Natalia SZYMLET, Maciej SIEDLECKI, Piotr LIJEWSKI, Barbara SOKOLNICKA
Politechnika Poznańska, Instytut Silników Spalinowych i Transportu, Poznań, Poland
e-mail: natalia.r.szymlet@doctorate.put.poznan.pl

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SPECIFIC EMISSION OF HARMFUL COMPOUNDS ANALYSIS FROM AN AGRICULTURAL TRACTOR IN A MODIFIED NRSC TEST

Summary

Non-road vehicles type approval tests consist of testing the combustion engines themselves on engine dynamometer stations. As a part of these tests, NRSC and NRTC tests are conducted. The many years of research conducted by the Poznan University of Technology revealed differences in the actual specific emission of toxic components of exhaust gases from agricultural machinery compared to the type approval tests. This is related to the different operating conditions of the internal combustion engine relative to the test cycles. For this reason, the authors conducted a study of the actual emission from an agricultural tractor in a 13-phase NRSC test, modified to more closely reflect real operating conditions. These points were determined on the basis of operating points obtained from tests in real operating conditions. Before the tests, the tractor engine was warmed up to its operating temperature, after which it was loaded by the power take-off shaft with a portable engine dynamometer system. Analyzers from the PEMS group were connected to the tractor's exhaust system, which allowed to determine the concentrations of exhaust components such as CO, HC, NO_x, PM, in the type approval testing process. The exhaust emission tests were extended with the solid particles number emission as well as their dimensional distribution, which while not limited through emission norms, is still very important from the point of view of human health and life. The analysis of the results allowed to determine the limit value excess level of specific compounds from the tractor.

***Key words**: emission, NRMM, modified NRSC test, PEMS*

ANALIZA JEDNOSTKOWEJ EMISJI ZWIĄZKÓW TOKSYCZNYCH Z CIĄGNIKA ROLNICZEGO W ZMODYFIKOWANYM TEŚCIE NRSC

Streszczenie

Testy homologacyjne pojazdów o zastosowaniu pozadrogowym polegają na badaniu pod kątem emisyjności samych silników spalinowych na stanowiskach hamownianych. W ich czasie prowadzone są testy NRSC (Non Road Stationary Cycle) i NRTC (Non Road Transient Cycle). Wieloletnie badania Politechniki Poznańskiej dowiodły różnic w rzeczywistej emisji jednostkowej składników toksycznych spalin z maszyn rolniczych w porównaniu do testów homologacyjnych. Związane jest to z odmiennymi warunkami pracy silnika spalinowego w stosunku do cykli badawczych. Z tego powodu autorzy przeprowadzili badania rzeczywistej emisji z ciągnika rolniczego w 13-fazowym teście NRSC zmodyfikowanym tak, by w większym stopniu odwzorowywał warunki rzeczywiste. Punkty te określono na podstawie uprzednio przeprowadzonych badań parametrów pracy w rzeczywistych warunkach eksploatacji. Po uzyskaniu temperatury roboczej oleju i cieczy chłodzącej silnik ciągnika był obciążany przez wał odbioru mocy samojezdną hamownią silnikową. Do układu wylotowego ciągnika podłączone były analizatory z grupy PEMS , które pozwoliły na wyznaczenie stężeń toksycznych składników spalin: CO, HC, NO_x, PM, rozszerzone o nielimitowaną, ale bardzo istotną z punktu widzenia zdrowia i życia ludzi emisję liczby cząstek stałych PN oraz ich rozkład wymiarowy. Analiza wyników pozwoliła na określenie emisji związków toksycznych względem wartości dopuszczalnych.

***Słowa kluczowe**: emisja, maszyny ruchome nieporuszające się po drogach, zmodyfikowany test NRSC, PEMS*

1. Introduction

According to the definition contained in the Regulation of the European Parliament and of the Council of the European Union of 14 September 2016, NRMM (*Non-Road Mobile Machinery*) is a mobile machine, mobile device or a vehicle with a body or wheels or without a body or wheels, not intended for carriage of passengers or goods on public roads [1]. These vehicles are usually equipped with compression ignition engines characterized by high emission values of nitrogen oxides (NO_x) and particles (in terms of weight and number). Due to the continued mechanization of agriculture and the modernization of farms, there is a significant increase in the number of new NRMM category vehicles being sold. According to forecasts, in 2020 it will exceed 5 million units of newly sold vehicles of this type. This means a twelve percent increase compared to 2012, while only a 3% increase is expected for trucks [2].

The increase in the number of NRMM category vehicles caused increased interest of legislators in the environmental pollution problem of this group of vehicles. Emission norms have changed over the years (Fig. 1), the current standard is called Stage 4 and it will continue to apply until 2019, depending on the engine power and the intended vehicle purpose.

Legislators assure that the Stage V standard and the RDE (*Real Driving Emissions*) procedure for vehicles with compression ignition engines will come into force in 2019. RDE means exhaust emissions testing in real operating conditions and is the best available method that gives complete and most reliable information on the real exhaust components emission values from this group of vehicles. Such tests are performed using PEMS mobile measuring equipment. Numerous studies by the Institute of Combustion Engines and Transport and other scientific and research units all over the world have clearly shown that the emission values obtained in real operating conditions differ significantly from the emission values obtained as a result of the research process in laboratory conditions, based on approved type approval tests, especially for the emission of nitrogen oxides and particulate matter [3, 4, 5, 6].

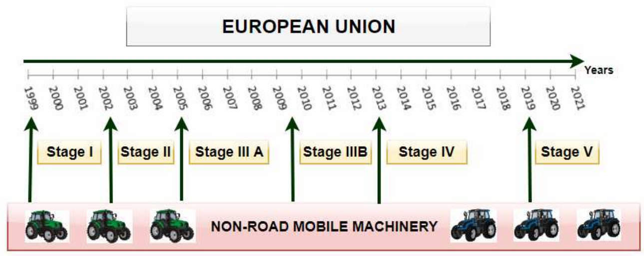

Fig. 1. Dates of introducing consecutive emission standards in Europe [7]
Rys. 1. Lata wprowadzania kolejnych norm emisyjnych w Europie [7]

Currently, the compounds limited by the legislation include solid particles (in terms of mass) and gaseous compounds, i.e.: CO_2, CO, NO_x and HC. The particle number limit (PN) for NRMM vehicle engines has not been established for existing standards. However, the nature of the particle size depending on their diameter (Fig. 2) shows that nanoparticles (particles with a diameter below 1µm) account for 90% of the total number of particles emitted by CI engines, while being only 10−20% of the total mass of solid particles emitted together with the exhaust gases. Thus, as the legislators have noticed the problem, a limit value of particle number equal to 1×10^{12} is to be introduced with the Stage 5 standard. This is in line with the guidelines of the European Parliament and the Council of the European Union in Regulation (EU) 2016/1628, which reads as follows: *"In order to ensure the regulation of smallest particulate pollutants emissions (0.1 µm and smaller), the Commission should have the authority to accept a quantitative approach to particulate pollutants emissions measurement, in addition to the current weight-based approach. The numerical measurement approach should use the results of the United Nations Economic Commission for Europe (UN/ECE) Particulate Measurement Program and should be in line with existing ambitious environmental objectives."* [1]

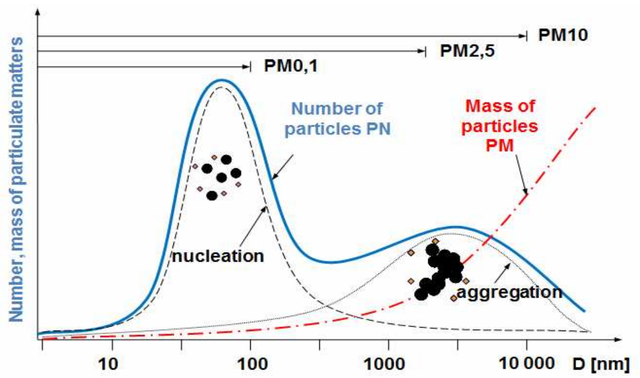

Fig. 2. The idealized relation between the size of particles and their number and mass for exhaust gases from the CI engine [8]
Rys. 2. Ideowa zależność wielkości cząstek stałych od ich liczby oraz masy dla spalin silnika ZS [8]

2. Test vehicle

The tested vehicle was an agricultural tractor, in line with the Stage IIIA/Tier 3 emission standard. The manufacturer equipped the vehicle with a 6-cylinder engine with a displacement of 7.1 dm^3 and a maximum power of 198 kW at 2300 rpm. The tractor was equipped with an DOC (*Diesel Oxidation Catalyst*) and EGR (*Exhaust Gas Recirculation*). Table 1 lists the technical data of the vehicle, while Fig. 3 shows the vehicle together with the measuring apparatus.

Table 1. Test vehicle technical data
Tab. 1. Dane techniczne obiektu badawczego

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 system	EGR, DOC
Emission standard	Tier 3/ Stage IIIA

Source: own study / Źródło: opracowanie własne

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Fig. 3. Picture of the tractor and the emission measuring equipment
Rys. 3. Obiekt badawczy wraz z aparaturą pomiarową

3. Research method
3.1. Type approval tests of NRMM vehicles

There are currently two worldwide type approval tests for NRMM vehicles – stationary NRSC test (*Non Road Stationary Cycle*) and dynamic NRTC test (*Non Road Transient Cycle*).

The NRSC stationary test is an 11-phase test (Fig. 4) performed on the engine dynamometer. It allows to determine the average emission of individual components of exhaust gases. The participation coefficients for each phase are determined based on the intended application of the tested engine [9].

The NRTC dynamic test came into force as a part of the Stage III standard and allows continuous measurement of toxic compounds emissions as well as fuel consumption for variable engine operation parameters (speed and load). Fig. 5 shows the evolution of the NRTC dynamic test.

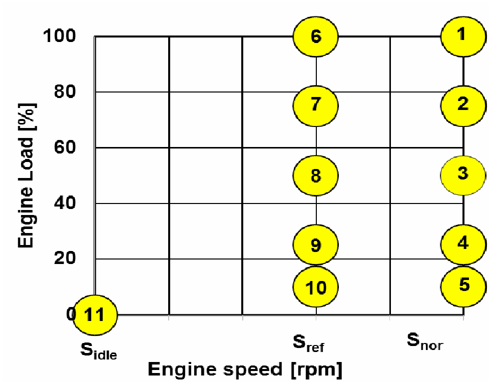


Fig. 4. The NRSC test measurement points [9]
Rys. 4. Schemat testu NRSC [9]

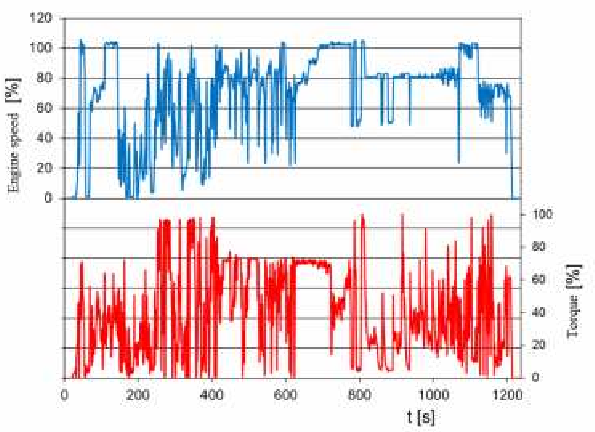


Fig. 5. The dynamic NRTC test [9]
Rys. 5. Schemat testu NRTC [9]

3.2. Modified NRSC test

The tests presented in this article have been performed using the modified stationary NRSC test. Numerous studies on NRMM vehicles of various roles have shown that the type approval tests do not fully reflect the actual operating parameters of the engines of this vehicles category [9]. The stationary NRSC test phases for the majority of the tested engines lie outside the ranges of rotational speeds and loads most frequently used in real operation (Fig. 6). In addition, the ranges of maximum engine loads are typically very rarely used.

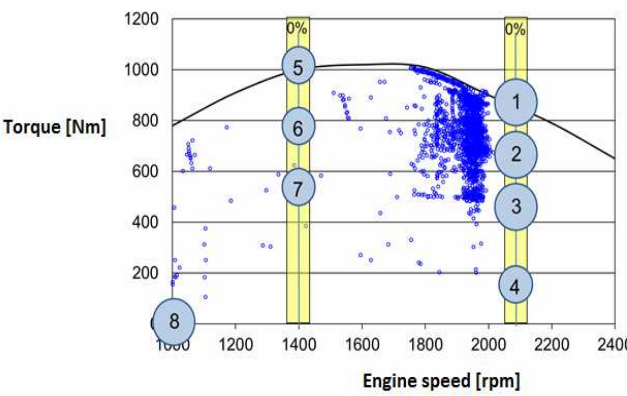


Fig. 6. Comparison of agricultural tractor engine operating range in real conditions with NRSC test points [9]
Rys. 6. Porównanie zakresu pracy ciągnika rolniczego w rzeczywistych warunkach eksploatacji z punktami testu NRSC [9]

Therefore, a new NRSC test was proposed, the engine operating points were condensed and their number decreased (Fig. 7). It was noticed that these engines normally operate in a very narrow range of medium rotational speeds and high loads, which is described in detail in [9]. Table 2 presents the parameters of the proposed modified NRSC test.

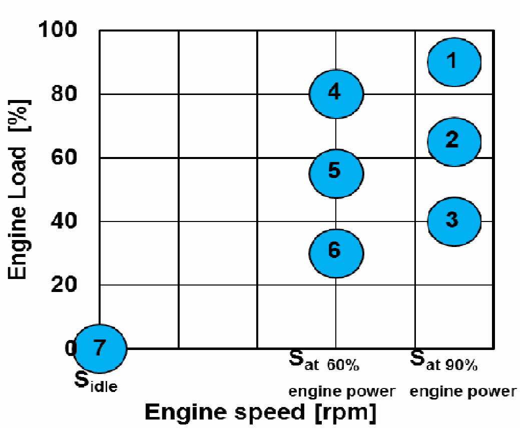


Fig. 7. The NRSC test points after modification [9]
Rys. 7. Schemat testu NRSC po modyfikacji [9]

Table 2. Modified NRSC test parameters [9]
Tab. 2. Parametry zmodyfikowanego testu NRSC [9]

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	90	2115	80	672	0,1
5	90	2115	55	462	0,1
6	90	2115	30	252	0,1
7	Idle	850	-	-	0,15

3.3. Measurement apparatus

The measurement of harmful compounds in laboratory conditions on the chassis dynamometer, thus simulating the real operating conditions, was performed using mobile devices from the PEMS group. The measurement of gaseous compounds, i.e. carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), and hydrocarbons (HC), was done with the SEMTECH DS device (Fig. 8a). The measurement of particulate mass was made using the AVL MSS apparatus (Fig. 8b), while the measurement of their number was performed with the TSI 3090 EEPS device (Fig. 8c).

a) b) c)


Fig. 8. Pictures of the exhaust measurement devices used: a) SEMTECH DS., b) AVL MSS, c) TSI 3090 EEPS [10, 11, 12]
Rys. 8. Widok aparatury pomiarowej: a) SEMTECH DS., b) AVL MSS, c) TSI 3090 EEPS [10, 11, 12]

In the case of the SEMTECH DS device the exhaust sample of the tested vehicle engine was taken from the exhaust gas mass flow-meter, from where it was transported via a heated conduit to the analyzer set (Fig. 9). Heating the duct to 191ºC is to prevent condensation of hydrocarbons as a result of temperature differences. Subsequently, the exhaust sample is subject to filtration to separate the solid particles. The sample prepared in this way is transported to individual analyzers, allowing to examine individual components of the exhaust gases.

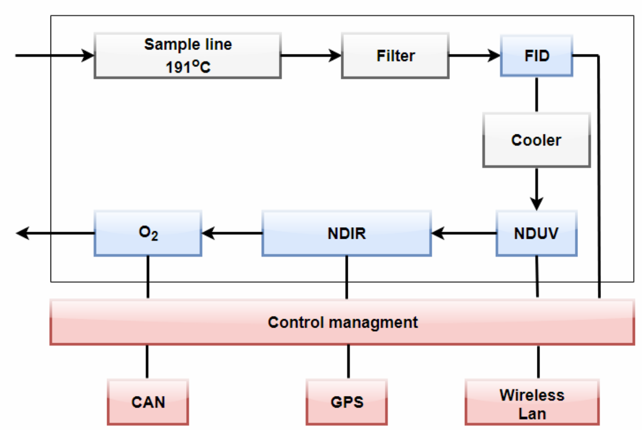


Fig. 9. SEMTECH DS operation schema [10]
Rys. 9. Schemat działania mobilnego analizatora SEMTECH DS. [10]

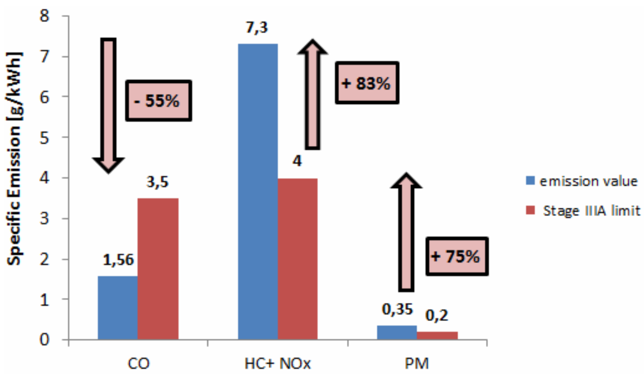
The first analyzer to which the sample is sent is the FID (*Flame Ionization Detector*), which makes it possible to determine the hydrocarbons emission. Then the gas flow is cooled to a temperature of around 4ºC and transported to the NDUV (*Non-dispersive Detector Ultra Violet*) analyzer, which tests for the content of nitrogen oxides. Then the carbon oxide and carbon dioxide content is determined using the NDIR (*Non-dispersive Detector Infrared*) analyzer. The measurement oxygen via an electrochemical analyzer is the last step. The vehicle is positioned by synchronizing the GPS system with the analyzer. The apparatus also enables connection to a WLAN network and communication with the CAN (*Controller Area Network*) [10].

The measurement of particulate mass was made using the AVL mobile analyzer MSS (*Micro Soot Sensor*), using the PAAS (*Photo Acoustic Soot Sensor*) method. This method consists in subjecting the solid particles to radiation with modulated light, which results in their periodic heating and cooling. This process leads to changes in the volume of the tested gas, which generates a sound wave. Measurements are performed by vibration-sensitive microphones that are tuned to work only in a certain range of amplitudes and frequencies. When the air is clean, no signal is detected, while when increasing the number of soot particles in the gas (increase in concentration), the sound signal increases. The exhaust gases are diluted in order to avoid soot condensation [11].

The particle number was measured using a TSI EEPS 3090 mass spectrometer (*Engine Exhaust Particle Sizer Spectrometer*). The exhaust gases are transported through the dilution system maintaining the temperature appropriate for the mass spectrometer. In the first step, the pre-filter stops the particles with a diameter larger than 1 μm, which are outside of the measuring range of the device. Then, after passing through the neutralizer, the particles are directed to the charging electrode; after obtaining an electric charge, they can be classified based on their size [12].

4. Results

The data obtained from the chassis dynamometer tests were analyzed and a specific emission value was determined on this basis (the mass of a given compound emitted relative to the work performed within one hour). This was done for every compound limited by the Stage IIIA standard. Moreover, the emission values obtained for simulated actual conditions were compared with the limits of the Stage IIIA/Tier 3 standard and significant differences were noted (Fig. 10).



Source: own study / Źródło: opracowanie własne

Fig. 10. Comparison of the agricultural tractor specific emissions and Stage IIIA standard limits
Rys. 10. Porównanie emisji jednostkowej ciągnika rolniczego i limitów normy Stage IIIA

The biggest discrepancy was recorded for the $HC+NO_x$ emissions, which was 83%. The particulate emission was characterized by a 75% difference between the emission for the modified NRSC test (based on RDE tests) compared to the Stage IIIA standard. Only the carbon monoxide emission was found to be within the emission limit values, which was related to the high efficiency of the oxidizing catalytic reactor. On this basis, it can be unequivocally stated that the emission obtained in near to real operating conditions significantly differs from the values of the current type approval tests done in accordance with the legal provisions. The validity of the modification of the current stationary test NRSC was also confirmed.

In addition, the specific emission of the particle number, which amounted to 1.41×10^{12} [-/kWh], was determined, but at the moment there is no limit set by the legislators for this emission value. Fig. 11 shows the dimensional distribution of solid particles in the exhaust gas tested. The particle size distribution confirms the significant number of particles with the smallest diameters emitted, as is characteristic of compression ignition engines. Local maxima exist for diameters of 6.94 and 34 nm. The total concentration of particulate matter reaches up to 20000/cm^3, which exceeds the ambient concentration value in the area by an order of magnitude.

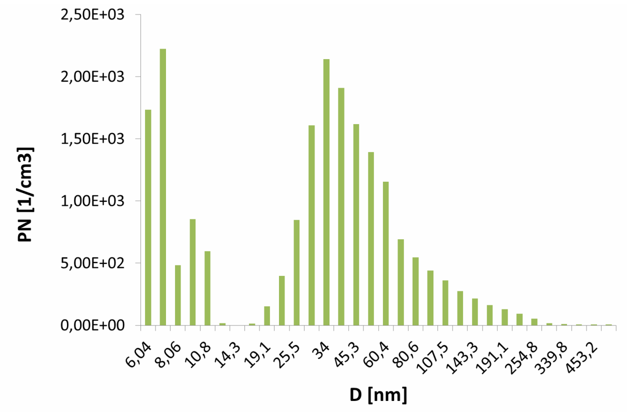


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Fig. 11. Average particle size distribution emitted from the tractor engine

Rys. 11. Rozkład wymiarowy cząstek stałych z ciągnika rolniczego

5. Conclusions

The performed research revealed that the toxic emission limits (Stage IIIA/Tier 3) are exceeded in a test that simulated real operating conditions.

Emission tests for the modified NRSC test confirmed the shortcomings of current testing methods for the emission of toxic compounds. Currently, the RDE test is the only way to determine real emissions obtained in real traffic conditions, also taking into account the specific engine operating conditions or the atmospheric conditions. Its final form in the case of NRMM vehicles should become official by 2019 with the introduction of Stage V emission limits. Moreover, it is necessary to regulate the emission of toxic compounds from NRMM vehicles already in operation - as of today such regulations do not exist.

One of the ways to limit exhaust emissions from the operation of NRMM vehicles is through retrofitting, which means retrofitting old machinery with modern exhaust aftertreatment systems. This idea is one of the main objectives of the European Parliament: *"Due to the long service life of non-road mobile machinery, modernization of engines already in use should be considered. Such modernization should in particular concern machines working in densely populated urban areas, in order to achieve compliance with EU legislation on air quality".* [1].

***Acknowledgement**: 05/52/DSPB/0260.*

6. References

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