding the decline of internal combustion engines (ICEs) used in passenger vehicles. However, until at least 2050, they are expected to remain the predominant propulsion systems. Internal combustion powertrains will continue to serve as the primary mode of transport, fulfilling the principles of sustainable mobility – meeting user demands while achieving economic and environmental stability, as well as ensuring driving range, which is a standard expectation for today's vehicles. Within this framework of sustainable development, the internal combustion engine still plays a vital role, and further advancements are expected in the coming years, as reflected in current development trends.

As a result, the power demand and fuel consumption of passenger vehicles are evolving, both of which are significantly influenced by the energy intensity of the acceleration process.

Broadly speaking, regardless of the type of power unit – whether internal combustion or electric – the challenge of efficient energy utilization under variable load conditions remains a relevant research issue, since the driver remains the final link in the power control process. Through the driver's subjective decisions, the instantaneous operating point of the drivetrain is determined, often unfavorably from both economic and ecological perspectives.

The powertrain control method proposed in this study for the acceleration process represents a compromise between fuel economy and vehicle dynamics, leading to a 51% reduction in fuel consumption. Using the T8 control line resulted in a drop in mileage-related CO_2 emission from 505 g/km to 250 g/km. Like any compromise, this one also requires certain concessions, among which dynamic performance should unquestionably yield to economic and environmental considerations. In this context, reduced fuel consumption (for ICEs) and lower energy usage (for electric drivetrains) result in lower CO_2 emissions, whether considered as direct (on-site) emissions or indirect (off-site) emissions, depending on the energy composition, which in many cases still includes fossil fuel-based electricity generation. As part of the research on the dependence of the accelerator pedal position on the crankshaft rotational speed, meeting the EOL assumptions, it was shown that in the acceleration process from a speed of 12.5 m/s to 35 m/s it is appropriate to use the acceleration pedal position range from 25% to 70%. Although the research was performed on one object, this range may prove adequate for other vehicles.

It is important to emphasize that such a reduction in vehicle dynamics contributes not only to environmental sustainability, but also to favorable operating conditions, reducing wear on drivetrain components, while still enabling dynamic acceleration within the scope of an economic power control line.

On the other hand, it must be recognized that in critical situations impacting occupant safety, the driver should always have full access to the drivetrain's maximum power output.

Nomenclature

BEV	battery electric vehicle
EOL	efficient optimal line
NEDC	New European Driving Cycle
IC	internal combustion
ICE	internal combustion engine
PHEV	plug-in hybrid electric vehicle
RDE	real driving emissions
TTW	tank to wheels

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