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Analysis of tractor particulate emissions in a modified NRSC test after implementing a particulate filter in the exhaust system

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Abstract. Retrofitting, which means retrofitting old generation engine systems with modern exhaust aftertreatment systems, is becoming increasingly popular, which allow vehicles to adhere to the newer and more stringent emission norms. This can save the operators of such vehicles money using older engineered designs without the need to design a new unit or buy an expensive new machine or vehicle. At present, there is a growing interest in emissions from off-road vehicles and the introduction of minimum limits for older vehicles that must be met in order to be able to allow for their operation. For the purposes of this article, the Stage IIIA farm tractor has been fitted with a particulate filter in the exhaust system. The study investigated the impact of the use of exhaust aftertreatment systems on particle emissions in terms of mass, size distribution and number using PEMS analyzers in the modified NRSC stationary test by engine loading, using a mobile engine dynamometer and comparison of test results.

1 Introduction

Agricultural vehicles are the largest subgroup of machines belonging to the NRMM category. This is due to a significant amount of area used for agriculture in Poland [1]. For decades of crop use, the work has been heavily mechanized and the average yield per hectare has increased significantly [2]. The use of an internal combustion engine, however, is associated with the emission of harmful compounds into the atmosphere. This is countered by the increasingly recent emissions standards for new vehicles, developed over several years [3].

Despite attempting to apply the hybrid system or even the total electrification of NRMMs, manufacturers have still not achieved satisfactory results in terms of powertrain size and its potential range [4]. Both the use of fuel cells and electrochemical batteries cannot currently compete with the energy density and power of fuels based on oil processing, as well as the time it takes to refuel. NRMM vehicles, despite their large size, usually do not have enough room to accommodate enough batteries to provide a range similar to that obtained on liquid fossil fuel [5, 6].

Recuperation, that is typical for modern vehicles, cannot be used in this case either. The driving speeds obtained in this case are small, which results in low kinetic energy, and the braking of the vehicle through the resistance of the work done causes it to stop very quickly [7]. Because of that, the energy consumption and the emission of the vehicle are not reduced as much as in the case of a personal cars [1, 8].

Current technology for the construction of internal combustion engines, however, does not allow for a drastic reduction of their environmental impact [9, 10]. For this reason, one of the current actions to protect the planet is to reduce emissions of older vehicles. This trend is called retrofitting, and is based on the use of modern exhaust gas aftertreatment systems [2]. Today's exhaust aftertreatment systems are usually small in size, and the advancement of the current technology allows the choice of materials and, above all, choosing the intermediate and active layers in such a way as to allow passive filter regeneration. It involves the use of nitrogen oxide (IV) to reduce the particle mass and size. Importantly, it does not require any changes in construction or control of the combustion engine. It is particularly desirable to reduce particle emissions in terms of number and mass as well as nitrogen oxides, emissions of which are reduced by the particle filter and selective catalytic reduction respectively [11].

These systems are currently standard issue in vehicles that meet the current Stage IV emission standard and will be present in Stage V [12] vehicles. Numerous studies have shown the efficacy of emission reduction systems in reducing emissions, especially in terms of particle mass and number [13-16]. Particularly, the latter value is important because it has been proven that nanoparticles are the most dangerous to humans, and those are precisely the particles most commonly emitted from diesel engines [17-20], its emission value for passenger vehicles and HDVs is also subject to limits.

Therefore, the chances of reducing the environmental impact are reflected in the retrofitting process. Quite a large reduction in limits, especially particulate matter,

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occurred in the Stage IIIB standard, which entered into force at the end of 2009-2011, depending on the engine power [21, 22]. This change was noticed by the German authorities and currently vehicles that do not meet at least Stage IIIB cannot participate in the construction work in the capital of Berlin. From the economics point of view, it is much better to use a modern exhaust aftertreatment system than to replace a fleet of vehicles whose value will be further reduced [2, 23].

This article presents the effect of the use of a particulate filter in the exhaust system of an agricultural tractor on the emissivity of particulate matter in terms of mass and number. The tests were carried out in a hall where the tractor was subjected to load with a mobile brake through the power take-off shaft.

2 Test vehicle

A Deutz-Fahr Agrotron X720 tractor was used for the tests. During the test, it was in the hall, where it was connected by a shaft from one side to the mobile chassis dynamometer (Fig. 1). The vehicle was checked for possible faults and was technically sound before testing. The tractor engine was heated to its operating temperature by the engine oil and the cooling liquid prior to testing. The basic data of the tractor internal combustion engine is presented in Tab. 1.

Fig. 1. Image of the tractor during test.

Table 1. Deutz-Fahr Agrotron X720 tractor technical parameters.

Engine type, number and arrangement of cylinders, number of valves	6-cylinder, 4 valves per cylinder, CI engine
Injection system	Common Rail
Displacement	7.1 dm^3
Cylinder diameter/piston stroke	115×149 mm
Maximum power	198 kW at 2300 rpm
Maximum torque	1050 Nm at 1400 rpm
Turbocharging	VGT turbocharger with intercooler
Aftertreatment systems	EGR, DOC, custom DPF filter
Emission standard	Tier 3/Stage IIIA

The Eggers-Dynamometer PT 301 MES mobile dynamometer was used to load the engine. This is an air cooled dynamometer based on the work of electric motors. The basic brake parameters are shown in Table 2. During the tests, a reduction ratio (2.1:1) relative to the engine speed was introduced to the brake software, which enabled the actual torque generated by the internal combustion engine to be used later to calculate the unit emissions.

Table 2. Basic technical parameters of the dynamometer used for the test.

Braking system	retarder
Coolant	air
Top engine speed	3600 rpm
Maximum torque	7200 Nm
Rotation direction	left/right

The particle filter cartridge with which the tractor was retrofitted was made of metal. Filters of this type are built by spiral coiling of previously catalytically coated sheets (Fig. 2), and then wrapping the insulating layer and dipping in a metal casing. The external dimensions of the filter used for the test are 870 mm length, maximum diameter of 400 mm, and the inlet and outlet with diameters of 100 mm. These dimensions were selected according to manufacturer’s recommendations based on the engine displacement. The filter was incorporated into the outlet system with steel pipes and sealed with high temperature tape and steel clamps (Fig. 3). It was thus precisely embedded in the exhaust gas flow axis.

Fig. 2. View of the DPF carrier used.

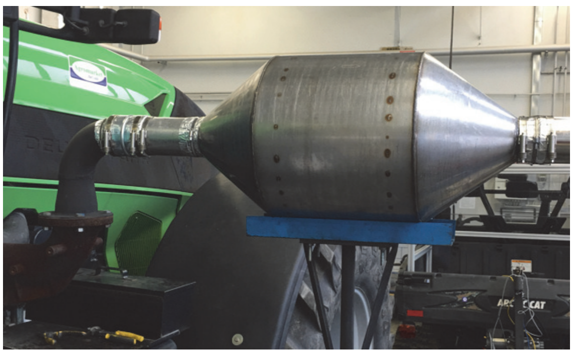

Fig. 3. DPF mounted in the exhaust system of the tested tractor.

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The standard tractor exhaust manifold (Fig. 4) has been replaced by an element that directs the exhaust gas in parallel to the substrate (Fig. 5). The authors have not decided to modify the standard exhaust system by altering the engine exhaust system, due to its large complexity (the intake manifold is integrated with the turbine which also contains the DOC), and by limiting the structural modifications of the tractor to a minimum. The diameter of the pipe has been chosen to match the standard exhaust system without damaging the exhaust.

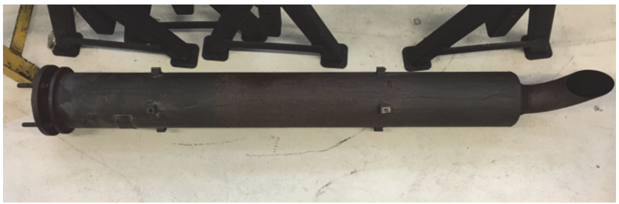

Fig. 4. Standard engine exhaust system.

Fig. 5. Exhaust system modifications for the test.

3 Apparatus used

The assessment of the exhaust emissions level was performed with the PEMS equipment measuring the concentration of the exhaust gas components. In the research described in the article, Semtech DS – a portable exhaust emissions analyzer manufactured by Sensors Inc. was used (Fig. 6).

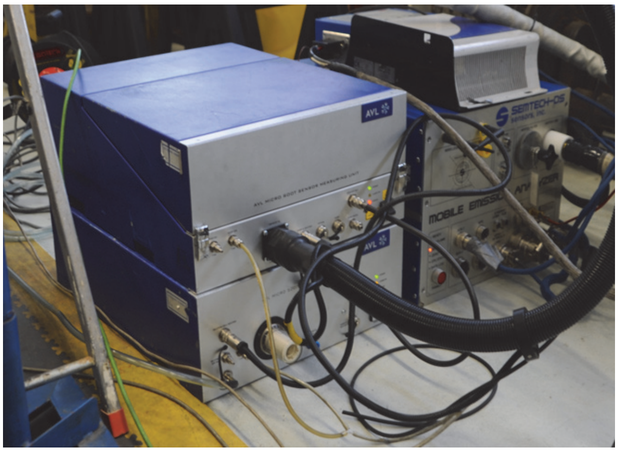

Fig. 6. SEMTECH DS and AVL Micro Soot Sensor analyzers during tests.

The entire volume of the exhaust gas from the exhaust system was sent to the mass flow meter (Figure 7) and then through a measurement probe (maintaining the temperature of 191 °C) to the analyzer [24]. The device filtered the exhaust gas to separate the particulate matter (PM). In the next step, the system measured the concentration of hydrocarbons in a FID (Flame Ionization Detector). The exhaust gas was then chilled to the temperature of 4 °C and the concentrations of nitrogen oxides (NDUV, Non-Dispersive Ultra-Violet), carbon monoxide/carbon dioxide (NDIR, Non-Dispersive Infrared) and oxygen (electrochemical analyzer) were measured. The device is compatible with the vehicle's on-board diagnostic system (recording of the operating parameters – engine speed and load) and GPS (latitude and longitude for determining the vehicle speed).

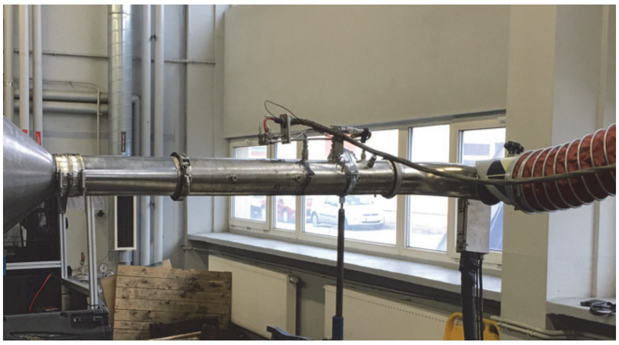

Fig. 7. View of the flow meter.

The authors used MSS (*Micro Soot Sensor*) by AVL (Fig. 6) for the measurement of particulate matter. The device uses laser light dispersion triggered by particulate matter contained in the exhaust gas. AVL MSS can determine the real time concentration of PM in the exhaust gas. The number of the particles was measured by EEPS TSI (Fig. 8).

In this device, the solid particles get an electrical charge and then they reach the electrodes, the larger the particle the further the electrode reached.

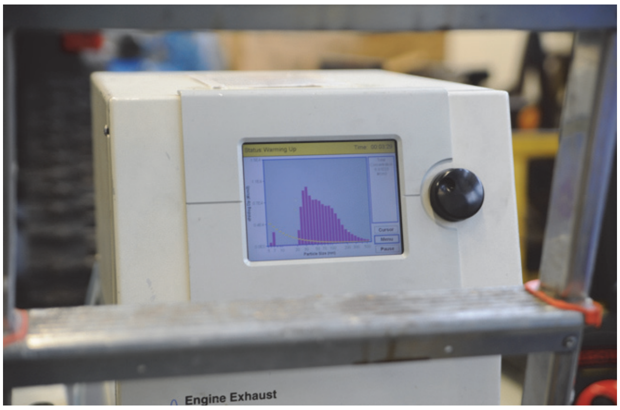

Fig. 8. TSI EEPS device during tests.

Before starting the measurements, the analyzers were calibrated with reference gases according to the manufacturer's guidelines. This calibration consists of providing a gas with a precise composition to individual analyzers. Each analyzer is provided with 5 gas canisters having different ratio of ingredients to each other and containing gases of the highest possible purity. This allows to restore the original characteristics of individual devices and guarantee measurement of the actual value of individual toxic components.

These operations were done every single cycle that was performed to make sure the results are comparable. In addition, the offset value was determined using outside air before the measurements. This action alleviates the impact of the environment in which the measurements are made on the results. None of the analyzers reported errors in operation during tests.

4 Research methodology

The tractor was tested in operating points according to the modified NRSC type approval test. This test was changed by prof. Lijewski based on the study of the operating points of the internal combustion engine of NNRM in real operation [25]. Various field work performed by agricultural tractors, combine harvesters and construction machinery was investigated. Based on the obtained results the engine's operating points have been changed compared to the NRSC test, which only partially maps the actual operation. Based on the research, it has been found that the range of the engine's operating points is much narrower than the test specifies. The points with the highest loads were shifted towards the lower loads and the points with the low loads of the engine were shifted upwards. No external load at the specified engine speeds has been added to the test to verify the behavior of the filter with low temperature exhaust and significant air excess ratio.

The differences relate to the load intervals used, the engine rotational speeds are selected in the same manner as in the norm, respectively 60 and 90% rotational speed at the maximum engine power. Such a test allows for better mapping of real conditions during stationary tests The operating points of combustion engine used in the studies are presented in Tab. 3 and Fig. 9.

The authors did not use the characteristics of the engine provided by the manufacturer. For the purpose of the tests, the actual external characteristics of the engine were drawn up and the torque at the given crankshaft rotational speed was determined.

Table 3. Engine operating points [25].

Point No.	Engine speed [% of the speed at maximum engine power]	Engine speed [rpm]	Load [%]	Load [Nm]	Weight
1	60	1410	90	878	0.15
2	60	1410	65	633	0.2
3	60	1410	40	390	0.2
4	60	1410	0	0	0.1
5	90	2115	80	672	0.1
6	90	2115	55	462	0.1
7	90	2115	30	252	0.15
8	90	2115	0	0	0.15
9	idle	850	–	–	0.2

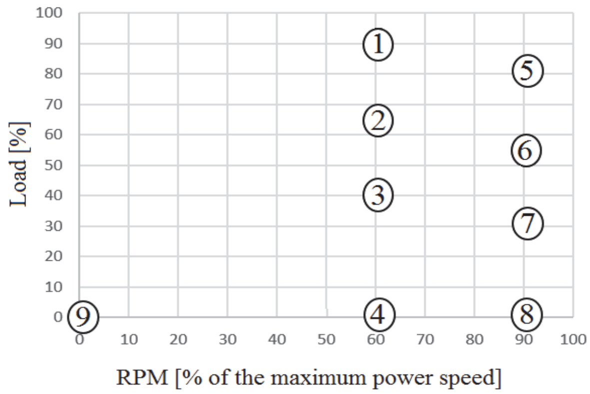

Fig. 9. The operating points of combustion engine [25].

At each operating point the engine worked for 60 second and the transition time between points was determined by the inlet and outlet exhaust gas temperature. The measurement was taken when the temperature has not changed more than 1 °C for a period of 10 seconds. The entire cycle was performed three times, and the presented results are the weighted average values of the obtained results.

5 Result analysis

Based on the concentration readings on the analyzers and the mass flow rate of the exhaust gas and the instantaneous engine power, the specific PM emissions were calculated (Tab. 4). In an similar manner, the specific particle number emissions were calculated using the volumetric concentration of particulate matter (Tab. 5).

Table 4. Results of specific PM emission with and without DPF.

Point No.	Engine speed [rpm]	Load [Nm]	Without DPF [g/kWh]	With DPF [g/kWh]
1	1410	878	0.43	0.06
2	1410	633	0.42	0.13
3	1410	390	0.64	0.33
4	1410	0	1.12	0.65
5	2115	840	0.73	0.15
6	2115	672	0.55	0.08
7	2115	462	1.10	0.25
8	2115	0	1.92	0.92
9	850	157	0.35	0.43
Weighted average	–	–	0.73	0.34

There is a noticeable decrease in particle mass at each point of the engine operation, which is particularly high for points where the engine is operating under heavy load (seven fold difference for the first operating point). It can be argued that the filter is more effective at higher exhaust temperatures where passive regeneration using nitrogen dioxide for oxidation of solid particles occurs. As the load decreases, the efficiency decreases. Increased emissions at idle may be caused by increased exhaust gas flow resistance at low exhaust gas

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temperatures preventing oxidation of the particles. Finally, the average test result for the system without a filter is 0.73 and the system with filter 0.34 g/kWh (Fig. 10). The obtained values of PM emission are much higher than limits even for Stage IIIA.

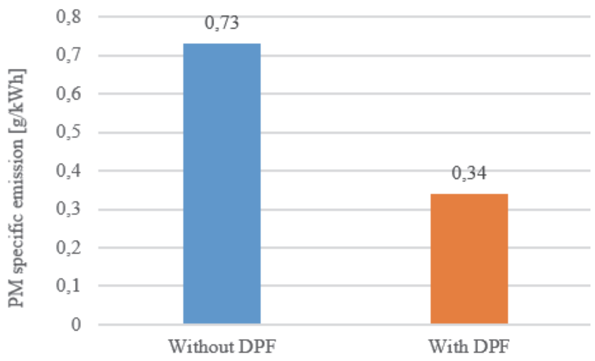

Fig. 10. Weighted average of the specific PM emissions for the system with and without the DPF.

For a number of particles, a similar relationship can be observed as for the mass, i.e. the most effective filter operation takes place at the highest load settings (operating points 1 and 5), where the number of particles decreases more than four times (Tab. 5). For points with a low load, the filter performance is similar to or greater than that of the standard exhaust system, again due to low exhaust temperature and no passive regeneration. As a result, the number of particles decreases almost twice from 1.81E+12 to 9.22E+11 (Fig. 11).

Table 5. Results of PN emission with and without DPF.

Point No.	Engine speed [rpm]	Load [Nm]	Without DPF [1/kWh]	With DPF [1/kWh]
1	1410	878	1.43E+12	3.27E+11
2	1410	633	9.79E+11	4.48E+11
3	1410	390	5.25E+11	8.79E+11
4	1410	0	3.71E+11	3.34E+11
5	2115	840	4.02E+12	8.35E+11
6	2115	672	4.04E+12	9.54E+11
7	2115	462	3.05E+12	2.63E+12
8	2115	0	4.75E+11	6.47E+11
9	850	157	2.94E+11	3.2E+11
Weighted average	–	–	1.81E+12	9.22E+11

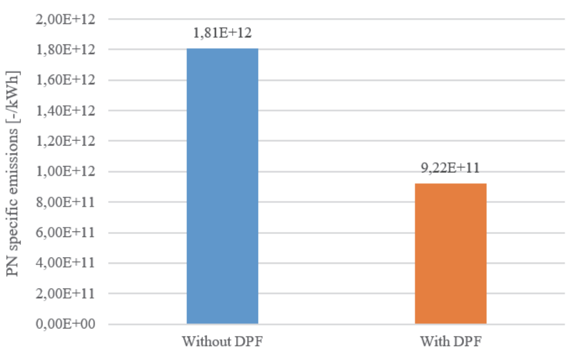

Fig. 11. Weighted average of the specific PN emissions for the system with and without the DPF.

The particle size distribution was also analyzed. This is particularly important because as mentioned the smallest particles are the most dangerous for humans, and the number itself does not provide the information on what particle size is permanently oxidized by the exhaust aftertreatment systems. The average particle size distribution for the standard system is shown in Fig. 12, and after using the DPF in the exhaust system is shown in Fig. 13.

It is noteworthy that the size distribution is very similar in both cases. There are fairly equal values for the smallest particles and for particles with the size of several dozen nanometers, the distribution is similar to a Gaussian curve. What differentiates these distributions is the scale used. After using the filter, a considerable reduction in the number of medium and large particulates in the exhaust gas can be observed. The values for the smallest particles are practically unchanged.

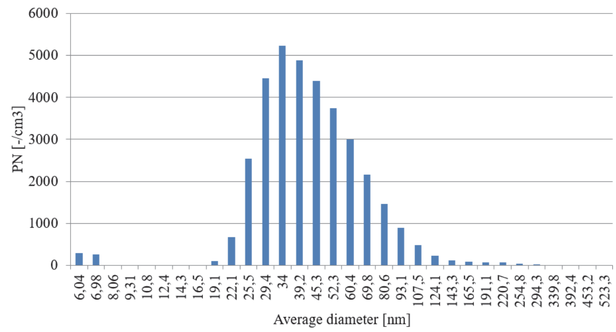

Fig. 12. The average particle size distribution of the standard exhaust system without DPF.

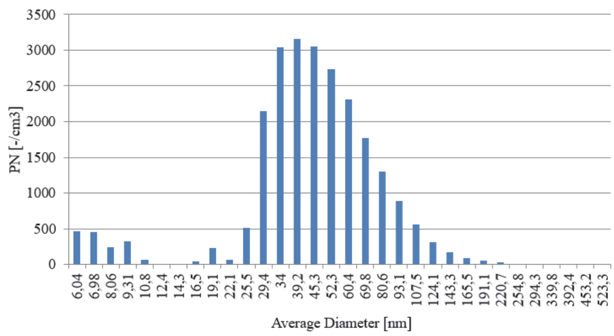

Fig. 13. The average particle size distribution of the standard exhaust system with DPF.

This demonstrates the efficiency of the filter in stopping and oxidation of large particles with little to no effect on small particles. In addition, the catalytic layer used could affect the reduction of large particles without complete oxidation.

6 Summary

Current trends in combustion engines aim to reduce their negative impact on the environment by combining it with other engine types (hybrids) or the use of alternative fuels (fuel cells, methane, LPG). The use of these solutions in NRMM vehicles causes a number of complications that make it as if for the next few years the CI internal combustion engine dominates the propulsion system of this group. It is characterized primarily by the availability of fuel and the ability to quickly refuel. The use of modern exhaust aftertreatment systems will allow to achieve the emission values that are not yet possible for several years, especially for nitrogen oxides and particulate matter. However, this applies to new vehicles, while older vehicles, whose emissions may be several times higher, are still in use.

For this reason, the popularity of downsizing, which means retrofitting vehicles with modern exhaust gas aftertreatment systems. This solution is relatively inexpensive, and the theoretical method allows for significant reduction of emissions especially PM, PN and nitrogen oxides.

The research carried out in the article concerned the retrofitting of a farm tractor with a universal particle filter with the size chosen relative to the engine displacement. Placing the filter in the exhaust system has measurable effects on particle emissions both in terms of number and mass of particulate matter. The use of the filter made it possible to reduce the emitted mass and number of solid particles from the exhaust system by a half.

The trend, which means retrofitting older tractors with newer exhaust aftertreatment systems, can generate positive environmental effects far exceeding the gains obtained through improving new constructions where the resulting effects are much smaller. In addition to the number of used vehicles, the new vehicles represent only a few percent of vehicles currently in use. The use of the modified NRSC test allowed the engine to work in conditions similar to those occurring during field operations. The reduction in the emissivity of the tested tractor would probably have been even greater if the filter was closer to the exhaust system (higher temperature) and if it had been optimized for that particular engine.

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