Article citation info:
MERKISZ J, LIJEWSKI P, FUĆ P, WEYMANN S. Exhaust emission tests from non-road vehicles conducted with the use of PEMS analyzers. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2013; 15 (4): 364–368.

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EXHAUST EMISSION TESTS FROM NON-ROAD VEHICLES CONDUCTED WITH THE USE OF PEMS ANALYZERS

BADANIA EMISJI ZWIĄZKÓW TOKSYCZNYCH SPALIN Z POJAZDÓW O ZASTOSOWANIACH POZADROGOWYCH Z WYKORZYSTANIEM ANALIZATORÓW PEMS*

The paper discusses the issue of exhaust emissions from non-road vehicle engines. In the first part of the paper American regulations on the procedures of engine testing in operation were briefly characterized. The said regulations are a novel solution and were introduced as one of the first of this type worldwide. In the next part of the paper the authors presented the results of the exhaust emission tests from a farm tractor performed under actual operating conditions during fieldwork. For this purpose PEMS (Portable Emissions Measurement System) was used. The tests were carried out for different test procedures such as the NTE (Not-To-Exceed) procedure. The analysis of the test results was performed chiefly in the aspect of the NTE test applicable in the U.S. The analysis pertains chiefly to the engine operating conditions and exhaust emissions. European legislation currently does not require such tests and that is why the presented tests are related to the American procedures. The performed tests and their analysis led to a formulation of conclusions related to the engine operating conditions and its exhaust emissions.

***Keywords**: non-road vehicles, measurement of exhaust emissions under actual operating conditions.*

Artykuł dotyczy problemu badań emisji związków toksycznych spalin z silników pojazdów o zastosowaniach pozadrogowych (non-road). W pierwszej części artykułu krótko scharakteryzowano przepisy amerykańskie nt. procedur badań silników w eksploatacji. Przepisy te są nowatorskim rozwiązaniem i zostały wprowadzone jako jedne z pierwszych tego typu rozwiązań na świecie. W dalszej części artykułu przedstawiono wyniki badań emisji związków toksycznych spalin silnika ciągnika rolniczego, wykonane w rzeczywistych warunkach eksploatacji, podczas wykonywania prac polowych. Do tego celu wykorzystano aparaturę PEMS (Portable Emissions Measurement System). Badania te wykonano dla różnych procedur badawczych, m.in. w teście NTE (Not-To-Exceed). Analizę wyników badań przeprowadzono głównie w aspekcie testu NTE, obowiązującego w Stanach Zjednoczonych. Analiza ta dotyczy przede wszystkim warunków pracy silników oraz emisji związków szkodliwych. Europejskie regulacje prawne w chwili obecnej nie nakładają obowiązku wykonywania takich badań, dlatego w zaprezentowane badania odnoszą się do procedur amerykańskich. Wykonane badania i ich analiza pozwoliły na sformułowanie wniosków dotyczących warunków pracy i emisji z silnika.

*S**łowa kluczowe**: pojazdy o zastosowaniach pozadrogowych, pomiary emisji w rzeczywistych warunkach eksploatacji.*

1. Introduction

For many years now works have been continued to reduce the negative impact of transport on the natural environment. A particular involvement of research and development centers is seen in works related to vehicle drivetrains and powertrains. In 2012 IARC (International Agency for Research on Cancer), a member of WHO (World Health Organization), in the report published in June 2012 qualified diesel exhaust gas to a group of carcinogenic factors [7]. Before that, diesel exhaust gas was classified as a group of 'probably' carcinogenic factors. Yet, in light of the latest research the diesel exhaust gas is classified as having the greatest carcinogenic risk [3, 14]. This is yet another factor that motivates to commit to research and development works aiming at a reduction of the negative impact of diesel engines on the environment. The works should focus on the technical solutions reducing the exhaust emissions and a development of research methods and equipment. Only the combination of solutions in the above fields may bring measurable effects such as the improvement of the ecological indexes of combustion engines. Non-road vehicles are mostly fitted with diesel engines. Besides, contrary to on-road vehicles they are technologically obsolete and the admissible emission limits are much more liberal. Hence, the necessity of a technological improvement of these engines aiming at their reduced impact on the human health and natural environment.

One of the most significant aspects of exhaust emission testing is the adopted methodology. In recent years methods of exhaust emission testing under actual operating conditions have been developing rapidly. This type of testing is used increasingly as it provides invaluable information on the actual on-road exhaust emissions, information that is not obtainable under laboratory conditions [1, 5, 6, 10]. That is

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** why the results of such tests are so desirable. Since this is a relatively new trend, the testing methodology is not yet fully developed and commonly recognized. From the publications on this subject we know that many issues still remain unresolved. One of these issues is the selection of engine operating conditions during the tests. It is important that the conditions are representative of a given type of vehicle and that the results are comparable. Another issue is the problem of engine operating conditions under research tests. The problem of engine operating conditions under laboratory tests has been drawn attention to earlier [2, 4, 8, 9, 13, 11, 12, 15]. From the relevant published works conclusions are drawn that the engine operating conditions (engine load and speed) in laboratory tests, for both on-road and non-road vehicles, are not compliant with the conditions of actual operation. Despite numerous investigations and analyses of this problem it still remains unresolved.

Tests conducted under actual operating conditions indicate that the engine operation of vehicles of different categories (HDV – Heavy Duty Vehicles, LDV – Light Duty Vehicles, non-road) is characterized by specific operating parameters e.g. traction vehicle engines utilize a wide range of engine speeds while engines of some of the vehicles of non-road applications operate in a very limited range of engine speeds [1, 6, 11, 12, 15]. It is thus worth analyzing whether the testing methodology should be individually selected for a given engine application and whether current testing procedures take this fact into consideration.

2. Exhaust emission regulations for non-road vehicles

The procedures applicable in exhaust emission testing for non-road vehicles have been described and analyzed in earlier works [11, 12]. This paper focuses on the procedures related to the exhaust emission testing under actual operating conditions. One of the first regulations pertaining to this type of measurements was introduced by Environment Protection Agency based in USA [16]. According to these procedures NTE test and emission limits in this test were introduced as an additional tool for exhaust emission control (NTE is also a standard related to the described procedure). These tests are conducted under actual engine operating conditions. The NTE test was initially introduced for HDV engines and since 2011 it has been applicable for some of the non-road vehicles.

The NTE tests are not tied to any specific driving cycle of a vehicle or engine work points. There is no predefined mileage or test time. The tests cover a range of engine operation that falls within the boundaries of the controlled NTE zone, and the measurements include stationary and dynamic conditions (Fig. 1). The exhaust emissions are averaged from the engine work cycle lasting a minimum of 30 seconds (a 30 second window).

The NTE test sets an control zone limited by specific engine speed and load values:

- minimum engine speed is determined analogically to the speeds determined in the ESC test: $n_{min} = n_{lo} + 0,15(n_h - n_{lo})$ (speed A in the ESC test is $n_A = n_{lo}+0,25(n_h - n_{lo})$),
- engine load equal to or greater than 30% of the maximum engine torque,
- from NTE all engine speeds and loads are excluded for which the engine obtains an effective power lower than 30% of the maximum power,
- engine manufacturer may apply for exclusion from NTE of the speeds and loads for which the fuel consumption (BSFC – Break Specific Fuel Consumption) does not exceed 5% of the minimum unit fuel consumption if the manufacturer expects the engine not to operate at these work points during regular operation. This does not apply to engines fitted with automatic transmission of a given number of speeds and vehicles fitted with manual transmission.

For EPA 2004 compliant engines the zones without particulate matter measurements were determined (depending on speed B in the ESC test). This does not apply to EPA 2007 compliant engines but in this case the manufactures may conditionally apply to EPA for exclusion of the PM measurement in these zones. Besides, the manufacturers may apply for a reduction of the NTE zone by a certain sub zone, if the operating time in this sub zone does not exceed 5% of the total operating time of the engine. These sub zones should have an elliptical or rectangular shape and its boundaries, at some point should be convergent with the boundary of the NTE zone.

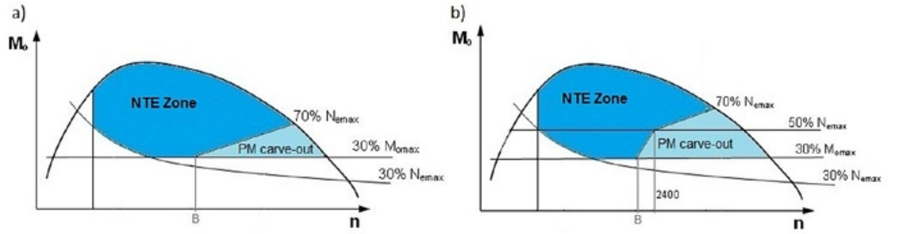

Fig. 1. Schematics of the NTE test for non-road engines, a) for engines of the maximum engine speed 2400 rpm, b) for engines of the maximum speed greater than 2400 rpm [16]

According to the requirements prescribed by the EPA all Tier - 4 compliant non-road vehicle engines must also comply with the NTE standard. For non-road vehicle engines of the power output greater than 130 kW the regulations have been applicable since 2011, for engines of the power output from 56–130 kW – since 2012 and for engines of the power output lower than 56 kW – since 2013. The unit exhaust emission limits in the NTE test have been set at 1.25 of the admissible unit emission of a single exhaust component from the Tier 4 standard. Only for engines that have the unit emission of nitric oxides lower than 2.5 g/kWh and the unit emission of particulate matter lower than 0.07 g/kWh this coefficient amounts to 1.5. The NTE regulations apply to the type approval tests and must be met for the whole engine life cycle [16].

The proposals of the future European regulations for HDV engines also provide for the exhaust emission tests in operation. A European equivalent of the NTE test is a proposal of a compliance test of the vehicle in operation with the requirements of the unit emissions, based on the determination of the emissions in the whole driving cycle as a function of engine operation expressed in kWh.

3. Methodology and object

In recent years interest in the on-road exhaust emission testing has grown significantly as this is the only way to obtain information on the actual exhaust emissions from a given vehicle. Such tests provide valuable and reliable test results that would otherwise be impossible to obtain under laboratory conditions on a chassis or engine dynamometer. The tests presented in the paper were carried out under actual conditions of operation of a farm tractor operating in the field using a cultivator (Fig. 2). The basic specifications of the tractor engine have been given in table 1.

The authors used Semtech DS by Sensors Inc. for the exhaust emission tests. This is a PEMS (Portable Emission Measurement System) analyzer that measures the concentration of the exhaust components (carbon dioxide, carbon monoxide, hydrocarbons and nitric oxides) and simultaneously measures the flow rate of the exhaust gas.

Table 1. The engine specifications of the tested farm tractor

Displacement / number of cylinders	6,4 dm^3/6
Number of cylinders /valves	6/12
Maximum power output	122 kW / 1900 rpm
Maximum torque	698 Nm / 1350–1500 rpm
Aspiration	VGT turbocharger
Injection system	Common rail, max pressure: 160 MPa
Aftretreatment system	Oxidation catalyst
Emission standard	Stage IIIB/Tier3

Fig. 2. The view of the tractor during the tests with the measurement equipment fitted

The measurement of the above emissions determines the vehicle on-road emission, unit emission and fuel consumption. The exhaust gas is introduced into the analyzer through a probe maintaining the temperature of 191°C. Then particulate matter is filtered out (diesel engines) and the exhaust is directed to the flame-ionizing detector (FID) where hydrocarbons concentration is measured. The exhaust gas is then chilled to the temperature of 4°C and the measurement of the concentration of nitric oxides (NDUV analyzer), carbon monoxide, carbon dioxide (NDIR analyzer) and oxygen follows in the listed order. The measurement of the oxygen concentration is realized with an electrochemical sensor. It is possible to add data sent directly from the vehicle diagnostic system to the central unit of the analyzer and use the GPS signal (Global Positioning System).

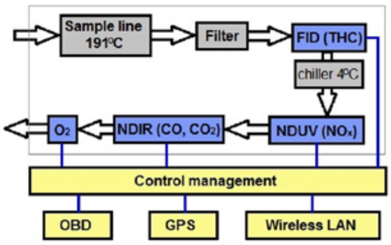

Fig. 3. Schematics of the Semtech DS analyzer

Table 2. Characteristics of SEMTECH DS – a portable exhaust emission analyzer

Parameter	Measurement method	Accuracy
Component concentration		
CO	NDIR – non-dispersive (infrared), range 0–10%	±3%
HC	FID – flame ionization, range 0–10 000 ppm	±2,5%
$NO_x = NO + NO_2$	NDUV – non-dispersive (ultraviolet), range 0–3000 ppm	±3%
CO_2	NDIR – non-dispersive (infrared), range 0–20%	±3%
O_2	electrochemical, range 0–20%	±1%
Sampling frequency	1–4 Hz	
Exhaust mass flow	Mass flow	±2,5%
	T_{max} to 700°C	±1% of the range
Warm-up time	15 min	
Response time	$T_{90} < 1$ s	
Supported diagnostic systems	SAE J1850/SAE J1979 (LDV)	
	SAE J1708/SAE J1587 (HDV)	
	CAN SAE J1939/J2284 (HDV)	

For the measurement of particulate matter SEMTECH-LAM (Laser Aerosol Monitor) was used. SEMTECH-LAM operates through laser light scattering and measures the concentration of fine particulate matter in the exhaust gas in real time. With two selectable ranges and variable dilution ratios, the analyzer is compatible with a variety of different engine types, vehicles and test conditions. It could be used as test stand equipment or for on-road testing. The dual sample port enables testing of the filter efficiency for engines fitted with a diesel particulate filter. The SEMTECH-LAM uses three mass flow controllers that are automatically adjusted to maintain the desired dilution ratio. The monitor contains a laser light scattering analyzer that measures fine particulates from 100 nm to 10 000 nm. The specifications of SEMTECH-LAM have been shown in table 3.

4. Test results and analysis

The conducted research enabled a determination of the exhaust emissions during the whole test cycle (the whole range of engine speeds and loads). The applied methodology enabled a determination of the exhaust emissions in the NTE test. The used methodology also allowed distinguishing of the NTE test complaint engine work points. Figure 4 shows the work points and the NTE test zone determined for the tested engine. During the tests the tractor was coupled to a cultivator. The aggregate operated in the filed. During the tests the tractor operated at four different speeds, which resulted in changes in the engine loads caused by the increase in the resistance of the cultivator as the speed grew. This is seen in figure 4. The work points of the engine are accumulated around certain engine speeds. From the data obtained during the tests it results that only 61% of the total operating time of the test cycle the engine worked in the NTE test zone (Fig. 4). The duration of the whole test cycle was 4337 s., 2645 s. of which the tractor engine operated in the NTE test. That constitutes 61% of the total test time, which means that as much as almost 40% of the engine time of operation is not covered by the NTE test. The NTE test did not cover the engine operating areas with small loads (up to approximately 280 N·m) and low engine speeds (up to 1300 rpm) including idle. Idle is a frequently used engine operating area when performing light agricultural tasks.

Since the test cycles covered the engine operation outside of the NTE zone this was reflected in the exhaust emissions. Figure 5 shows the exhaust emission test results for the whole test cycle and for the NTE test. What is characteristic is that in the NTE test the exhaust emission of all toxic components is lower. The greatest differences are for hydrocarbons and nitric oxides. The emission of these components is lower in the NTE test by 25 and 23% respectively (Fig. 6). We also have a substantial difference in the emission of particulate matter. In the NTE test it is lower by 13% as compared to the emission from the whole test cycle. The smallest difference was observed for the emission of carbon monoxide, which was 9%. Based on the obtained

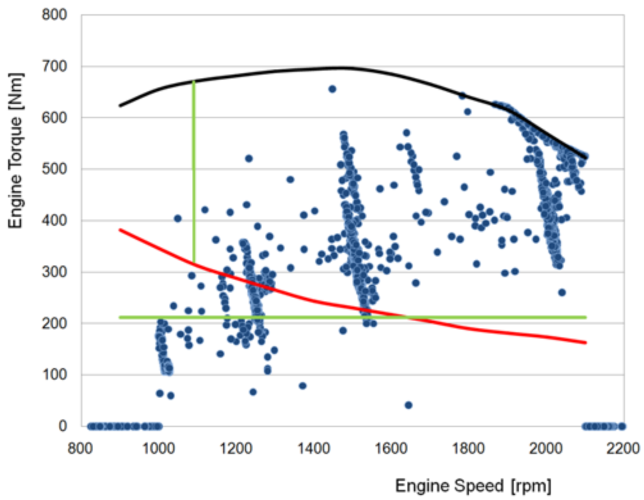

Fig. 4. Characteristics of the maximum engine torque of the tested engine. The work points and the NTE zone marked

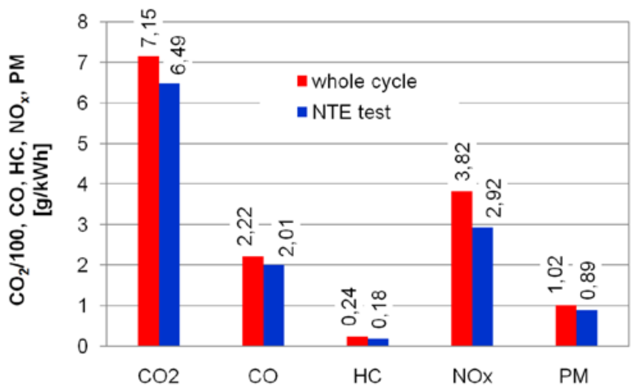

Fig. 5. Unit emission of the exhaust components from the tested engine under actual operating conditions

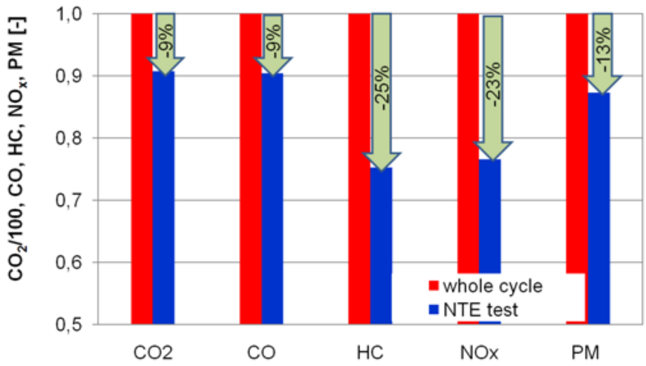

Fig. 6. Relative exhaust emissions from the engine of the tested tractor under actual operating conditions

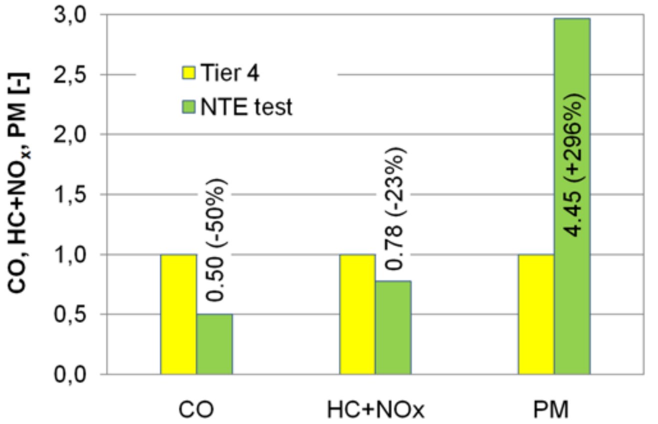

Fig. 7. Relative exhaust emissions from the engine of the tested tractor under actual operating conditions

results we can also conclude that the engine operating area in the NTE test was more advantageous in terms of fuel consumption than the whole test cycle because the unit emission of carbon dioxide in the NTE test was lower by 9%.

Figure 7 shows relative exhaust emissions from the engine of the tested tractor during operation under actual operating conditions as compared to the Tier 3 limits. The emission of carbon monoxide and the sum of the emissions of hydrocarbons and nitric oxides is lower than the Tier 3 limit while the emission of PM exceeds this limit significantly – it is almost three times higher.

5. Conclusions

Exhaust emission testing of non-road vehicles is a necessity. No emission control exists over most of these vehicles. The NTE test included in the American emission legislation is one of the first proposals of this type, yet we need to consider whether this proposal fully lives up to the requirements and conditions of non-road vehicle operation. The test results and their analysis presented in this paper prove that in the case of farm tractors the NTE test zone does not entirely reflect the actual tractor engine operation. In the case of the tests described in the paper almost 40% of the engine operating time fell outside of the NTE test zone. We should thus consider whether the procedure of this test should be modified. It seems it is purposeful to seek such testing solutions that will more accurately reflect engine actual operating conditions. The European proposal prescribes the determination of the exhaust emissions in operation based on the determination of work performed by the engine during the tests. We need to stress that the exhaust emission testing methodology under actual operating conditions is currently in its infancy an it will certainly be modified as the experience and additional information in this matter extends. Another problem are the emission limits for tests conducted under actual operating conditions. The regulations on the NTE test prescribe that these values are not to be greater than 1.25 of the limits included in the type approval standard (Tier 4). Based on the results presented in the paper and authors' experience we can state that meeting these requirements may be very difficult, especially for particulate matter. The test described in the paper is one of the first in its type and its results and conclusions motivate to continue works on this subject. The final determination of the requirements pertaining to the testing methodology for non-road vehicles under actual operating conditions requires a more extensive research on a greater number of objects performing a greater variety of works.

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