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EFFECT OF LOCAL AIRFLOW RESTRICTION IN THE INTAKE SYSTEM ON THE CHARACTERISTICS OF A NATURALLY ASPIRATED SPARK-IGNITION ENGINE

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Abstract

One of the most important elements influencing the functioning of internal combustion engines is the intake system, whose task is to supplycold, fresh and filtered air to the combustion chambers of the engine. So far, the capacity tests of the intake system have focused on the appropriate selection of its geometry and diameter, which had a direct impact on the airflow rate, and thus on the performance of the vehicle. In this article, the focus is on conducting research consisting of placing the airflow restriction element in a specific locationin the intake system of a naturally aspirated spark-ignition engine. After the necessary preparations, authors made measurements of the engine performance (power and torque) and airflow rate in the intake systemvia original MAF sensor mounted in intake system and Chassis Dynamometer Interface via OBD protocol. After the engine parameters were measured, the test results were compared with the reference characteristics obtained during the measurements prior to the modification of the stock intake system. The article is crowned by conclusions based on the results of the measurements.

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Introduction

Internal combustion engines are machines that convert chemical energy into mechanical energy and, to date, are the most popular source of propulsion for cars, trucks, buses, ships and aircraft (ZAJĄC 2009). A large proportion of internal combustion engines are still spark-ignition engines, in which it is necessary to supply an appropriate amount of air through the engine's intake system to form a stoichiometric air-fuel mixture. By making changes to the intake system, you can directly influence the characteristics of the engine. In this study, the authors focused on investigating the impact of modification of the intake system of a naturally aspirated engine on its external characteristics and selected parameters. In the literature collected so far, one can find the results of research related to the capacity of the intake system, however, they were based on changing the diameters of the entire pipes that make up the engine intake system. On the other hand, the authors of the article carried out research consisting of placing an element limiting the airflow at a specific point of the intake system of a naturally aspirated engine with spark ignition.

Literature review

The intake system of an indirect fuel injection engine is the component responsible for delivering fresh charge to the engine cylinders. In direct injection engines, on the other hand, it is responsible for supplying only fresh air. The internal flows that occur in internal combustion engines are very turbulent. Turbulent flow is a flow that is irregular, and chaotic, with unforeseen movements of parts of the fluid, as well as vortices (ELSNER 1987, BAKUNIAK 2013). Turbulent flow occurs when the Reynolds number exceeds the value of 2300. The Reynolds number expresses the ratio of the inertial force to the viscous (friction) force during fluid motion. The Reynolds number is a dimensionless quantity (JEŻOWIECKA-KABSCH, SZEWCZYK 2001). A properly designed intake system is characterized by the lowest possible resistance to the flow of the medium, which allows for a high cylinder filling ratio (ŚWIĘCICKI 2015). Issues related to modifications of the intake system of an internal combustion engine were addressed by KOŁODZIEJ and HENNEK (2017), who in their work described the study of the influence of the change in the geometry of the intake system on the flow of the medium carried out using the digital imaging anemometry (DPIV) method. It has been observed that changing the original inlet to the intake manifold designed by the car manufacturer to a straight inlet causes a deterioration of the flow velocity fields of the medium. With 50% throttle opening and an engine speed of 5,500 rpm, the difference in flow velocity between the inlets was as much as 0.831 m/s. During the research, it was also noted that regardless of the throttle position and the set engine speed, the intake system with the original intake manifold inlet fitted results in higher average flow velocities compared to the straight intake in the study area of the intake system (KOŁODZIEJ, HENNEK 2017).

Benbella Shannak, on the other hand, researched the exhaust gas composition of a four-cylinder four-stroke spark-ignition engine. The research methodology assumed the study of the effect of changes in rotational speed and diameter of the inlet pipe in the engine intake system on the content of hydrocarbons and carbon monoxide in the exhaust gas (SHANNAK et al. 2006). The influence of the geometry of the intake system on the functioning of the internal combustion engine was also studied by Heinz Heisler. In his thesis, he conducted research on the influence of the dimensions of the intake pipes of a spark-ignition engine on the volumetric efficiency of the engine. The research showed that as the diameter of the intake pipe decreased, the air velocity in the intake system increased (HEISLER 1995). A similar study was carried out by Rodrigo Caetano Costa on a four-cylinder spark-ignition engine. These studies concerned the effect of the length and diameter of the intake pipe on changes in volumetric efficiency. The research showed that at higher engine speeds, higher volumetric efficiency was achieved with the use of a larger diameter pipe, and at lower engine speeds with smaller diameter tubes. The increase in volumetric efficiency in the cylinders translated into an increase in engine power and torque (COSTA et al. 2013). Also in the paper (KOMORSKA et al. 2018), in the research on the on-board diagnostics system, a defect in the form of cross-sectional throttling in the engine intake system was used and how the on-board diagnostics system reacted to this type of fault was observed. Much literature focuses on the design and optimization of internal combustion engine intake systems, mainly for various types of racing (SINGHAL, PARVEEN 2013, CHEN et al. 2014, NORIZAN et al. 2017, SHAH et al. 2022), but also in vehicles intended for use on public roads (PATIL et al. 2005, BOODANUR et al. 2019).

As can be seen, previous research has focused on the use of intake system components of a specific diameter and length, as well as their impact on engine characteristics. On the other hand, no information was found about the study of the influence of the element in the form of a shutter, used point-wise in the intake system of a naturally aspirated spark-ignition engine. Therefore in this article the authors undertook to investigate, how the point restriction of the airflow sucked to the engine, for example by a very dirty air filter or by damaged elastic elements of the intake system, would influence the vehicle engine parameters and whether the vehicle OBD system would be able to signal and diagnose such a condition.

Method

The tested object was a naturally aspirated spark-ignition engine designated M54B25(256S5), equipped with multi-point indirect fuel injection. The exact technical data of the test object are summarized in Table 1.

Table 1

Engine Specifications

Parameter	Value
Number and arrangement of cylinders	6, inline
Cylinder diameter	84 mm
Stroke	75 mm
Displacement	2,494 cm3
Compression ratio	10,5:1
Maximum power	141 kW (192 hp) at 6,000 rpm
Maximum RPM	6,500 rpm
Maximum Torque	245 Nm at 3,500 rpm

Source: based on ETZOLD (2018).

In addition, the tested engine was equipped with a variable intake manifold length system (Single DISA Valve), which is designed to increase the engine torque in the low engine crankshaft speed range and increase the power in the upper engine speed range (Training documentation for the M54 engine designation, M54engMS43/ST036/6/2000, Revision Date: 6/2000. BMW AG).

To determine the external characteristics of the tested engine, a two-axle chassis dynamometer MAHA LPS3000 was used. The characteristics of the dynamometer are summarized in Table 2.

Table 2

Characteristic parameters of the MAHA chassis dynamometer LPS3000

Parameter	Value
Axle load (maximum)	2,500 kg
Minimum track width	800 mm
Maximum track width	2,300 mm
Minimum wheel diameter	12”
Eddy Electro Brake	260 kW/one axle
Top speed	250 km/h
Wheel power (maximum)	260 kW
Speed	0-10,000 rpm
Measurement accuracy	± 2% worth Measured

Source: Operating manual for LPS 3000 power control chassis dynamometer for passenger cars.

After the preparation of the vehicle and the test stand (Fig. 1), the first measurement was carried out on the original, unchanged intake system to obtain the reference characteristics of the tested engine. The main pipe of the intake system had an internal diameter of 70 mm. After the reference measurement, the modification of the engine’s intake system, i.e. the main pipe of the intake system, was started (Fig. 2).

Fig. 1. The appearance of the vehicle and the test rig for carrying out tests

Fig. 2. The shutter connector mounted in the main engine intake pipe

A set of special connectors was prepared for the tests, with the help of which modifications to the intake system were made. Inside the connectors, there were shutters of various diameters (Tab. 3). The shutters were a local restriction of airflow in the engine's intake system. Figure 3 shows the design of one of the airflow restrictors equipped with a shutter, which was used during the tests in the intake system of the test vehicle. The location of the airflow restrictor equipped with a shutter was chosen in such a way as to only limit the airflow. The introduced airflow disturbances did not cause any disturbances in the operation of the vehicle engine.

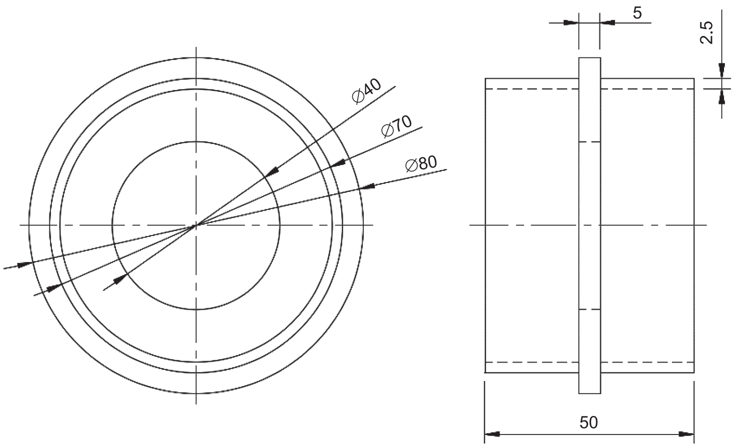

Fig. 3. The design of the airflow restrictor equipped with a shutter (hole in shutter – Ø40) used during the tests in engine's intake system

Table 3

Intake shutter diameters

Diameter of the aperture of the intake connector [mm]	Percentage of the intake aperture diameter relative to the stock intake pipe [%]
20	28.6
30	42.9
40	57.1
50	71.4
60	85.7

Source: Author's elaboration.

After modifying the intake system of the prepared vehicle, a series of measurements were carried out. The measurements were made one by one without detaching the vehicle from safety belts in the chassis dynamometer.

It allowed to save the same conditions, for example – tension force of the safety belts which protected the vehicle, position of the vehicle on rollers in the chassis dynamometer and ambient temperature in the testing room. Temperature in the testing room oscillated around 25°C, but fresh air blow system from outside of chassis dynamometer provided air temperature inside intake system around 16–17°C, what was recorded by chassis dynamometer software based on collected data via OBD connector in the vehicle. Based on the results obtained, supplementary measurements were carried out for the range of changes in the diameter of the intake system, which caused the greatest changes in the maximum parameters of the engine. After the measurements, the reference characteristics were compared with the operational characteristics obtained after the modification in the intake system. Measurements were made for each of the prepared connectors, to determine the external characteristics of the engine for each case.

Results and their analysis

The first measurement of engine parameters (power and torque) was carried out for the stock engine, with the original intake system. The obtained external characteristics of the engine are shown in Figure 4.

The tested engine obtained a maximum power of 148.4 kW at 5,985 rpm and a maximum torque of 259.2 Nm at 3,560 rpm during the reference measurement. The obtained results are higher than the parameters declared by the manufacturer, which were respectively 141 kW at 6,000 rpm, and 245 Nm at 3,500 rpm.

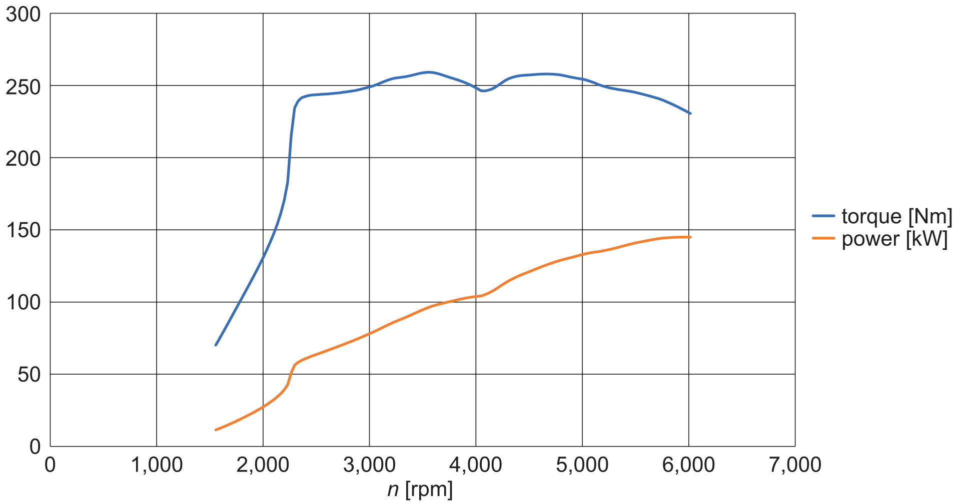

Fig. 4. External characteristics of the engine obtained for the standard intake system

This was followed by a series of measurements with the fittings listed in Table 3 installed in succession. After performing the test with a connector with a diaphragm diameter of 50 mm, the power and torque results were very similar to those obtained during the test with the original, unchanged intake system. Therefore, no measurement was made for the last connector – the connector with a diaphragm diameter of 60 mm. During the tests, it was observed that the greatest differences in the analyzed engine parameters (power and torque) occur between connectors with 20–30 mm diaphragms. Therefore, for this range of aperture diameters, the measurements were supplemented with the apertures listed in Table 4.

Table 4

Diameters of supplementary shutters of the intake system

Diameter of the intake connector aperture [mm]	Percentage of the diameter of the intake system shutter related to the standard intake pipe [%]
22	31.42
24	34.29
26	37.14

Source: Author's elaboration.

Based on the data obtained during the tests, the engine power waveforms were plotted depending on the engine speed and the airflow restrictor installed in the main intake pipe. The waveforms are shown in Figure 5.

In the 1,540–2,030 rpm speed range, all engine power waveforms are very close to each other, despite the airflow restrictors installed in the main intake pipe. In this speed range, the lowest rate is the engine power waveform with a 22 mm diameter airflow restrictor fitted (Fig. 5, designation ⌀22) and the highest rate in this rpm range is the power band of the standard intake engine (Fig. 5, designation OEM) and the power band of the engine with a 30 mm diameter airflow restrictor fitted (Fig. 5, designation ⌀30) tags.

As the engine speed increases above 2,030 rpm, the engine power waveforms gradually separate. In the 2,030–3,240 rpm speed range, in addition to the gradual separation of the power graphs, there is also a displacement in instantaneous power increases to higher engine speeds. The largest displacement in the instantaneous power values in the above-mentioned rpm range is characterized by the power course of the engine with a 24 mm diameter airflowrestrictor installed (Fig. 5, designation ⌀24), and the smallest displacement in the increase in instantaneous power values in this range is characterized by the power course of the engine with a 30 mm diameter airflowrestrictor installed (Fig. 5, designation ⌀30) tags. The offset of the instantaneous power increase in the power

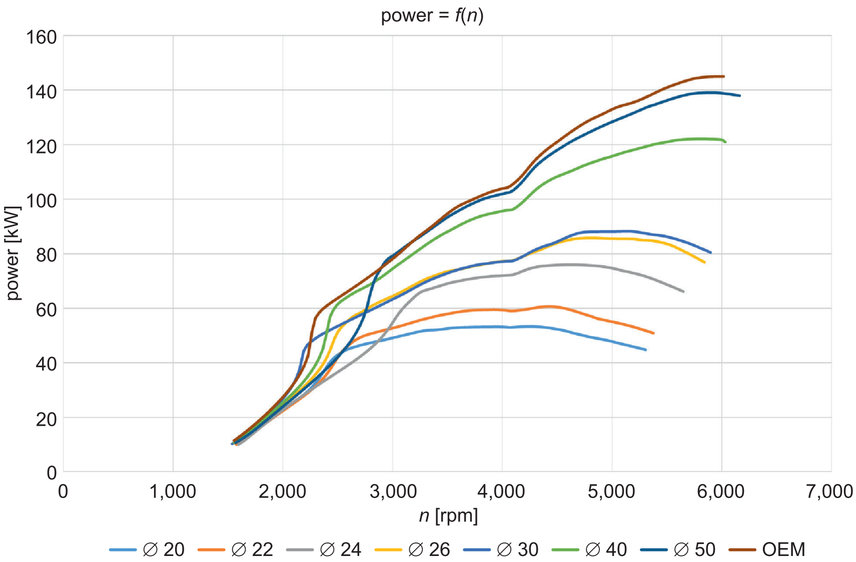

Fig. 5. Engine power waveforms as a function of engine speed for each test variant

band of an engine with a 30 mm diameter airflow restrictor installed in this range is smaller than the offset of the instantaneous power increase occurring in the power band of an engine with a standard intake system.

Once the 3,240 rpm speed is exceeded and increased, the instantaneous power increase decreases as the diameter of the airflow restrictor hole decreases. When the engine reaches ~4,000 rpm, there is another increase in instantaneous power values. This increase in power when the rotational speed of ~4,000 rpm is reached is less and less as the diameter of the flow restrictor bore decreases. The smallest increase in instantaneous power values in the ~4,000 rpm range – max rpm – is characterized by the power waveform of the engine with a 20 mm diameter airflow restrictor installed, and the largest increase in instantaneous power values in the mentioned rpm range is characterized by the engine with a standard intake system.

During the development of the test results, it was also observed that after exceeding the rotational speed of ~4,000 rpm with the reduction of the diameter of the airflow restrictor hole, the increases in instantaneous power values do not progress to the maximum engine speed, but end at lower engine speeds. The smallest increase in instantaneous engine power is characterized by the engine power waveform with a 20 mm diameter airflowrestrictor installed (Fig. 5, designation ⌀20), and the largest increase in instantaneous power values is characterized by the power band of the engine with the standard intake system. A comparison of the maximum engine power values depending on the airflow restrictor installed in the main intake pipe is shown in the diagram in Figure 6.

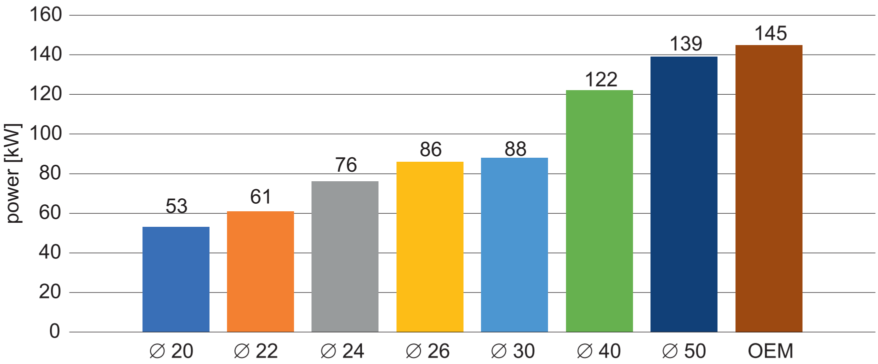

Fig. 6. Comparison of maximum engine power values depending on the airflow restrictor installed in the main intake pipe

During the analysis of the power waveforms, it was noticed not only that the maximum power value depends on the installed airflow restrictor, but also the dependence of the rotational speed at which it is achieved on the aforementioned airflow restrictors. A comparison of the engine speeds at which the maximum engine power is achieved depending on the installed airflow restrictor is shown in the diagram in Figure 7.

Based on the data obtained during the tests, the torque waveforms of the engine were also plotted. The waveforms are shown in Figure 8.

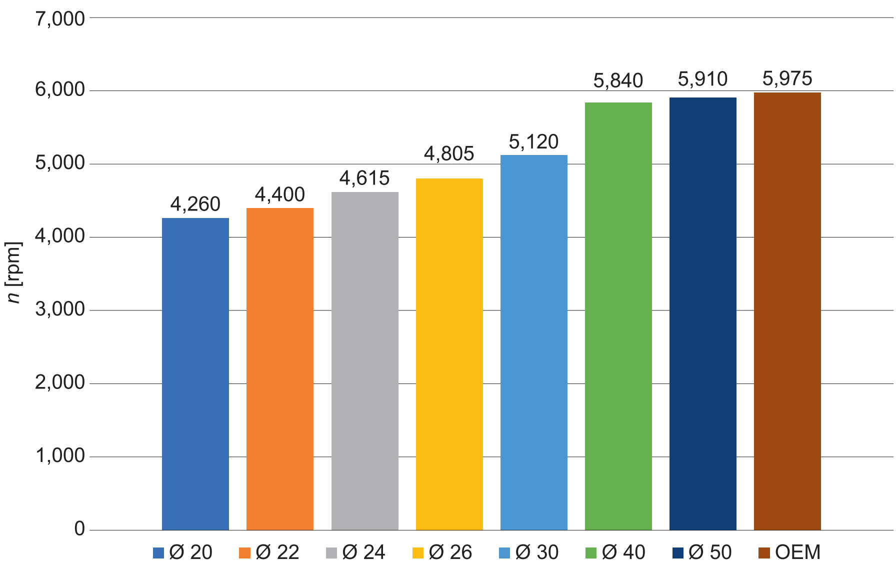

Fig. 7. Comparison of engine speed values at which maximum engine power is reached depending on the airflow restrictor installed in the main intake pipe

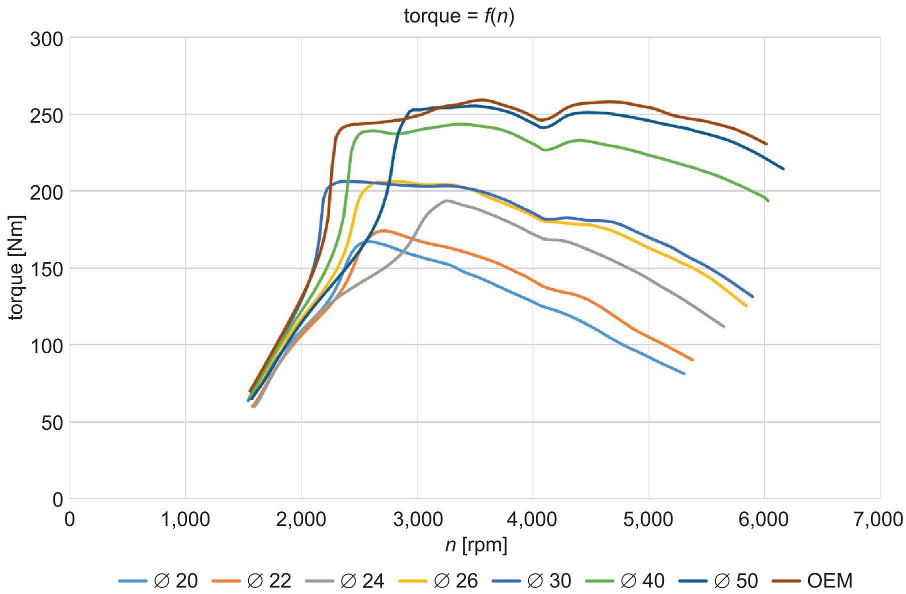

Fig. 8. Engine torque waveforms as a function of engine speed for each test variant

At the beginning of the measurements, i.e. in the speed range of 1,540–2,030 rpm, all engine torque waveforms are similar to each other, despite the airflow restrictors installed in the main pipe of the intake system. In this speed range, the lowest runs are the torque waveforms of the engine with 22 mm and 24 mm diameter airflow restrictors installed (Fig. 8, designation ⌀22, ⌀24), and the highest rate in this rpm range is the torque waveform of the engine with a 30 mm airflow restrictor installed (Fig. 8, designation ⌀30) and the torque waveform of the engine with the stock intake system (Fig. 8, designation OEM). As the engine speed increases above 2,030 rpm, the engine's torque waveforms gradually separate.

In the 2,030–3,240 rpm speed range, in addition to the gradual separation of the torque graphs, there is also a displacement in instantaneous increases in torque values to higher engine speeds, similar to the engine power waveforms. The largest displacement in the increase in instantaneous torque values in the range of rotational speeds 2,030–3,240 rpm was characterized by the torque course of the engine with a 24 mm diameter airflow restrictor installed (Fig. 8, designation ⌀24), and the smallest displacement in the increase in instantaneous torque values in this range was characterized by the torque band of the engine with a 30 mm diameter airflow restrictor installed (Fig. 8, designation ⌀30). The displacement in the instantaneous torque increase in the torque of an engine with a 30 mm diameter airflow restrictor in this interval is smaller than the torque increase in an engine with a stock intake system.

After exceeding the 3,240 rpm speed and increasing it, a significant increase in instantaneous torque values occurs only in the torque waveforms of the engine with the stock intake system and with 40 and 50 mm diameter airflow restrictors. The aforementioned increase in torque in the above-mentioned torque waveforms progressed to rotational speeds of 3,560, 3,370 and 3,480 rpm respectively.

When the engine reaches ~4,000 rpm, the torque curves are curbed and the instantaneous torque values increase again. The curvature of the torque waveforms at the mentioned speed is the result of the Single DISA Valve actuating. This increase in instantaneous torque values occurring after reaching ~4,000 rpm is smaller and smaller as the diameter of the airflow restrictor bore decreases.

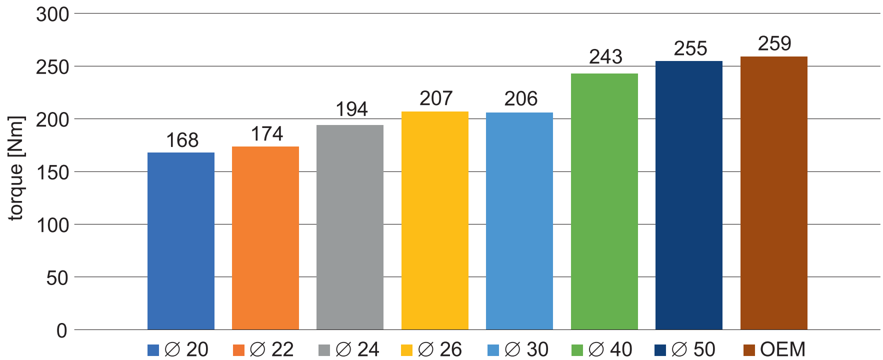

Fig. 9. Comparison of maximum engine torque values depending on the airflow restrictor installed in the main intake pipe

During the development of the test results, it was also observed that, as with the engine power waveforms, as the diameter of the airflow restrictor changes, the value of the maximum torque achieved by the engine changes, as well as the maximum torque value is reached at a different speed value. A comparison of the maximum engine torque values depending on the main intake airflow restrictor is shown in the graph in Figure 9, and a comparison of the engine maximum torque values depending on the installed airflow restrictor is shown in the graph in Figure 10.

As expected, the value of the maximum torque increases with the diameter of the installed airflow restrictor. On the other hand, if the maximum torque value changes with the increase in engine speed on the characteristics, it should be noted that with the 30 mm diameter airflow restrictor used in the intake system, the maximum torque is achieved at the lowest engine speed.

During the dyno measurements, other engine parameters were also recorded. One of them was the airflow rate in the intake system. This measurement was carried out using the OBD module (via OBD protocol) included in the Chassis Dynamometer Interface, and the measurement of airflow in the intake system

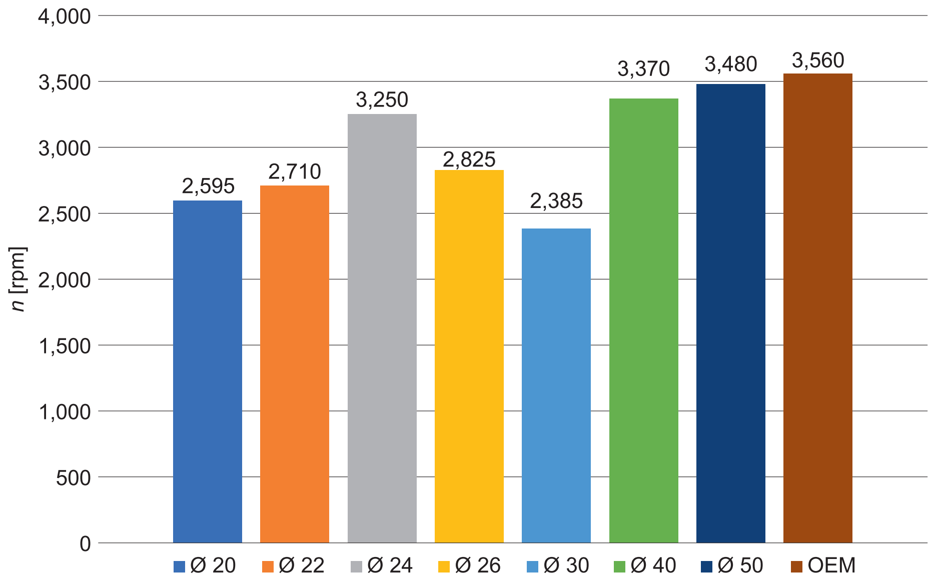

Fig. 10. Comparison of the engine speed values at which the maximum engine torque is reached depending on the airflow restrictor installed in the main pipe of the system

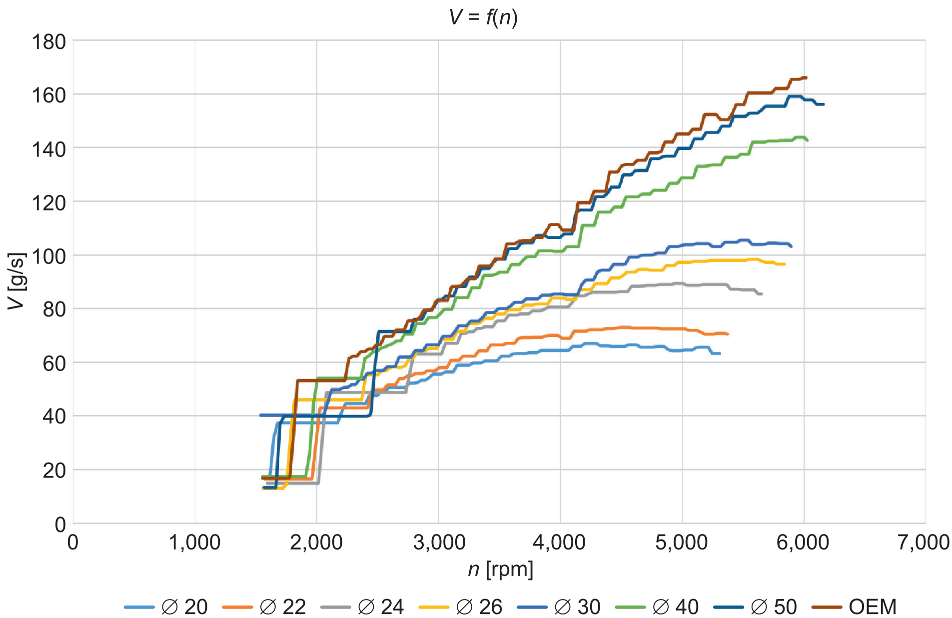

Fig. 11. Evolution of the intake airflow rate depending on engine speed and the installed airflow restrictor

was carried out by a original MAF sensor (wire thermoanemometer), in which the electrical system generates a signal sent to the engine control unit(in this case – BMW MS43 ECU). This signal is dependent on the intensity of the current flowing through the wire, which is cooled by the air sucked in by the motor (Schneehage 2017). The patterns of changes in the airflow rate as a function of engine speed and the airflow restrictor used are summarized in Figure 11.

Based on the obtained airflow rate waveforms (Fig. 11), the results were compiled and a diagram of the relationship between the maximum value of the airflow rate and the degree of capacity of the restrictor (Tab. 3, 4) installed in the engine intake system was developed. The resulting relationship is shown in Figure 12.

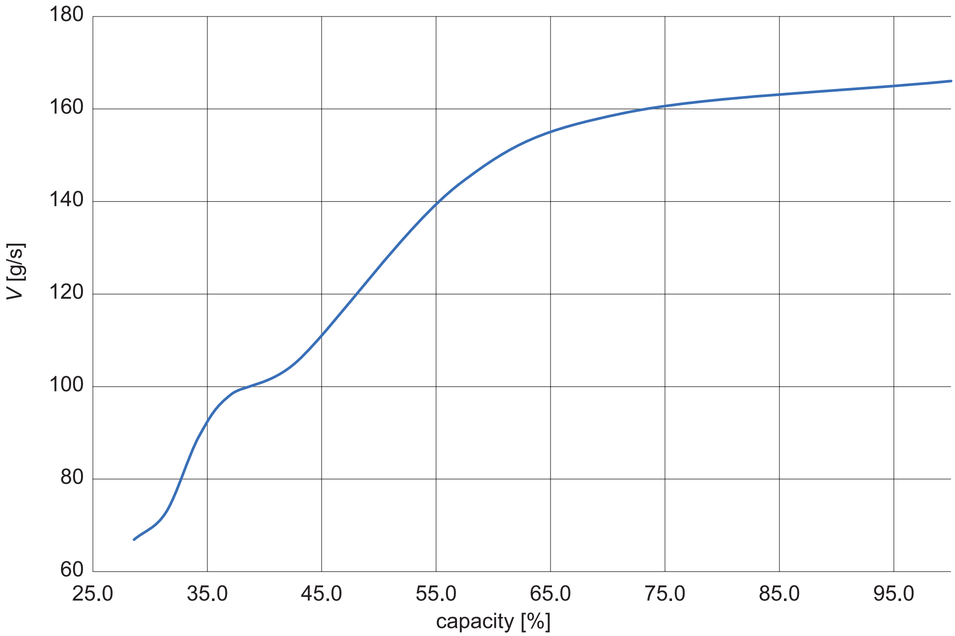

Fig. 12. Dependence of the maximum airflow rate on the amount of flow of the restrictor mounted in the engine intake system

Based on the relationship shown in Figure 12, it should be noted that installing airflow restrictors in the intake system to approx. 60% of its nominal capacity does not significantly change the value of the maximum airflow rate to the engine. Below this value, however, there is a sharp reduction in the airflow rate, which is reflected in a significant reduction in the engine's power and torque values.

Conclusions

As a result of the conducted research and the analysis of their results, it was observed that the introduction of changes in the engine intake system directly affects the values of engine operating parameters. By reducing the diameter of the air passage in the main intake pipe to 28.6% of the nominal diameter by installing a designed airflow restrictor, the maximum engine power was reduced by 63.22% and the maximum torque by 35.37%, compared to the nominal values of these parameters measured during the reference measurement of the engine with the stock intake system. As a result of the use of the aforementioned airflow restrictor, the maximum value of the airflow rate in the engine intake system has also changed. The maximum airflow rate has decreased by 59.7% from the nominal value.

The change in airflow in the main pipe of the intake system as a result of the use of airflow restrictors also affected the displacement in instantaneous increases in power and torque values in the 2,030–3,240 rpm speed range and transfer the instantaneous increases in airflow rates in the 1,610–2,790 rpm speed range to higher speeds. The displacement in the instantaneous increases in the values of the mentioned parameters in the range of rotational speeds 2,030–3,240 rpm and 1,610–2,790 rpm occurred regardless of the flow restrictor used. The engine with a 34.3% airflow restrictor was characterized by the smallest displacement in the instantaneous power and torque increases in the 2,030–3,240 rpm speed range to higher engine speeds, and the smallest displacement in increases in the aforementioned rpm range was characterized by an engine with a 42.9% airflow restrictor. The largest displacement in instantaneous increases in the airflow rate in the rotational speed range of 1,610–2,790 rpm was characterized by an engine with an airflow restrictor with a capacity of 34.3%, and the smallest displacement in instantaneous increases in the value of airflow rate in the mentioned speed range was characterized by an engine with a mounted airflow restrictor with a capacity of 42.9%. It should be noted that during the entire series of tests carried out, the engine control unit (ECU) did not detect or report any fault codes. Only based on the airflow rate values did the engine control unit make the appropriate adjustments to ensure the optimal air/fuel mixture.

Therefore, the modifications made to the engine intake system, in the form of the installation of a connector with an airflow restriction shutter, remain unnoticed for the OBD on-board diagnostics system. On the one hand it shows the imperfection of the OBD system, for which this type of irregularity in the intake system are impossible to diagnose and signalization for driver. It can cause a significant deterioration in the dynamics of the vehicle's engine for example by damages elastic elements of the intake system or gross service negligence such as exploitation of the air filter cartridge despite it is considerable soiling. On the other hand, obtained results show that in some cases, it allows to additional secure the car for example when car is use in a rental company or when we want to share car for young, inexperienced drivers. The installation of a properly selected airflow restrictor or even adjustable shutter in the vehicle's intake system may reduce engine's dynamics while remaining a invisible modification for user which is behind the steering wheel of vehicle.

References

BAKUNIAK W. 2013. *Flow simulations of the intake manifold for the Formula Student car*. Poznan University of Technology, Poznań.

BOODANUR R., PANWAR A., KULKARNI S.K., JADHAV A.B. 2019. *Air intake system optimization for passenger car engine*. SAE Technical Paper 2019-26-0044. https://doi.org/10.4271/2019-26-0044

Chassis dynamometer for LPS3000 power control for passenger cars. User Manual D10523BA1-D01.

CHEN C.W., DU W., SUN J.Q., LIU W., CHANG Y., DONG W. 2014. *Simulation analysis and design of intake restrictor of FSAE race car*. Applied Mechanics and Materials, 602: 751-756.

COSTA C.R., DE MORAIS HANRIOT S., SODRE J.R. 2013. *Influence of intake pipe length and diameter on the performance of a spark ignition engine*. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 36(1): 29-35. https://doi.org/10.1007/s40430-013-0074-2

ELSNER J.W. 1987. *Turbulence of flows*. PWN, Warszawa.

ETZOLD H.-R. 2018. *This is how it's done: care – maintain – repair Belt 102: BMW 5 Series, Type E39, Sedan/Touring, from December 1995 to June 2003*. Wydawnictwa Komunikacji i Łączności, Warszawa.

HEISLER H. 1995. *Advanced engine technology*. Elsevier Science &Technology, Amsterdam.

JEŻOWIECKA-KABSCH K., SZEWCZYK H. 2001. *Mechanika płynów*. Oficyna Wydawnicza Politechniki Wrocławskiej, Wrocław.

KOŁODZIEJ S., HENNEK K. 2017. *The effect of engine of intake system design on air distribution in the intake manifold*. Autobusy, 6(18): 794-799.

KOMORSKA I.M., WOŁCZYŃSKI Z., BORCZUCH A. 2018. *Fault diagnostics in air intake system of combustion engine using virtual sensors*. Diagnostyka, 19(1): 25-32. https://doi.org/10.29354/diag/80972

NORIZAN A., RAHMAN M.T.A., AMIN N.A.M., BASHA M.H., ISMAIL M.H.N., HAMID A.F.A. 2017. *Study of intake manifold for Universiti Malaysia Perlis automotive racing team formula student race car*. Journal of Physics. Conference Series, 908(1): 012069.

PATIL A.S., HALBE V.G., VORA K.C. 2005. *A System Approach to Automotive Air Intake System Development*. SAE Technical Paper 2005-26-011. https://doi.org/10.4271/2005-26-011

SCHNEEHAGE G. 2017. *Czujniki układu sterowania silnika w praktyce warsztatowej. Budowa, działanie i diagnozowanie za pomocą oscyloskopu*. Wydawnictwa Komunikacji i Łączności, Warszawa.

SHAH S.S., SINGH K., MARTIN L.J., JEROME STANLEY M. 2022. *Design, Development, and Validation of an Intake System for an FSAE Racecar*. In: *Energy and Exergy for Sustainable and Clean Environment*. Vol. 2. Eds. V.E. Geo, F. Aloui, p. 401-413. Springer Nature Singapore, Singapore.

SHANNAK B., DAMSEH R., ALHUSEIN M. 2006. *Influence of air intake pipe on engine exhaust emission*. Forsch Ingenieurwes, 70: 128-132. https://doi.org/10.1007/s10010-006-0022-8

SINGHAL A., PARVEEN M. 2013. *Airflow optimization via a venturi type air restrictor*. WCE, London.

ŚWIĘCICKI K. 2015. *Design of the intake system of an internal combustion engine*. Institute of Fundamentals of Machine Design, Silesian University of Technology, Gliwice.

Training documentation for the M54 engine M54engMS43/ST036/6/2000. Revision Date: 6/2000. BMW AG.

ZAJĄC P. 2009. *Silniki pojazdów samochodowych i podstawy budowy oraz główne zespoły i układy mechaniczne*. Wydawnictwa Komunikacji i Łączności, Warszawa.