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Analysis of the CO_2, NO_x emission and fuel consumption from a heavy-duty vehicle designed for carriage of timber

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Abstract. The paper presents the results of measurements of the CO_2 and NO_x emission and fuel consumption recorded under actual operating conditions of a heavy-duty vehicle designed for loading and carriage of timber. The tests were performed on a specially designed test route that reflected the arrival of the vehicle to the felling site in the forest, the loading process and return to the lumberyard. The route ran through paved (asphalt) and unpaved (forest) portions. Its total length was 8.6 km. An advanced PEMS (Portable Emission Measurement System) device was used for the measurement of the exhaust emissions – SEMTECH DS by Sensors Inc. The paper analyses the CO_2 and NO_x emission and fuel consumption on all portions of the test route and presents a comparison between the forest and asphalt roads.

1. Introduction

In developed countries for the last 20 years the system of tree felling has changed significantly. First, the commonly used axes were replaced with chainsaws and then specialized machines were applied capable of cutting and processing trees for transport in the amount of up to 350 m^3 of timber (Figure 1). The method of transport of timber to the storage site has also changed Transporting timber out of the forest is realized by vehicles fitted with specialized grabber cranes for loading and unloading of the cut trees. These vehicles fall into the homologation category of heavy-duty vehicles (HDV) and must comply with the applicable emission standards [1-4].

Figure 1. Example of modern machines for shearing in the forest [5].

The group of heavy-duty vehicles varies in terms of the role of a vehicle in the transport task. We can distinguish heavy-duty vehicles used for long haulage, distribution vehicles, special vehicles and city buses and coaches. Currently, all listed vehicles are fitted with technologically advanced engines with complex aftertreatment systems that, compared to engines manufactured several years ago, are characterized by a greater volume-to-power ratio, reliability and durability. Aside from modern engines, heavy-duty vehicles are also equipped with systems that assist the driver in the reduction of the fuel consumption and extension of life of many functional components – telematic systems that control the driver's behavior and supervise the operation of the entire powertrain [6]. The mentioned equipment ensure a consequent decrease of the negative impact of heavy-duty vehicles on the natural environment.

Out of the discussed group of vehicles, the heaviest work is done by special vehicles operated in the non-road areas. In this case, the experience and behavior of the driver under given operating conditions have the greatest influence on the exhaust emissions and fuel consumption. It is noteworthy that under non-road conditions a precise evaluation of parameters is difficult. Hence, the measurements of CO_2 and NO_x were performed under actual conditions of operation using state-of-the-art technology based on portable PEMS devices. The object of the investigations was a heavy-duty vehicle designed for transport of timber and the measurements were performed on a road/non-road test route.

2. Research methodology

2.1. Characteristic of the route

The tests were performed under actual conditions of operation of a heavy-duty vehicle designed for loading and transport of timber on both, paved (asphalt) and unpaved roads. In order to accurately reflect the operating conditions of this type of vehicles the tests were performed in the following configuration (Figure 2):

a) run to the loading site:
- paved road (portion A–B),
- unpaved road (portion B–C),

b) timber loading (point C),

c) run to the unloading site:
- unpaved road (portion C–D),
- paved road (portion D–A).

The total length of the test route was 8.6 km, 5.3 km of which were unpaved forest roads.

Figure 2. The test road section used in the on-road emission test for the heavy-duty vehicle.

2.2. The test vehicle
The test vehicle was a tractor-trailer system (MAN TGA 26.440) of the 6x6 axle configuration designed for transport of timber (table 1, Figure 3). The vehicle was fitted with a 324 kW (440 KM) Euro IV engine. An additional equipment of the tested object was the EPSILON E165Z95 crane for loading and unloading of timber. In the tested heavy-duty vehicle, a two-axle semi-trailer with the rear twist beam axle was applied.

Table 1. Characteristics of the test object.

Parameter	Value
Engine capacity	10.5 dm3
Number of cylinders/configuration	6 / straight
Maximum power output	324 kW @1900 rpm
Maximum torque	2100 Nm @1000-1400 rpm
Emission standard	Euro IV
Exhaust gas aftertreatment	MAN PM-KAT®
Crane type	EPSILON E165Z95 fitted with grabbers

Figure 3. A heavy-duty vehicle during the exhaust emission test under actual operating conditions.

2.3. Research equipment
For the measurement of the emission of CO_2 and NO_x, a PEMS device was used (SEMTECH by Sensors Inc.) designed for testing of exhaust emissions under actual conditions of operation (Figure 4). This is a unique combination of measurement and recording device of the following parameters [5, 7]:

a) CO and CO_2 concentration (NDIR–Non-Dispersive Infrared analyzer), $NO_x = NO+NO_2$ (NDUV–Non-Dispersive Ultraviolet analyzer), THC (FID–Flame Ionization Detector), O_2 (electrochemical sensor);
b) Mass flow of the exhaust gas–Pitot tube-based flow meter,
c) Ambient conditions – ambient pressure, temperature, humidity;
d) Vehicle position and speed–GPS system;
e) Data from the vehicle on-board diagnostic system.

Thanks to the mentioned measurements ensure, a comprehensive analysis of the vehicle exhaust emissions under actual operating conditions is possible allowing for the actual measurement conditions such as driving technique, ambient conditions, traffic congestion, etc.

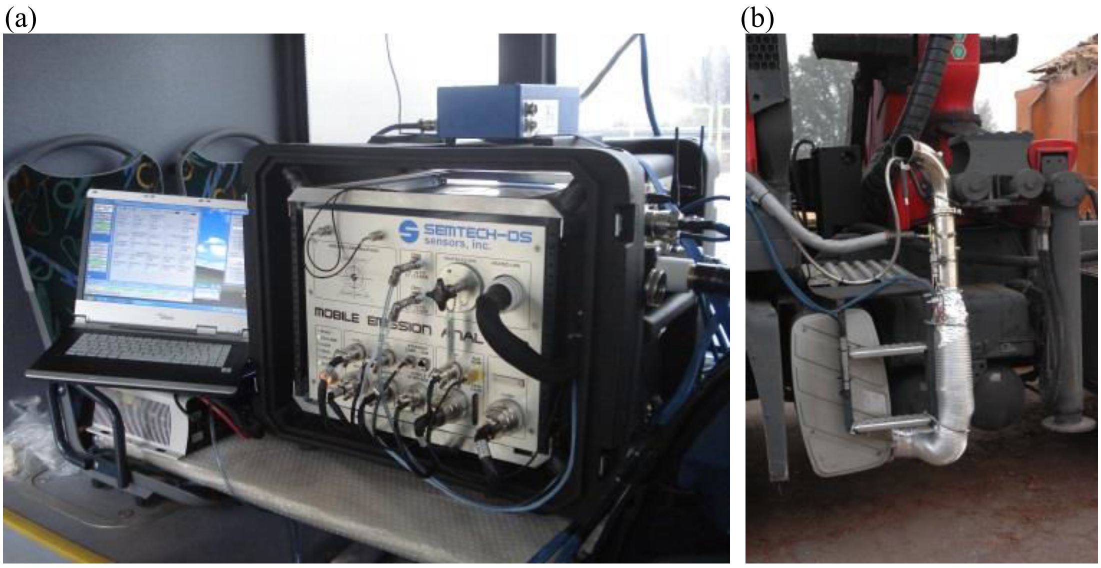

Figure 4. The SEMTECH DS analyzer (a) and the exhaust gas flow meter (b).

3. Analysis of results

3.1. Measurement conditions

The first stage of the test route covered the distance from the lumberyard to the felling site (Figure 5). The length of this portion was 2.1 km, 1.7 km of which were paved (asphalt) roads (table 2). In this road section the maximum speed of the vehicle reached 50 km/h. The next stage of the test was timber loading performed using the grabber crane fitted on the tested object. The crane has a hydraulic system powered through a power take off from the vehicle transmission. The timber loading constituted 46.8% of the entire measurement time.

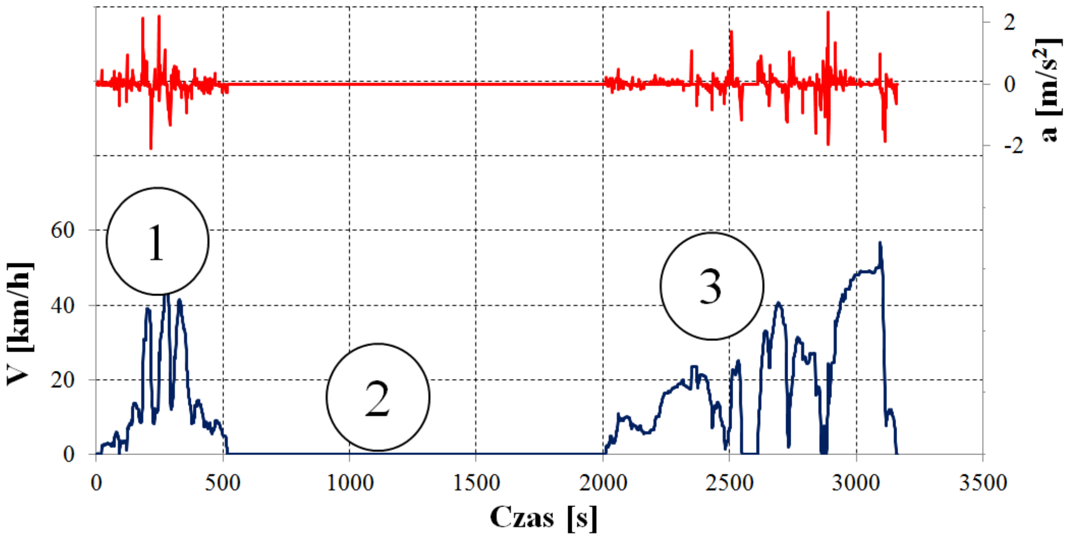

Figure 5. The vehicle speed and acceleration during the test.

Table 2. Characteristics of the parameters describing the vehicle driving profile.

Parameter	Unit	To the forest		Loading	To the lumberyard	
		Paved (asphalt) road	Unpaved (forest) road	–	Paved (asphalt) road	Unpaved (forest) road
Share	[%]	11.5	5.0	46.8	21.8	14.9
V_{max}	[km/h]	50.0	15.9	–	56.8	23.6
$V_{ave.}$	[km/h]	17.1	8.6	–	25.7	12.2
Distance	[km]	1.7	0.4	–	4.9	1.6

The last stage was the run of the vehicle with timber to the lumberyard. In this stage, paved roads prevailed in the vicinity of the town of Czarnkow. This stage revealed the greatest changes in the vehicle acceleration conditioned by the road infrastructure. The average speed on the paved roads of the vehicle was 25.7 km/h and on the forest road – 12.2 km/h. Such varied conditions of the test route had impact on the vehicle exhaust emissions (CO_2, NO_x) and fuel consumption. The measurements were performed on a sunny day without rainfall. The forest roads were passable and the all-wheel-drive system was not used (applied under difficult road conditions only).

3.2. Emission of CO_2, NO_x and fuel consumption

The greatest emission of CO_2 occurred in the last stage of the test route – the run from the felling site to the lumberyard (Figure 6). This was caused by the vehicle's greater average speed on this road section, compared to the first stage. The speeds were 18.9 and 12.8 km/h respectively. Higher vehicle speed is a result of production of greater effective power by the vehicle. Another factor influencing the CO_2 emission is the fact that the vehicle was fully loaded with timber during the run to the lumberyard (20 000 kg). When the vehicle is loaded, the average value of the engine torque increases, which increases the fuel consumption, which again is translated into higher combustion temperature inside the cylinders. Such conditions facilitate the formation of NOx, whose level depends on the temperature and pressure inside the combustion chamber. In the performed tests the emission of NO_x was close to the emission of CO_2 (Figure 7). Based on the obtained data the on-road emission of NO_x was determined (ratio of the mass of generated exhaust component to the covered distance):

a) to the loading site12.9 g/km:
- paved (asphalt) – road14.1 g/km,
- unpaved (forest) – road7.8 g/km,

b) to the unloading site –10.0 g/km:
- unpaved (forest) – 5.1 g/km,
- paved (asphalt) – 11.7 g/km.

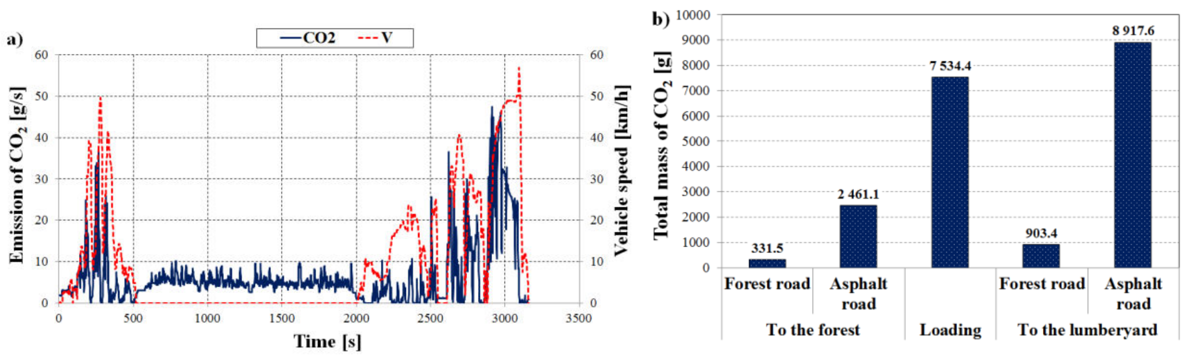

Figure 6. The emission of CO_2 and vehicle speed during the tests(a), total mass of CO_2 (b).

The vehicle, when on the way to the unloading site, had lower emission than when it was on the way to the forest. This was related to the operation of the EGR system (exhaust gas recirculation) fitted in the engine. During the run to the forest from the lumberyard, the EGR system may have supplied a lower amount of exhaust gas to the combustion chamber because it operated at low engine loads and low temperature inside the combustion chamber. During the run to the lumberyard with the trees, the engine operated at higher average load, which translated into greater mass of the recirculated exhaust gas.

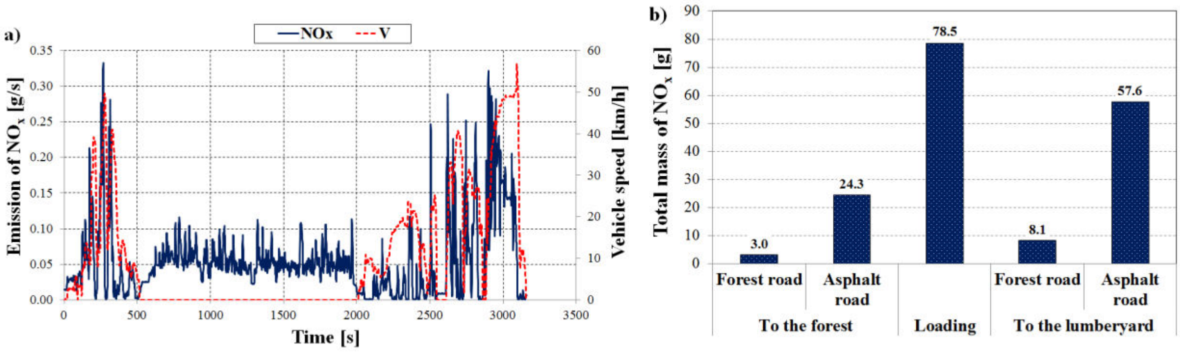

Figure 7. The emission of NO_x and vehicle speed during the tests(a), total mass of NO_x (b).

Second-by-second fuel consumption of the vehicle was determined based on the carbon balance method. This method is used mainly to determine fuel consumption based on the measured emission of CO_2, CO and THC. In order to determine the values of second-by second fuel consumption, this method was appropriately modified. A full description of the method modification can be found in earlier authors' publications [8]. For this test cycle, the second-by-second fuel consumption was determined exclusively based on the CO_2 emission rate. For heavy-duty diesel vehicles it is admissible because the values of CO and THC for this group of vehicles do not significantly influence the accuracy of determination of the carbon balance method based fuel consumption.
This is confirmed by the fact that the second-by-second fuel consumption was similar to the CO_2 emission rate (Figure 8a). Upon summing up the fuel consumption from individual stages of the test route, it was observed that the greatest amount of fuel was used by the vehicle when running from the forest to the lumberyard (Figure 8b).

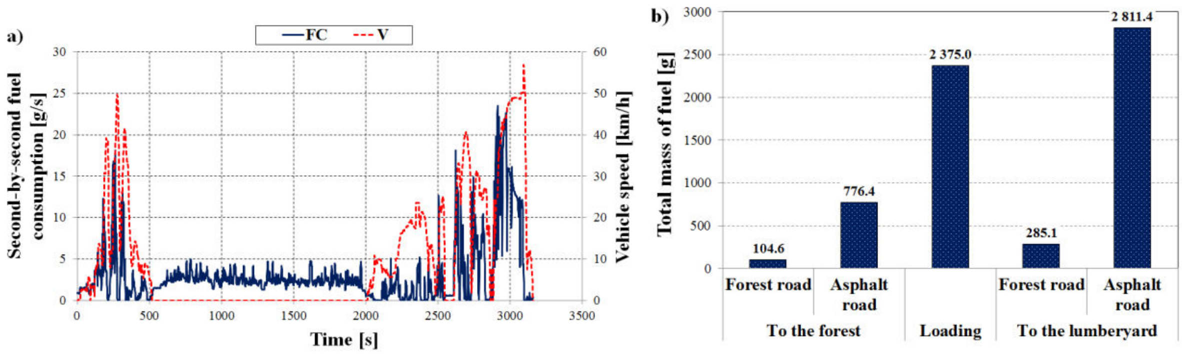

Figure 8. Second-by-second fuel consumption of a vehicle and its speed (a), total mass of fuel (b).

This confirms the above statements that higher average vehicle speed and applying a load to the vehicle translates into greater engine usable parameters (torque and power output) that higher fuel consumption is attributable to. Attention should also be drawn to increased fuel consumption when loading of the cut trees. Its maximum value was 3.2 g/s and it was greater than the maximum fuel consumption during the run to the loading site by the forest road.

Based on the second-by-second fuel consumption the fuel consumption of the vehicle was determined:

a) to the loading zone – 50.2 dm^3/100 km:
- paved (asphalt) road – 53.9 dm3/100 km,
- unpaved (forest) road – 33.1 dm3/100 km,

b) to the unloading zone – 56.7 dm^3/100 km:
- unpaved (forest) road – 21.4 dm3/100 km,
- paved (asphalt) road – 68.2 dm3/100 km.

Obtaining lower fuel consumption during the run to the loading site by the forest roads compared to the run to the lumberyard using the same roads was caused by additional manoeuvring of the vehicle on the tree-felling site to adjust the vehicle position before the loading procedure could begin. The manoeuvring was difficult because the terrain in the loading site was marshy.

4. Conclusion

The application of a portable measurement system (SEMTECH DS) in the tests of a heavy-duty vehicle used in the transport of trees in the forest allowed measuring the emission of CO_2 based on which the level of fuel consumption and NO_x emission were determined in a driving cycle reflecting day-to-day operation of this type of vehicles – paved asphalt roads and unpaved forest roads as well as loading and unloading of trees. This allowed determining the influence of the conditions of work on the exhaust emissions and energy demand of the vehicle engine. To date, only average fuel consumption was determined from a given period of vehicle operation. The paper also presented the fuel consumption of the vehicle during the tree loading procedure, whose maximum values were greater than the value recorded during the vehicle run on the forest road. The emission of NO_x during the tests may have been influenced by the EGR system that most likely, in the initial stage of the tests, supplied less exhaust gas to the cylinders due to lower engine loads and lower temperature of the exhaust gas at this stage. The tests were performed in good weather conditions and the forest roads were fully passable. It was not necessary to use the all wheel drive system. The authors plan further research using the applied method under more severe conditions. This will allow an accurate determination of the influence of heavy-duty tree-transporting vehicle working conditions on the fuel consumption.

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