THE ANALYSIS OF THE OPERATING CONDITIONS OF FARM MACHINERY ENGINES IN REGARD TO EXHAUST EMISSIONS LEGISLATION

P. Lijewski, J. Merkisz, P. Fuc

ABSTRACT. *An analysis was conducted of actual operating conditions of farm machine engines with respect to currently applicable tests. The tests were performed on a farm tractor, farm harvester, and self-propelled forage harvester. Results of the investigations and analyses related to operating conditions of the said engines while operating in the field. An analysis was performed in which ranges of the most frequently used engine speeds and loads were determined. In addition, select results of the exhaust emissions measured under actual operating conditions of the farm machinery are presented. A PEMS (Portable Emissions Measurement System) equipment was used for the tests, and the emission of NO_x (Nitric Oxides) and PM (Particulate Matter). NO_x and PM are key pollutants in diesel engines as indicated by results. Conclusions following the comparison of the actual operating conditions with the NRSC (Non-Road Stationary Cycle) and NRTC (Non-Road Transient Cycle) research cycles indicate that the measurement range in the American NTE test seems too wide in the context of the obtained results. The obtained results force a discussion related to the necessity of modifying the applicable test procedures.*

Keywords. *Agricultural engineering, Engines, Emissions testing.*

Transport is one of the main sources of air pollution. For many years the development of motor vehicles has been determined by the regulations minimizing their impact on the natural environment. Apart from preserving air quality, an important aspect is the minimization of use of natural resources (crude oil). In the latest report, International Agency for Research on Cancer (IARC) one of the World Health Organization (WHO) departments clearly classifies diesel exhaust gases as carcinogenic (IARC Press Release No. 213; 2012, Attfield et al., 2012; Silverman et al., 2012). Since 1988 the diesel exhaust gases have been qualified as 2A group (classified by IARC) - a group of substances most probably carcinogenic. Having analyzed the latest research results, the WHO scientists are today of the opinion that they have sufficient evidence to state that diesel exhaust gases contribute to the development of lung cancer. It is noteworthy that the engines of tractors and other farm machinery have a significant share in the exhaust emissions from the transport sector. This particularly pertains to nitric oxides and particulate matter (Emission factor program Task 8c, 2004; Favre, 2011; Friedrich, 2008). These factors force the engineers to take every action leading to the reduction of emissions from these engines. Due to the perils related to the exhaust emissions from motor vehicles, legislative bodies introduce emission limits that are increasingly stringent. A good example is the emission limits for PM and NO_x for non-road vehicle engines of the rated power of 130 to 560 kW. The emission limits for both PM and NO_x in the Stage IV standard introduced in 2013 (type approvals) have been reduced by over 95% as compared to the Stage I limits introduced in 1998 (fig. 1).

Analyzing the development of non-road vehicle engines we can observe applications of solutions taken from the on-road vehicles, i.e. diesel particulate filters, initially fitted only in the on-road vehicles and only later fitted in non-road vehicles (Dreisbach, 2005; Moser 2005; Leverton, 2005; Poli, 2005). Aside from the development of technologies aimed at reducing exhaust emissions (Diesel Particulate Filter, Selective Catalytic Reduction etc.) there comes the advancement of the legislation, research methods, and research equipment.

The exhaust emissions from non-road vehicles are a serious problem. As compared to the on-road vehicles, the non-road ones are characterized by higher fuel consumption and higher exhaust emissions. The comparative tests carried out on a tractor and a delivery truck described by Merkisz (2011) have shown that the fuel consumption of the farm tractor was more than three times higher and its exhaust emissions were several times higher (nitric oxides six times higher). The scale of the problem is confirmed by the more liberal exhaust emission limits for

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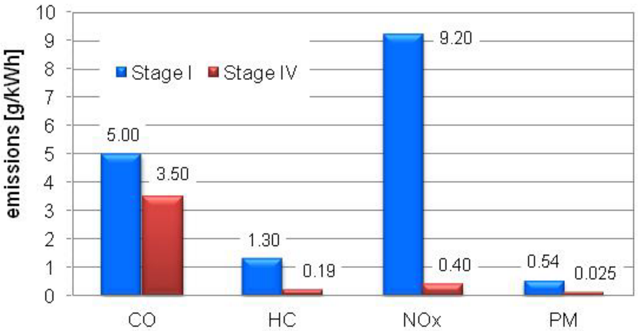

Figure 1. Comparison of the Stage I and Stage IV emission limits for non-road vehicle engines of the rated power of 130 to 560 kW.

non-road vehicles in comparison to the on-road ones (AVL, 2006). In the case of the non-road vehicles, the limits are much more relaxed as compared to limits for the on-road vehicles.

ANALYSIS OF REGULATIONS ON NON-ROAD VEHICLE EMISSIONS

The first regulations for non-road vehicles, both in Europe and in the United States, appeared in the 1990s. The regulations have since changed, where the first subsequent amendments consisted of implementing greater restrictions as to the emissions. The applicable and future restrictions, both European and American, have been listed in tables 1 and 2.

The analysis of the applicable regulations on the most important automotive markets allows for the formulation of several observations. The positive aspect of the current European, American and Japanese regulations is the assumption of some common solutions, e.g. the emissions are measured in one stationary test NRSC (fig. 2). The dynamic NRTC (fig. 3) test is also a common European-American solution. Some similarity also occurs during the introduction of new restrictions, e.g. in both Europe and the United States the admissible exhaust emission levels and dates of their implementation depend on the engine effective power (fig. 4). It is obvious that the most viable solution would be the unification of the regulations, if not globally, then at least throughout the major automotive markets, i.e. in Europe, the United States, and Japan. This would reduce the costs the manufacturers incur in relation to the implementation of their products on the market. In fact, this postulate applies not only to the non-road vehicles, but also to other vehicle groups.

Table 1. The emission limits (Stage IIIA and IIIB) and dates of their introduction in Europe for non-road vehicle engines (AVL, 2006).

Engine Power (kW)	Implementation Date[a]	CO g/(kWh)	HC g/(kWh)	NO_x g/(kWh)	PM g/(kWh)
		Stage 3A			
130-560	01.2006	3.5	NO_x+HC-4,0		0.2
75-130	01.2007	5.0	NO_x+HC-4,0		0.3
37-75	01.2008	5.0	NO_x+HC-4,7		0.4
19-37	01.2007	5.5	NO_x+HC-7,5		0.6
		Stage 3B			
130-560	01.2011	3.5	0.19	2.0	0.025
75-130	01.2012	5.0	0.19	3.3	0.025
56-75	01.2012	5.0	0.19	3.3	0.025
37-56	01.2013	5.0	NO_x+HC-4.7		0.025

[a] Not applicable to engines operating at constant engine speed.

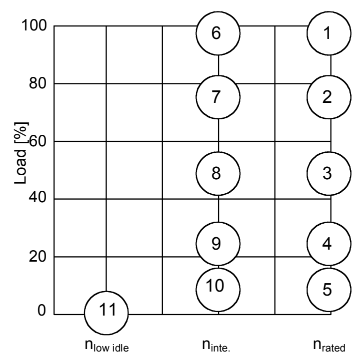

Figure 2. Diagram of the 11-phase test ISO 8178 (AVL, 2006).

Table 2. The emission limits (Tier 3 and Tier 4) and dates of their implementation in the USA for non-road vehicle engines (AVL, 2006).

Engine Power (kW)	Implementation Date	CO g/(kWh)	HC g/(kWh)	NMHC+NO_x g/(kWh)	NO_x g/(kWh)	PM g/(kWh)
			Tier 3			
37-75	2008	5.0		4.7		
75-130	2007		-			Tier 2
130-220	2006			4.0	-	
225-450	2006	3.5				
450-560	2006					
			Tier 4			
<8	2008	8.0	-	7.5	-	0.4[a]
8-19	2008	6.6	-	7.5	-	0.4
19-37	2008	5.5	-	7.5	-	0.3
	2013	5.5	-	4.7	-	0.03
37-56	2008	5.0	-	-	-	0.3[b]
	2013	5.0	-	-	-	0.03
56-130	2012-2014[c]	5.0	0.19	-	0.4	0.02
130-560	2011-2014[d]	3.5	0.19	-	0.4	0.02

[a] Tier 2 is applicable by 2010 for direct injection (DI) engines, with manual start-up.
[b] 0.4 if the engine reaches 0.03 in 2012.
[c] Ref. NMHC, NO_x, PM, option 1: 50% of the engines comply in the years 2012-2013; option 2: 25% of the engines must comply with all in the years 2012-2014, from 31 December 2014.
[d] PM, CO from 2011; NO_x, HC - 50% of the engines must comply in the years 2011-2013.

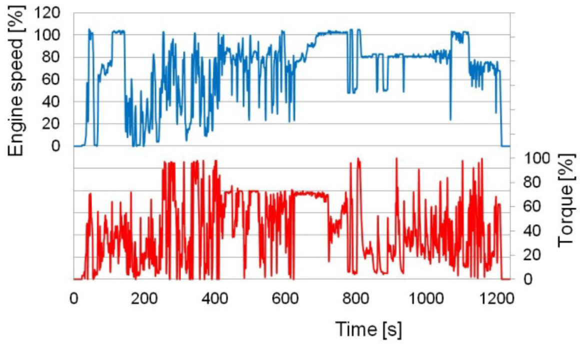

Figure 3. NRTC test course (AVL, 2006).

In the United States the Environmental Protection Agency (EPA) introduced a Not-to-Exceed test (NTE) and emission limits in this test are used as an additional instrument of the exhaust emission control. These tests are performed under actual operating conditions of the engines. It should be stressed that the NTE test is the first of its kind as regards to emission measurement worldwide. The NTE test was initially introduced for the Heavy Duty Vehicles (HDV) engines and since 2011 it has been applicable for some non-road vehicles.

The NTE tests are not based on any particular driving cycle or engine operating points. There is no specified test mileage or duration. The tests cover the engine operating range that falls in the range of the NTE control including steady state and transient conditions (variable engine speed and load). The exhaust emissions are averaged from a minimum time of 30 s.

In the NTE test, the engine operation map the control zone is determined (NTE zone, fig. 5) and limited by individual engine speed and load values. The control zone is determined by the following courses of the engine speeds and loads:

- For all engines the engine speed 15% above the A speed of the European Stationary Cycle (ESC).
- Engine load equal or higher than 30% of the maximum engine torque.
- Engine load equal or higher than 30% of the maximum engine power.
- All engine operating points for which the fuel consumption Brake Specific Fuel Consumption (BSFC) does not exceed 5% of the minimum engine BSFC. The engine manufacturer may request to exclude these points from the tests if the engine does not operate under regular conditions of operation. This requirement does not cover vehicles fitted with manual transmission or automatic transmission with a specified number of speeds.
- The control zone covers only the engine operating points for which the power is greater than 30% of the maximum engine power.

For the engines compliant with the EPA in 2004 and now subject to the NTE tests, a PM carve zone was distinguished covering high engine speeds and low engine loads. The emission of PM in the points falling within this zone does not have to comply with NTE requirements.

For the 2007 and later model year engines, the PM carve zone was eliminated. The engine manufacturer may request to exclude this zone from the NTC test if the engine is not fit to work in this zone and the engine manufacturer may request to exclude the operating points from the NTE zone if their share in the total engine operating time is less than 5%. This area should have an elliptical or rectangular shape and a part of it should fall outside the NTE test zone.

The non-road vehicle engines meeting the Tier 4 standard must also meet the NTE requirements. For this group of vehicles, these regulations have been applicable since 2011 for engines with power output exceeding 130 kW and since 2012 for engines with power output from 56 to 130 kW. For engines with power output below 56 kW, these regulations will be applicable as of 2013. For most of the engines the emission limits in the NTE test have been set as 1.25 of the admissible emission of each exhaust component of the Tier 4 standard. The NTE multiplier is 1.5 only for the engines that meet the limits of NO_x 2.5 g/kWh and PM 0.07 g/kWh. Appropriate NTE regulations apply for the homologation tests as well as for the whole engine life cycle.

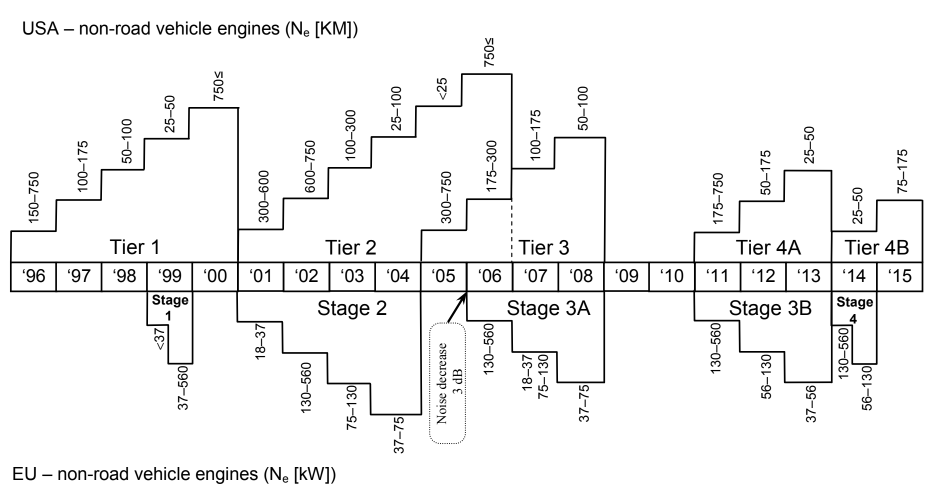

Figure 4. Exhaust emission standard implementation stages for non-road vehicles in the United States and Europe (AVL, 2006).

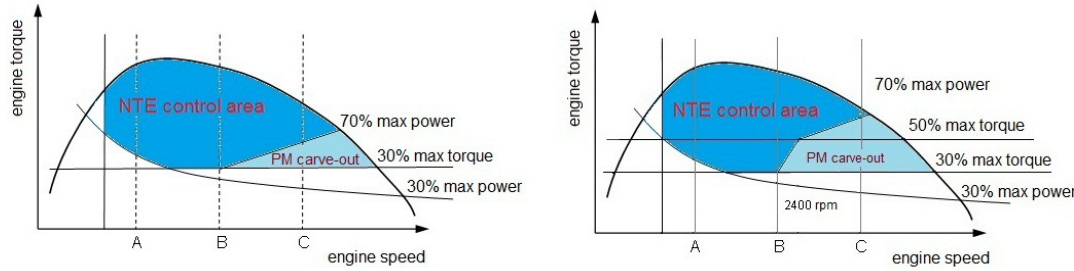

Figure 5. NTE control zone for U.S. engines, for C less than 2400 rpm (left) and for C greater than 2400 rpm (A, B, C - speed for the ESC cycle).

Methodology

For the selected machinery (a farm tractor – Stage IIIA engine, a harvester – Stage IIIA engine and a self-propelled forage harvester – Stage IIIB engine) the authors carried out tests which measured the exhaust emissions and recorded the engine operating data (engine speed and load). The tests were performed under actual operating conditions of the machines while performing field work. During the test, the farm tractor operated with a harrow, the harvester cut rye, and the forage harvester picked up maize. The view of the tractor fitted with the measurement equipment has been shown in figure 6.

In order to measure the concentration of the exhaust emissions, the authors used a portable SEMTECH DS analyzer by Sensors, Inc. (Saline, Mich.). The schematics of the analyzer have been shown in figure 7. The analyzer measured the concentration of the emissions and simultaneously the mass flow rate of the exhaust gas. The exhaust gas, introduced to the analyzer through a probe maintaining a temperature of 191°C, was then filtered out of PM and directed to Flame Ionizing Detector (FID) where hydrocarbons (HC) concentration was measured. Then the exhaust gas was cooled down to 4°C and the following measurements were made in order: the concentration of NO_x in Non Dispersive Ultraviolet (NDUV) analyzer, CO (carbon oxide), and CO_2 (carbon dioxide) in Non Dispersive Infrared (NDIR) analyzer O_2. The PEMS system allowed for adding data sent directly from the vehicle diagnostic system to the central unit of the analyzer and

Figure 6. The view of the farm tractor with the measurement equipment.

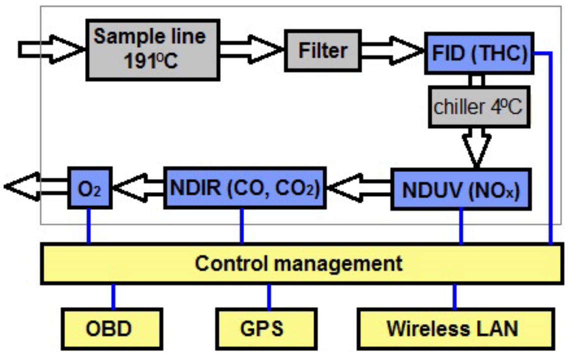

Figure 7. A diagram of a portable analyzer SEMTECH DS; exhaust gas flow channels (arrow) and electrical connections circled (blue line).

making use of the Global Positioning System (GPS, table 3). In the test, the authors measured the exhaust emissions and also, for the purpose of comparison, recorded the signals from the on-board diagnostic system, e.g. engine speed, load, vehicle speed, and the temperature of the intake air. Some of these signals served to specify the time density maps presenting the share of the operating time of a vehicle in actual operating conditions.

For PM measurement the authors used the SEMTECH LAM (Laser Aerosol Monitor). The SEMTECH LAM operates on a laser light scattering and provides the concentration of fine particulate matter in the exhaust 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

Table 3. Characteristics of the portable exhaust analyzer SEMTECH DS.

Parameter	Measurement Method	Accuracy
1. Emissions		
CO	NDIR, range 0-8%	±3%
HC	FID, range 0-10.000 ppm	±2%
NO_x=NO+NO_2	NDUV, range 0-2500 ppm	±3%
CO_2	NDIR, range 0-20%	±3%
O_2	Electrochemical, range 0-25%	±1%
2. Data storage capacity	Over 10 h at 1 Hz data acquisition rate	
3. Vehicle interface capacity	SAE J1850 (PWM), SAE J1979 (VPW) ISO 14230 (KWP-2000) ISO 15765 (CAN), ISO 11898 (CAN) SAE J1587, SAE J1939 (CAN)	

automatically adjusted to maintain the desired dilution ratio. A pump pulls the diluted sample through the monitor. The monitor contains a laser light scattering analyzer that measures fine particles from 100 to 10,000 nm. The specification of SEMTECH LAM has been shown in table 4.

RESULTS AND ANALYSIS

Based on the engine speed and load recorded during the measurements, the authors created time density

Table 4. The specification of SMTECH LAM.

Measurement Range:	0 to 40 mg/m^3 0 to 700 mg/m^3
Dilution	Selective ratio
Particle size	100 to 10,000 nm
Resolution	0.01 mg/m^3
Drift	<0,25mg/m^3 over 6 h
Sample flow	1.5 LPM
Sample rate	5 Hz (internally up to 100 Hz)
Output	RS232 Analog 0 to 5 VDC option
Power supply	12 to 24 VDC or 110 to 240 VAC
Operating temperature	0 to 40ºC

characteristics of the engines of the tested machines. They have been presented in figures 8-10. The tested engines operated in a narrow range of engine speeds and mostly with engine loads greater than 50%. For engine loads greater than 50%: the tractor engine operated for 89% of the time, the harvester - 93% of the time, and the self-propelled forage harvester - 69% of the time. The authors recorded the greatest spread of the engine speed for the farm tractor. The results show that while operating in the field, engines of the tested machines worked in a similar pattern. The use of engine speeds exceeding the most frequently used ones resulted mainly from the u-turns at the end of the field and in preparing the machinery for work. In the case of the self-propelled forage harvester, the engine frequently operated in the range of maximum loads, which often resulted in a drop in engine speed.

During the investigations, the authors also carried out exhaust emissions measurements. This article presents only the results for PM and NO_x as the key exhaust components for diesel engines (fig. 11-13). The authors present the emission of NO_x and PM in relation to the engine speed. The emission presented in the graph reflects the nature of

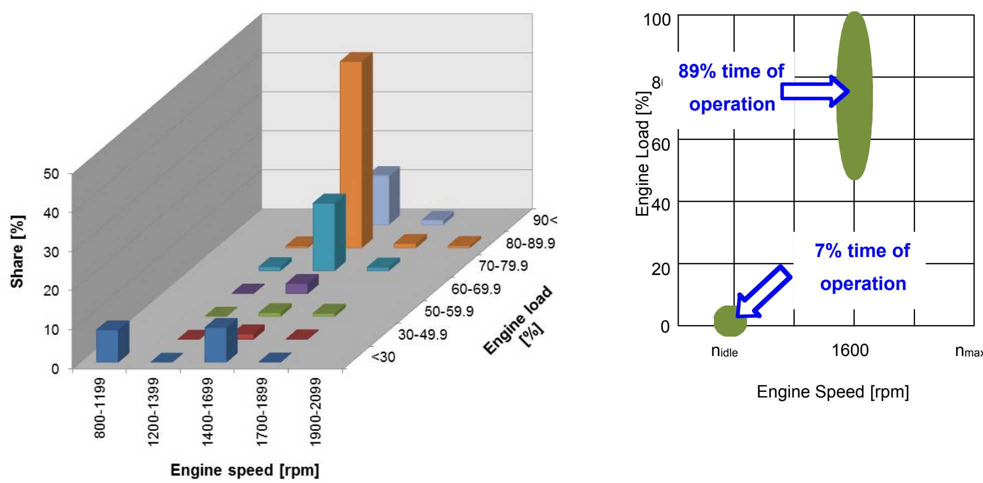

Figure 8. Time density characteristics and the most frequently used engine operating ranges of the farm tractor.

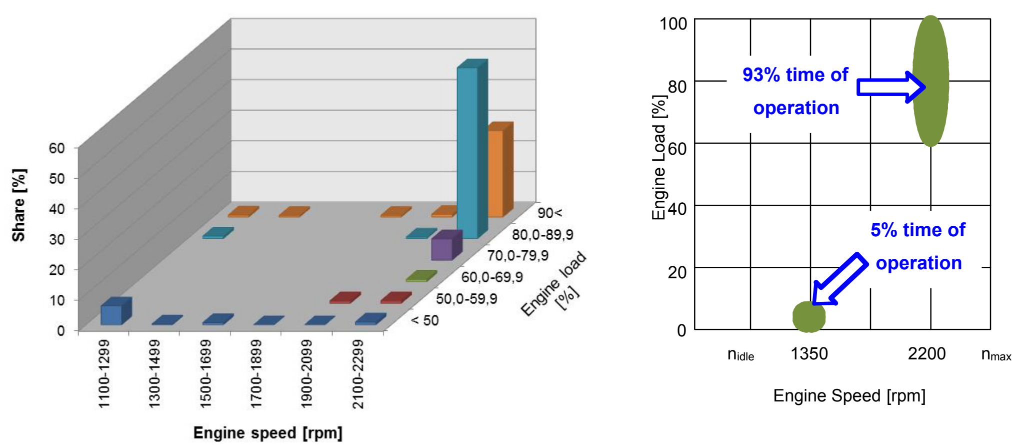

Figure 9. Time density characteristics and the most frequently used engine operating ranges of the harvester.

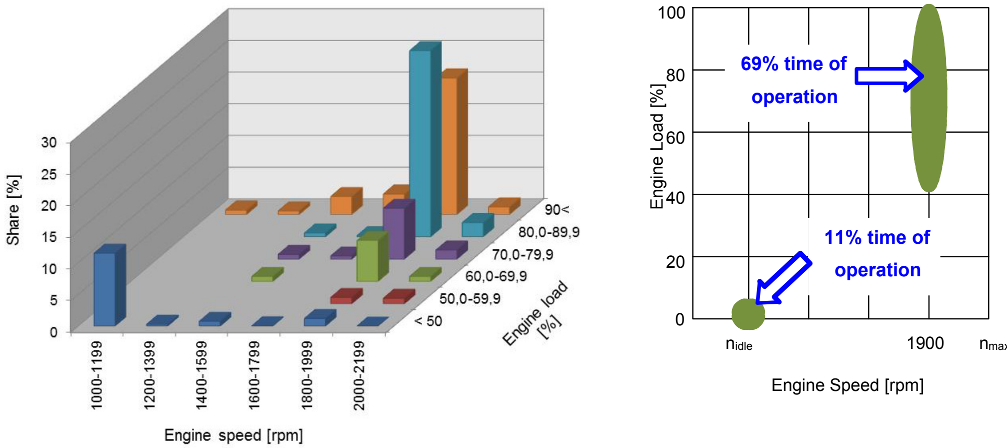

Figure 10. Time density characteristics and the most frequently used engine operating ranges of the self-propelled forage harvester.

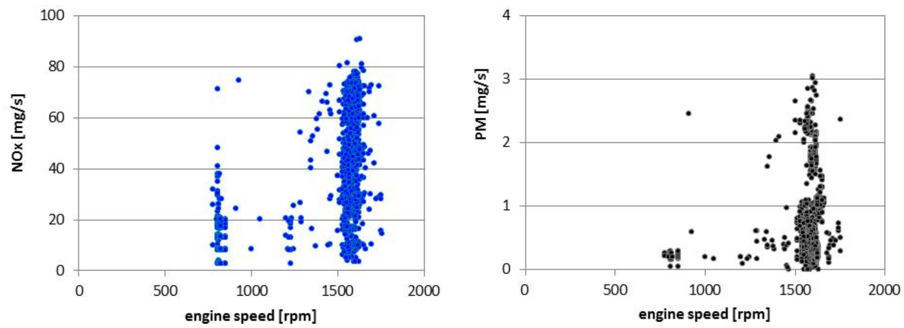

Figure 11. The emission of PM and NO_x from the farm tractor.

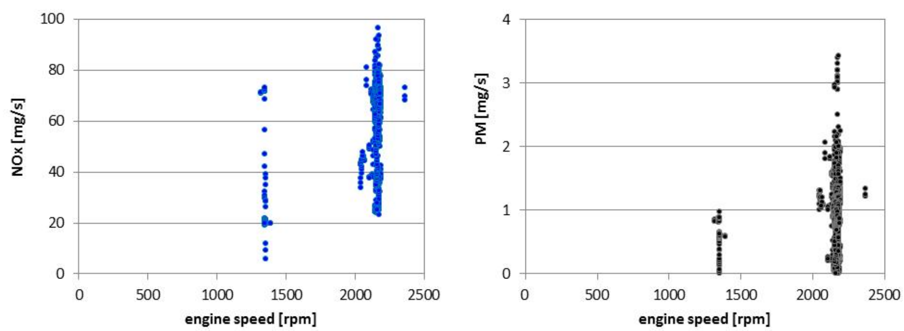

Figure 12. The emission of PM and NO_x from the harvester.

the operation of the tested machines. The emission concentrated around the most frequently used engine speeds. The emission, taking place outside of the said main areas, is a result of the u-turns made by the machines at the end of the field. Obviously, the share of these areas depends on the characteristics of the field and the most advantageous situation is when the number of u-turns is the lowest. It is then expected that the character of the engine operation will be even more similar to the engines operating at a constant speed.

When comparing the results of the measurements of the emissions obtained under actual operating conditions to the emission limits prescribed for the tested engines, only the emission of NO_x from the farm tractor and the emission of PM from the farm harvester was lower against the limit. For the rest of the tested machines, the measured emission of PM and NO_x under actual operating conditions was greater than the admissible limits (fig. 14).

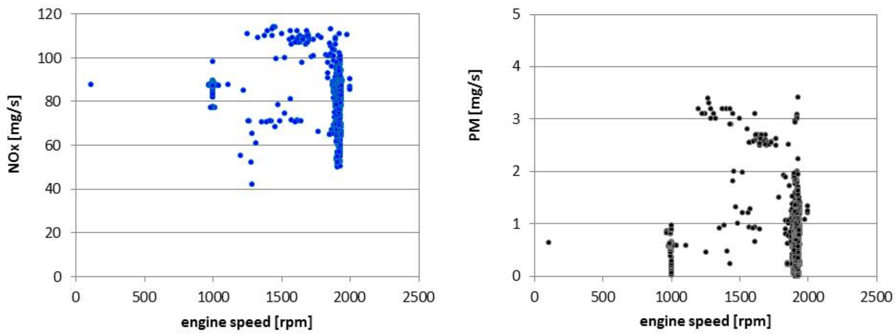

Figure 13. The emission of PM and NO_x from the self-propelled forage harvester.

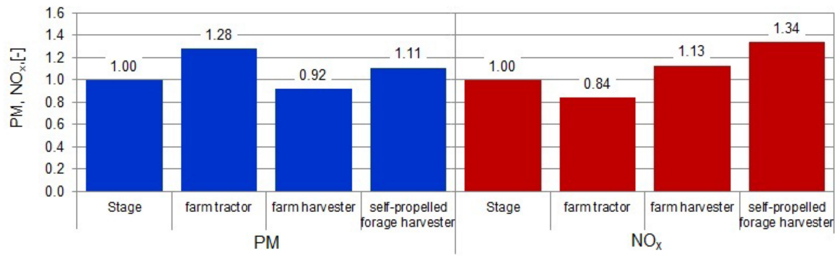

Figure 14. Comparison of the relative exhaust emission of PM and NO_x (under actual operation) with the emission limits.

CONCLUSIONS

From the obtained data related to the operating conditions of the selected farm machines, results show that during field work, these engines operate in a very narrow range of engine speeds and loads. During field work the nature of the operation of these engines is closer to power generator engines rather than traction engines. The obtained data require analysis in the aspect of the currently applicable homologation tests. The measurement range in the American NTE test seems too wide in the context of the obtained results. The obtained results force a discussion related to the necessity of modifying the applicable test procedures. Perhaps actions need to be taken to develop tests that would more perfectly reflect the actual operating conditions of farm machinery. The results presented in this article pertain to only three machines and the decision on the modification of the tests must be taken based on widely conducted research that includes a greater number of machines and varied work performed by these machines. This is particularly the case for farm tractors that are used in a variety of applications involving different engine loads. The development of new tests would reduce the exhaust emissions from farm machinery engines because their technological advancement would be based on the most frequently used ranges of their operation.

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APPENDIX

BSFC – Break Specific Fuel Consumption
CO – Carbon monoxide
CO_2 – Carbon Dioxide
EPA – Environmental Protection Agency
ESC – European Stationary Cycle
FID – Flame Ionization Detector
HDV – Heavy Duty Vehicle
HC – Hydrocarbons (THC – Total Hydrocarbons)
GPS – Global Positioning System
IARC – International Agency for Research on Cancer
LAM – Laser Aerosol Monitor Detector
LAN – Local Area Network
PEMS – Portable Emission Measurement System
PM – Particulate Matter
n – engine speed
N_e – engine power
NDIR – Non Dispersive Infrared Detector
NDUV – Non Dispersive Ultraviolet Detector
NO_x – Nitric Oxides
NRSC – Non Road Stationary Cycle
NRTC – Non Road Transient Cycle
NTE – Not-to-Exceed Test
OBD – On-Board Diagnostic
WHO – World Health Organization