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Selection of a Particulate Filter for a Gasoline-Powered Vehicle Engine in Static and Dynamic Conditions

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Abstract: Current challenges in terms of exhaust emission limits are related to the reduction of the particle numbers in spark ignition direct injection engines. The article concerns the analysis of the thermodynamic parameters of engine operation, allowing the selection of the particulate filter configuration and its technical parameters. The designed system consisting of an internal combustion engine and an exhaust system with an exhaust gas treatment system should be sufficient to meet ecological requirements in the form of reducing particulate matter emissions. The analysis of particulate matter emissions for the system without a filter and with a filter installed in the engine exhaust system was carried out for the mass, number and dimensional distribution of particulate matter. The result was an assessment of filtration efficiency for the entire spectrum of particulate diameters in the identified engine operating ranges. As a result, it was found that the particulate filter used in the engine exhaust system effectively reduces the particle number due to the greater filtration efficiency of large particles. The summary of the work related to the analysis of the ecological parameters of a spark ignition engine with direct fuel injection was a simulation of road tests of a vehicle with the proposed modified vehicle exhaust system equipped with a particulate filter. For this configuration, the analysis of particulate number emissions in the parameterized engine operating areas showed that it is possible to meet the particulate number emission limits, and the obtained road emission results are fully acceptable in terms of the obtained absolute values.

Keywords: gasoline vehicle; gasoline particulate filter; exhaust emissions; dynamic conditions

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1. Introduction

The negative environmental impact of combustion vehicles remains significant despite various solutions introduced in the automotive industry over the last decades. A shift towards pro-environmental policy aims to deal with the issue of excessive greenhouse gas emissions from combustion vehicles intended for road use. The depletion of non-renewable energy resources affects the development of the automotive industry. In the long term, ensuring a constant supply of crude oil and energy consumption issues have become very important aspects of the ongoing development of the automotive industry. The constantly increasing number of combustion vehicles operated on public roads increases concerns about excessive emissions of gaseous pollutants, solid particles and nanoparticles into the atmosphere. According to the WHO [1], the main threat to human health caused by motor transport sources is nanoparticles that contribute to cancer risk. Various legal acts were established to prevent this, introducing increasingly stringent limits on exhaust emissions, as well as systems of various penalties or incentives and subsidies regarding fuel consumption and the type of fuel used [2–4]. Currently, it is assumed that the exhaust emissions during the actual use of a vehicle are poorly reproduced in laboratory conditions; therefore, research methods are changing, and measurements in road conditions are being introduced [5,6]. Emissions in real-world conditions will become more important when such measurements become a legal requirement [7].

2. The Issue of Environmental Protection in the Case of Road Transport

Since 1990, carbon dioxide emissions from transport have increased by around 29%, with motor vehicles responsible for 12% of total emissions in the European Union (EU). As part of the "2030 Package", the EU has set a 30% emission reduction target compared to 2005 for sectors outside the emissions trading system. The general conditions established by the European Union were aimed to seek further restrictions. The plan is to reduce automotive emissions to 95 g/km in 2020 and to 68–78 g/km in 2025 [8]. Similar trends will also apply in the United States and Japan (Figure 1).

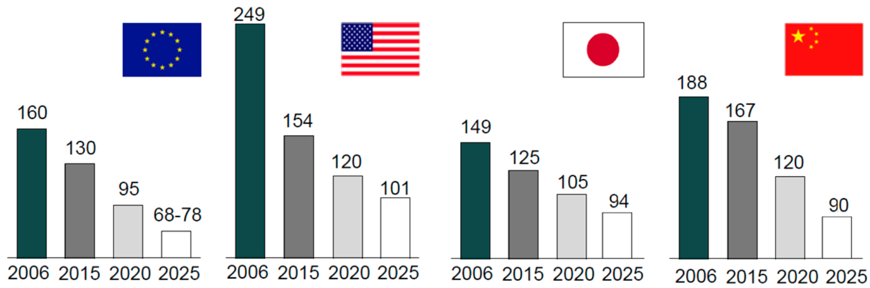


Figure 1. The planned reduction in carbon dioxide emissions in regions around the world [9,10].

Gasoline vehicles have great potential for reducing fuel consumption and, therefore, carbon dioxide emissions. Trends such as hybridization or gasoline direct injection are in the spotlight and have been partially implemented in current vehicles. A turbocharged spark ignition direct injection (SI DI) engine can be effectively used in accordance with the idea of down-sizing, maintaining the same operating efficiency while significantly reducing fuel consumption. However, a disadvantage of the gasoline direct injection (GDI) engine is the emission of nanometric particles [11,12], the actual extent of which can be determined mainly during operation. This is mainly related to the very high fuel injection pressure value (values up to approximately 400 bar are achieved) and significant fuel fragmentation. The requirement to determine the actual exhaust emissions from vehicles and the real driving emissions (RDE) procedure (real driving emissions) was introduced as a result of efforts to reduce the discrepancies between the results of laboratory tests and tests done in real traffic. A significant number of scientific studies have shown that laboratory testing procedures, in particular the type approval tests, did not constitute the best solution for emission testing (including fuel consumption). They provide significantly underestimated values compared with the results achieved during actual vehicle operation (Figure 2) [13].

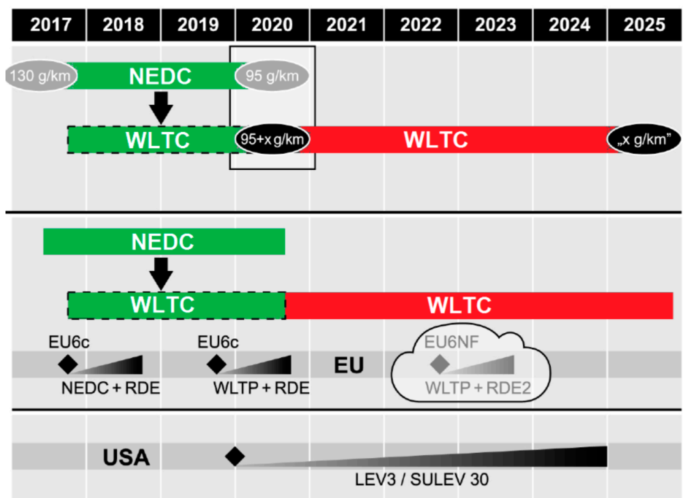


Figure 2. New regulations, the year of their implementation and effects on fuel consumption measurements (carbon dioxide emissions) and road tests.

Mobile devices for real driving emissions measurement are widely available nowadays and will soon be a legal requirement in the EU. However, the problem of linking the actual emissions with those determined in laboratory conditions still remains. Additionally, despite recent changes in legislation, many legal and technical elements regarding RDE remain unregulated [14–17]. The above factors push research and development activities to focus on the development of new low-emission vehicles, the use of alternative fuels, the introduction of new, more ecological types of engines, as well as the modification of exhaust gas aftertreatment systems. The above analysis shows that never before have emission tests, which involve weighing and counting particulate matter, measuring the amount of carbon dioxide produced, fuel consumption, as well as testing the efficiency of emission-limiting components, been so important from the point of view of industry and science. The development of regulations regarding the emission of harmful exhaust gas components in recent years has forced car manufacturers to improve the design of emission aftertreatment systems further. On the other hand, because the concentration of individual harmful components in the exhaust gases of modern engines is decreasing, it is necessary to develop methods for measuring these emissions. When measuring emissions from modern engines, it so happens that the concentration of individual measured exhaust gas components (diluted with air) is similar to the concentration of these components in the ambient air that was used to dilute the exhaust gas (or the same).

3. Aims

The main aim of the article was to analyze the ecological parameters of a supercharged spark ignition engine with direct fuel injection. The literature study and the authors' own experience have led to the conclusion that meeting the ecological requirements of the Euro 6c standard by vehicles powered by SI DI engines will not require changes in the verification of permissible emission values of gaseous compounds. Modification will be necessary, however, in terms of meeting the requirements for the number of particulate matter emissions, which is expected to lead to the use of gasoline particulate filters (GPF) in their exhaust systems, similar to those already used in diesel engines.

The realization of this research goal will require determining the ecological status of SI DI engines, for which the scope of work will be as follows:

1. Determine the ecological parameters of a supercharged spark ignition engine with direct fuel injection in the conditions of real road driving.
2. Determine the possibilities of improving the ecological condition of the engine to the level of subsequent ecological norms–with most attention given to the particulate matter emissions.
3. Possibilities of implementing exhaust aftertreatment systems (particulate filters) using thermodynamic analysis of fast-changing variable parameters to determine the exhaust gas temperature in the engine exhaust system.
4. Determine the engine operating parameters from real driving conditions (engine operating points—$T = f(n)$) for testing the SI DI engine on an engine dynamometer with the use of a particulate filter.
5. Analyze the possibilities of selecting the functional parameters of a particulate filter for a spark ignition engine with direct gasoline injection.
6. Determine the ecological benefits of the new solution, which involves retrofitting the standard engine aftertreatment system with a particulate filter, by comparing the results of road tests before and after the introduced modifications.

The tests were carried out in dynamic engine operating conditions during real vehicle driving. The analysis includes a summary of tests of ecological and thermodynamic parameters in actual vehicle operation. The research took into account the emission of gaseous compounds but focused in particular on the emission of the mass, numbers and dimensional distribution of particulate matter from the perspective of how necessary using a particulate filter is in order to meet the new legal regulations of the European Union and the particulate matter limits.

The development of a specific system—an exhaust aftertreatment system containing a particulate filter intended for vehicles with a supercharged spark ignition engine with direct fuel injection, and performing ecological tests to confirm the validity of the adopted solution would also confirm reaching the stated scientific goal of this article.

4. The Issue of Solid Particles Emission Limit

Many strategies exist for minimizing the formation of solid particles in the combustion chamber [18]. The first strategy assumes control of the entire combustion process and engine operating conditions. First of all, this strategy ensures that the temperature in the combustion chamber is sufficient to enable a complete combustion of the air–fuel mixture. Another way to prevent particle emissions is to minimize the oil layer in the combustion chamber. However, the most effective way to control the combustion process is to control the engine warm-up process after a cold start using an intelligent cooling system [19]. This solution has been used in many vehicles. The second strategy focuses on controlling the entire combustion process to ensure optimal efficiency [20]. This is achieved by ensuring optimal swirl of the fuel mixture, optimizing the speed of movement of the fuel mixture and preventing the formation of areas with a locally rich mixture composition. Moreover, the ignition delay parameter can be controlled and used to increase the exhaust gas temperature, which has a significant impact on the efficiency of the exhaust gas aftertreatment system. The third strategy aims to control the air intake conditions [21]. This can be achieved by providing sufficient air volume, optimizing valve coverage, implementing a variable valve timing system and optimizing the exhaust gas recirculation (EGR) system. Ultimately, the process of particulate formation is strongly linked to the fuel injection process. Therefore, there is a great need to implement optimal fuel injection models, minimize excessive wall wetting and improve the entire injection system by increasing the injected fuel pressure, ensuring high fuel temperature and using multi-stage fuel injection. Therefore, some design innovations are hybrid injection systems, which involve the simultaneous operation of direct (DI) and indirect (MPI) fuel injection systems.

The simultaneous use of these strategies may lead to a synergistic effect, further reducing the solid particle formation rate. However, the particle formation process cannot be completely avoided. In this context, the exhaust aftertreatment system plays a key role in reducing the mass and number of particulate matter released into the atmosphere. Improving the effectiveness of the exhaust aftertreatment system can be achieved by promoting the oxidation processes of particulate matter in the exhaust manifold. This is normally achieved by regulating engine operating parameters, which ensures high exhaust gas temperature and the supply of the appropriate amount of oxygen. It is also important to reach the operating temperature (T50) in a relatively short time, which determines the efficiency of the catalyst.

The worst-case scenario assumes expanding the overall shape and complexity of the exhaust aftertreatment system by adding particulate filters. Currently, diesel engines are usually equipped with this type of solution. However, in relation to spark ignition engines with direct injection, there is still an ongoing debate in the political and economic context about the validity and necessity of introducing GPF technology. On the one hand, this solution would reduce the overall particulate emissions to negligible values, but on the other hand, it is associated with high development and deployment costs. As of today, car manufacturers have not yet made a final decision on whether to use GPF systems or stick to other solutions. In summary, there are many methods of reducing particulate emissions, with varying degrees of effectiveness. However, in the context of the future, it is important to make a wise choice using the most effective and cheapest possible strategy—at least from the consumer's point of view.

According to the results presented in [22,23] (Figure 3), the use of GPF significantly reduced PN emissions to a level comparable to that of PFI engines. Unfortunately, this solution is still in the development phase due to economic and technical problems in its application. The estimated cost of a GPF is EUR 50–230 [24]. Manufacturers also take into account technical aspects, which are filter size, its location in the exhaust aftertreatment system and filter structure.

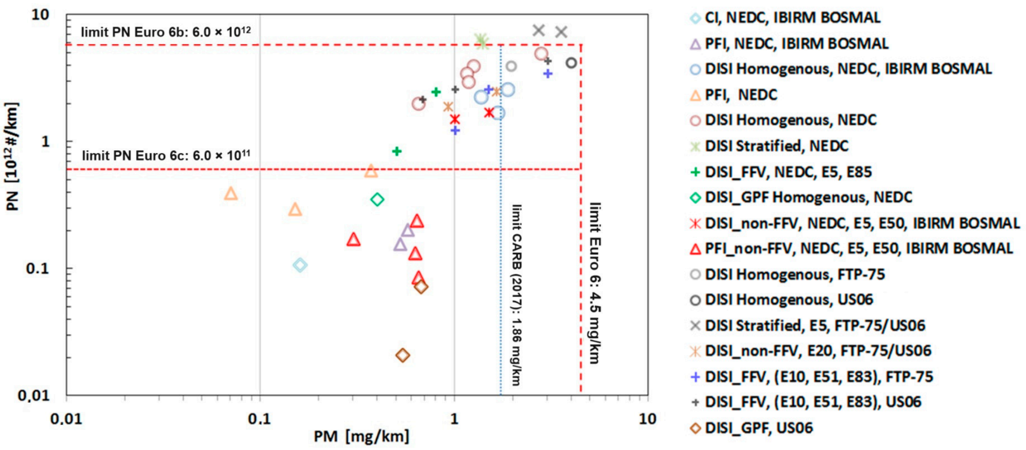


Figure 3. PM and PN exhaust emissions map for the presented engine system types (based on data from [22,23,25]).

The development of new DI SI engines creates a new problem for spark ignition engines—particulate emissions. Due to the continuous development of internal combustion engines, both compression and spark ignition, many countries have introduced more stringent and complex exhaust emission norms. In Europe, not only is the mass of particulate matter legally limited but the number of particles emitted from diesel and SI DI engines is limited as well. The problem for manufacturers is the future PN Euro 6c standard, which is to apply to SI DI engines. SI engines with direct fuel injection, which are already available on the market, do not meet future requirements for the particulate number emission (PN).

5. Research Method

5.1. Test Object

The research plan assumed that tests of ecological and fast variable parameters would be carried out during actual operation and on a stationary test stand using a mobile system for measuring exhaust pressure and emissions. This system could register any available data regarding the engine and vehicle operating parameters via the controller area network (CAN) bus. Data from the vehicle controller were used to determine the engine speed, engine load, vehicle speed, fuel flow rate and coolant temperature. It should be noted that the exhaust emission test results obtained during road tests were actual values for a given type of vehicle and concern specific road conditions. Such conditions make it possible to estimate the degree of environmental impact of the tested vehicles and their engines during their typical operation. The tests carried out on a stationary testing stand will be dictated by the need to modify the engine exhaust system.

Road tests were carried out on a car equipped with a supercharged spark ignition engine with direct injection, compliant with the Euro 6c exhaust emission standard (engine characteristics are shown in Figure 4). The aim of the research was to determine the road emission of compounds contained in vehicle exhaust gases in accordance with the requirements of the standard and to define the engine operating points in real driving conditions, thus enabling further tests on a stationary test bench.

Technical parameters of the tested vehicle were the following:

- Engine type spark ignition
- Displacement 1197 cm^3
- Piston stroke 75.6 mm
- Cylinder diameter 71 mm
- Compression ratio 10
- Maximum engine power 63 kW at 5000 rpm

- Maximum torque — 160 Nm at 1500–3500 rpm
- Boost — supercharger
- Camshaft location — DOHC
- Number of valves — 2 valves per cylinder
- Injection type — direct

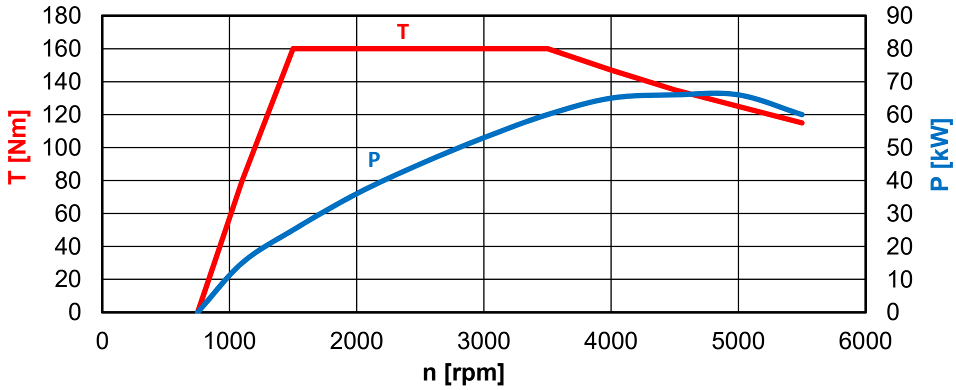


Figure 4. The torque and power characteristics of the tested engine.

5.2. Measuring Equipment

Semtech DS mobile analyzer from Sensors was used to measure the concentration of harmful exhaust compounds. The device characteristics are given in Table 1. It enabled the measurement of the concentration of the exhaust compounds CO, NO_x and CO_2. The central unit of the analyzer received data directly from the vehicle's diagnostic system and a GPS location signal. It is advised to use the mentioned configuration of measurement equipment for assessing exhaust emissions in real traffic conditions, as given by the existing literature on the use of portable emissions measurement systems in connection with data recorded from on-board diagnostic systems.

Table 1. Technical specifications of the Semtech DS device used to make measurements and to read data from the on-board diagnostics system in the tested vehicle.

Parameter	Measurement Method	Accuracy
CO	NDIR, range 0–10%	±3% of the measurement range
NO_x = (NO + NO_2)	NDUV, range 0–3000 ppm	±3% of the measurement range
CO_2	NDIR, range 0–20%	±3% of the measurement range
O_2	electrochemical, range 0–20%	±1% of the measurement range
Exhaust gas flow	Mass flow rate	±2.5% of the measurement range
Compatible diagnostics systems CAN	OBD: ISO, CAN, VPW, PWM	–

The Semtech DS analyzer was designed mainly to measure the concentration of harmful exhaust gas components in passenger cars and heavy agricultural and construction vehicles. The DS version enabled the measurement of emissions from both engines powered with petrol and natural gas. All components of the Semtech DS analyzer were designed to be as close in specs to laboratory-class measurement devices as possible and, at the same time, able to meet the special requirements for vehicle emission monitoring devices. Meeting these requirements necessitated a maximum reduction in weight, size and energy consumption of the device while reducing susceptibility to vibrations, temperature changes and other external factors that could distort the results. It can be used to monitor emissions from various vehicles in motion, as well as for testing engines on a dynamometer. The analyzer meets the requirements of Standard 1065 [26] for exhaust emission measurements with Portable Emission Measurement Systems (PEMS).

The TSI 3090 EEPS™ (Engine Exhaust Particle Sizer™ Spectrometer) analyzer was used to measure the number of particles (Table 2). It was able to measure a discrete range of particle diameters (in the range from 5.6 to 560 nm) emitted in exhaust gases based on their different speeds (Figure 5). Thanks to the ability to record measurements at a frequency of 10 Hz, the analyzer could be used to measure particulate emissions in transient engine states.

Table 2. Technical specifications of the TSI 3090 EPSS™.

Operating Features	Value
Particle size range	5.6 to 560 nm
Particle size resolution	16 channels per decade (32 total)
Electrometer channels	22
Time resolution	10 size distributions/s
Sample flow	10 L/min
Sheath air	40 L/min
Operating temperature	0 to 40 °C

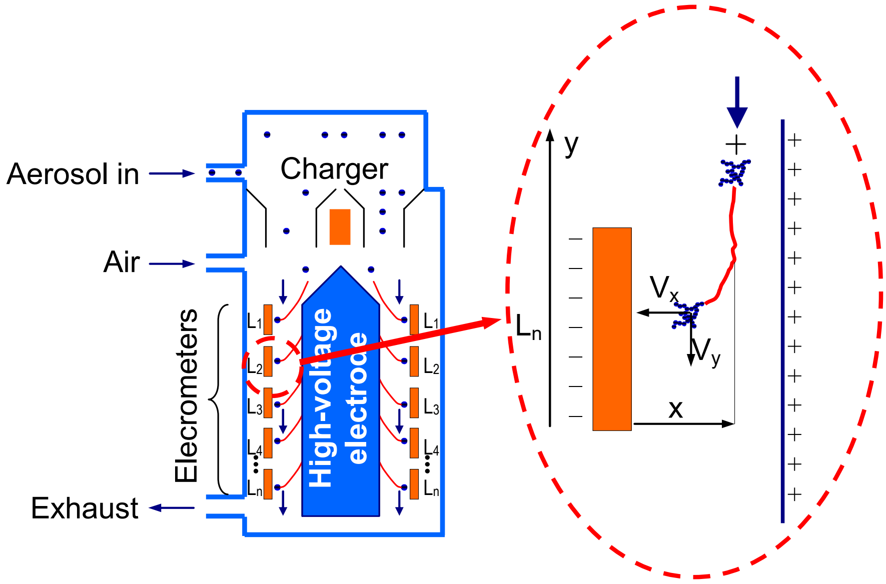


Figure 5. Method of measuring the dimensional distribution of particulate matter by a TSI EEPS mass spectrometer; V_x, V_y—components of the particle velocity moving between the electrodes; $L_1 \ldots L_n$—segregating electrodes.

The schematics of the connection of the described devices are shown in Figure 6.

A measurement system consisting of the following elements was used to measure the temperature and pressure of exhaust gases (Table 3):

- For temperature measurement—thermoelectric sensors (thermocouple) made by Czaki with the designation TP-204 (K);
- For pressure measurement—PR-21Y series sensors from Keller;
- Iotech Personal DAQ 3000 signal converter.

Table 3. Specifications of devices used to measure the exhaust gas temperature and pressure.

Parameter	Temperature Measurement	Pressure Measurement	Iotech Personal DAQ 3000	
			Voltage	Thermocouple
Range	−40–1100 °C	0–0.4 MPa	−10 V–10 V	−200–1200 °C (type K)
Accuracy	±0.5%	±0.25% of range	±0.031%	±1.8 °C

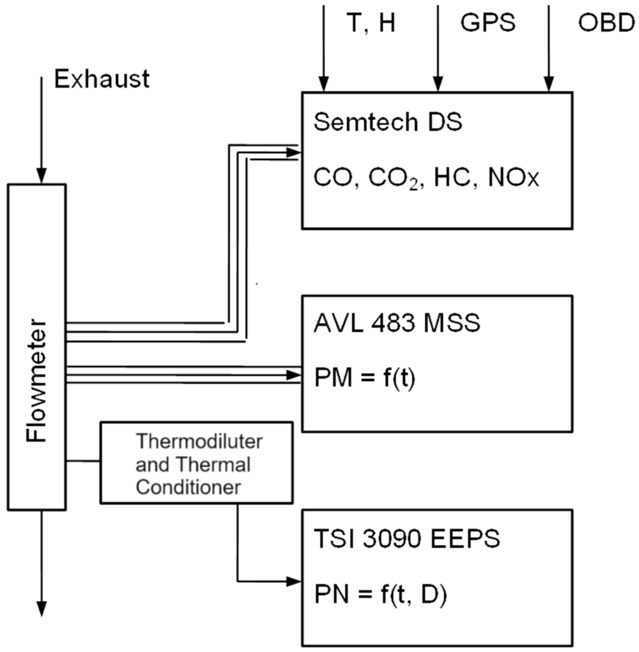


Figure 6. Connection schematic of the measuring devices used.

The Iotech Personal DAQ 3000 signal converter included a USB interface and an A/D converter (1 MHz/16 bit). There were 16 single-ended analog inputs (8 differential inputs), 4 analog outputs, 24 digital input/output lines and the device could be programmed in 7 ranges from ±100 mV to ±10 V. Information from the sensor was transmitted to a computer that recorded data at a given frequency.

A special data acquisition system was used to record the rapidly changing variables of the tested engines, which could perform calculations and analyses from the recording in graphical form in real-time. Rapidly changing variables, such as pressure inside the cylinder and the signal from the crankshaft position sensor, were recorded at a frequency of 1 MHz. Equipment was used to record processes occurring inside the AVL IndiMicro 602 combustion chamber to study rapidly changing variables (Table 4). Information necessary for the proper operation of the cylinder pressure recording system was obtained from the position of the crankshaft. The signal informing about the position of the crankshaft was obtained from an inductive sensor cooperating with the toothed pulley via an analog-to-digital converter AVL Universal Pulse Conditioner 389Z01. The signal received from the analog-to-digital converter made it possible to record the change in cylinder pressure as a function of the crankshaft position of the tested SI engine.

Table 4. Technical specifications of the AVL IndiMicro 602 analyzer.

Parameter	Value
Analog input channels	4 channels for piezoelectric sensors
Sampling frequency	1 MHz per channel
ADC resolution	16 bit
Analog input signal	±10 V
Digital input channel	2 channels
CAN interface	Yes
Input range (piezoelectric)	Up to 14,400 pC
Linearity	±0.01% of the range
Filters	2, 5, 10, 20, 50, 100 kHz
System	IndiCom Mobile

The pressure signal is fed to the recording computer from a pressure sensor cooperating with the appropriate measurement line. Piezoelectric pressure sensors are usually used to record rapidly varying pressures in the engine cylinder (Figure 7). These sensors use the piezoelectric effect, which involves the generation of an electric charge by a quartz crystal under the influence of a force applied to it. This type of transducer must cooperate with a charge amplifier, which converts the charge generated by the crystal into electrical voltage. This voltage is then recorded by a measurement card installed on the computer. The data obtained in this way are saved on the disk and can be further analyzed.

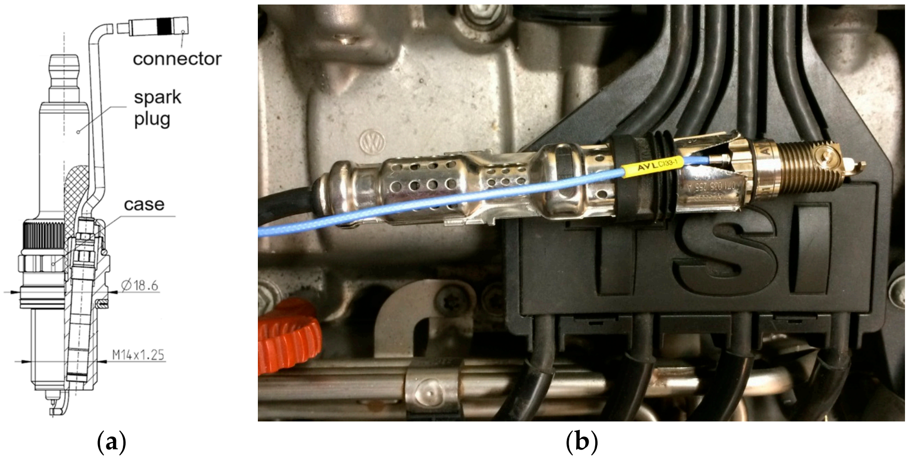


Figure 7. Piezoelectric pressure sensor integrated with the spark plug: (**a**) cross-section; (**b**) picture.

5.3. Method of Assessing the Range of Engine Operational Parameters

In order to determine the operating ranges of the combustion engine with the highest share of operating time and the exhaust emission rates, vehicle and engine operating parameters were also recorded. During the trip, parameters related to the vehicle (including vehicle speed and acceleration) as well as parameters related to engine operation (including rotational speed, load and coolant temperature) were recorded with a frequency of 1 Hz. The recorded changes in rotational speed n = f(t) and engine load Z = f(t) allowed for the creation of two-dimensional engine operating characteristics based on the test results. The most important issue in such characteristics is determining the number of rotational speed intervals and the number of relative load intervals to group the data points into. Properly determining those intervals enables the subsequent generalization of the obtained results. The authors propose, in accordance with the assumptions presented in previous publications [27], to determine the number of intervals based on the following:

- The minimum average value of adjacent elements in individual intervals (i, j), which is a measure of data variability in these intervals—smaller values were the basis for assuming that the middle point of a given interval is representative of the real engine operating conditions in that interval;
- An equal number of rotational speed intervals (N) and load intervals (K);
- Limiting the maximum total number of intervals to 100.

Determining the division of the operating area common to all engines requires the adoption of a standard test duration. It was assumed that this should be a period not shorter than the test length specified in the RDE requirements (3600–5400 measurement points). Determining the intervals began with the values of N and K, which were 5 × 5. The adopted values for dividing the engine operating area allowed the filling of almost all elements (i, j), which was not fully consistent with reality. For the sample data, the maximum runtime in an interval was 37.7%, with a maximum variability value of 19.7%, while the average value of the standard deviation (only for filled intervals) was 4.06. The same procedure was repeated for subsequent values of N and K, increasing them by one unit up to a value of 10. By comparing the obtained average variability values for the entire operating field, a relationship was obtained (Figure 8), which showed that the division that was most consistent with the requirements was dividing the engine operating area into K × L elements with values of 10 × 10.

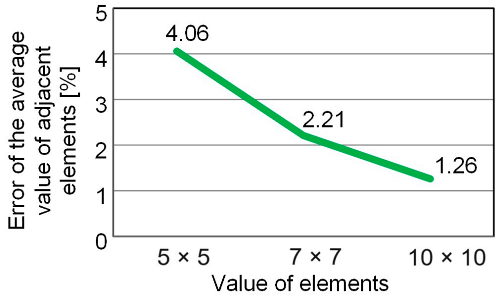


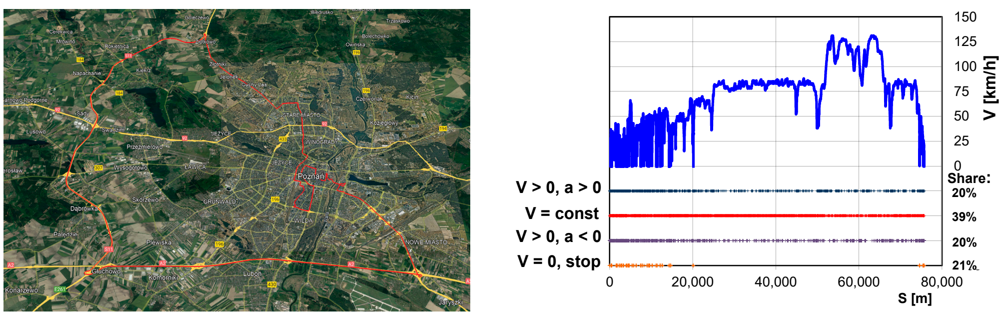
Figure 8. Results of the interval division analysis from the number of elements equal to 5 × 5 up to 10 × 10.

Designated, parameterized operating ranges of combustion engines in real traffic conditions can be a determinant for conducting exhaust gas toxicity tests using mobile exhaust emission analyzers. The presented issue has no equivalent in legal regulations, but it may be an indication of the possibilities of the ecological assessment of vehicles in real operation. It may be another way to assess the technical condition of vehicles, characterized by a detailed assessment of the vehicle's emission. Such a procedure may be performed in road traffic parallel to emission procedures at vehicle inspection stations.

6. Research Results and Analysis

6.1. Exhaust Emissions Tests in Real Driving Conditions

The measurements were performed 4 times in real driving conditions on urban, rural and highway routes. The average travel distance is 80.21 km along the test route (Figure 9a). The test route was designed in such a way as to meet the requirements described in the regulations [14,15], with particular emphasis on its topography. In the first stage, the validity of the research tests was verified because the validity determines the selection of measurement points for further analyses performed in the article. An example route is shown (Figure 9b). The research route was divided into three cycles: urban (0–60 km/h), rural (60–90 km/h) and motorway (over 90 km/h). Despite the similar test route, both the results of the obtained speed value and its average values in individual parts of the test are not the same. However, the drive route parameters defined by acceleration, constant speed, braking and standstill are similar.



(**a**) (**b**)

Figure 9. The test route chosen for the research (**a**) and example of a vehicle speed curve and vehicle driving parameters (**b**).

The validity of the test parameters confirmed the correct performance of the road tests, which resulted in an analysis of the ecological and thermodynamic parameters obtained in the test and an analysis of the selection of engine operating points used in further tests. During tests of a vehicle with an SI DI engine, measurements of the concentration of gaseous compounds (CO, NO_x) and particulate matter (mass and number concentration) in the exhaust gases were made, as well as measurements of the changes in engine speed and load—parameters read from the vehicle diagnostic system.

The recorded data of individual pollutant concentrations allow for the establishment of the relationships that characterize the impact of the engine's dynamic properties on the exhaust emission when considering the measurement results from the entire test route. The dynamic engine properties were taken into account indirectly, using the division of the entire range of rotational speed and load of the engine in real driving conditions to create graphs of the emission rate of individual exhaust gas components. This data is presented on the engine characteristics in terms of rotational speed and load.

By relating the given exhaust emission values to the engine rotational speed and load, characteristic relationships of the tested engine parameters were obtained, where the following information could be deduced:

- The maximum emission rate of carbon monoxide (Figure 10a) is approximately 70 mg/s and occurred at a rotational speed in the range of 2500–3000 rpm and a load in the range of 20–70%;
- The maximum emission rate of nitrogen oxides (Figure 10b) is approximately 2–3 mg/s and occurred at a rotational speed of 1500–2000 rpm and a load value in the range of 10–30%,
- The maximum emission rate of particle number (Figure 10c) is approximately 8×10^{13} 1/s and occurs for engine rotational speeds in the range of 1000–2000 rpm and a load in the range of 20–30%.

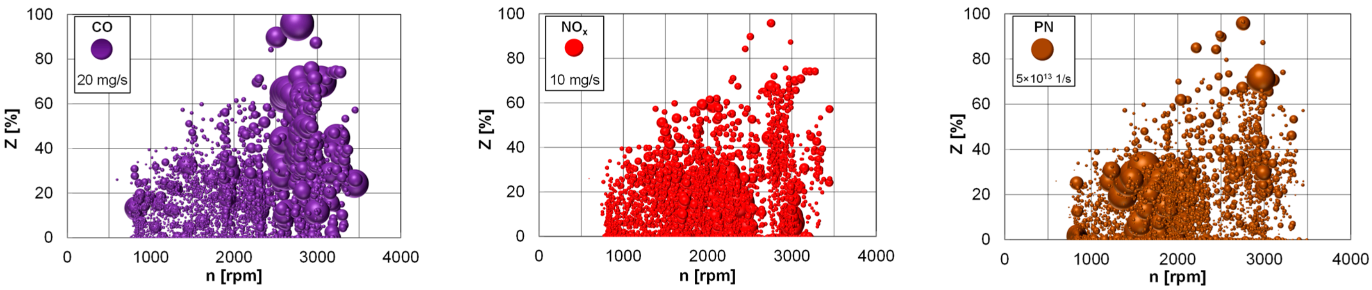


Figure 10. Exhaust emission intensity values recorded in drive tests of the SI DI vehicle on the test route for particle number: (**a**) CO; (**b**) NO_x; (**c**) PN.

The road emission results were determined in accordance with the procedure presented in the legal directives [16,17], which limited the reporting of results only to the values of road emissions of carbon monoxide, nitrogen oxides and the number of particles. The following values were obtained:

- Road emissions of carbon monoxide in the urban section—0.13 g/km, in the rural section—0.18 g/km and in the motorway section—0.4 g/km; throughout the entire test, a mean value of 0.24 g/km was obtained (Figure 11a);
- Road emissions of nitrogen oxides in the urban section—0.038 g/km, in the rural section—0.015 g/km and in the motorway section—0.009 g/km; throughout the entire test, a mean value of 0.021 g/km was obtained (Figure 11b);
- Road emission number of particles in the urban section—2.5×10^{12} 1/km, in the rural section—2.1×10^{12} 1/km and in the motorway section—1.6×10^{13} 1/km, with a mean value of 2.3×10^{12} 1/km obtained for the entire test (Figure 11c).

The obtained road emissions values of exhaust components (carbon monoxide, nitrogen oxides and particle number) were used to determine emission indicators, whose maximum permitted legal value in 2022 was 1.5 (the value of the indicator was obtained by dividing the value of road emissions by the road carbon monoxide emission limit of

1000 mg/km, road emission limit of nitrogen oxides of 60 mg/km and the emission limit of particle number of 6×10^{11} 1/km). Thus, the following values were obtained:

- Road carbon monoxide emission indicator in the urban section—0.13, in the rural section—0.18 and in the motorway section—0.4; and the mean value of 0.24 was obtained in the entire test (Figure 12a);
- Road nitrogen oxide emission indicator in the urban section—0.48, in the rural section—0.19 and in the motorway section—0.11; while, in the entire test, a value of 0.26 was obtained (Figure 12b);
- Road emission indicator of the particle number in the urban section—4.1, in the rural section—3.6 and in the motorway section—2.7, while a value of 3.8 was obtained in the entire test (Figure 12c).

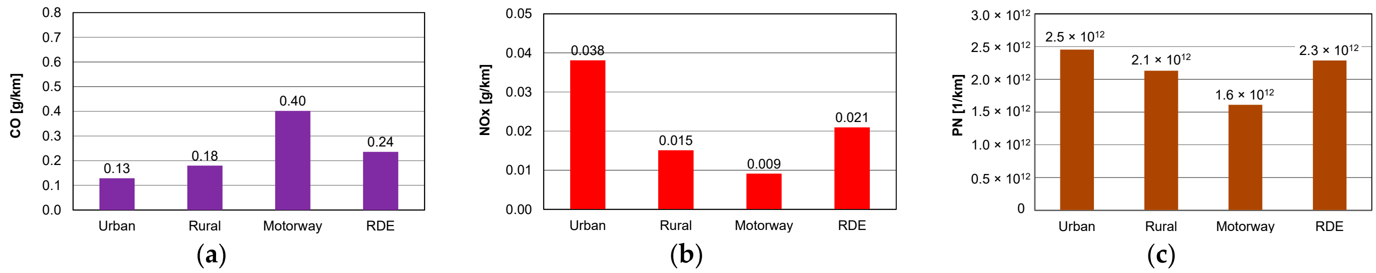


Figure 11. Road emissions of carbon monoxide (**a**), nitrogen oxides (**b**) and particle number (**c**) obtained in individual sections of the test as well as the overall mean value from the entire test.

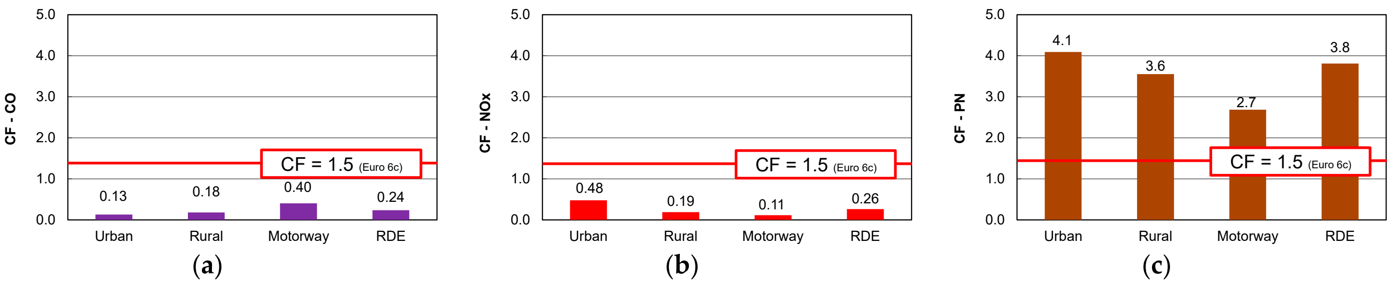


Figure 12. Emission indicators of carbon monoxide (**a**), nitrogen oxides (**b**) and particle number (**c**) obtained in individual sections of the RDE test.

The presented summary has shown that only the indicator of particle number emission does not meet the legal requirements for the permissible emission indicator value. Therefore, the solution to this issue is to retrofit the tested engine with a particulate filter. However, this required analyzing the thermodynamic parameters of the combustion process in the SI DI engine, as well as estimating the exhaust gas temperature in the entire engine exhaust system. Such an analysis was carried out in the next chapter of the work.

6.2. Analysis of Thermodynamic Parameters of an SI DI Engine

Knowing the temperature in the combustion chamber and the temperature at the exhaust system outlet was to make the decision whether to accept or reject the thesis about the possibility of using a particulate filter in the engine exhaust system. Additionally, knowing the temperature values in the entire engine exhaust system can allow us to estimate the best location of such a filter. Detailed tests on these aspects were performed on a testing stand after selecting the characteristic operating points of such an engine. Using the recorded maximum cylinder pressure curves obtained in road tests, a two-dimensional characteristic of this parameter (in MPa) was made in the engine speed and engine load coordinates (Figure 13).

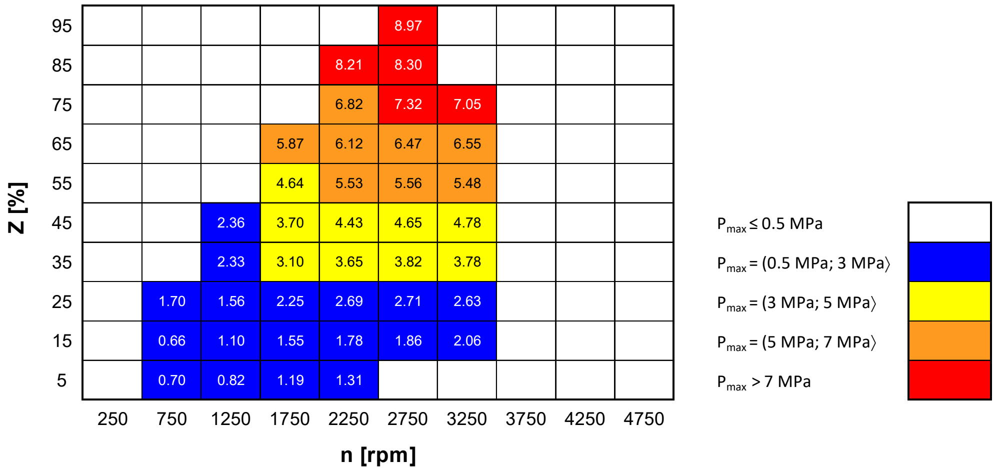


Figure 13. Maximum pressure distribution in the combustion chamber in rotational speed–engine load coordinates during road tests.

Analyzing this chart shows that the highest pressure was achieved for the engine operating area, contained within the rotational speed in the range of 2000–3500 rpm and engine load in the range of 70–100%. For this range of engine operating parameters, the maximum pressure value exceeds 7 MPa. For medium load values and rotational speeds, the maximum combustion pressure is observed in the range from 3 MPa to 7 MPa, and for the smallest load values for the entire rotational speed range, it does not exceed 2–2.5 MPa. The value of the maximum combustion temperature was determined using the maximum cylinder pressure characteristics in the same ranges of rotational speed and engine load (Figure 14). The nature of the distribution of the maximum combustion temperature values is very similar to the distribution of the maximum pressure values. The highest value of the combustion temperature was found for the engine load in the range of 70–100% and the engine speed in the range of 2000–3500 rpm. In this range, the value of the maximum combustion temperature is 2000–2500 K (red area in Figure 14). This value decreases in the medium load and medium rotational speed range, reaching values of approximately 1000–1200 K. For the lowest rotational speed and load values, the measured temperature values do not exceed the range of 600–800 K.

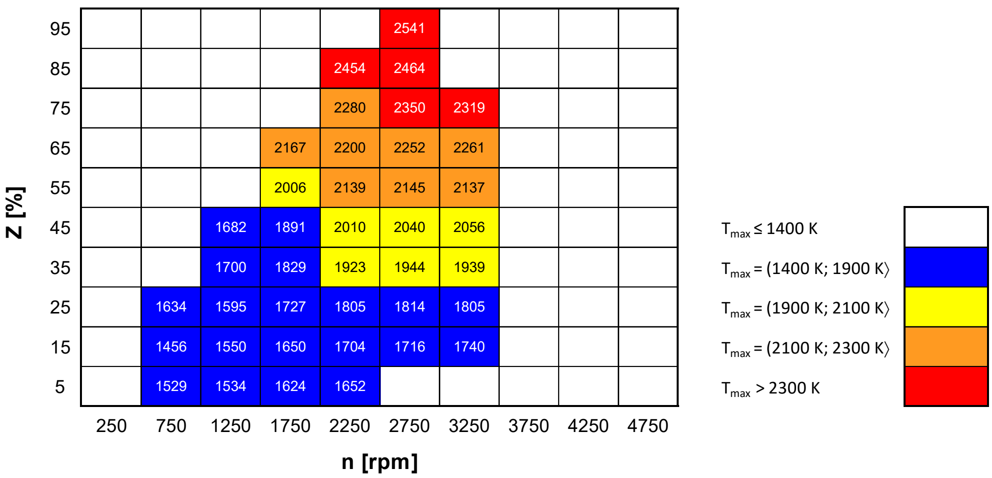


Figure 14. Maximum temperature distribution in the combustion chamber in rotational speed–engine load coordinates during road tests.

The obtained exhaust gas temperature values at the end of the vehicle's exhaust system (at the point where the exhaust gas sample was taken) allowed for the determination of a similar temperature distribution relationship in this area (Figure 15). The analysis of this data showed that the nature of the data distribution is different—mainly, the exhaust gas temperature measured at the end of the exhaust system depended on the engine speed and varied only slightly based on the engine load. A change in the engine load at a rotational speed of 2750 rpm caused this temperature to change by less than 30 K.

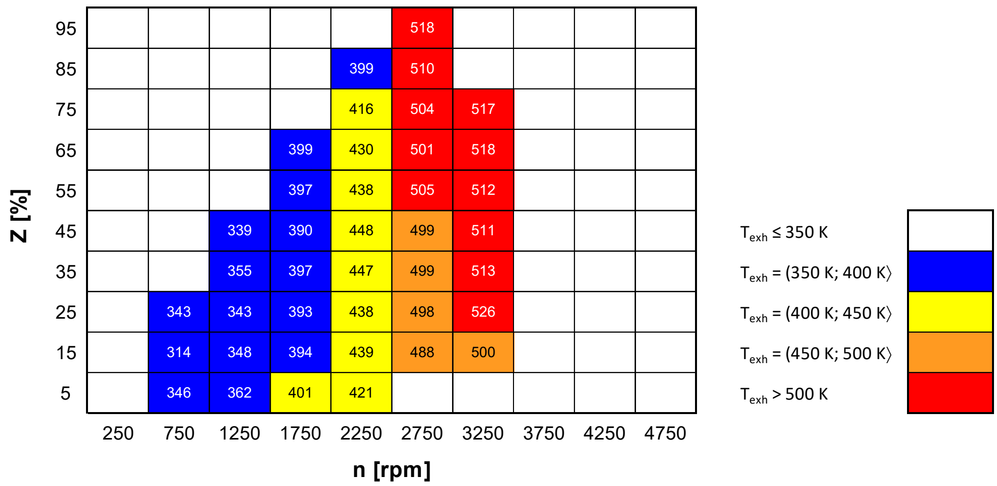


Figure 15. Distribution of exhaust gas temperature values (measured at the endpoint of the exhaust system with an exhaust gas flow meter) relative to the engine rotational speed and load during road tests.

Analyzing Figures 14 and 15 shows that the temperature drop in the engine exhaust system (after assuming that the exhaust gas temperature after the exhaust valve was 70% of the maximum combustion temperature) is in the range of 700 to 1300 K, which meant that the use of a particle filter in the engine exhaust system is possible. It should be taken into account that the temperature drops on the turbocharger is approximately ΔT_{turbo} = 100–200 K (lower values for the minimum exhaust gas temperature and a larger value drop for the maximum exhaust gas temperature). Therefore, the following section is used to specify the engine operating points for which a thorough thermodynamic and ecological analysis of its operation should be carried out.

6.3. Selection of Engine Operating Points Based on the Road Test Data

The presented analysis, concerning journeys in accordance with the RDE road test standard requirements, allowed for the selection of driving conditions that were used to determine the engine operating areas, which were then selected for static tests on an engine dynamometer. The selection of engine operating points was made based on a parametric analysis using the method where the share of the duration of the engine operating in a given range of parameters in the entire road test. In order to achieve this, a two-dimensional characteristic was used in the engine speed–engine load coordinates, where the share of engine operating time in a given area of the characteristic was the third variable. The selection algorithm was presented both in relation to the percentage load of the engine and also in engine speed–torque coordinates, knowing the characteristics of the engine used for road tests. The latter approach made it possible to easily translate the data obtained from road tests (selected engine operating points) into input data used for further stationary research. The selection of points was made using all the viable performed trips, and the final result was averaged. By doing this, the uniqueness of road tests was also taken into account, and the further analysis presented was not burdened with data that would be insufficiently representative of reality (Figure 16).

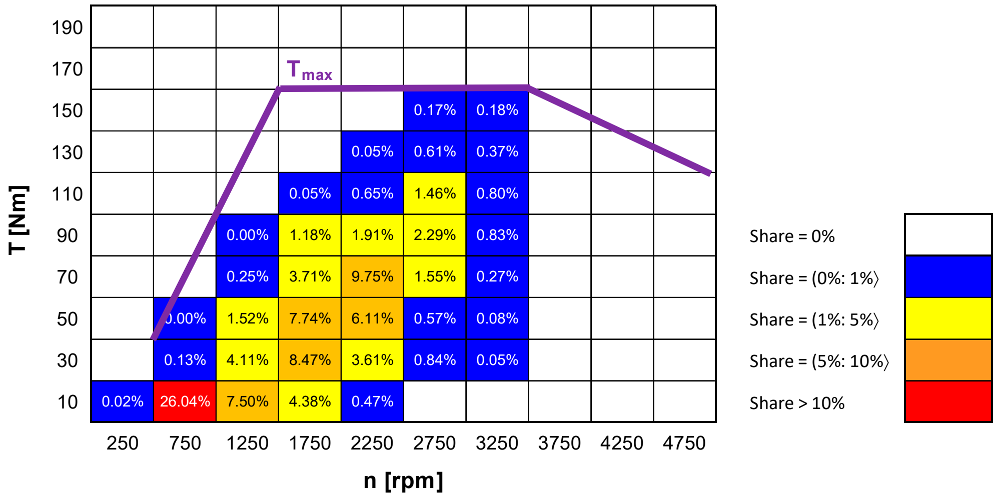


Figure 16. The averaged two-dimensional characteristic u = f(n, T) from four trips with the torque curve marked.

The points selected for further testing on the engine dynamometer should be characterized by a large share of operating time in the overall engine operating characteristics. Therefore, it was decided to abandon several dozen points from Figure 16 and replace them with several data points that were characterized by a significant share of occurring during engine operation. After narrowing and averaging the data (the arithmetic mean of individual cells adjacent to cells with the highest operating time share value was determined), operating areas were selected (Figure 17), which were used for further research.

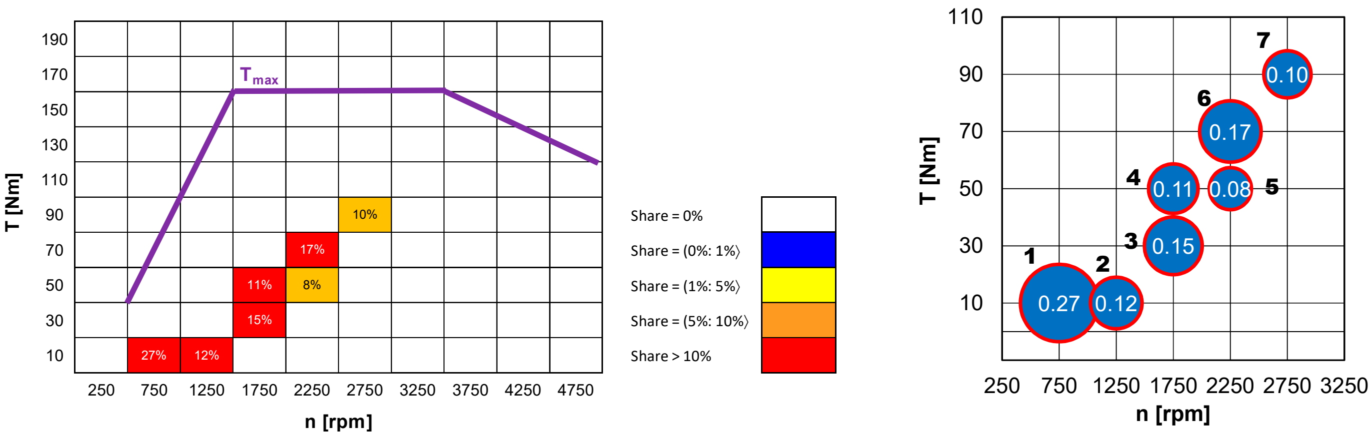


Figure 17. The selected engine operating points used in the next step of research presented in the engine operating characteristics.

Unfortunately, the selection of characteristic engine operating points did not coincide with the highest temperature values in the exhaust system. However, this did not prevent the implementation of the dissertation's further plan because the selected engine operating points partially coincide with the highest values of particle number emissions.

6.4. Selection of a Particle Filter for the SI DI Engine Used in the Further Research Steps

It is estimated that solid particles contained in the exhaust gases of gasoline engines have a morphology comparable to those emitted by diesel engines. Fractal analysis has shown the similarity of particulate matter aggregates from gasoline direct injection engines to particulate matter from diesel engines. In SI DI engines, aggregated particles mainly contain chain structures consisting of several to several hundred primary particles. The agglomeration of smaller particles on the aggregates is the result of the combustion of the mixture created during late fuel injection. Solid particles formed in this way contain a significant number of aggregates (including primary particles) with sizes smaller than 20 nm [28]. When burning mixtures obtained with late fuel injection, a much larger share of the smallest nanoparticles can be found than in those formed with early injection. These nanoparticles are usually characterized by a graphene structure and sizes in the range of 9–25 nm. An increase in the load when the engine is operating at lower rotational speeds and with an increasing injection advance angle will result in the formation of primary particles with larger diameters.

Due to the selection of engine operating points at which the maximum exhaust gas temperature did not occur, it was assumed that the selected catalytic set would be of the TWC + GPF type in separate parts, with the TWC being used in a close-coupled configuration and the particulate filter in the underfloor configuration covered with a catalytic layer, which supports oxidation and reduction reactions.

By choosing a catalytically coated GPF filter, it was possible to increase the oxygen concentration locally, which could allow the filter to be regenerated. When the engine operated in the lean mixture combustion mode, both the oxygen concentration and the exhaust gas temperature were sufficient to carry out the oxidation of particulates (filter regeneration). Lower concentration of particulate matter from gasoline engines meant a negligible increase in filter temperature caused by exothermic reactions, which is important due to lower requirements in terms of additional thermal insulation between the filter and the vehicle body as well as the possibility of using filters with a much smaller ratio of the filter carrier volume to the engine displacement volume. Vehicles with SI DI engines require this ratio to be in the range of 0.7–0.85. For this reason, the particulate filter used should have a volume of 0.85–1.0 dm^3 (the engine had a displacement of 1.2 dm^3).

Typical cell density for a filter intended for gasoline engines is in the range of 200–400 cells per square inch (cpsi), and the wall thickness is 0.4–0.8 mm. However, the notation regarding the construction of the filter is simplified, such as 5/220, for example, indicates a wall thickness of 0.5 mm and 220 cells per square inch.

Both the number of cells per square inch and the wall thickness affect the open area of the inlet. In the proposed catalytically coated filter, the inlet area will be smaller (than for filters without catalytic coating); therefore, the thickness of the catalytic layers should be selected according to the above-mentioned parameters, which affect the exhaust gas flow resistance. It was decided to use an innovative particulate filter with the following parameters, taking into account all the above-mentioned issues (the view of the tested filter is in Figure 18):

- Particulate filter in underfloor configuration covered with a catalytic layer that supports oxidation and reduction reactions;
- Filter volume—1 dm^3;
- Wall thickness—0.5 mm;
- Number of cells per square inch—300 cpsi;
- Open inlet cross-section area—88%;
- Porosity—65%.

Figure 18. The filter used for research.

The next stage presented the results of comparative stationary tests using the engine and exhaust system (basic and modernized) carried out on a dynamometer.

6.5. Verification Tests of the Modified Combustion Engine Exhaust System Assembly

Tests were carried out on a stationary dynamometer stand with the engine operating points determined based on the tests in real conditions; points on the engine characteristics are shown in Figure 19. It was assumed that the permissible rotational speed error for a measurement point was ±50 rpm, and the torque error was ±2% T_{max} for the tested rotational speed. The engine operating time and measurement of characteristic parameters (including temperature, pressure, pollutant concentration and exhaust gas flow rate) at individual measurement points was obtained after thermal stabilization of the engine and exhaust system, which ranged from 5 to 10 min time, depending on the engine operating point.

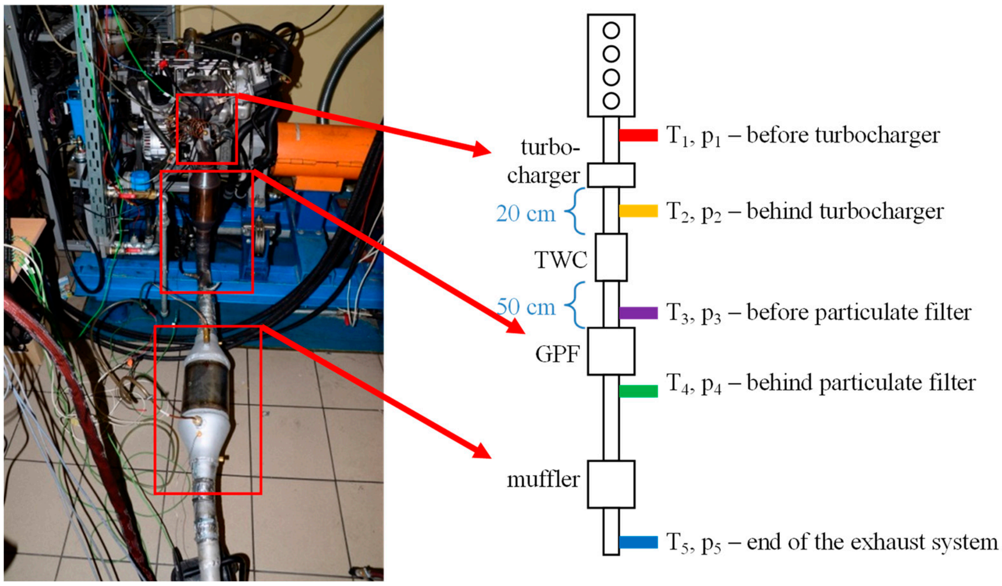


Figure 19. The engine test stand with its main parts.

The research was carried out in two stages:

- The first stage consisted of measuring thermodynamic and ecological parameters before the particulate filter was added to the exhaust system;
- The second stage consisted of comparing only the ecological results obtained before and after the particulate filter was added; such an approach was chosen because the combustion process thermodynamic parameters did not change due to the installation of the particulate filter in the exhaust system.

In the next stage, the engine thermodynamic parameters obtained in the dynamometer tests were discussed, which mostly meant determining the maximum combustion temperature in static engine operating conditions. It was also important to determine the temperature of the exhaust gases leaving the cylinder. This value was determined by determining the temperature change in the cylinder as a function of the crankshaft position.

The tests were carried out for each selected data point (described by engine rotational speed and torque values) in steady engine thermal state conditions (coolant temperature was over 85 °C). The obtained exhaust gas temperature values during the opening of the exhaust valve were used to determine the temperature in front of the turbocharger (Figure 20), which, due to the too-small distance between the turbocharger and the end of the exhaust manifold, was not determined using a thermocouple. This value was determined from the analysis of pressure and temperature graphs in the combustion chamber at the point of opening the exhaust valve at a crankshaft rotation angle of 162 °CA. The results shown in Figure 21 were obtained assuming a temperature drop between the opening of the outlet valve and the compressor inlet space of approximately 200 K.

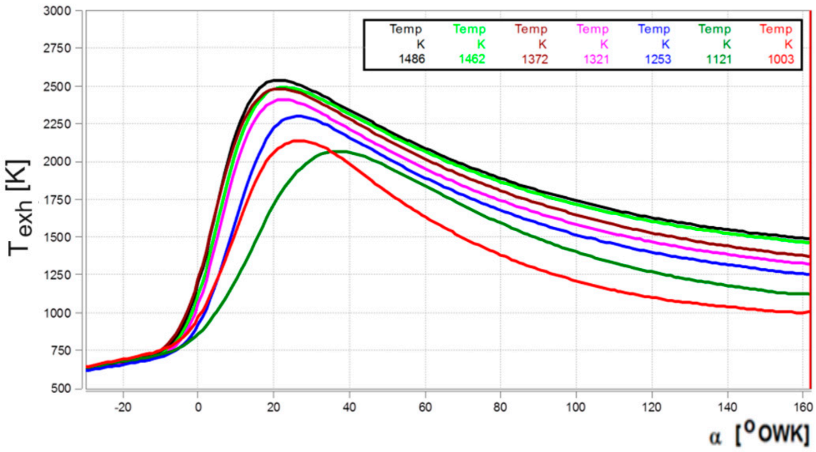


Figure 20. The determined values of exhaust gas temperature when the exhaust valve opens (the temperature values correspond to the engine operating points in Figure 17).

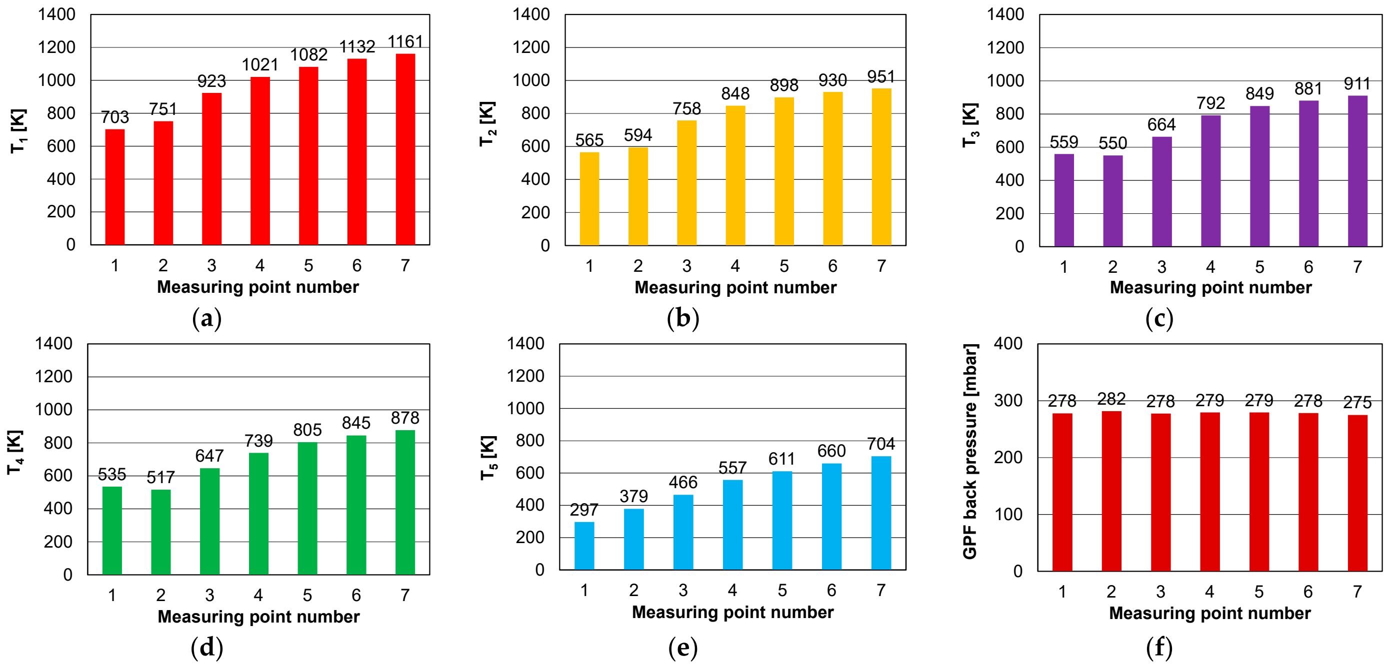


Figure 21. Summary of temperatures upstream of the turbocharger (**a**); downstream of the turbocharger (**b**); upstream of the GPF (**c**); downstream of the GPF (**d**); at the end of the exhaust system (**e**); pressure drop values across the GPF (**f**) at individual measurement points during tests on an engine dynamometer (the colors are as shown in Figure 19).

For each measurement point, the values of the following variables were determined:

- Temperature upstream of the turbocharger (T_1);
- Temperature downstream of the turbocharger, which was also the temperature ahead of the TWC catalytic converter (T_2);
- Temperature upstream of the GPF, which was also the temperature downstream of the TWC converter (T_3);
- Temperature downstream of the GPF (T_4);
- Temperature at the end of the exhaust system, measured at the point where the exhaust gas flow meter was installed (T_5);
- Pressure upstream of the GPF (p_3);
- Pressure downstream of the GPF (p_4).

The pressure values p_3 and p_4 made it possible to determine the back pressure in the particulate filter and verify the correctness of its selection for the tested engine. The collective values of thermodynamic parameters at each measurement point are summarized in Figure 21.

Based on the determined thermodynamic parameters (temperature and back pressure), it should be concluded that the operating temperature of the particulate filter was within the range of 550–900 K, which suggests that it should be possible to use a passive particulate filter for this engine, as well as an active filter, which would be subject to periodic regeneration.

6.6. Ecological Analysis of the Performed Changes

The analysis of ecological parameters included measuring the number and dimensional distribution of the emitted particles, for which comparative tests were performed before and after modifying the exhaust system and retrofitting it with a GPF (Figure 22).

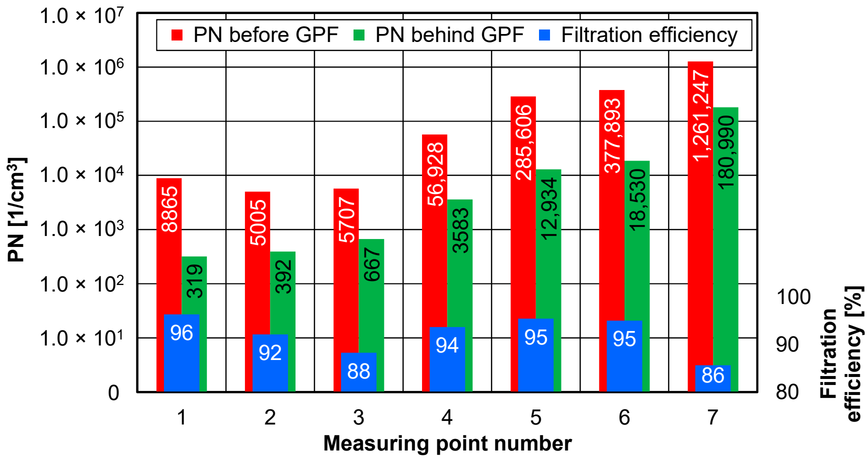


Figure 22. Measurement results of particle number per volume unit and filtration efficiency of the tested GPF used at individual measurement points.

It was assumed that the measurement results of the particle number, related to a unit volume (Figure 22), would be presented as the rate of particle number emission (in units 1/s; Figure 23), and such values would only be used in the calculation of the final results. The filtration efficiency was not given in Figure 23 because the efficiency is the same as the values shown in Figure 22, assuming a constant exhaust gas flow rate at the measurement point.

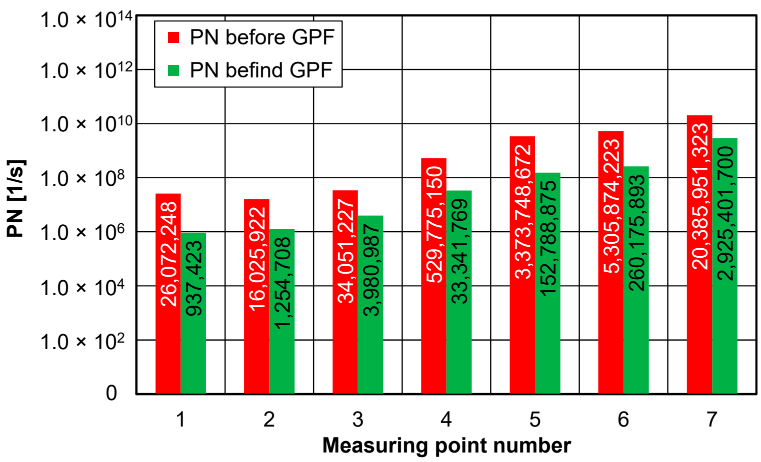


Figure 23. Results of the calculated particle number exhaust intensity with the GPF filter used at individual measurement points.

If the measurement points were to be treated equally, the filtration efficiency result would be 88.6%, with the particle number emission intensity before the GPF is added into the exhaust system being 4.3×10^9 1/s, and after the GPF is added, this value is 4.8×10^8 1/s (Figure 24a). If the measuring points were to be assigned the determined weights (weight 0.27 for point 1, weight of 0.12 for point 2, weight of 0.15 for point 3, weight of 0.11 for point 4, weight of 0.08 for point 5, weight of 0.17 for point 6, weight of 0.1 for point 7) the filtration efficiency result would be 89.2%, the particle number emission intensity before the GPF is added would have been 3.3×10^9 1/s, and after the GPF is added, it would be 3.6×10^8 1/s (Figure 24b).

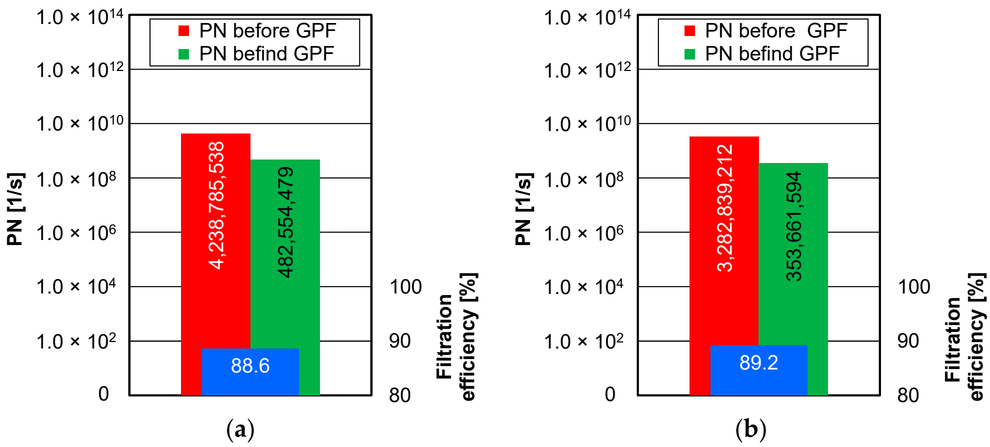


Figure 24. Particulate matter number emission intensity before and after the GPF filter for two cases: (**a**) without taking into account the duration shares of points in the entire measurement cycle, (**b**) taking into account the duration shares of points (vehicle operating time in the RDE road test).

The conclusions that were drawn based on the comparison of the obtained results were that higher efficiency values (although the difference was only 0.6 percentage points: 89.2% vs. 88.6%) were obtained in the case of the weighted average, which was mainly due to the fact that the measurement points where the particle number emission intensity was not at its maximum had the largest shares of operating time.

The determined overall filtration efficiency was satisfactory (over approximately 90%); however, the following section presents a detailed analysis of the dimensional distribution of particulate matter and the filtration efficiency of the GPF used expressed in the ranges of particle diameters.

For all measurement points, the particle diameter did not exceed 450 nm; however, due to the requirements quoted in the literature to indicate particles smaller than 23 nm (standard conditions), in this part of the considerations, it was decided that the dimensional determination of solid particles size will begin from the value of 19 nm. Therefore, the considered particulate range for all (seven) measurement points ranged from 19 nm to 453 nm.

As shown by tests of the several measurement points, the effectiveness of the GPF used was variable. It was greater for large particles and smaller for particles with very small diameters. The presented research results of the filtration efficiency for solid particles show that the limiting particle size at which filtration efficiency exceeded 95% is a diameter of 80 nm. Hence, the average value of filtration efficiency was determined for particles smaller than 80 nm, and then another filtration efficiency was determined for particles with diameters over 80 nm (Figure 25). The analysis of this figure shows that the filtration efficiency for particles smaller than 80 nm is in the range of 83–91%, while for larger particles, the efficiency is greater and ranges from 93% to 99%.

The conducted research demonstrates the significant impact of using particulate filters in vehicles with spark ignition engines with direct fuel injection. The average value of particulate filtration efficiency is approximately 90% (i.e., 10 times lower emissions; where in the tests of a standard vehicle described at the beginning of the article the road particle number emission limit was exceeded by 3.8 times) and is sufficient for vehicles with SI DI engines to meet the exhaust emission limits required by RDE tests.

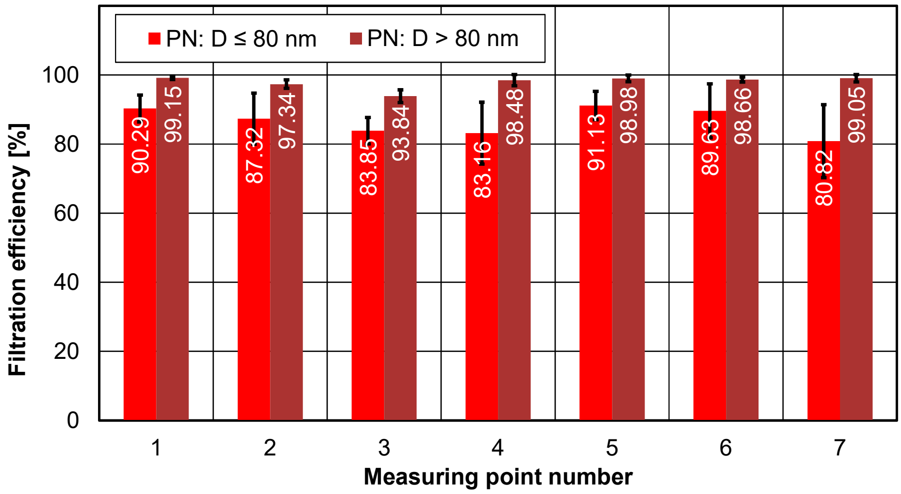


Figure 25. Particulate matter filtration efficiency for various particle diameter ranges smaller than 80 nm and larger than 80 nm for the tested engine operating points (done on an engine dynamometer).

6.7. The Environmental Assessment of the Proposed Exhaust System Modification

After determining the filtration efficiency of the proposed exhaust aftertreatment system using a particulate filter intended for cars equipped with spark ignition engines with direct injection, an attempt was made to estimate the ecological benefits of such a solution. Therefore, it was proposed that determining the exhaust emission of just the particle number in real vehicle driving conditions using the proposed solution should be carried out according to an algorithm that takes into account the particulate filtration efficiency of the GPF for the calculated individual ranges of particulate diameters:

1. Determine the filtration efficiency of the GPF for all particle diameters emitted during the performed stationary dynamometer tests as the average of seven measurements;
2. Determine such filtration efficiency for ranges of particle diameters in stationary engine test conditions;
3. Determine the particle number emission for the previously presented road conditions before adding the GPF in all the diameter ranges obtained from point (2) in the form of two-dimensional characteristics relative to the engine speed and load;
4. Determine the particle number emitted after adding the GPF into the exhaust system, taking into account the filtration efficiency in individual particle diameter ranges in two-dimensional characteristics of engine speed and load;
5. Determine the road emissions of the number of particles for the exhaust system with the proposed exhaust aftertreatment system modification, taking into account the characteristics of the vehicle's share of operating points duration and the comparison with the results obtained in the RDE test for the vehicle.

The considered research problem could be summarized through the total assessment of the GPF filtration effectiveness in individual engine operating ranges, determined by the rotational speed–load coordinates. Such an assessment was made (Figure 26), and it shows that the largest area (47%) is assigned an efficiency in the range of 88–90%, and for an area amounting to 39% of the total, the efficiency is over 90%.

The particle number emission was determined for a vehicle equipped with a GPF by taking the average particle number emission intensity and other necessary data from tests in real road conditions (including the average test duration and average test distance). The results of such calculations are presented (Figure 27), and they have shown that the total number of particles for the simulated drive of a vehicle with a particulate filter is

2.9×10^{11} 1/km (Figure 27a). Assuming that the emission limit for the particle number is 6×10^{11} 1/km, the emission conformity factor (CF) is equal to 0.48 (Figure 27b).

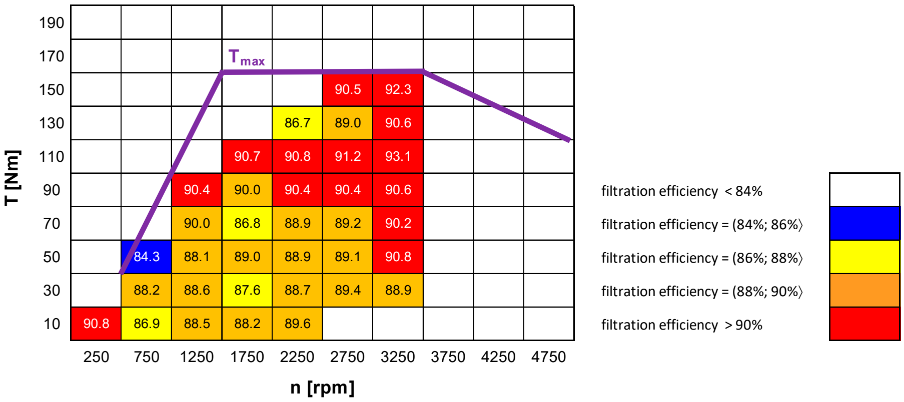


Figure 26. Filtration efficiency (expressed as a percentage) of the GPF filter in relation to the number of particles for diameters greater than 19 nm.

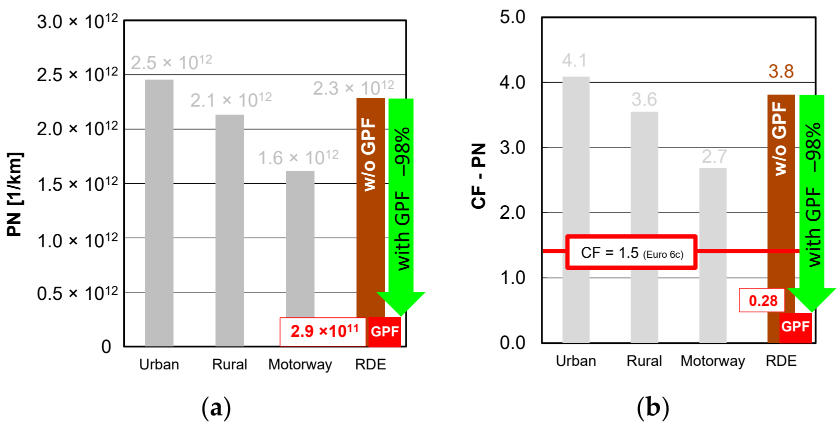


Figure 27. The change in road particle number emissions obtained throughout the RDE test (**a**) and the change in the particle number emission factor obtained in the RDE test (**b**).

The use of particulate filters in passenger cars with gasoline engines with direct fuel injection could bring measurable ecological benefits in the form of a reduction in the emitted particulate matter, in particular, the particle number PN. It has been estimated that the use of a GPF in such vehicles would allow for a particle number emission reduction of approximately 90%, which could allow, for example, meeting the exhaust emission limits for RDE tests. In the case of vehicle equipment, this limit was met with approximately a 75% margin, which indicates that even doubling the number of particle emissions during operation would not result in an increase in the number of particulate matter emissions to exceed the permissible legal limit values.

7. Conclusions

Direct gasoline injection is currently the most common supply system used in new spark ignition engines. Attempts to modify it are primarily related to the modification of the combustion system, and at the same time, these systems are increasingly becoming similar to high-pressure diesel fuel injection systems. This means that when the fuel injection pressure is significantly increased, solid particles with dimensions up to several dozen nanometers are also formed in SI DI engines in notable numbers. Since the introduction of the Euro 6 standard for passenger cars, these pollutants have been subject to legal regulations in homologation tests.

The article presents the development process of a solution to the issue of particle number emissions in the form of the following:

- Carrying out road tests using a test vehicle equipped with a gasoline engine with direct fuel injection; the tests did not indicate that the permissible emission limit values for gaseous pollutants were exceeded, but the number of particle emissions was found to have been exceeded significantly;
- A proposal to use an innovative GPF in the exhaust aftertreatment system installed in the engine exhaust;
- An ecological assessment on an engine dynamometer using the analysis of rapidly varying and thermodynamic parameters of the solution used;
- An assessment of the environmental benefits of the proposed solution in tests in real road driving conditions was performed in accordance with the RDE procedure.

The selected stages were developed according to the author's proposal for assessing the operating ranges of an internal combustion engine based on two-dimensional characteristics in the coordinates of engine speed–load (or precisely torque). This approach facilitated the division of the entire operating range of the combustion engine into operating areas, which, following road tests, were used to select several key operating points where a detailed assessment of the fast variable and ecological parameters of the test vehicle was performed.

The developed road test methodology allowed us to specify the measurement methods that can be used for the qualitative exhaust emissions assessment from various means of transport. The proposed solution is scalable to other combustion engines used, e.g., in hybrid vehicles. It can also be used to evaluate exhaust aftertreatment systems in diesel vehicles and off-road vehicles. The solution can be integrated with existing vehicles and with new-generation vehicles. The methodology is universal and can be applied to all vehicles using combustion engines.

Directions for further work may be as follows: an ecological assessment in real operating conditions of exhaust gas treatment systems other than those proposed in this work (e.g., integrated TWC and GPF); determine the impact of the use of modernized exhaust gas treatment systems on the road emissions of other exhaust gas components and fuel consumption; the modification of engine control algorithms taking into account the need for periodic regeneration of the gasoline particulate filter.

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Abbreviations

CF	Conformity factor
D	Particle diameter
DI	Direct injection
EGR	Exhaust gas recirculation
EU	European Union
FID	Flame ionization detector
GDI	Gasoline direct injection
GPF	Gasoline particulate filter
MPI	Multi-point injection
n	Engine speed
NEDC	New European Driving Cycle

NDIR	Non-dispersive infrared analyzer
NDUV	Non-dispersive ultraviolet analyzer
PEMS	Portable emission measurement system
PM	Particulate matter
PMD	Paramagnetic detector
PN	Particle number
RDE	Real driving emissions
SI	Spark ignition
T	Torque
TWC	Three-way catalyst
u	Share
V	Vehicle speed
WHO	World Health Organization
WLTC	Worldwide harmonized light-duty vehicle test cycle
WLTP	Worldwide harmonized light-duty vehicle test procedure
Z	Engine load

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