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PRELIMINARY EVALUATION OF EMISSIONS FROM OFF ROAD MOBILE MACHINERY OPERATING IN REAL WORKING CONDITIONS

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Abstract

The paper presents results of the pollutants emission measurements from the exhaust system of the forklift truck as a representative of the off-road mobile machinery operating in real conditions. Directive 96/68/EC does not include spark ignition engines with maximum power output greater than 19 kW.

In order to check the emission characteristics of the off-road mobile machinery equipped with such engine, the tests have been carried out of the H16T type forklift truck, manufactured by Linde company, fuelled with LPG. The portable analyzer (PEMS) Semtech-DS by Sensors was used for the measurements. It allowed making the necessary calculations to determine the road – test pollutants emission as a function of time. The tests included emission testing in stationary conditions and roadside emission testing of the forklift truck.

The paper contains illustrations with many figures and tables showing CO, CO_2, THC and NO_x emissions versus speed, time and fork load of the tested machine. It contains discussion on the possibility of road emission measurements expressed in g/km for off-road machineries as well as usefulness of these measurements using portable emission measurement systems for the off-road machinery.

Keywords: *exhaust emission, environment, off road mobile machinery*

1. Introduction

The principles of testing, measurement methods and admissible values for vehicles (mobile machinery) of the off-road applications concerning the emission of pollutants emitted by the combustion engine can be broadly divided into those relating to:
– type approval (conformity of production),
– operation in real conditions.

With regard to the type approval of the above mentioned, the testing principles, measurement methods and emissions limits are contained in [1–12], i.e.:

1. The system of UN-ECE Regulations 96 [1] (96.01 amendments [2], 96.02 [3]). Regulations concerned the principles of research, measurement methods and admissible values of the controlled pollutants emissions from the tractors powered by the compression ignition engines (CI). Principles of research and the measuring method in a stationary test were similar to those found in the stationary test, then in force, for the heavy vehicles engines of M and N categories. The phase cycle 8 – replicating the phase sequence on a hot engine, (for the aforementioned heavy vehicles 13 – phase) was applied. The amendments to the Regulation (96.01 [2] and 96.02 [3]) introduced it‘s widening by which it covers the tractors used in forestry, and generally the tractors in question, with a maximum net power greater than 18 kW but not exceeding 560 kW. Therefore, with these amendments it also includes compression-ignition engines powered by the diesel oil for the Non-Road

Mobile Machinery having a maximum net power greater than 18 kW but not exceeding 560 kW, operating at variable engine speed as well as in machines of above mentioned maximum net power range, operating at constant engine speed. The amendment (96.02 [3]) includes, apart from the D, E, F, G engines categories, also engines of H, I, J, K categories, specifying for them admissible values for the exhaust pollutants emissions and provides the requirements for determining emission deterioration factors in the durability test (HK category engines). It also introduces a phase cycle 5 – with respect to engines operating at constant speed.

2. The system of EU Directive 77/537/EEC [4] (exhaust smoke from diesel-powered engines of the agricultural tractors, the principles of research, methods of measurement (stationary test and free acceleration) and admissible values are similar to those laid down in Directive 72/306 / EEC [5] on the exhaust smoke of the cars powered by the compression ignition engines, but less severe) - amendment: Directive 82/890/EEC [6], Directive 97/54/EC [7] and Directive 97/68/EC [8] (revisions: Directive 2001/63/EC [9], Directive 2002/88/EC [10], Directive 2004/26/EC [11], Directive 2006/105/EC [12], Directive 2011/88/EU [13]) and Directive 2000/25/EC [14] (the amendment: Directive 2005/13/EC [15], Directive 2006/96/EC [16], Directive 2010/22/EU [17], Directive 2011/72 / / EU [18], Directive 2011/87/EU [19]).

Directive 97/68/EC [8] refers to limiting the emission of gaseous and particulate pollutants in the exhaust gases of internal combustion engines of the non-road mobile machines powered by the spark ignition as well as self ignition engines and sets up the procedures of testing this type of engines (engine family) This Directive 97/68/EC [8] represents an essential directive in the above mentioned subject. This refers to the compression ignition engines with a maximum net power (as defined in this directive) between 37 and 560 kW.

The second Directive 2002/88/EC [10] refers to the spark-ignition engines (category S) of the maximum net. power up to 19 kW installed in the equipment adapted for manual operation and not adapted for manual operation.

Third Directive 2004/26/EC [11] refers to the compression ignition engines with a maximum net power of 19 kW, up to 560 kW, installed in mobile non-road machines and the following three stages in the reduction of gaseous pollutants emissions and particulates in the exhaust of these engines. It refers to the powered railcars and locomotives, and engines for the propulsion of inland waterways transport, as well as engines used for the purposes other than those mentioned above, not exceeding the mentioned power range.

Fourth Directive 2006/105/EC [12] introduces modifications to the Directive 97/68/EC [8] in the numbering of type-approval certificates in respect of the codes attributed to each EU member state.

Fifth Directive 2011/88/WE [13] introduces such changes as "the flexible formula", for example, in the form of increasing the percentage of the annual number of devices introduced by manufacturer, which have engines used differently, than to power railcars, locomotives and inland waterway vessels. It also introduces alternative solutions relying on introducing to the market a fixed number of engines according to "the flexible formula". 2011/88/WE Directive [13] envisages the introduction of the phase V engines type approval, which should be based, subject to technical feasibility, on the requirements relating to the Euro VI emissions level, concerning the large capacity trucks.

Directive 97/68/EC [9] does not apply to the engines powering: vehicles as defined in Directive 70/156/EEC [20] (as amended) and Directive 92/61/EEC [21] (as later amended) and agricultural tractors as defined in Directive 74/150/EEC [22] (as later amended). Additionally, in order to be covered by this Directive, the engines must be installed in the machines that meet the specific requirements described in the Directive. Directive 97/68/EC [8] does not include the following applications of the internal combustion engines: vessels, except vessels used for navigation on inland waterways, aircraft, recreational vehicles (snowmobiles, motorcycles not used on the roads, off-road vehicles).

For compression ignition engines used in accordance with Directive 97/68/EC, the following tests are applicable [8, 11]:

– pollutants emissions stationary test NRSC (Non Road Stationary Cycle), which is used to measure emission of carbon monoxide, hydrocarbons, nitrogen oxides and particulates in stages I, II, III A (at the manufacturer's request the NRTC test is applied), III B (NRSC for the measurement of gaseous pollutants emissions and the NRTC to measure particulate emissions, at the request of the manufacturer NRTC test is used to measure gaseous emissions) and IV (NRSC for the measurement of gaseous pollutants emissions and the NRTC to measure particulates emissions, at the request of the manufacturer, the NRTC test is applied for the measurement of gaseous pollutants emissions) from the appropriate engine types described in Annex I of the Directive and:
– pollutants emissions dynamic test NRTC (Non-Road Transient Cycle), which is used to measure carbon monoxide, hydrocarbons, nitrogen oxides and particulate matter normally in stages IIIB and IV from the appropriate engine types described in Annex I of the Directive,
– for the engines intended for use in inland waterway vessels, the testing procedure applied complies with the ISO 8178 [23] standard and IMO (International Maritime Organisation) MARPOL (International Convention for the Prevention of Pollution from Ships),
– for the engines intended to power railcars, the NRSC test is used to measure the emission of gaseous pollutants and particulate emissions in stages III A and III B,
– for the engines intended for propulsion of locomotives, the NRSC test is used to measure the emission of gaseous pollutants and particulate pollutants in stage IIIA and stage IIIB.

3. The test object and the measuring equipment

The test object was a forklift truck manufactured by Linde H16T powered by LPG, whose main specifications are listed in Tab. 7. This forklift truck is shown in Fig. 1.

Tab. 1. Technical data of a forklift truck tested

Type	H16T-02
Serial number	H2X350M02267
Year of manufacture	2001
Lifting capacity	1600 kg
Type of engine	VW/026.2
Engine power / revolutions	25 kW / 2300 rpm
Number of cylinders	4
Engine capacity	1000 cm^3
Fuel type	LPG

For the purpose of tests, the portable analyzer (PEMS)-DS Semtech Sensors was used. The set consisted of:

– CO analyzers operating on the NDIR principle,
– CO_2 analyzer operating on the NDIR principle,
– heated hydrocarbon analyzer operating on the FID principle with the heated sampling line,
– nitrogen oxides analyzer operating on the NDUV principle,
– temperature and ambient air humidity sensor,
– barometer,
– a device for measuring the vehicle speed operating on the principle of triangulating the vehicle’s position relative to geostationary satellites (GPS),
– flow Sensors, Inc. company. 107-SE01 with number 34 637, with 2 inches diameter of to measure the flow rate of exhaust gasses from the engine exhaust system.

Fig. 1. The forklift truck with the equipment installed for the measurement of gaseous pollutants emissions in the real conditions

Semtech-DS device was equipped with a recorder of the measurements results and allowed to make the necessary calculations to determine the road – test pollutants emission as a function of time.

4. The tests results

Forklift truck, officially called the lifting trolley has a lifting mechanism, and is a working machine designed primarily for vertical movement of goods and their transport over short distances. The nature of its work is different from the performance characteristics of the typical vehicle, because maximum emissions from the machine may occur in situations where the forklift is in place and is lifting a load. In this case, road emission, and therefore emissions relative to the distance travelled by the machine becomes unusable parameter due to the stationary nature of the machine work. Under these conditions, the best parameter to analyze would be unit pollutants emission referred to the work done by the engine, but the difficulties of measuring the torque of the engine installed in a machine make such measurement impossible.
For this reason, the analysis of the pollutants emissions from the exhaust system of the forklift truck operating in real conditions should include two operating states:

- road emissions, expressed in g / km, when the machine is moving,
- intensity of pollutants emissions mass, expressed in [g/s], when the truck is stationary and when it is lifting the load installed on the fork lift.

4.1. Pollutants emissions in the stationary conditions

The emissions tests in stationary conditions consisted of lifting, several times, the weights, each weighing 0, 450, 900 and 1350 kg, from the ground to the maximum lifting height of the forklift truck. Payload 0 kg means that during the trial only the lift stacker was raised (no load). Fig. 2 shows the results of measurements of the mass pollutants emissions intensity calculated, inter alia, based on the recorded concentrations of exhaust components. In order to improve the readability of the figure, the recorded runs were synchronized with the first registered run. Before the tests, the machine's engine was hot.

Analysing the graphs shown in Fig. 2, one can see that each run of the lifting fork, regardless of the weight of the load, causes the increase of the mass emission intensity of the analyzed exhaust component flow. When lifting hoist the engine will automatically resets from the idle speed to regulated operation at a rated speed (2100 rpm). The increase in emissions continues until the forklift

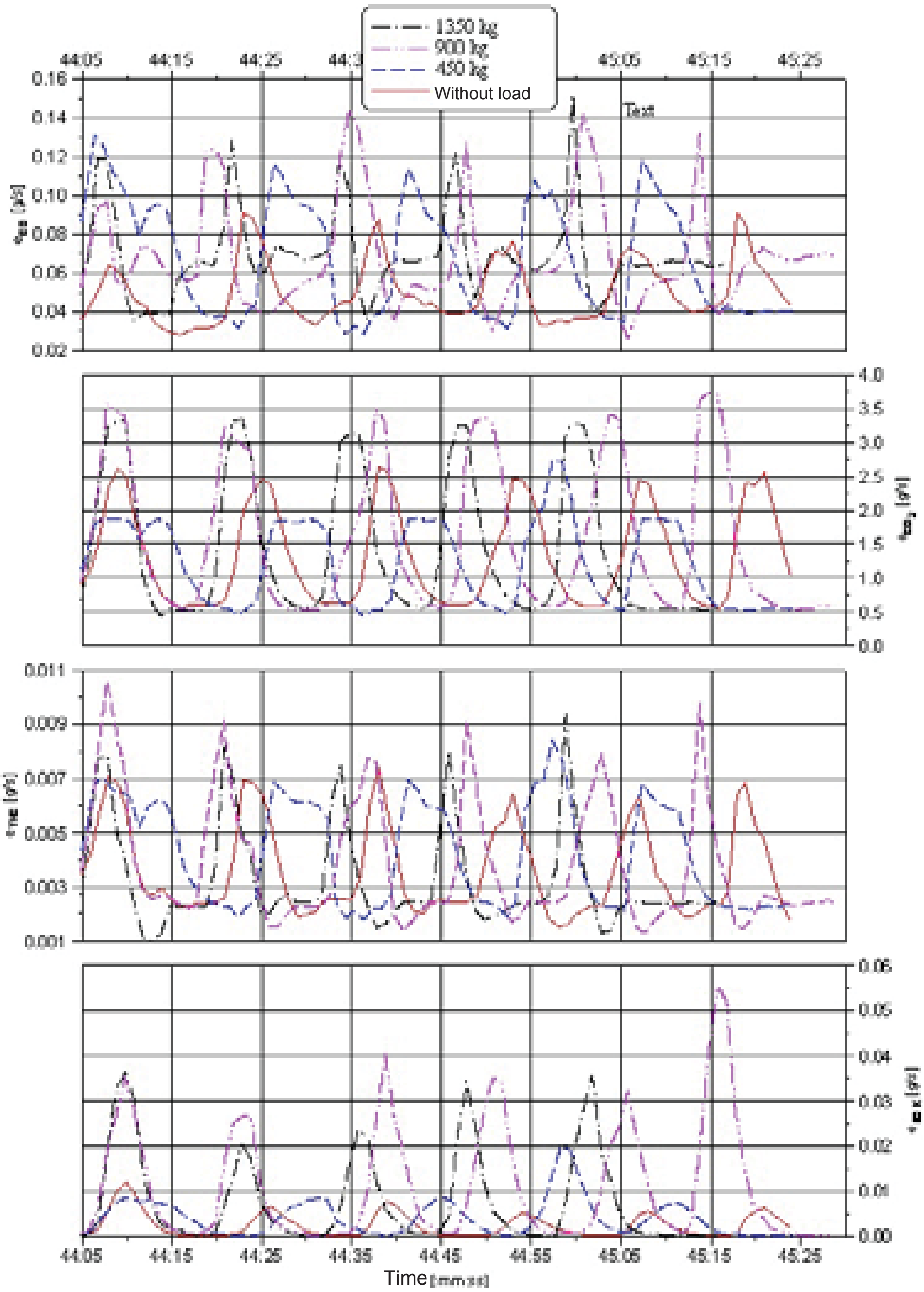

Fig. 2. The course of pollutants emission intensity from a forklift truck during lifting loads of different weights

hoist reaches its maximum upper position. Then the operator would shut down the lift hoist drive, causing the engine go back to idle. In the load-lifting mode, we deal practically with two engine operating states:

– the work on idle when the lift does not raise the load (not used),
– the work with the engine speed close to rated speed while lifting loads, when the engine load is automatically selected depending on the weight of the load.

The mass emissions intensity rates read of the Fig. 2 on idle are shown in Tab. 2.

Figure 3 shows solid line representing the mass dependence of the average emission intensity (average value of the graphs in Fig. 2), as a function of the load lifted. In addition, the dotted line in Fig. 3 indicates the course of the maximum emission intensity values of the analyzed components as the function of mass of the load lifted.

Tab. 2. The intensity of the emission of exhaust components during the forklift truck engine idling

Type of gas	Flow intensity
CO_2 [g/s]	0.5
CO [μg/s]	30
THC [μg/s]	20
NO_x [μg/s]	0

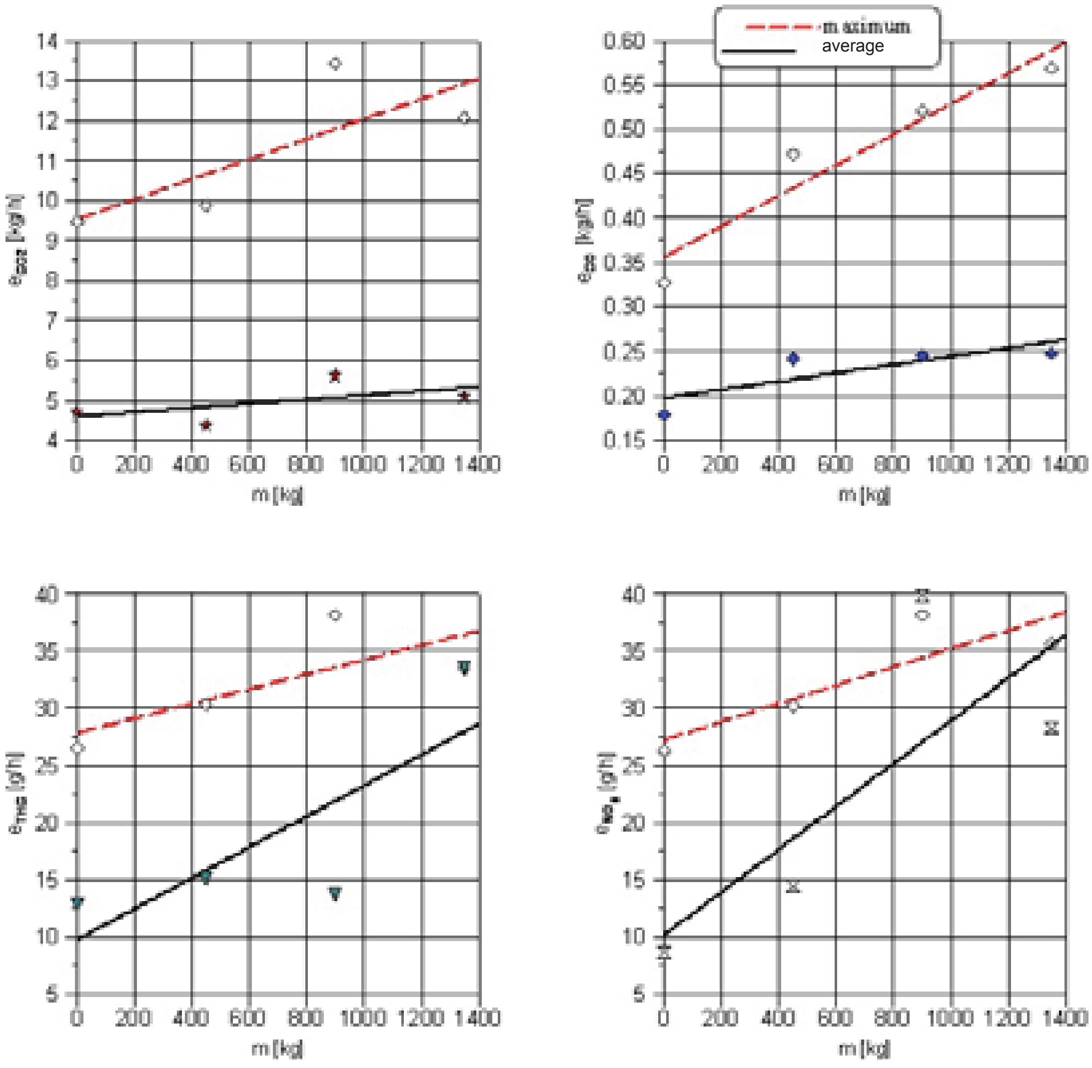

Fig. 3. The course of the emission intensity changes from the forklift H16T-02W as a function of the load lifted

Pollutants emission intensity from a forklift truck ready to lift the load depends on the proportion of the lifting time in the overall work of the truck. On one hand, it cannot be less than the minimum values shown in Tab. 2, on the other hand cannot be larger than the values shown by broken lines in Fig. 3. The solid line in Fig. 3 shows the characteristic, for this kind of work, change of the averaged mass emission of the exhaust components as a function of the load lifted, for the performance characteristics shown in Fig. 2 (repeated lifting of the same load).

By analyzing the curves shown in Fig. 3 one can see that the test machine is characterized by relatively high CO emissions at moderately low THC and NO_x emissions. This is characteristic of spark ignition engines. In case of a diesel engine without exhaust after-treatment system, we would have much higher NO_x emissions. In the engine tested, possibly due to a slight enrichment of the fuel-air mixture, a clear decrease in NO_x emissions occurred at the expense of the CO increase.

4.2. Road emission from the forklift truck

The road emission occurs when we deal with the moving emission source, where the mass emission value can be related to the distance travelled by the test vehicle or machine. In order to determine the road emissions of the forklift truck, the research tests were performed mapping the work of the truck in actual working conditions. Test cycle consisted of several seconds idling (after engine warm-up), lifting a payload of 450 kg, making a straight section of the road with a length of about 60 meters, turning back and driving the same stretch again. Several such measurements were taken and because their results were consistent with each other, Fig. 4 shows an example of course No. 6 selected from the group of seven runs recorded. Fig. 4 shows the changes in the emissions mass intensity of these gases. In addition, this figure has been supplemented by courses of the trolley's speed and distance covered by the test machine during the test.

The diagrams represent summary of the test results (Fig. 5) illustrating the course of the road emissions of the forklift truck tested, as the function of the velocity of this machine. This picture shows fairly good consistency between the tests made during the passage 3 and passage 6, which means that a satisfactory reproducibility of the results between individual tests was achieved during the tests.

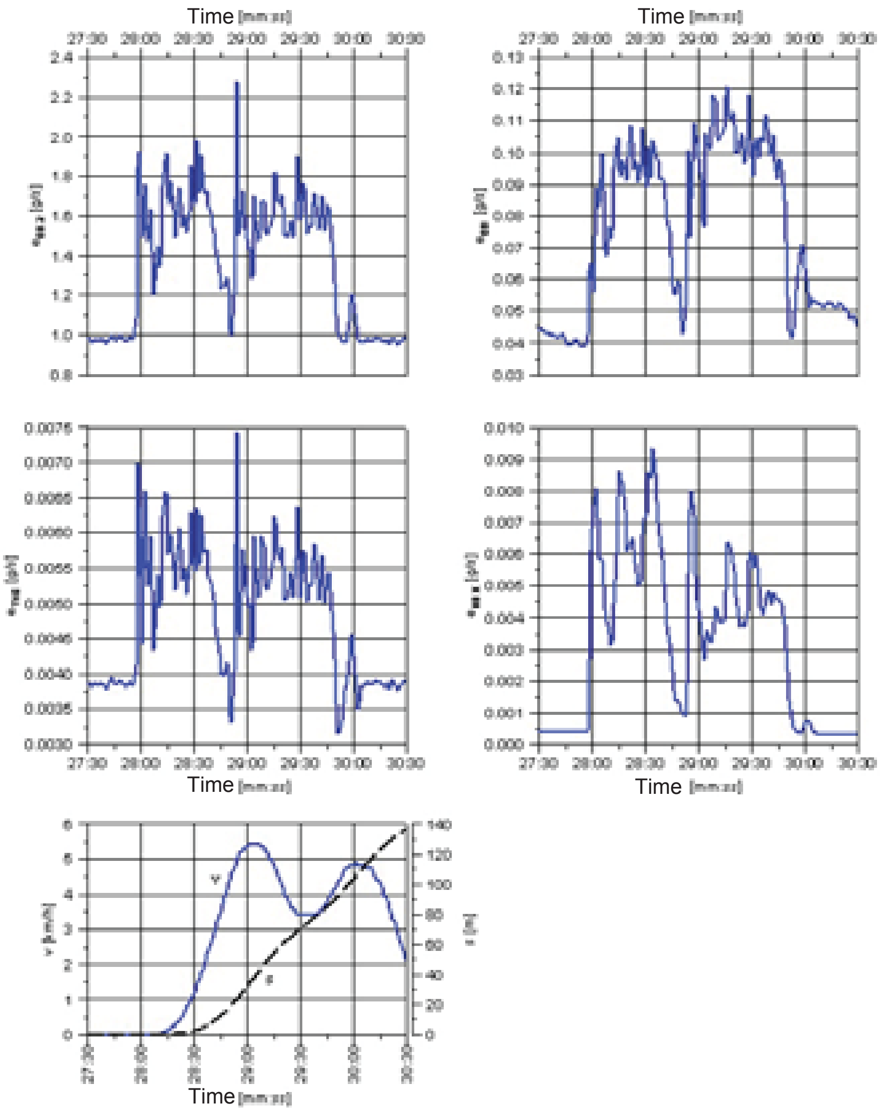

Fig. 4. Change in emission intensity of selected exhaust components emitted from a forklift truck moving during operation; run No. 6

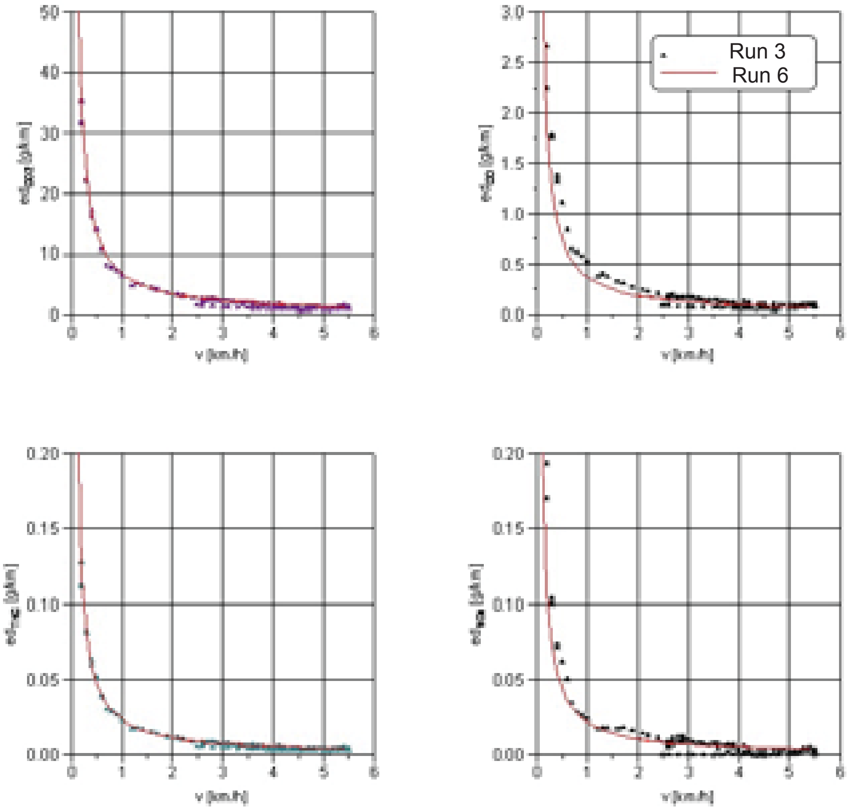

Fig. 5. Change in the road emissions of the selected exhaust components emitted from a forklift truck as a function of speed

Analyzing the courses shown in Fig. 5, one can note that the curves depicting the road emissions are hyperbolas running towards infinity at a speed close to zero, while on the other hand, they tend to approach a constant value with the speed increasing. Practically, the road emissions reach a constant value after attaining the speed of 5 km/h by the forklift truck. The average road emissions during each test run can be determined based on averaging all recorded data points. The results of these calculations are presented in Tab. 3.

Tab. 3. Average road emission determined during tests of the forklift truck

Type of gas	Road emission [g/km]
CO_2	4.43
CO	0.32
THC	0.016
NO_x	0.025

5. Conclusions

The results obtained and their analysis allow concluding that:

- intensity of the pollutants emissions mass from the forklift increases with the increase of the load weight being lifted,
- due to the road emission values asymptotic striving towards infinity at a speed close to zero, the road emission is not a good parameter to be evaluated for a vehicle speed of less than 1 km/h,
- low speeds developed by the forklift truck cause the influence of the mass changes of the load carried on the road emissions to be incomparably smaller than the impact of the speed,
- the forklift truck is characterized by high CO emission, hence the attention should be paid to limit its work in confined spaces to the minimum required.

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