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Influence of the Particulate Filter Use in the Spark Ignition Engine Vehicle on the Exhaust Emission in Real Driving Emission Test

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ABSTRACT

The introduction of new exhaust emissions norms for motor vehicles forces manufacturers to rely on th new technologies of exhaust gas aftertreatment and emission reduction. The past studies by the authors demonstrated a significant emission of nanoparticles from the gasoline engines with direct fuel injection, especially dangerous for the human health and life. The latest solution is a particulate filter designed for spark ignition engines, introduced in parallel with a norm limiting their number emission. The research conducted within the article concerned testing its effectiveness by measuring the vehicle equipped with and without the filter under real driving conditions. The drive cycle was made in accordance with the requirements of the RDE (Real Driving Emission) standard using PEMS (Portable Emissions Measurement System) equipment. The values of harmful gaseous components and solid particles were measured in terms of mass and number. The comparison of emission results indicated a significant efficiency of the filter in terms of particle weight and number reduction. The dimensional distribution of particle diameters were also analyzed, which changed as a result of the filter. The authors believe that the filter efficiency is the result of much higher temperatures of exhaust gases than in the case of diesel engines, which causes the incineration.

Keywords: Real Driving Emission, emission, gasoline particulate filter, particulate matter

INTRODUCTION

Cars emit harmful compounds from their exhaust systems during the engine operation. When fuels are combusted in engines, substances are emitted into the atmosphere contributing to the environmental degradation and harming the human health. Their harmfulness to the environment has been noticed well in the past [Giechaskiel et al. 2014, Merkisz et al. 2016, Rymaniak 2017, Fuc et al. 2018]. Restrictions in the case of PC (Passenger Car) vehicles were introduced in the form of exhaust emission norms for the toxic components released into the atmosphere. The exhaust components that were given limit values, in accordance with the current EURO 6 norm, include road emissions [g/km] of carbon monoxide, hydrocarbons, nitrogen oxides and particulates in terms of mass and number [EU Regulation 2014]. Particulate emissions have already been limited in diesel-class PC vehicles, mainly due to the properties of diesel engines. This limit was introduced in the EURO 5 norm implemented in 2011 [Yamamoto et al. 2014]. The development of spark-ignition (SI) internal combustion engines has led to the direct injection of gasoline into the combustion chamber, becoming the only solution that is currently encountered in SI engines [Pielecha 2014]. Many years of research by co-authors and research centers in the country and in the world have shown excessive nanoparticles emission, similarly to how it was in the case of the diesel engines [Jong et al. 2019, Mu et al. 2019].

When testing the content of particulate matter suspended in the air, PM10 and PM2.5 indicators are taken into account, which means suspended particles with a diameter lesser or equal to 10 and 2.5 micrometers, respectively. In the case of car exhaust, the particles contained in the exhaust are at least an order of magnitude smaller and reach mostly up to several nanometers [Mayer, Czerwinski and Scheidegger 1996, Lijewski, Merkisz and Fuc 2013]. Their size is directly related to their penetrative capacity into the human respiratory system and, as a result, reaching alveoli and entering the bloodstream [Andrzejewski et al. 2017] (Fig. 1). This increases the incidence of diseases of the upper respiratory tract, on top of their carcinogenic effect.

For this reason, in September 2017, the EURO 6c emission norm came into effect for new engines and vehicles, which reduced the limit number of particulates to the same level as for vehicles with CI engines. Since then, this limit has been set at $6 \cdot 10^{11}$ /km and is measured during the World Harmonized Transient Cycle test [EU Regulation 2014].

The introduction of this limit, as well as a new type of approval procedures resulted in numerous design changes in the SI engines on the market [Fuc et al. 2018, Mu et al. 2019]. Most of the vehicles were equipped with particulate filters in the exhaust system, as was the case with the tested vehicles [Honda 2018]. In terms of design, the filter itself is very similar to the structure of the filters used for diesel engines and built on the principle of wall-through, denoting filtration through alternately blinded channels with porous walls permeable to gaseous particles (scratches) while retaining solid impurities [Kruczynski 2012, Rymaniak, Ziolkowski and Gallas 2017] (Fig. 2).

The filter requires periodic regeneration, meaning the oxidation of accumulated particles. In order to carry out this process, first of all, a temperature of about 580°C is required, which in the case of gasoline engines is easier to achieve than in diesel engines [Kruczynski 2012, Mu et al. 2019].

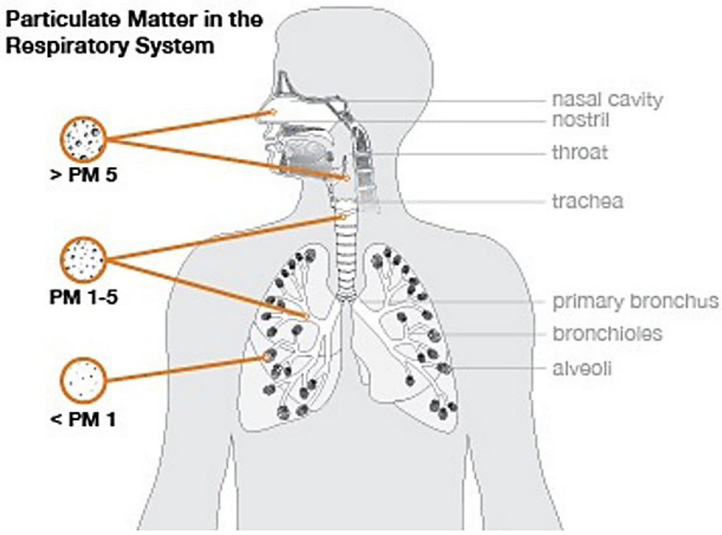

Fig. 1. Diagram of particles penetration into the human respiratory system depending on their diameter [Siedlecki et al. 2017]

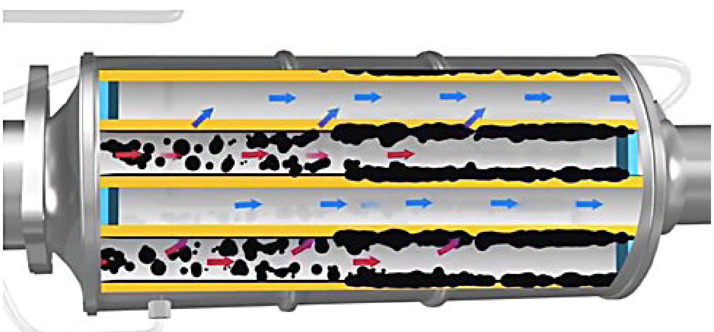

Fig. 2. Particulate filter principle of operation [Semtech 2000]

RESEARCH METHOD

The vehicles tested for the needs of this article were an example of retrofitting an existing engine by the manufacturer with a gasoline particulate filter (GPF) of (Fig. 3) in an effort to meet the newer emission norm.

The engines used were manufactured with the downsizing technology trends (Table 1). The total mass of vehicles during the tests was about 1600 kg including operating liquids, and research equipment.

The test route used was marked out in accordance with the requirements of RDE testing . This means the selection of appropriate sections (Fig. 4), but also taking into account the road inclination, and above all the congestion occurring on the route, because the basic parameter for the test drives is the vehicle speed. The test must consist of three sections, i.e. urban, rural and highway driving. Their length must be between 23 and 43% of the total distance, and the travel speed should be in the ranges of 0 to 60, 60–90 and 90–140 km/h for the three sections, respectively. The test duration should not exceed 2 hours, and the minimum distance in each section is 16 km [EU Regulation 2014].

Apparatus from the PEMS (Portable Emissions Measurement System) group was used for the research. It is a group of mobile devices that enable measuring the concentration of individual toxic components present in the exhaust gases. The measurement is carried out indirectly with the help of a set of analyzers, and the use of an exhaust gas flow meter in the exhaust system enables to determine the mass of the tested exhaust component.

The first analyzer used was SEMTECH DS. Sensors Inc. (Fig. 5A). It was used for measuring the gaseous components and testing the instantaneous exhaust gas flow and through the SEMTECH EFM-HS Module (High Speed Exhaust Flow Meter). The exhaust gas sample is transported through a heated line, the temperature of which is around 191°C, to prevent condensation of hydrocarbons on its walls [Semtech 2000]. The sample prepared in this way, after filtering out the solid particles, goes to a flame ionization analyzer, powered by hydrogen. Then the sample is cooled and passed along to the absorption analyzers (NDIR and NDUV), and finally to the electrochemical oxygen sensor. The system communicates with the OBD (On-Board Diagnostics) system of the vehicle, which allows the engine operating parameters to be read, as well as with the GPS receiver.

The EEPS TSI 3090 analyzer was used to measure the particle number (Fig. 5B). It is a particle counter that – in addition to measuring the number of particles – can also be used to determine their size distribution. It also enables mass calculation based on particle density data. The particles transmited to the analyzer are charged positively and then repelled by a centrally located electrode, repelling the charged particles to smaller negatively charged plates. The larger particle, due to the greater mass, hits the lower electrode, which allows determining the particle size.

Prior to testing, the analyzers were calibrated with the manufacturer's reference gases and zeroed just before testing using ambient air.

RESULTS

The tests were carried out around noon, which resulted in meeting all the RDE test requirements. The obtained results of engine rotational speed and load during the drive (Fig. 6) show a high variability of the measured values. For the

Fig. 3. View of tested vehicles with testing equipment: A) vehicle without GPF, B) vehicle with GPF

Table 1. Technical data of the tested vehicle engine [Honda 2018]

Ignition type	Spark ignition
Injection system	Direct
Displacement	998 cm^3
Number of cylinders	3
Number of valves	12
Maximum power	95 kW at 5500 rpm
Maximum torque	200 Nm at 2250 rpm
Approval norm	EURO 6c

purposes of the tests the start-stop system was turned off, which can be seen by the minimum rotational speeds of the engine crankshaft. The increased speed while traveling on the highway can be noted.

The results of toxic road exhaust emissions in the urban, rural and highway sections are presented graphically in Figures 7, 8 and 9, respectively.

The emission of nitrogen oxides and hydrocarbons during the urban section (Fig. 7) is higher in the case of the solution without filter; however, the emission of nitrogen oxides is lower. This behavior may indicate a strong oxidizing effect of the filter, supporting the operation of the standard exhaust aftertreatment system, i.e. Three Way Catalyst, also oxidizing the nitrogen contained in the exhaust gas to nitrogen oxides. The difference reaches 100%.

The exhaust emission results during the rural section did not show the same pattern as the urban section results. Again, carbon monoxide and hydrocarbons are higher than in the case of a vehicle with a filter; however, the differences in nitrogen oxides emissions could also be observed and this time they were quite significantly in favor of a solution with a filter (Fig. 8). In the two other compounds, the differences were smaller than in the urban section drive, but they were still present.

The motorway drive produced the results which were significantly different from the previous two drive sections (Fig. 9). The hydrocarbon and nitrogen oxides emissions were practically the same, with the differences being smaller than the measuring error of the test apparatus. Again, as in every section, the difference in the carbon monoxide emissions between the two test vehicles was significant, and reached a triple value for the no-filter solution. Once again, it would indicate a significant oxidation potential of the filter, or a change in the parameters controlling the engine operation in relation to the older engine. After an increase in the carbon monoxide emissions between sections and nitrogen oxides, there was also a gradual increase in instantaneous engine loads, but this was not reflected in the hydrocarbon emissions.

However, the main goal of the article was to assess the impact of the filter presence on particulate matter emissions. The results are summarized in Figure 10. In all cycles, the impact of the filter is clearly visible, and the value obtained outside the urban drive was even lower than in the approval norm (6E+11/km). The greatest difference occurred during the rural drive section and it reached almost an order of magnitude. The reason for such a significant variation may be the generation of sufficient temperature for the process of passive filter regeneration during this drive section and the filter becoming cleaner. It can also be stated that without the filter it would not be possible to meet the norm limits, even with a Conformity Factor of 2.1.

The authors, due to the capabilities of research equipment, extended the research to include the particle dimensional distribution analysis. This value is not monitored in any way for the vehicle type approval procedure; however, it allows a better assessment of the particulate emissions in

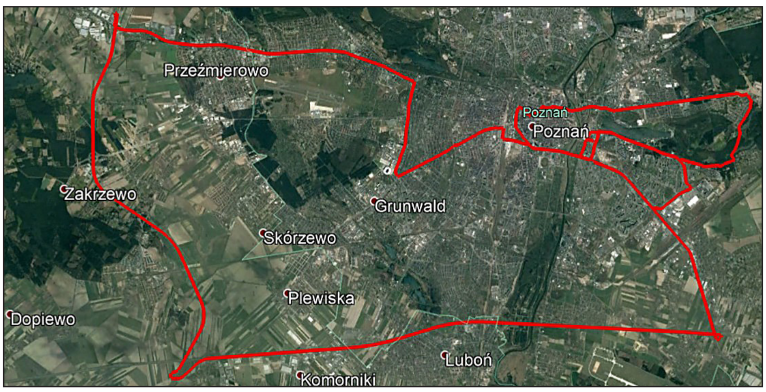

Fig. 4. The test route used (source: Google maps)

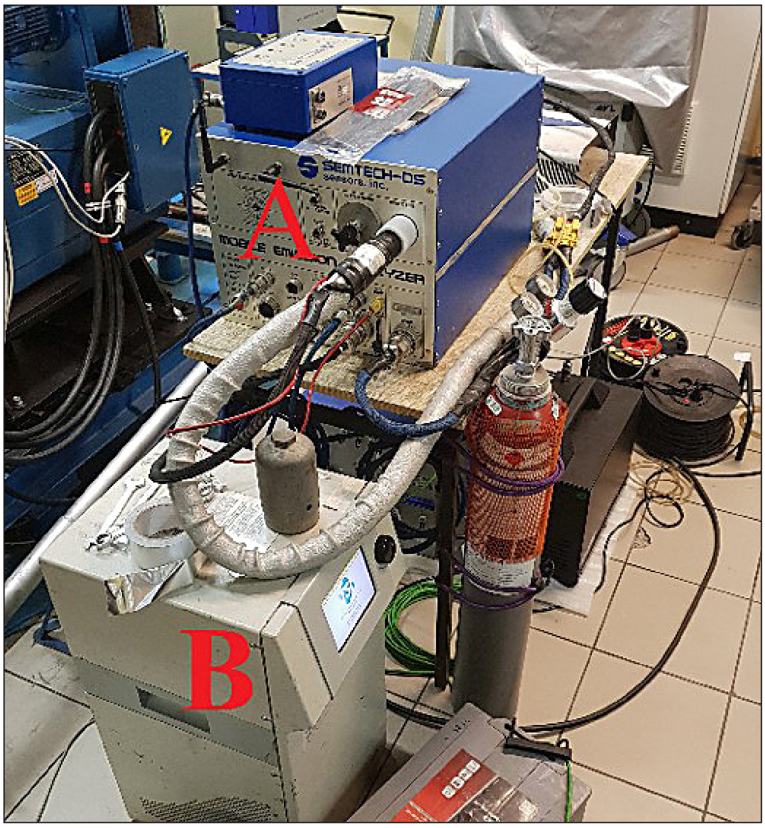

Fig. 5. PEMS apparatus during the calibration process: A) SEMTECH DS, B) EEPS TSI

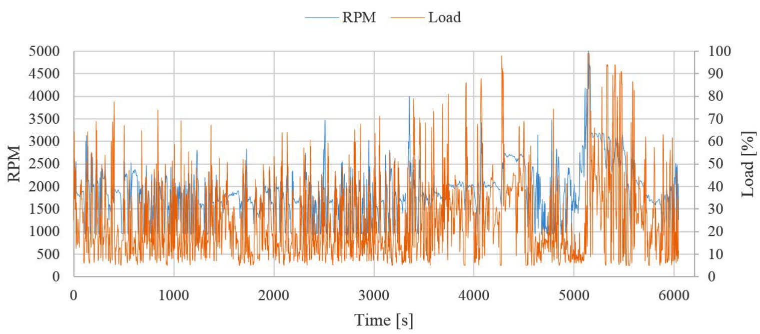

Fig. 6. RPM and load of the engine during test

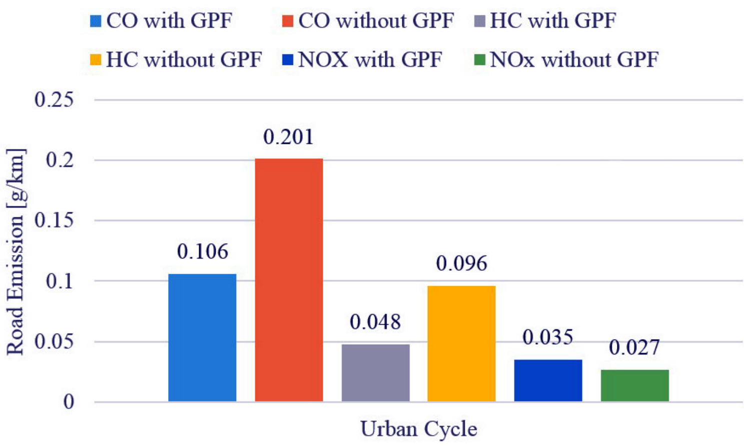

Fig. 7. Road emission results of gaseous exhaust components in the urban section

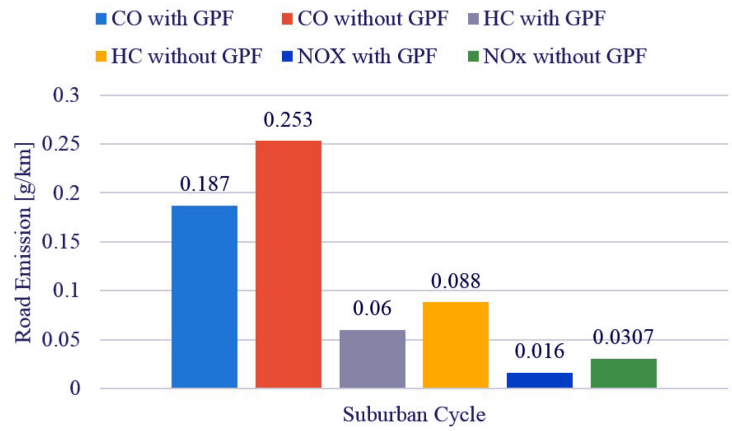

Fig. 8. Road emission results of gaseous exhaust components in the rural section

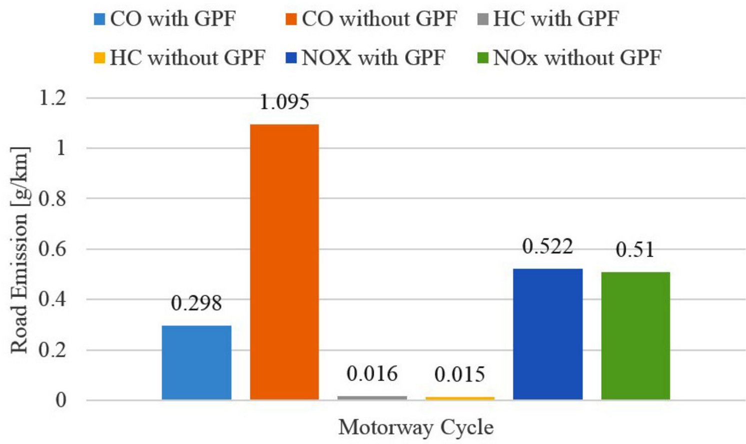

Fig. 9. Road emission results of gaseous exhaust components in the highway section

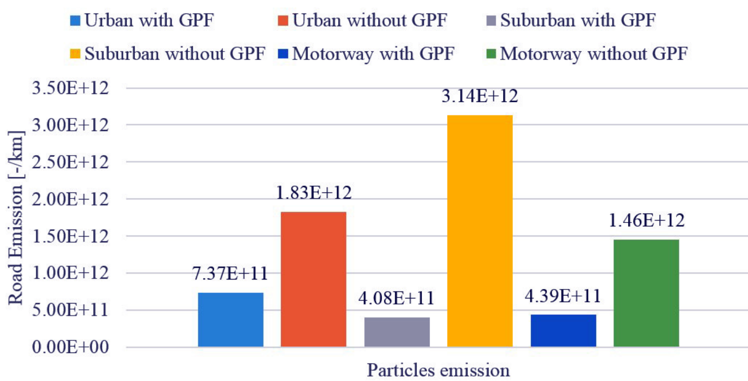

Fig. 10. PN emission during tests with and without GPF

terms of the impact on humans, indicating their approximate diameters (Fig. 11). At this point, it should be noted that the shapes of the particles are usually very different from a regular sphere, even though they are usually schematically represented this way as PM.

The results obtained clearly show the filter operation and its effect. It works on all tested particle diameters, which is a very desirable phenomenon in the field of exhaust gas aftertreatment. The chart shows two distinct peaks in the 10 and 50 nm range, depicting nucleation and aggregation of solid particles [Giechaskiel et al. 2014]. It is particularly technically difficult to remove the particles with the smallest diameters due to the need to use high numbers of cells per square

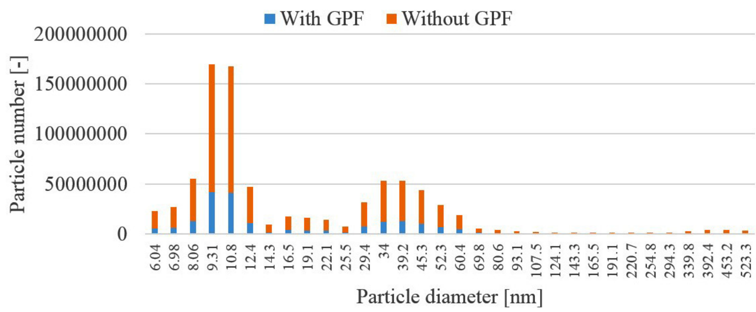

Fig. 11. Particulates size distribution during tests with and without particulate filter

inch, which results in a significant increase in the flow resistance and, thus, the fuel consumption of the vehicle. The explanation of the filter effectiveness may again be related to significant exhaust gas temperature values and the possibility of continuous passive regeneration when driving with increased engine load, which was the case in the rural and highway sections. The results obtained are summarized in Table 2, where the reference value is the result for a vehicle without a particulate filter.

Table 2. Relative toxic exhaust emission results for a test drive cycle of vehicles with GPF and without GPF (=100%)

Section/toxic compound	CO	HC	NO_x	PN
Urban	-47%	-50%	30%	-60%
Rural	-26%	-32%	-48%	-87%
Motorway	-73%	7%	2%	-70%

CONCLUSIONS

The tests performed for the article were carried out in accordance with the requirements of the European Union Directive concerning the type approval procedure of PC-class vehicles due to the exhaust emission of toxic components. They were conducted in the Poznań agglomeration on a specially designed route under similar traffic conditions. The obtained exhaust emission results of gaseous components – apart from carbon monoxide – cannot be used to assess the operation of the new exhaust aftertreatment system in the vehicle. In the case of carbon monoxide, a clear decrease is visible in the results when the filter is present, which may be associated with strong oxidation of exhaust components.

The particle number emissions analysis indicates a significant reduction in these values regardless of the test section, aside from the urban section, additionally resulted in a value lower than the limit of the current EURO 6d norm. The conducted particle dimensional distribution analysis indicates non-selective filter operation and reduction of the emission of particles of all diameters with maximum performance in the range of several nanometers, i.e. particles particularly dangerous to human health.

The analysis provided in the article indicates a significant improvement in the ecological indicators of the vehicles tested and this type of research will be continued in the future by the authors under laboratory conditions when mapping of the test drive cycle on a dynamic brake station in order to ensure the repeatability of the measurement conditions.

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REFERENCES

1. Commission Regulation (EU) No 136/2014 of 11 February 2014.
2. Giechaskiel B., Maricq M., Ntziachristos L., Dardiotis C., Wang X., Axmann H., Bergmann A., Schindler W. 2014. Review of motor vehicle particulate emissions sampling and measurement: From smoke and filter mass to particle number. J. Aerosol. Sci., 67, 48–86.
3. Honda's 2018 Engines data.
4. Pielecha I. 2014. Diagnostics of stratified charge combustion under the conditions of multiple

gasoline direct injection. Journal of Thermal Analysis and Calorimetry, 118, 217–225. https://doi.org/10.1007/s10973–014–3956–3.

5. Merkisz J., Fuć P., Lijewski P., Pielecha J. 2016. Actual emissions from urban buses powered with diesel and gas engines. Transport Research Arena TRA2016 Book Series: Transportation Research Procedia, 14, 3070–3078, https://doi.org/10.1016/j.trpro.2016.05.452
6. Jong An, Seok & Geun Choi, Jong & Young Jeong, Jae & Seok Cho, Yong. (2019). A Study on experimental analysis of PN emissions of turbocharged GDI engines for meeting the regulations of gasoline PN. Transactions of the Korean Society of Mechanical Engineers, B. 43, 119–125. https://doi.org/10.3795/KSME-B.2019.43.2.119.
7. Kruczyński S.W. 2012. Eksploatacja trójfunkcyjnych reaktorów katalitycznych – dezaktywacja termiczna. Eksploatacja i Niezawodność, 14(3), 239–242.
8. Rymaniak L. 2017. Comparison of the combustion engine operating parameters and the ecological indicators of an urban bus in dynamic type approval tests and in actual operating conditions. MATEC Web of Conferences, 118, 00009.
9. Rymaniak L., Ziolkowski A., Gallas D. 2017. Particle number and particulate mass emissions of heavy duty vehicles in real operating conditions. MATEC Web of Conferences, 118, 00025.
10. Mayer A., Czerwinski J., Scheidegger P. Trapping Efficiency Depending on Particle Size. SAE 960472.
11. Andrzejewski M., D. Gallas, P. Daszkiewicz, A. Merkisz-Guranowska, Stawecka H. 2017. The latest technical solutions in rail vehicles drives. MATEC Web of Conferences, 118, 00015.
12. Mu M., Sjöblom J., Sharma N., Ström H., Li X. 2019. Experimental Study on the Flow Field of Particles Deposited on a Gasoline Particulate Filter. Energies, 12, 2701.
13. Fuć P., Lijewski P., Siedlecki M., Sokolnicka B., Szymlet N. 2018. Analysis of particle mass and number emission from an SI engine with direct fuel injection and a particulate filter, IOP Conference Series: Materials Science and Engineering, 421, 042019.
14. Lijewski P., Merkisz J., Fuc P. 2013. Research of exhaust emissions from a harvester diesel engine with the use of portable emission measurement system. Croatian Journal of Forest Engineering, 34(1), 113–122.
15. Semtech DS. and EEPS TSI Manuals, 2000.
16. Siedlecki M., Galant M., Rymaniak L., Ziolkowski A. 2017. Badania emisji zanieczyszczeń pojazdu wyposażonego w silnik z bezpośrednim wtryskiem benzyny w rzeczywistych warunkach eksploatacji (in Polish). Autobusy, 12, 404–409.
17. Kazuhiro Y., Kenta M. 2014. Diesel exhaust after-treatment by silicon carbide fiber filter. Fibers, 2, 128–141. https://doi.org/10.3390/fib2020128.