OPTIMIZATION OF FUEL CONSUMPTION AND PERFORMANCE OF INTERNAL COMBUSTION ENGINE

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Optimization methods play a key role in the design and control of modern powertrains in the current automotive industry. Emphasis is placed primarily on the implementation of optimization algorithms and predictive models that are used by engine control units. These are intended to ensure effective control of torque, fuel consumption and vehicle dynamics in real time depending on driving conditions and driver requirements. The aim of the paper was therefore to describe the results of research conducted in the field of multi-parametric optimization of fuel consumption and performance of a four-cylinder atmospheric internal combustion engine with a cylinder capacity of 1,390 cm^3. Optimization of the operating parameters of the powertrain, such as fuel consumption and performance, was carried out with a view to the possibility of implementation into control algorithms and predictive models applicable to engine control units. The benefit of the proposed optimal operating mode of the powertrain, aimed at minimizing fuel consumption and maximizing its output power, is the achievement of high operating efficiency while maintaining favorable dynamic characteristics of the engine.

KEYWORDS

efficiency, engine performance, fuel consumption, optimization, torque

1 INTRODUCTION

Optimization methods penetrate all areas of industry, including the modern automotive industry. Although optimization methods were used only to a limited extent in the early days of the automotive industry, today vehicle development is no longer possible without them [Li 2024]. At first, they were used mainly to meet primary goals, but today they also solve very difficult and problematic tasks [Ortner 2018].

In addition, trends in the application of optimization methods in recent times are mainly oriented towards optimization with the aim of achieving such control of input factors that the desired optimized outputs are achieved [Zhang 2024]. In the automotive industry, optimization is also used in the design of engine operating modes with a view to achieving high efficiency of vehicle operation. It finds its application in the design of control algorithms and models that define the conditions of direct communication between sensors and actuators in the vehicle [Gomez-Miranda 2025, Kondrat 2025]. The task of sensors is to capture the driver's requirements and convert them into a signal understandable to the engine control unit. The engine control unit receives this signal and based on the implemented algorithms and models, sends a signal to the actuators. These then adjust the engine operating parameters to the desired value, ensuring that the driver's requirements for accelerating, decelerating or maintaining the vehicle at a constant speed are met. At the same time, these systems must enable dynamic changes to the main engine operating parameters within milliseconds. This ensures good vehicle controllability and at the same time stability and efficiency of its operation [Huang 2023]. Such targeted control of the operating parameters of the car's power unit can very effectively prevent unnecessary waste of input energy, which will contribute to an overall increase in system performance and efficiency [Srinivasan 2025].

In the past, cars used separate control units with limited communication capabilities [Straka 2014]. Therefore, optimization methods in car development were applied only exclusively to the design of simple control of the operating parameters of the vehicle's power unit in order to achieve the required performance parameters [Katrasnik 2003]. At the same time, optimization algorithms supported only basic functions such as engine operating parameters without mutual interaction with other vehicle subsystems [Perdoch 2025]. Their main function was therefore to control engine speed and torque [D'Errico 2011]. However, this is not enough today. With the increasing demands for maximizing engine performance with regard to its energy-efficient operation and at the same time with regard to the growing complexity of vehicle architecture, the need for multiparametric optimization of these parameters has gradually increased [Krenicky 2018, Menzel 2020, Yang 2024]. The implementation of optimization theory in practice has opened up new possibilities for vehicle manufacturers to integrate multiple vehicle subsystems into one coordinated control unit [Sawulski 2019, Krenicky 2022]. The latter is currently responsible for decision-making at a higher level and at the same time its task is to ensure the harmonious operation of all vehicle subsystems. It can precisely control the inputs to achieve the desired optimized outputs of the vehicle's operating parameters [Li 2022].

The energy management strategy is also based on the possibility of optimizing the performance and consumption depending on the input operating parameters such as driving style, road characteristics, traffic situation, etc. [Malega 2017]. Then, the optimization of the vehicle's performance and energy consumption is performed by the control unit, which continuously calculates the required torque based on several parameters, including driver inputs, traction conditions and vehicle limitations [Srinivasan 2021]. Its operation is based on implemented control algorithms and predictive models, which serve it to optimize the delivery of the required power with regard to operating efficiency [Geng 2025, Weiss 2020]. The result of the optimization process also depends on which algorithms and control models are implemented in the engine control unit [Qiao 2019, Vagaska 2022]. Based on them, the control unit optimizes the engine's operating performance and thus ensures that all components cooperate to maximize its efficiency. These facts led us to conduct research in the field of optimizing fuel consumption and performance of the car's power unit. It was a four-cylinder gasoline atmospheric combustion engine with a cylinder capacity of 1,390 cm^3. The aim of the research was to design the optimal operating mode of the combustion engine in order to achieve the highest possible efficiency of its operation.

2 CHARACTERISTICS OF THE OUTPUT POWER PARAMETERS OF A GASOLINE ATMOSPHERIC COMBUSTION ENGINE

The output power parameters of a naturally aspirated gasoline combustion engine are usually characterized by torque, which is usually given in Nm, and power, which is given in kW or PS. In the case of power, it is the amount of energy that the combustion engine produces over a certain period of time. However, the power of the combustion engine itself is directly related to its speed and torque [Wang 2022]. Torque affects the acceleration capabilities of the vehicle. It is known that an engine with high torque usually offers better traction and acceleration [Zhukova 2019]. At the same time, it varies significantly over a wide range of engine speeds. This curve is characterized by the so-called torque curve.

Most engines reach their maximum torque approximately in the middle of the operating speed range. For a naturally aspirated engine, this is often between 2,000 rpm and 4,000 rpm. In the remaining engine speed range, the torque value is usually lower and therefore also affects the actual engine power itself. Although it is generally true that maximum engine power is usually achieved at a higher rpm than maximum torque is achieved, this is not always the case. This is due to the mathematical relationship between instantaneous torque and the corresponding engine speed [Zhukova 2019]. As rpm increases beyond the point of maximum torque, the engine's torque output begins to decrease, but the multiplier effect of higher rpm can continue to increase power until torque drops too dramatically to sustain further power increases [Pollak 2022].

As can be seen in Fig. 1, the torque T_K on the crankshaft is created by the force F_P acting on the connecting rod pin through the connecting rod at a distance a_K from the crankshaft rotation axis.

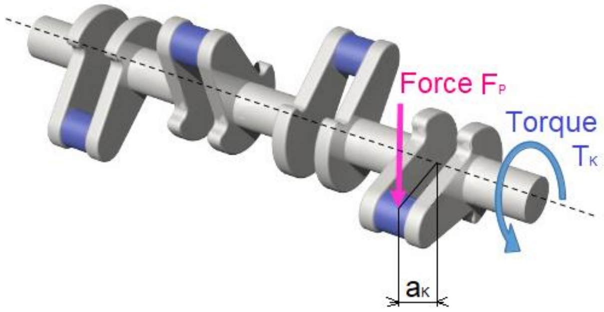

Figure 1. Torque T_K emitted on the crankshaft by the force F_P on the arm a_K

The torque T_K acts on the crankshaft at each connecting rod pin whenever the piston is in the working stroke. The magnitude of the force F_P acting on the connecting rod pin depends on the pressure in the engine combustion cylinder [Rimar 2023]. The higher the pressure [Ruzbarsky 2023] in the engine combustion cylinder, the higher the force F_P will act on the connecting rod pin [Panda 2012] and at the same time emit a higher output torque T_K on the crankshaft.

At the same time, the length of the arm a_K also has a decisive influence on the magnitude of the torque T_K acting on the crankshaft and the overall balance of the engine. Although an arm that is too long has a positive impact on increasing the crankshaft torque T_K, on the other hand it can lead to unbalanced engine operation and at the same time to increased forces in the connecting rod journals and crankshaft bearings [Panda 2019]. Based on the above, it follows that the engine torque depends on the piston area.

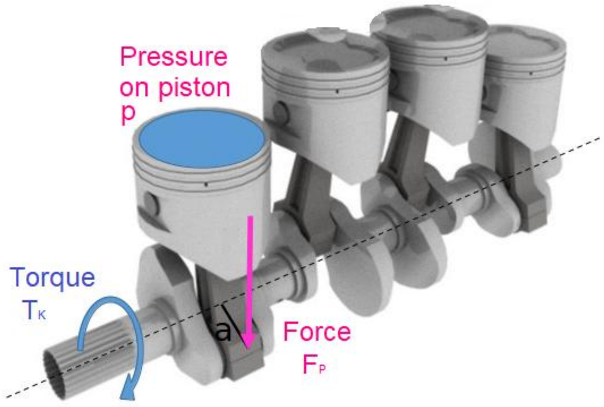

Figure 2. The pressure p performed on the piston of an internal combustion engine due to the explosion of fuel and expansion of gases

Assuming that the piston head is flat, and its diameter is equal to the cylinder bore, then the piston area A_p is defined by equation (1):

$$A_p = \frac{\pi \cdot B^2}{4}, \tag{1}$$

where B is the diameter of the cylinder of the internal combustion engine.

The force F_p acting on the piston is defined by the relation (2):

$$F_p = p \cdot A_p, \tag{2}$$

where p is the pressure acting in the cylinder of the internal combustion engine (Fig. 2).

In the event that all the force acting on the piston is transmitted to the connecting rod, where it emits the crankshaft torque T_K, then its magnitude is defined by relation (3):

$$T_K = F \cdot a_K, \tag{3}$$

where a_K is the distance of the connecting rod pin axis from the axis of rotation of the crankshaft of the internal combustion engine.

Then the power of the internal combustion engine P_M is defined as the work that is performed in a certain time, defined by the product of the torque T_K and the angular velocity ω according to the relation (4):

$$P_M = T_K \cdot \omega, \tag{4}$$

where the equation (5) applies to convert the angular velocity ω from rpm to rad/s:

$$\omega = n_K \cdot \frac{\pi}{30}, \tag{5}$$

where n_K is the crankshaft speed of the internal combustion engine.

Modern cars usually have an engine torque curve written in the electronic control module (ECM). Based on the current engine speed and load requirements, the latter interpolates the required torque value T_K. In this case, information about the load of a spark-ignition internal combustion engine is obtained based on the pressure in the intake manifold. In the case of a diesel internal combustion engine, this is based on the injection time or the mass of the fuel. At the same time, the torque value of the internal combustion engine also depends on the temperature and pressure of the intake air. This means that the torque of the internal combustion engine and its overall performance depend on the combination of speed, engine load and operating conditions.

3 DEPENDENCE OF FUEL CONSUMPTION ON THE POWER OF A SPARK-IGNITION INTERNAL COMBUSTION ENGINE

Fuel consumption in a vehicle's internal combustion engine depends on many factors. First of all, it depends on the engine design itself, then on the friction ratios of its individual parts, the temperature of the engine and the intake air, the properties of the fuel and many other factors. Factors such as driving style, road conditions, etc. are also key. In addition, frequent acceleration and braking also increase fuel consumption in the engine. Consumption is also affected by the weight of the vehicle and its load. In general, the heavier the vehicle or its load, the more fuel the engine consumes. The aerodynamic resistance of the vehicle, which is especially noticeable at higher speeds, also contributes to fuel consumption in the engine.

In addition to the above factors, the fuel consumption in the engine is also closely related to its working volume of cylinders. It is also known that the volume of fuel charge for one cylinder of an internal combustion engine, which is replaced during each individual working cycle, will be approximately equal to the cylinder displacement V_{sm}. If the cylinder is almost filled with air of volume V_{vzd} and partially vaporized fuel V_p, then the volume of the fuel mixture is given by their product according to equation (6):

$$V_{sm} = V_{vzd} + V_p \tag{6}$$

Analogously, this also applies to the mass filling of the cylinder m_{SM}, which is replaced during each engine working cycle, when the mixture is formed by the mass of air m_{vzd} and the mass of fuel m_p according to equation (7):

$$m_{sm} = m_{vzd} + m_p \tag{7}$$

If the excess air coefficient is also applied, then the following relation (8) applies for the stoichiometric ratio λ:

$$\lambda = \frac{m_{vzd}}{L_{vt} \cdot m_p}, \tag{8}$$

Based on the stoichiometric ratio λ, it is then possible to express the mass of fuel m_p as a function of the amount of supplied air m_{vzd} according to equation (9):

$$m_p = \frac{m_{vzd}}{L_{vt} \cdot \lambda} \tag{9}$$

where L_{vt} is the air consumption. For perfect combustion of the fuel mixture in an internal combustion engine, its value is required to be at the level of 14.7 kg. Subsequently, based on the obtained values, it is possible to calculate the fuel consumption in liters. The density of gasoline ranges from 700 kg.m^{-3} to 750 kg.m^{-3} or from 0.7 kg.l^{-1} to 0.75 kg.l^{-1}.

It follows that fuel consumption in an internal combustion engine is mainly given by specific fuel consumption, i.e., how much fuel is needed to produce the energy needed to drive the vehicle. The amount of energy produced is of course dependent on the engine speed and load. The total mass of the fuel mixture, i.e., the mixture of gasoline and air, depends on its stoichiometric ratio, which for an ideal mixture is 14.7 kg of air per 1 kg of gasoline. This ratio corresponds to the value λ = 1. However, in practice there are cases when a richer mixture ($\lambda < 1$) is used to increase the performance of the internal combustion engine or a leaner mixture ($\lambda > 1$) for the sake of fuel economy. Therefore, it is necessary to find a suitable compromise between the performance of the internal combustion engine and its consumption in order to achieve the highest possible efficiency of its operation.

In the following Fig. 3 shows a set of graphs depicting the dependence of the fuel consumption of a gasoline atmospheric combustion engine on its speed in the range of 2,000 rpm to 4,000 rpm and the value of the stoichiometric ratio λ (0.8, 0.85, 0.9, 0.95, 1.00, 1.05, 1.10, 1.15 and 1.2).

From the above results it can be observed that the lowest fuel consumption in a gasoline atmospheric combustion engine with a cylinder capacity of 1,390 cm^3 is at the level of approximately 3.9 l per hour of operation. This consumption is achieved at low engine speeds (approximately 2,000 rpm) and a stoichiometric ratio λ = 1.2. At the same time, it can be observed that the fuel consumption in a given engine increases linearly with increasing engine speeds and decreasing stoichiometric ratio λ. Based on this, it can be observed that at speeds of approximately 4,000 rpm and a stoichiometric ratio λ = 0.8 this engine reaches a consumption of 11.5 l per hour.

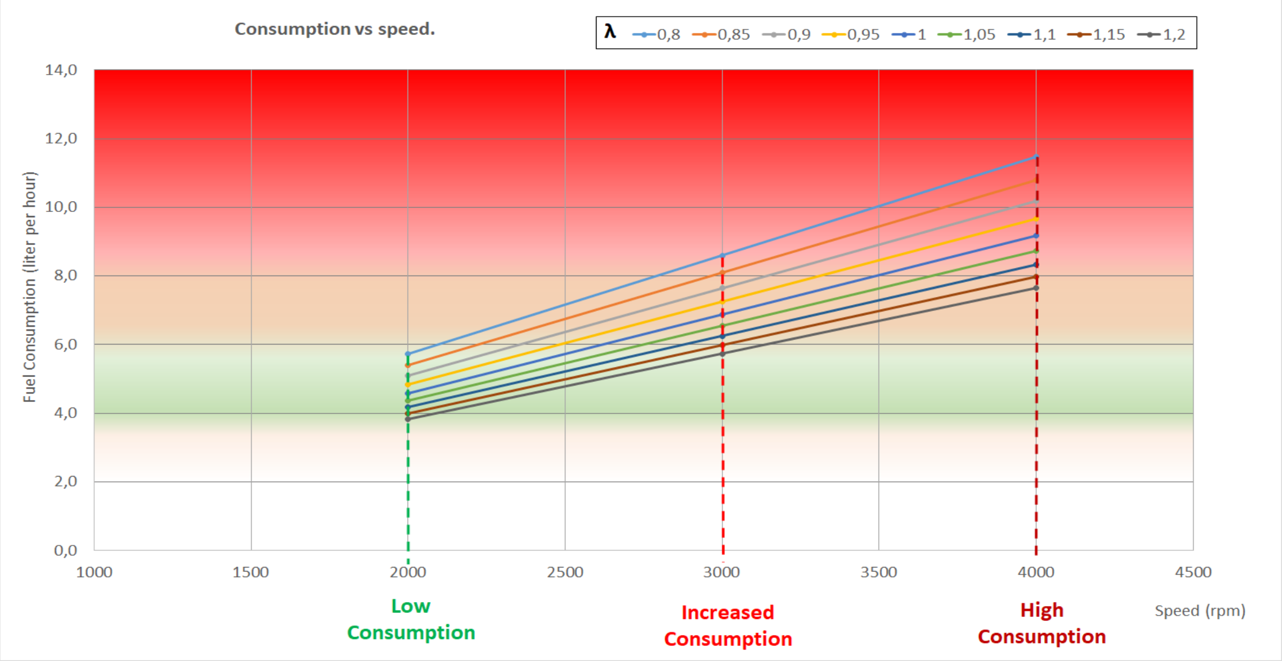

Figure 3. Dependence of fuel consumption on engine speed and stoichiometric ratio λ

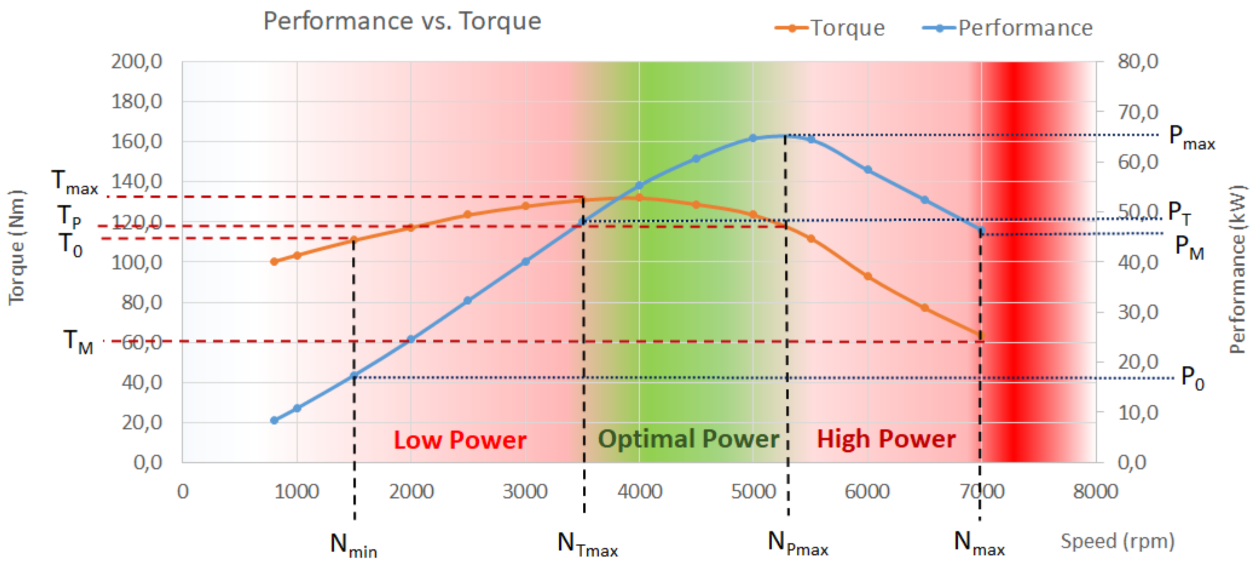

Figure 4. Dependence of the power of internal combustion engine with a cylinder capacity of 1,390 cm^3 on torque

Fuel consumption in an internal combustion engine also depends on the engine power. This is also dependent on the current torque and the corresponding engine speed. In the following Fig. 4, you can see the dependence of the power of the considered internal combustion engine with a cylinder capacity of 1,390 cm^3 on the torque and engine speed.

From the above graph in Fig. 4, it is possible to observe the dependence of power on torque of a gasoline atmospheric combustion engine with a cylinder capacity of 1,390 cm^3 at different engine speeds. At the same time, several important facts regarding its effective operation can be observed from the above dependencies. The given gasoline atmospheric combustion engine operates in the range of minimum N_{min} = 1,500 rpm and maximum N_{max} = 7,000 rpm stable speeds at full load. At minimum speeds, the engine must run smoothly, without oscillation or stalling. At the same time, it must also allow operation at maximum speeds without any damage to the structure. From the graph, it is possible to observe the value of torque T_0 at the level of 110 Nm and power P_0 at the level of 17 kW at a minimum engine speed of 1,500 rpm, and at the same time the value of torque T_M at the level of 60 Nm and power P_M at the level of 45 kW at a maximum engine speed of 7,000 rpm. The maximum torque value T_{max} is reached by the engine at 132 Nm at N_{Tmax} = 3,500 rpm and the maximum power P_{max} is reached at 65 kW at N_{Pmax} = 5,200 rpm. Then the value P_T represents the engine power at 48 kW, which is reached at maximum engine torque T_{max} = 132 Nm and engine speed N_{Tmax} = 3,500 rpm. The value T_p represents the engine torque at 119 kW, which is reached at maximum engine power P_{max} = 65 kW and engine speed N_{Pmax} = 5,200 rpm.

It follows from the above that the low torque zone is represented by the area between the minimum engine speed Nmin and the engine speed with maximum torque N_{Tmax}. It is true that the higher the torque in this area, the better the acceleration capabilities of the combustion engine. However, when the engine is running in this area at full load and the engine speed is reduced, the result is a decrease in engine torque and its stop. This is an unstable torque area in which the engine should only operate to a limited extent.

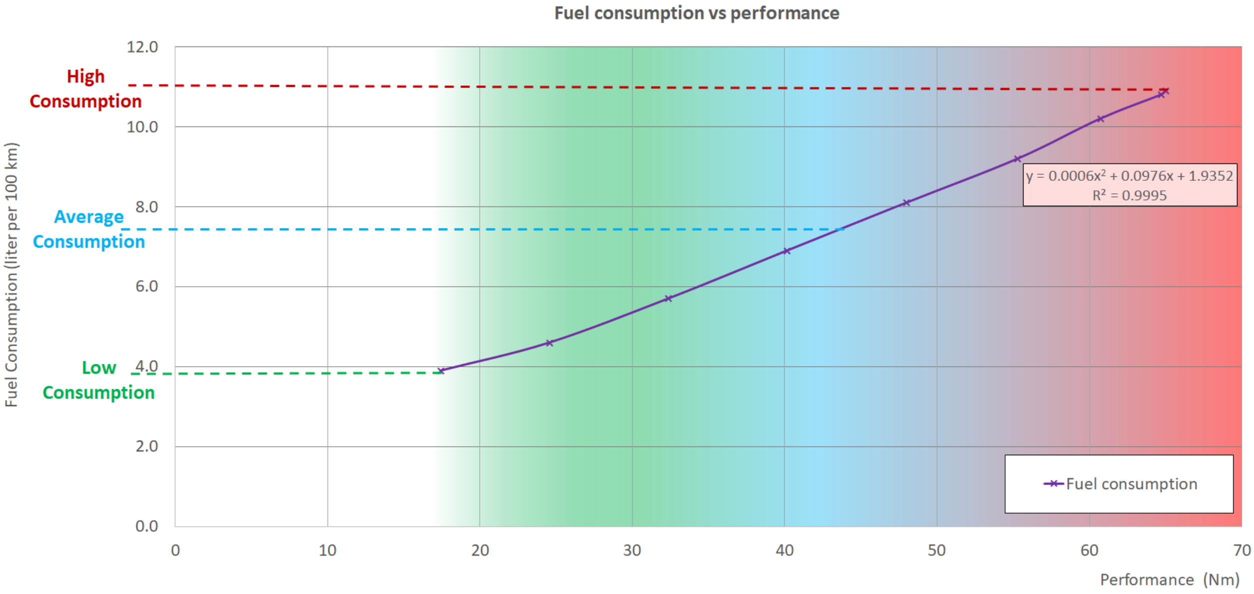

Figure 5. Dependence of fuel consumption on the power of an atmospheric combustion engine in the range of 20 Nm to 65 Nm

The area between the engine speed with maximum torque N_{Tmax} and the engine speed with maximum power N_{Pmax} defines the power band. In this area, the engine generally has the smoothest operation and the best power to torque ratio. If the engine speed is maintained between the engine speed with maximum torque N_{Tmax} and the engine speed with maximum power N_{Pmax} and the engine speed with maximum load increases in this area, the engine speed will decrease. However, on the other hand, the output torque will increase, compensating for the increased engine load. This is the stable torque area in which the engine should operate for the vast majority of its operating time. The last area is the area between the engine speed with maximum power N_{Pmax} and the engine speed with maximum power N_{max}. This is the high-power area in which the engine has the highest engine output. This is of course reflected in better engine acceleration. However, since this is a power range in which the engine is under enormous load, this range should only be used in operation for a limited period of time to avoid engine damage [Husain 2021, Mascenik 2024].

The graph in the following Fig. 5 shows the dependence of the fuel consumption of a gasoline atmospheric combustion engine on its power in the range of 20 Nm to 65 Nm at a stoichiometric ratio $\lambda = 1.0$.

From the graph in Fig. 5 it can be observed that the lowest fuel consumption in a gasoline atmospheric combustion engine with a cylinder capacity of 1,390 cm^3 and a stoichiometric ratio $\lambda = 1.0$ is at the level of approximately 3.9 l per hour of operation. This consumption is achieved at a power of approximately 17.5 Nm. At the same time, it can be observed that at a stoichiometric ratio $\lambda = 1$ the fuel consumption in a given engine increases linearly with increasing power, up to a level of approximately 65 Nm, where it reaches a consumption of approximately 10.9 l per hour.

4 OPTIMIZING FUEL CONSUMPTION AND PERFORMANCE OF THE COMBUSTION ENGINE WITH A CYLINDER CAPACITY OF 1,390 CM^3

In general, it can be stated that optimizing fuel consumption and internal combustion engine performance is a complex process that involves balancing two conflicting goals. Conflicting goals because achieving high internal combustion engine performance is undoubtedly associated with higher fuel consumption. To a certain extent, fuel consumption can be reduced quite effectively, but a significant reduction in fuel consumption also brings with it a significant reduction in engine performance. However, this is undesirable. One solution to the problem is the application of optimization. Fuel consumption can be optimized with respect to internal combustion engine performance. This is usually done with the support of advanced methods such as modelling and simulation, while digital models of the internal combustion engine are created. These are then used to predict how changes in one input parameter will affect the efficiency of the entire system without physically modifying it. Sophisticated mathematical algorithms such as genetic algorithms or machine learning methods are used, which analyze huge amounts of data and look for the best possible compromise between performance and fuel consumption. In addition, the responses of the combustion engine and consumption are experimentally measured with respect to various input parameters, thereby creating a mathematical model whose task is to define the optimal settings of power and fuel consumption for efficient engine operation.

Modern vehicles now use complex ECUs to continuously control and monitor the combustion process in real time. Their control system is then based on a specific selection from a set of optimal solutions, also known as the Pareto front. From this pool, it is then possible to select those settings configurations that best suit a specific engine application. This is a Pareto optimal solution, which is applied when there is no other solution that would improve the overall efficiency of the combustion engine, for example by reducing fuel consumption without worsening engine performance. The Pareto front represents a graphical representation, usually a curve or surface in a multidimensional space, of all Pareto efficient and non-dominated solutions. The Pareto front therefore does not provide a single, best solution, but rather a set of the best possible compromises. It allows you to visually see and assess the trade-offs between different goals and choose the final solution that best meets the specific requirements for the economical and efficient operation of the combustion engine.

As part of the research, the power and torque of the considered spark-ignition internal combustion engine with a cylinder capacity of 1,390 cm^3 were optimized using the graphical optimization method. The Fig. 6 shows the result of the graphical optimization.

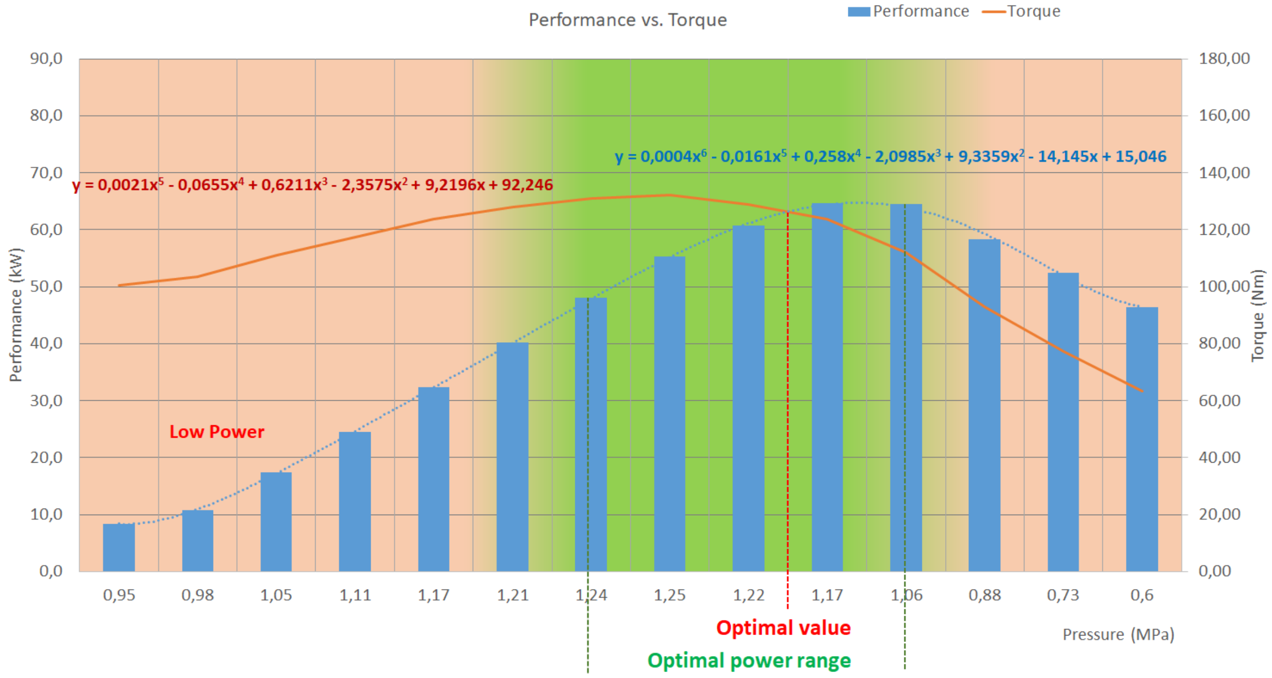

Figure 6. Graphical optimization of power and torque of an atmospheric spark-ignition internal combustion engine with a cylinder capacity of 1,390 cm^3

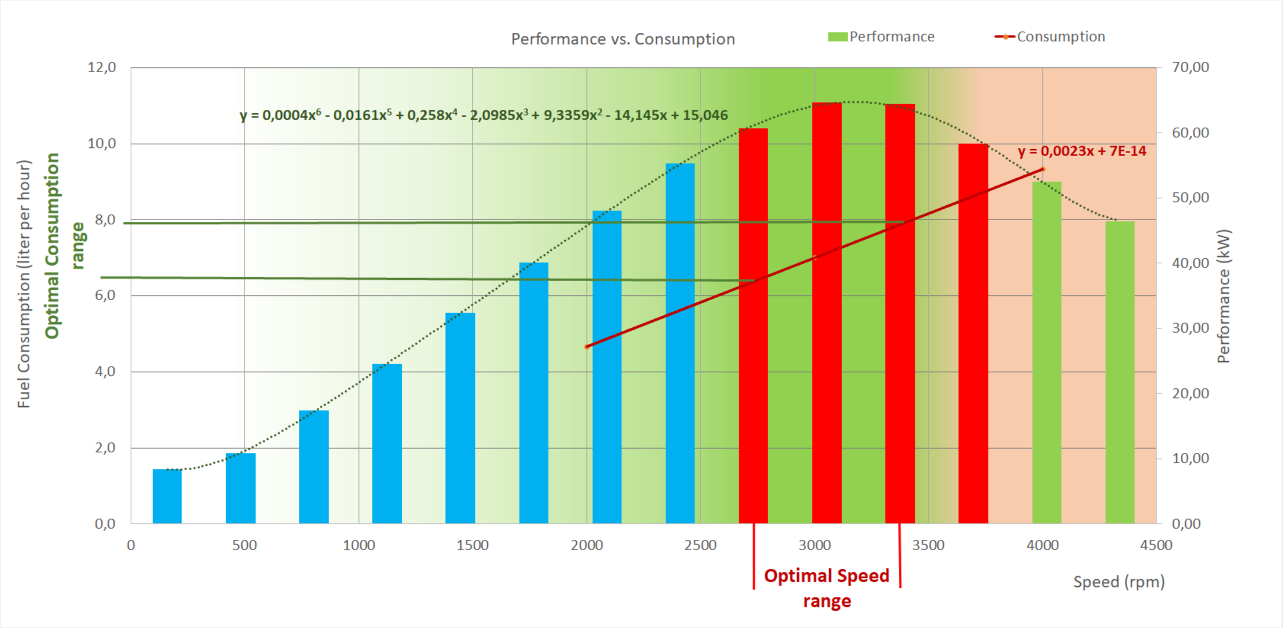

Figure 7. Graphical optimization of fuel consumption and power of an atmospheric spark-ignition internal combustion engine with a cylinder capacity of 1,390 cm^3

Based on the performed graphical optimization, it can be stated that the optimal power band of the given atmospheric spark-ignition internal combustion engine with a cylinder capacity of 1,390 cm^3 ranges in the pressure range of 1.24 MPa to 1.06 MPa. The optimal value can be considered a torque of 125 Nm and a power of 63 kW at a charging pressure of 1.2 MPa.

Subsequently, as part of the research, the fuel consumption and performance of a spark ignition internal combustion engine with a cylinder capacity of 1,390 cm^3 was optimized using a graphical method. Figure 7 shows the result of the graphical optimization.

Based on the performed graphical optimization, it can be stated that the optimal power range of the given atmospheric spark-ignition internal combustion engine with a cylinder capacity of 1,390 cm^3 ranges from 37 kW to 43 kW. This engine power can be achieved at a torque of 125 Nm to 130 Nm and an engine speed of 2,750 rpm to 3,400 rpm. Based on the values of these output engine power parameters, the fuel consumption in the given engine is predicted to be 6.3 to 7.8 l per hour of operation.

5 CONCLUSIONS

For every atmospheric spark-ignition internal combustion engine, its fuel consumption is undoubtedly linked to its performance. At the same time, the general rule is that higher engine performance also means higher fuel consumption, because more energy needs to be converted per unit of time. However, this increased fuel consumption can be corrected to a certain extent by applying appropriate optimization methods. Their application can achieve, if not directly, a reduction in fuel consumption or an increase in engine performance, but mainly an improvement in its overall operating efficiency. Therefore, the research conducted was focused on finding solutions for achieving high efficiency in the operation of an atmospheric spark-ignition internal combustion engine with a cylinder capacity of 1,390 cm^3. It was found that the lowest fuel consumption in a given engine, at a level of approximately 3.9 l per hour of operation, can be achieved at the lowest stable engine speed and a stoichiometric ratio $\lambda = 1.0$. At the same time, through the performed graphical optimization, it was found that the optimal power band of the given combustion engine is in the range of 37 kW to 43 kW with a torque of 125 Nm to 130 Nm and an engine speed in the range of 2750 rpm to 3,400 rpm. Subsequently, based on the values of these performance parameters of the combustion engine, its fuel consumption was predicted at the level of 6.3 to 7.8 l per hour of operation.

From the above, it follows that the optimization performed did not achieve either the lowest consumption or the highest performance of the given internal combustion engine, but it did achieve higher efficiency of its operation. This will at least partially prevent energy waste. This means that more energy is spent on the work performed by the internal combustion engine, which will achieve higher efficiency of its operation. In addition, it was found that fuel consumption is usually the lowest when the engine operates at the point of greatest efficiency with a stoichiometric ratio λ approaching the value of 1.0. At the same time, this is the area in which the internal combustion engine achieves high torque even at lower rpm. This is because the engine achieves maximum volumetric efficiency in this area, which means that optimal combustion of the air-fuel mixture is applied. Although identifying the optimal area of fuel consumption and performance of an atmospheric internal combustion engine always requires an individual approach, the benefit is higher overall efficiency of its operation.

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