MEASUREMENT OF EXHAUST EMISSIONS FROM FARM MACHINERY UNDER ACTUAL OPERATING CONDITIONS WITH THE PEMS EQUIPMENT – SELECTED ISSUES

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Abstract: The paper discusses the problem of exhaust emissions from farm machinery. The paper presents selected results of the measurements of exhaust emissions (CO, HC, NOx, PM) from farm machinery under actual operating conditions, during fieldwork. For the tests, the authors used a portable exhaust emissions analyzer (PEMS) for the measurement of gaseous exhaust emissions and for the measurement of the emissions of particulate matter. The analyzers provide an on-line measurement of the concentrations of the exhaust components under actual operating conditions. The tests performed under actual operating conditions provide invaluable information regarding the exhaust emissions. In the paper, the authors analyzed the relations between the engine operating parameters and the exhaust emissions. Despite differences in the methodology, the authors also presented a comparison of the obtained results with the currently applicable exhaust emission limits in order to draw attention to this issue.

Introduction
Engines of non-road applications are a group of extremely wide scope of application that includes: engines for hand-held equipment (mowers, handheld chainsaws etc.), power generator engines and engines of non-road mobile machinery (NRMM). The NRMM group includes farm tractors and construction machinery. The engines of the NRMM vehicles are currently the largest group of all non-road vehicles, and according to forecasts, their share will grow [6] (fig. 1).

The ecological aspects and the reduction of the production costs combined with the quality of the agricultural products are today the main factors that spur on the advancement of farm production technologies. In Europe, classic plowing system of production prevails, which is an energy consuming technique but ensures high efficiency and high quality of products. A very important aspect of all fieldworks is the fuel consumption/CO2 emission (energy consumption) and the exhaust emissions. The question of environment pollution by tractors and farm machinery during fieldwork becomes increasingly significant. The engines driving the tractors and other farm machinery are, of course, subject to homologation tests for compliance with the exhaust emissions standards, but the current advancement of the measurement techniques provides new measurement possibilities. Engines of NRMM (Non-Road Mobile Machinery) vehicles such as farm tractors and farm machinery are tested on engine tests beds in stationary and dynamic tests. Today much attention is drawn to testing under actual conditions of operation (RDE – Real Driving Emissions). Such tests are being introduced to the homologation procedures and, in the coming years, will cover all vehicle categories. European homologation procedures will eventually include RDE tests. That will also be the case for the NRMM engines. Tests under actual operating conditions of farm tractors and farm machinery as well as other NRMM have been carried out for a few years now [4, 5, 9, 10, 11]. In these works, attention is drawn to the fact that the exhaust emissions under actual conditions of operation are usually higher than the admissible limits determined in laboratory tests [5, 10, 11]. According to the authors, the problem results from the non-representativeness of the engine operating parameters in the tests. In the exhaust emissions tests, it is desired...
that the testing conditions reflect the actual conditions of operation, which renders the results most reliable. The reproduction of the actual conditions of engine operation in laboratory tests was a subject of investigations and analyses in many works [1, 3, 7, 8, 10-12]. The conclusions from the literature published thus far, clearly confirm that the engine operating parameters (load and speed) in the laboratory tests for both the road and non-road vehicles, diverge from the parameters of actual operation. This problem, despite numerous research and analyses, has not yet been resolved. Therefore, in recent years, we can see a dynamic advancement of PEMS equipment and methodology of testing under actual conditions of operation. This type of research is novel and the results of such research are highly demanded.

RDE tests are introduced to homologation procedures of vehicles of all categories, including NRMM. In the Stage V legislation, an ISM (In-Service Monitoring) procedure is introduced requiring tests performed with the use of PEMS under actual operation. The final version of the procedure is not yet fully developed and accepted but all agree that RDE tests are necessary and should be included in the homologation procedures [2].

RDE equipment and methodology

Currently applicable homologation legislation for heavy-duty vehicles (Euro VI) and the heralded proposal of future test procedures for this as well as other vehicle groups included the application of tests performed under actual driving conditions. This type of research however, requires technologically advanced equipment (PEMS) that is increasingly often proposed by automotive measurement equipment manufacturers in their portfolio (AVL List GmbH, Horiba Ltd. And Sensors Inc.). This type of equipment can be used for testing machines and vehicles fueled with different fuels such as gasoline, diesel fuel, CNG, LPG or oxygenated fuels. This also requires the application of special filters or exhaust gas diluters. Besides, the discussed equipment is characterized by high sampling frequency – a minimum of 1 Hz up to 500 Hz (e.g.: EFM-HS – High Speed Exhaust Flow Meter).

Due to the fast varying parameters of engines under actual conditions of operation and the advancement of aftertreatment systems, the equipment must be characterized by high measurement accuracy. The recording of ambient conditions is also necessary (pressure, temperature, humidity) as they have great impact on the measured values, which is why additional corrective calculations are necessary. Therefore, the said measurement equipment often includes solutions (sensors, algorithms) that perform such procedures. What is more, the equipment must be characterized by low energy consumption, low weight and size, let alone high reliability. In order to perform a full analysis of the impact of a given type of powertrain and the motion parameters of city buses on the environmental indexes the following were utilized: SEMTECH DS (exhaust component concentration, oxygen content exhaust gas mass flow) as well as AVL MSS (used to determine the concentration of PM).

The presented measurement equipment is a unique set of analyzers allowing the determination of energy consumption and environmental performance of vehicles under actual conditions of operation:

- SEMTECH DS (Fig. 2) – designed for the testing of gaseous exhaust components: NDIR: CO [%], CO₂ [%]; FID: THC [ppm]; NDUV: NO [ppm], NO₂ [ppm] and O₂ [%] electrochemical;
- AVL MSS (Micro Soot Sensor – Fig. 3) – used to calculate the concentration of PM [mg/m³] with the photo-acoustic method;
- TSI 3090 EEPS™ (Engine Exhaust Particle Sizer™ Spectrometer – Fig. 3) – allows determining of the size distribution of PM [nm];
- SEMTECH ECOSTAR – allows measurement of both gaseous components and particulates (mass and number);
- AVL OTR (On The Road) OPACIMETER – used to test the exhaust gas opacity [%];
- SEMTECH LASAR – allows determining of the content of the exhaust gas including NH₃, N₂O, CH₄ [ppm].

![Fig. 2. Semtech DS analyzer used for the measurement of gaseous exhaust components under actual conditions of operation](image-url)
Exhaust emissions measurements under actual operation of farm tractors and machines were performed during regular fieldwork. During the measurements, the tractor was coupled with a seed drill, the harvester collected rye, and the beet-harvesting machine collected sugar beet. The test cycles during the measurements were not different from typical working conditions during the said activities, which is why one can state that the obtained results represent the actual exhaust emissions during fieldwork. The results of the emission measurements were analyzed as performed on the tractor with the seed drill, the combine harvester, and the beet-harvesting machine. The investigated machines and their technical specifications have been presented in table 1.

### Table 1

<table>
<thead>
<tr>
<th>Machinery and measurement equipment during the test</th>
<th>Displacement</th>
<th>Architecture</th>
<th>Bore, Stroke</th>
<th>Maximum Power Output</th>
<th>Maximum Torque</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement: 7.1 dm³</td>
<td></td>
<td>Straight 6, 4 valves per cylinder</td>
<td>115 x 149 mm</td>
<td>198 kW/2300 rpm</td>
<td>1050 Nm/1400 rpm</td>
<td>Fitted with VGT intercooled turbocharger, EGR, common rail, Tier 3/Stage IIIA compliant</td>
</tr>
<tr>
<td>Displacement: 9.3 dm³</td>
<td></td>
<td>Straight 6, 4 valves per cylinder</td>
<td>115 x 149 mm</td>
<td>230 kW/2200 rpm</td>
<td>1550 Nm/1400 rpm</td>
<td>Fitted with VGT intercooled turbocharger, EGR, common rail Tier 3/Stage IIIA compliant</td>
</tr>
<tr>
<td>Displacement: 16.0 dm³</td>
<td></td>
<td>V8, 4 valves per cylinder</td>
<td></td>
<td>444 kW/1800 rpm</td>
<td>2800 Nm/1080 rpm</td>
<td>Fitted with: intercooled turbocharger, EGR, pump nozzle injection system Tier 3/Stage IIIA compliant</td>
</tr>
</tbody>
</table>

### Results and analysis

The performed investigations determined the following exhaust emissions: CO, HC, NOₓ, and PM as well as fuel consumption (the emission of CO₂). It is noteworthy that the obtained results depend on a variety of factors such as type of soil, terrain conditions, driver skills, ambient conditions as well as the machine itself and its technical condition. The analysis of the exhaust emissions from all investigated vehicles was performed for the entire measurement cycle i.e. the measurements initiated when the machine started fieldwork and were finished when the machine completed fieldwork. In order to assess the emissions of individual exhaust components an emission index was defined:

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The adopted emission index is a measure of emission changes of individual exhaust components against the applicable European and American standards. The index may assume a value from $(0; \infty)$. If its value is greater than 1, it signifies a higher emission under actual operation compared to the admissible one. If its value is lower than 1, it signifies a lower emission under actual operation compared to the admissible one. If the index equals 1, the emission under actual operation is tantamount to the admissible one.

For all tested machines, the PM emission index was greater than 1 (Fig. 4). The lowest value of this index was recorded for the combine harvester – 1.95 and its highest value for the beet-harvesting machine – 1.45. Also, the NO$_x$+HC emission index for all tested vehicles was greater than 1 (Fig. 5). The highest value of this index was recorded for the combine harvester (1.95). Aside from the collective emission of NO$_x$ and HC (as per the guidelines of Stage III and Tier 3), the emission of NO$_x$ alone was also presented. From this comparison it results that it is NO$_x$ that had the significant share in the total NO$_x$+HC emission. Based on the performed research, it was observed that the emission of the most troublesome exhaust components for diesel engines (PM and NO$_x$) under actual operation is higher than the admissible values set forth in the homologation procedures.

The performed research confirms that for the NRMM vehicle category, the main problem in actual operation is still the emission of NO$_x$ and PM. The advancement of the engines of these vehicles should aim at limiting of these particular exhaust components. In this respect, the potential is great, which is confirmed by solutions applied in on-road vehicles that can be easily transferred to the NRMM vehicles.

The performed tests also allowed an analysis of the engine operating parameters during fieldwork. The performed analysis enabled identification of the most frequently used engine work areas and determining the operating time share of these areas (Fig. 7–9). The operation of the tested engines is characterized by a very narrow operating area (range). The limitation of this area mainly results from the range of applied engine speeds, not the torque range. Compared to the on-road vehicles, where a wide range of engine speeds and torques is used, farm tractors and machinery during fieldwork use a narrow range of engine speeds. For the investigated cases, more than 90% of the operating time, the tractor operated in the range $1950 \pm 50$ rpm, the combine harvester $2100 \pm 50$ rpm and the beet-harvesting machine $1250 \pm 50$ rpm. For the investigated machines, the range of load was much wider (the widest for the combine harvester). For a given engine speed it varied from approx. 10 to 80% of the maximum torque.
Such specific operating conditions of engines are not yet allowed for in the applicable exhaust emissions and fuel consumption tests for farm tractors and farm machinery. This is particularly the case for the NRTC (Non-road Transient Cycle) test [13], where the range of engine speed variations is very wide and it should be noted that it is more suitable for on-road engines. This is, most likely, one of the main reasons for the divergence of the emission results between laboratory tests and tests performed under actual operation.

Conclusions

Reducing the exhaust emissions requires a continuous search for new solutions in the area of construction and design of combustion engines and methods of their testing. The paper has shown selected aspects of testing of exhaust emissions from farm tractors and machinery under actual operating conditions. The results obtained in the research confirm that RDE tests are, by all means, necessary, as they provide invaluable information impossible to obtain under laboratory conditions. The advantage of RDE tests is the fact that they include factors that are difficult to reproduce in the laboratory (driver’s or machine operator’s
behavior, ambient conditions, terrain etc.), but heavily influence the exhaust emissions. It is therefore fully justified to introduce RDE testing to homologation procedures. It is important, however, that these procedures must be developed and adapted to the specificity of operation of engines fitted in farm tractors and farm machinery. This specificity is much different from the on-road engine applications. A factor stimulating this advancement is appropriate exhaust emissions legislation. The advancement of exhaust emissions measurement technology has created new possibilities in terms of the methods used in RDE. One may suppose that it is this particular method that will be further improved and will gain in importance. The aim of the legislators and the manufacturers should be the acknowledgement of measurements under actual operating conditions to be one of the main methods in homologation testing. Proper works in this respect should finish without delay and the introduced legislation should have global outreach.

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