Research of Exhaust Emissions from a Harvester Diesel Engine with the Use of Portable Emission Measurement System

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Abstract – Nacrtak

This paper presents the test results of exhaust emissions from the engine of a wheeled harvester. On the basis of the present analysis, the ranges of most frequently used engine loads and speeds were determined. The obtained time density characteristics (distribution of engine speeds and loads in time) of the engines were referred to the measuring points of the exhaust emission homologation test. During the measurement of the exhaust emissions, the machine was in the forest engaged in tree cutting. Exhaust emission tests from non-road vehicle engines are currently performed on engine test beds in the NRSC and NRTC tests. The present methodology is a new solution that could be used in the future as a basis for the development of harvesting technology aimed at reducing exhaust emissions from engines. During the tests, the authors also measured the amount of timber harvested during the felling process in order to be able to relate the emission results to the amount of the generated product. Harvesters are more and more often used in forest operations but they still have to compete with handheld (gasoline powered) chainsaws and that is why in this paper the authors included a comparison of the exhaust emissions from a chainsaw with the emissions from the engine of a harvester. The authors used a portable analyzers (SEMTECH DS and LAM manufactured by SENSORS) for the measurement of the exhaust emissions. The said analyzer can measure the concentrations of exhaust gas components in an on-line mode, while the engine is running under field conditions.

Keywords: exhaust emissions, harvester, chainsaw, on-board measurement

1. Introduction – *Uvod*

Exhaust emissions are one of the most important issues related to transport and industry. For many years, the impact of the environment pollution (including that coming from transport) on climatic changes have been discussed. The negative impact of exhaust emissions on human health and human natural environment, however, is beyond doubt. When harvesting timber, despite the obvious influence of exhaust emissions on the environment (atmosphere, flora, etc.), there is a particular hazard that chainsaw operators are exposed to when using motor chainsaws. Chainsaw operators work very often in an environment with a high concentration of hazardous exhaust components. Chainsaw operators are exposed to the emission of PAH and nanoparticles (Czerwinski et al. 2001; Laanti et al. 2001; Jacke et al. 1996). Despite recently observed changes in the European Union member states (Central and Eastern Europe in particular) related to the mechanization of forest operations and use of harvesters, still most of the work is done with the use of motor chainsaws (equipped with gasoline engines).

The literature related to the problem of exhaust emissions generated during tree harvesting is chiefly based on test stand research performed in laboratories and estimates under actual operating conditions. There are numerous works aimed at implementing technological solutions in order to reduce exhaust emissions and fuel consumption such as the use of catalytic aftertreatment (Schlossarczyk et al. 2004), improvement of the charge exchange (Rodenbeck et al.

2006) or application of the stratified scavenging method (Ohtsuji and Kobayashi 2002). A wide variety of technical solutions for chainsaw engines was presented by Zahn (2000), who investigated fuel injection, engine lubrication, stratified scavenging and catalytic aftertreatment. Another ecological aspect related to tree harvesting is the emission of lubricating oil. According to Hartweg and Keilen (1988) while harvesting trees, the soil may absorb up to 0.2 dm^3 of oil from the engine per 1 cubic meter of harvested timber. Similar values are given by Sonnleitner (1992). This is an indication of a serious ecological problem, and hence there are numerous papers on this issue. One of the proposals to solve the problem is the application of biodegradable oils and hydraulic fluids (Ahola 1998; Wightman et al. 1998). A comparison of the emission level and the operating parameters of the chainsaw engines using mineral and vegetable oils have been presented by Skoupy et al. (2010). There are also numerous publications related to the estimation and calculation of exhaust emissions during machine tree harvesting. In many cases, particular stress was put on the emission of GHG. In his publication, Athanassiadis (2000) presented the results of the estimation of energy requirements and the amount of emissions from chainsaw engines and heavy-duty diesel vehicles used for timber harvesting. In this paper, the emissions of CO_2, CO, HC, NO_x and PM were estimated related to 1 cubic meter of harvested timber. The tests were performed for diesel fuels and RME and for mineral and vegetable lubricating oil. Results of similar investigations were presented by Berg and Karjalainen (2003) and Karjalainen and Asikainen (1996). In their publications, they presented the emission of GHG and fuel consumption from machinery used in silviculture, forest improvement work, wood harvesting and timber transportation. In these works, the authors also presented a comparison of fuel consumption while harvesting timber with chainsaws and harvesters. The problem of fuel consumption and exhaust emissions was also addressed by Nordfjell et al. (2003) and Klvac et al. (2012). These works, however, are related to forwarders and cableway systems.

The investigations presented in this paper are slightly different. The majority of publications related to the exhaust emissions is based on calculated or estimated values (Athanassiadis 2000; Klvac and Hosseini 2010; Klvac et al. 2012; Nordfjell et al. 2003; Skoupy et al. 1996 and many others). In the present paper, the emission measurements were performed while the harvester was working. The fuel consumption was determined based on direct measurements using the carbon balance method – the most accurate method of fuel consumption measurement.

The investigations presented here have been carried out with a method that uses a PEMS analyzer. The tests under actual operating conditions are one of the latest technologies in exhaust emission measurement (Merkisz et al. 2010). Thanks to the above-mentioned method, the authors could determine the actual emissions generated during the operation of a harvester and a chainsaw. The tests related to the exhaust emissions are usually carried out in laboratories, on chassis or engine dynamometers. The results of these tests may determine the emission class of the engine or the vehicle but do not entirely reflect the actual emissions. The measurements of the exhaust emissions under actual operating conditions are very valuable as they enable the determination of the emission depending on the existing engine operating conditions (a machine or a vehicle). Consequently, this methodology is now generally recognized as a very important complementing component of tests performed in laboratories. Furthermore, scientific research centers or legislative bodies consider introducing the on-road exhaust emission testing of homologation procedures (Walsh 2011).

2. Testing methods and equipment
Ispitne metode i oprema

The tests were performed on a harvester equipped with a diesel engine. The technical specifications are

Table 1 Basic technical specifications of the harvester
Tablica 1. *Osnovne tehničke značajke harvestera*

Capacity/number of cylinders *Kapacitet/broj cilindara*	6.8 liters/6 cylinders in-line *6,8 litara/6 cilindara, linijski*
Maximum power output *Najveća snaga*	129 kW @ 2000 rpm 129 kW *pri* 2000 min^{-1}
Maximum torque *Najveći zakretni moment*	780 Nm @ 1300–1400 rpm 780 Nm *pri* 1300–1400 min^{-1}
Cooling system *Rashladni sustav*	Coolant forced circulation *Vodeno hlađenje*
Compression ratio *Omjer kompresije*	17:1
Supercharging *Prednabijanje*	Turbocharged *Prednabijanje plinskom turbinom*
Injection system *Sustav ubrizgavanja*	Common rail *Ubrizgavanje sa stalnim tlakom*
Engine emission regulations *Norma ispušnih plinova*	Stage III A/Tier 3

Table 2 European (Stage) and American (Tier) exhaust emission limits for the harvester engine

Tablica 2. *Europske (Stage) i američke (Tier) granične vrijednosti emisije ispušnih plinova za motor istraživanoga harvestera*

CO, g/kWh	HC, g/kWh	NO_x, g/kWh	PM, g/kWh
Stage IIIA			
5.0	NO_x + HC – 4.0		0.3
Stage IIIB			
5.0	0.19	3.3	0.025
Tier 3			
5.0	NO_x + HC – 4.0		0.3
Tier Interim 4			
5.0	3.54		0.02

shown in Table 1. The engine of the tested harvester complies with the Stage IIIA (US Tier 3) standard. The testing methodology in both European and American exhaust emission regulations is the same. There are two types of tests, the stationary NRSC and the dynamic NRTC (Fig. 1). In section 3, the authors compared the exhaust emissions obtained under actual operating conditions with the Stage IIIA and Tier 3 limits because the tests should reflect most accurately the actual conditions of engine operation. The authors also compared the exhaust emissions from the harvester and chainsaw. The basic technical specifications

Table 3 Basic technical specifications of the chainsaw

Tablica 3. *Osnovna tehničke značajke motorne pile lančanice*

Engine displacement *Obujam motora*	50.2 cm^3
Power *Snaga*	2.5 kW
Recommended max. bar length *Preporučena najveća duljina vodilice*	45 cm
Sound power level *Razina buke*	112 dB(A)
Weight (without bar/chain) *Masa (bez vodilice i lanca)*	5.2 kg
Engine emission regulations *Norma ispušnih plinova*	Stage II

of the chainsaw are shown in Table 2. At the moment of testing, the chainsaw was used for approximately 6 months.

The measurements were done under actual operating conditions of the machine while felling trees, delimbing and cross-cutting tree trunks into 2 meter logs. The harvester prepared for testing with the measurement equipment during forest operations is presented in Fig. 2. The works were performed in a pinewood

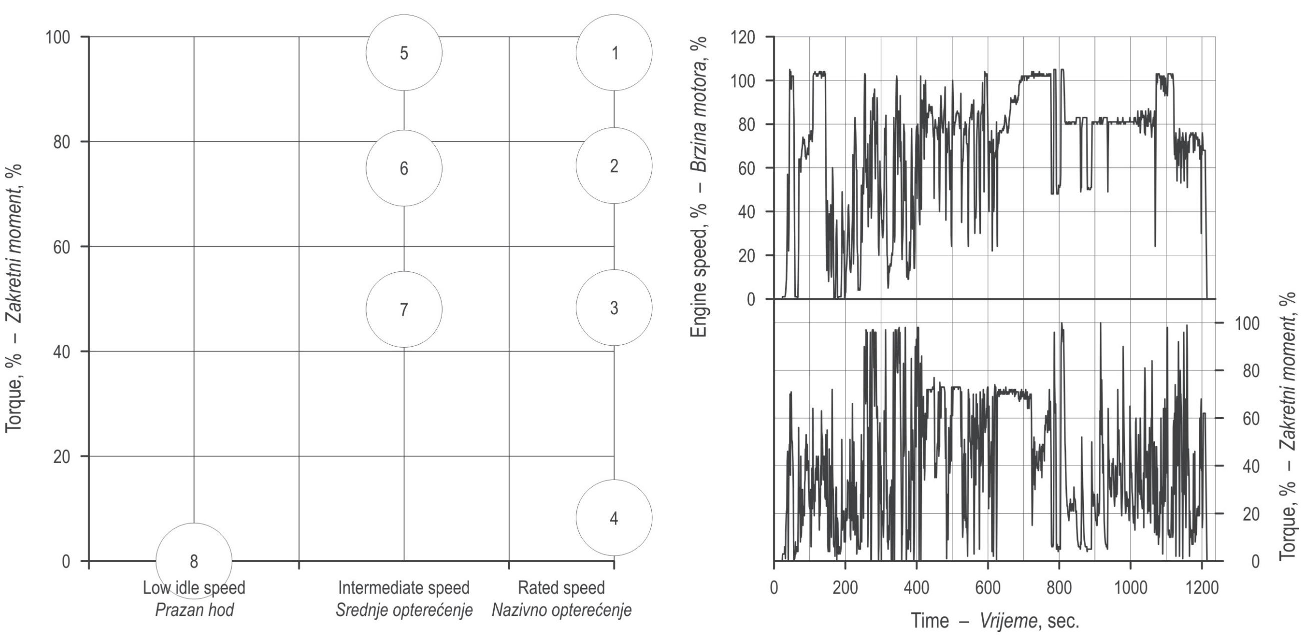

Fig. 1 Exhaust emission tests (harvester engine)

Slika 1. *Ispitivanja emisije ispušnih plinova (motor harvestera)*

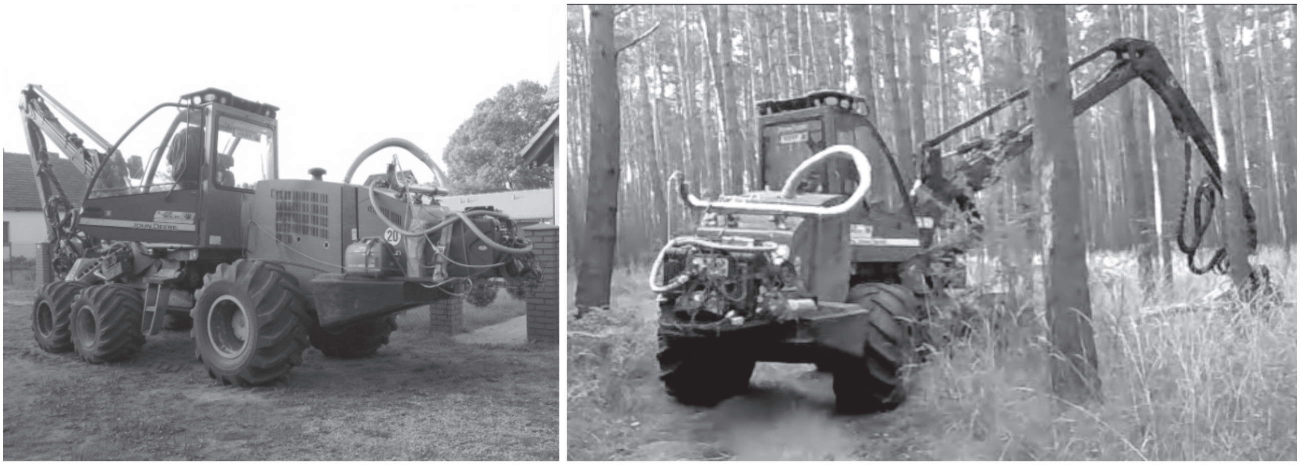

Fig. 2 Forest harvester with the exhaust emission measuring equipment
Slika 2. *Izgled harvestera opremljenoga mjernom opremom za mjerenje emisije ispušnih plinova*

forest. The diameter of trees cut ranged approximately between 20 and 30 cm. The works were performed on a relatively small area of approximately 1 ha but during the tests the vehicle covered a distance of 2.3 km. The location and the trajectory of the harvester are shown in Fig. 3. It took 4 hours to complete the whole testing cycle of the machine operation. A similar work was performed during the exhaust emission tests of a chainsaw (tree felling, delimbing and cross-cutting). The authors made sure that the felled trees were pines.

In order to measure the concentration of exhaust emissions, a portable exhaust emissions analyzer SEMTECH DS by SENSORS was used (Fig. 4, Shahinian 2007). The analyzer measures the concentration of the exhaust components and simultaneously measures the flow rate of the exhaust gases. The exhaust gases are introduced into the analyzer through a probe maintaining the temperature of 191ºC. Then the particulate matter is filtered out (diesel engines) and the exhaust is directed to the flame-ionizing detector (FID), where HC concentration is measured. The exhaust gases are then cooled down to the temperature of 4ºC and the measurement of concentration of NO_x (NDUV analyzer), CO, CO_2 (NDIR analyzer) and O_2 follows in the listed order. It is possible to add data sent directly from the vehicle diagnostic system to the central unit of the analyzer and make use of the GPS signal (distance accuracy 0.05 % – <50 cm per km, velocity accuracy 0.2 km/h, averaged over 4 samples). The GPS signal is mainly used in the tests of on-road vehicles. In investigations

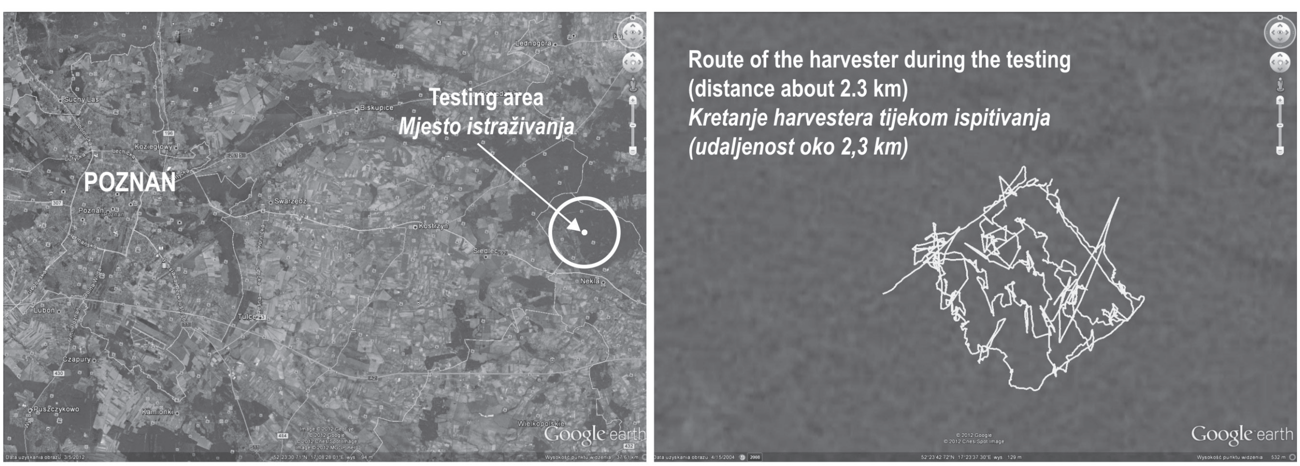

Fig. 3 Testing area and harvester route during testing (created at gpsvisualizer.com)
Slika 3. *Mjesto istraživanja i kretanje harvestera tijekom ispitivanja (gpsvisualizer.com)*

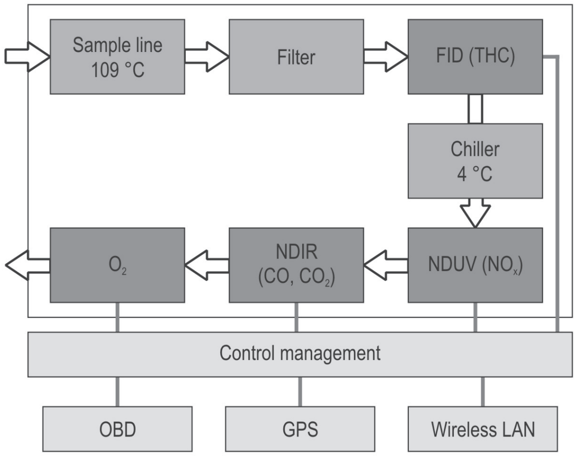

Fig. 4 A diagram of a portable analyzer SEMTECH DS; exhaust gas flow channels (arrow) and electrical connections circled (line)

Slika 4. *Dijagram prijenosnoga analizatora SEMTECH DS, protok ispušnih plinova (strelica) i električne veze (linija)*

Table 4 The specification of SMTECH-LAM

Tablica 4. *Specifikacija SMTECH-LAM-a*

Measurement Range *Raspon mjerenja*	0–40 mg/m^3 0–700 mg/m^3
Dilution *Razrjeđivanje*	Selective Ratio *Selektivni omjer*
Particle Size *Veličina čestica*	100–10 000 nm
Resolution *Preciznost*	0.01 mg/m^3
Drift *Odstupanje*	<0.25mg/m^3 over 6 hours <0.25mg/m^3 *tijekom* 6 *sati*
Sample flow *Brzina protoka uzorka*	1.5 dm^3/min
Sample rate *Frekvencija uzorkovanja*	5 Hz (internally to 100 Hz) 5 Hz (*interno do* 100 Hz)
Output *Izlaz*	RS232 Analog 0 to 5 VDC option RS232 *Analogni* 0 do 5 VDC *opcijski*
Power supply *Napajanje*	12 to 24 VDC or 110 to 240 VAC 12 do 24 VDC *ili* 110 *do* 240 VAC
Operating temperature *Radna temperatura*	0–40 °C

similar to the ones presented here, when the vehicle operates in a limited area, on-road emissions are not measured and GPS is of secondary importance. Measurements of emissions were made in test and, for the purpose of comparison, signals from the on-board diagnostic system were recorded, e.g. engine speed, load, vehicle speed, temperature of intake air. Some of these signals served to specify time density maps presenting participation of operating time of the vehicles in actual operation conditions.

For PM measurement, the SEMTECH Laser Aerosol Monitor (LAM) was used. The SEMTECH-LAM operates on the basis of 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 motor types, vehicles and test conditions. It could be used as test cell equipment or for on road testing. The dual sample port enables testing of filter efficiency, for engines equipped with a diesel particulate filter. The SEMTECH-LAM uses three mass flow controllers that are 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 particulates from 100 nm to 10 000 nm. The specification of SEMTECH-LAM are shown in Table 4.

3. Results of tests and discussion
Rezultati ispitivanja i rasprava

The performed tests, apart from the possibility of determining ecological properties, enable an analysis of engine parameters under operation (Fig. 5). In the

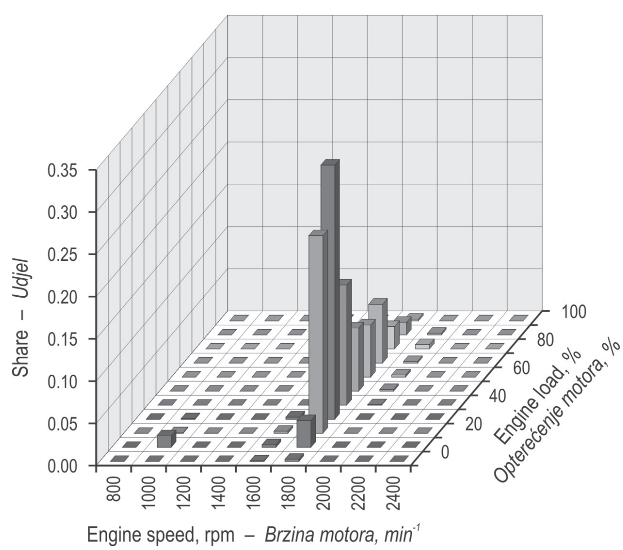

Fig. 5 Time density of harvester engine during the test under actual operating conditions

Slika 5. *Udjel brzina i opterećenja motora tijekom istraživanja harvestera*

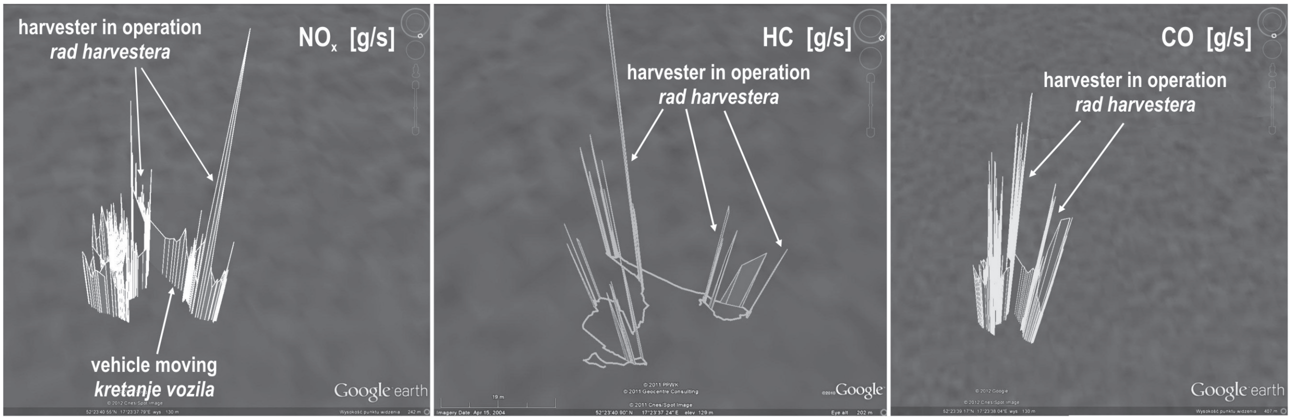

Fig. 6 Exhaust emissions during harvester operation overlain on the map (created at gpsvisualizer.com)
Slika 6. *Kartografski prikaz emisija ispušnih plinova tijekom rada harvestera (gpsvisualizer.com)*

case of machinery tested, the engine operated in a very narrow range of engine speeds and namely 1700–1800 rpm. The most frequently used range of loads was 20–50% of the maximum engine load. The range of 50–70% had a slightly lower share. Besides the above shares of engine operation, the share of idle speed was also recorded (3%). The main engine operation range was outside the range of NRSC phases, as is in other non-road vehicles (Merkisz and Lijewski 2010; Noren and Pettersson 2001).

Fig. 6 presents graphs showing the exhaust emissions overlain on a map with the marked vehicle route during operation. These graphs are only a 15-minute portion of the test. The authors decided to present only a fragment of the route because the presentation of the whole test would result in an excessive density of lines on the map, which would render the graphs illegible. The graphs clearly show an increased emission of all the exhaust gas components in the spots where the harvester felled and processed trees as compared to vehicle idling. The increased emission probably results from the changes in the engine load while felling trees.

Fig. 7 presents the exhaust emissions from a harvester under actual operating conditions. The obtained results were compared to the limits of Stage IIIA and Tier 3. The emission of CO and HC is lower than the values set forth in the Stage IIIA and Tier 3 standards. The emission of PM and NO_x during the harvester operation is much higher though (almost three times higher than the limits set forth in Stage III).

The authors also performed an analysis of the exhaust emissions related to harvester work – the amount of timber harvested. Fig. 8 presents the exhaust emissions related to 1 cubic meter of timber harvested. Such an analysis enables a global assessment of pollution generated by harvesters operating on large forested areas. A similar analysis was performed for fuel consumption/CO_2 emission. During harvester tests lasting over 4 hours the fuel consumption was 11.3 dm^3/h, which was 0.69 dm^3 related to 1 cubic meter of timber harvested. The emission of CO_2 was 1810 g related to 1 cubic meter of timber harvested. Other authors have obtained slightly different values related to the evaluation of fuel consumption by harvesters. Athanassiadis (2000) recorded fuel consumption of

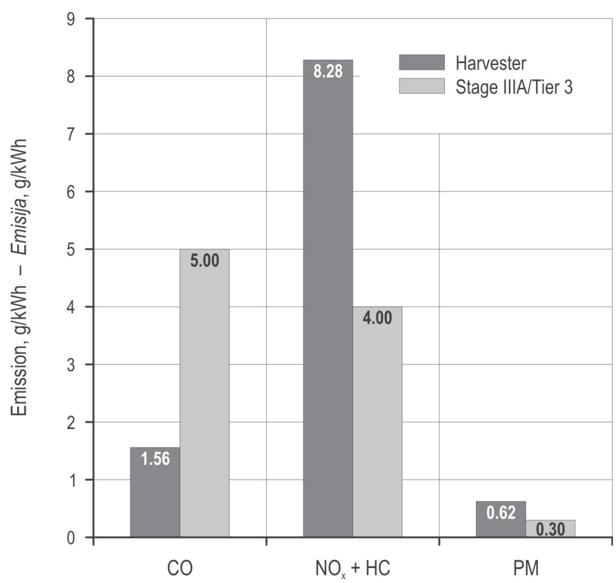

Fig. 7 Exhaust emissions from a forest harvester under actual operating conditions compared to Stage IIIA and IIIB standards (based on AVL Current and Future Exhaust Emissions Legislation 2007)
Slika 7. *Usporedba emisije ispušnih plinova harvestera u radnim uvjetima s razinama propisanim normom*

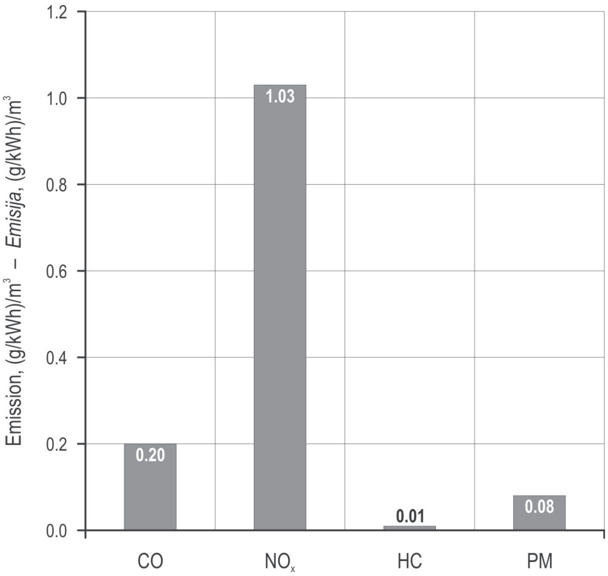

Fig. 8 Exhaust emissions from a forest harvester under actual operating conditions related to 1 cubic meter harvested

Slika 8. *Emisije ispušnih plinova harvestera u stvarnim radnim uvjetima po izrađenom kubnom metru*

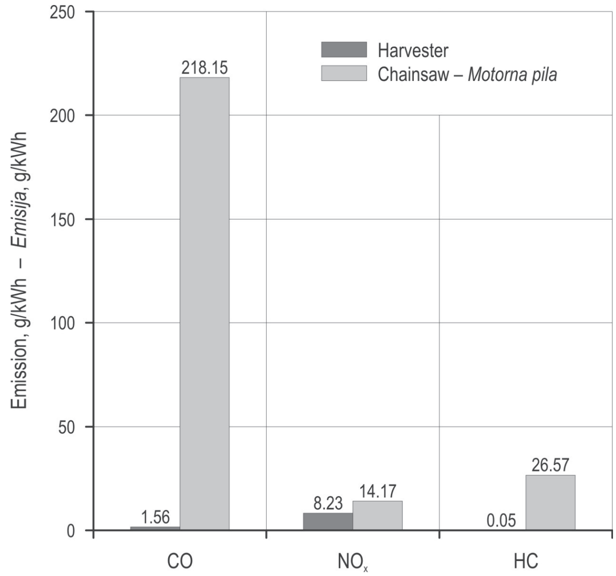

Fig. 9 Comparison of exhaust emissions from a chainsaw and a harvester measured under actual operating conditions

Slika 9. *Usporedba emisija ispušnih plinova motorne pile lančanice i harvestera izmjerenih u radnim uvjetima*

1.14 dm^3 related to 1 cubic meter of timber harvested (this is approximately 3030 g of CO_2 related to 1 cubic meter of timber harvested). In turn, Berg and Karjalainen (2003) stated that fuel consumption of the harvester in their study fell within 12–16.5 dm^3/h. In contrast, Karjalainen and Asikainen (1996) reported the emission of CO_2 from the harvester at the level of 1857 g related to 1 cubic meter of timber harvested, which is a value similar to the one obtained in the present paper. However, it is important to note that according to most publications, fuel consumption from harvesters is not measured with the use of the carbon balance method, which might be one of the reasons for different results obtained from different studies. Furthermore, fuel consumption of any harvester depends on a number of factors such as machine operator, terrain leveling, type of trees harvested, weather conditions, etc. and this makes direct comparisons of these studies even more difficult.

As far as the chainsaw is concerned, during the tests its fuel consumption was 0.38 dm^3/h, and when related to 1 cubic meter of timber harvested it was 0.26 dm^3. These values were lower than the ones found in other publications (e.g. Karjalainen and Asikainen 1996). As mentioned above, fuel consumption of chainsaws, as much as that of harvesters, depends on a number of factors.

In many European countries, forest operations are often carried out with chainsaws driven by gasoline

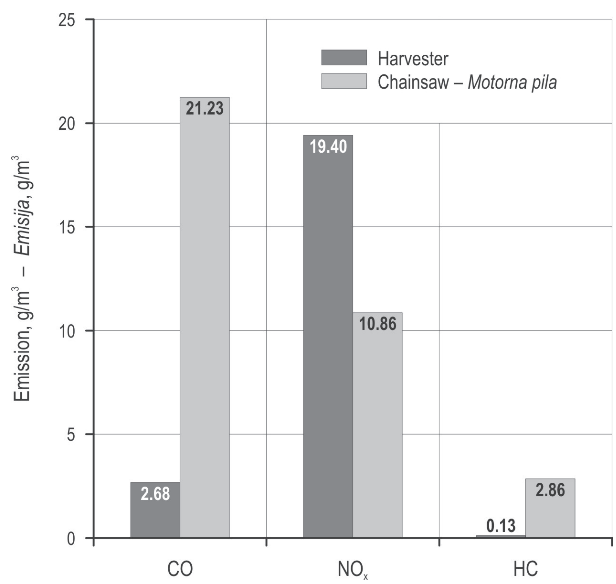

Fig. 10 Comparison of exhaust emissions from a chainsaw and a harvester measured under actual operating conditions related to 1 cubic meter of timber harvested

Slika 10. *Usporedba emisija ispušnih plinova motorne pile lančanice i harvestera izmjerenih u radnim uvjetima po izrađenom kubnom metru obloga drva*

engines. Harvesters are not widely used in Europe – Eastern Europe in particular (e.g. Poland). In Poland in 2008 there were 157 (Anon. 2011) harvesters i.e. one in 58 000 ha of forested land. For comparative purposes, the authors also tested exhaust emissions from a chainsaw under actual operating conditions. The comparison of exhaust emission from the chainsaw and harvester is presented in Fig. 9. The exhaust emissions from a chainsaw are much higher than the emissions from a harvester e.g. for HC the emission is several hundred times higher and for CO over 100 times higher. The smallest differences were recorded for the emission of NO_x. To fully understand the differences in the ecological properties between the machines, their efficiency needs to be taken into account. It is estimated that the efficiency of the harvester equals that of 4 chainsaws. Besides, the occupational safety considerations are clearly against chainsaws.

Fig. 10 presents the exhaust emissions related to 1 cubic meter of timber harvested. The emission of CO and HC was much higher for the chainsaw while the emission of NO_x was higher for the harvester.

4. Conclusions – *Zaključci*

The presented results of exhaust emission tests performed under actual operating conditions of harvesters during tree harvesting diverge from the Stage IIIA and Tier 3 standards. One should note the engine operating conditions, time density characteristics (time density of the engine operation) in the aspect of the applicable NRSC 8 phase test. From the performed investigations it results that the engine of a harvester operated at a relatively constant speed and at partial loads. It seems that the present method can be successfully used to estimate the ecological burden while performing forest operations. In Poland it is a significant issue as forests cover 29% of the country area i.e. 9.1 million ha. The presented test results support the replacement of gasoline chainsaws with harvesters. Such a solution is much better from the ecological point of view and in terms of occupational safety.

In further works related to exhaust emissions, the authors plan to carry out research related to other forest machinery (e.g. forwarders), which would allow a total estimation of the environmental burden generated by these machines. Moreover, in the future, the authors plan to conduct tests that will qualitatively evaluate the emissions of particulate matter generated by a harvester under actual operating conditions i.e. determine the PM number and the PM size. As other studies show, it is the PM number and the PM size rather than the PM mass emission that appear to be instrumental in the PM impact on human health (e.g. Metz 2003). Moreover, it should be noted that harvesters are powered by diesel engines and the IARC report published in June 2012 clearly classifies diesel exhaust as carcinogenic (IARC 2012). This report is based on years of research of the impact of diesel engines on human health (Attfield et al. 2012; Silverman et al. 2012). The above facts fully encourage the continuation of the research with a view to reducing the exhaust emissions from engines including those used in silviculture.

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Abbreviations – *Kratice*

CO – Carbon Monoxide – *Ugljikov monoksid*
CO_2 – Carbon Dioxide – *Ugljikov dioksid*
EPE – Estimate of Position Error – *Procjena greške položaja*
GHG – Greenhouse Gases – *Staklenički plinovi*
FID – Flame Ionization Detector – *Detektor ionizacije plamena*
GPS – Global Position System – *Globalni pozicijski sustav*
HC – Hydrocarbons – *Ugljikovodici*
IARC – International Agency for Research on Cancer *Međunarodna agencija za istraživanje raka*
LAM – Laser Aerosol Monitor – *Laserski monitor aerosola*
NDUV – Non-Dispersive Ultra-Violet – *Neraspršujuća ultraljubičasta*
NO_x – Nitric Oxides – *Dušikovi oksidi*
NRSC – Non-road Stationary Cycle – *Necestovni stacionarni ciklus*
NRTC – Non-road Transient Cycle – *Necestovni ciklus kretanja*
OBD – On Board Diagnostics – *Dijagnostika na vozilima*
PAH – Polycyclic Aromatic Hydrocarbons – *Policiklički aromatski ugljikovodici*
PEMS – Portable Emissions Measurement System *Prijenosni sustav za mjerenje emisija*
PM – Particulate Matter – *Čestice čađe*
RME – Rapeseed Methyl Esters – *Metilni esteri repičinoga ulja*

Sažetak

Istraživanje emisija ispušnih plinova dizelskoga motora harvestera uporabom prijenosnoga sustava za mjerenje emisija

U radu se istražuju emisije ispušnih plinova harvestera i motorne pile pri pridobivanju drva. Predstavljena je poredbena analiza glavnih spojeva u ispušnim plinovima (ugljikov monoksid, dušikovi oksidi, ugljikovodici i čestice čađi). Autori su proveli i analizu potrošnje goriva spomenutih strojeva pri sječi i izradbi drva. U šumskim se operacijama sve češće koriste harvesteri, no još se uvijek moraju natjecati s motornim pilama pogonjenima benzinom. Uprvo su zbog toga autori uključili u rad i usporedbu emisija ispušnih plinova motorne pile s emisijama motora harvestera. Analizom dostupne literature u vezi s potrošnjom goriva i utjecaja na okoliš šumskih strojeva dolazi se do zaključka da je većina radova temeljena na laboratorijskim ispitivanjima i izračunima. U ovom je radu primijenjen drugačiji istraživački pristup. Istraživanje emisija ispušnih plinova i potrošnje goriva provedeno je u stvarnim radnim uvjetima tijekom pridobivanja drva (borovine). U tu su svrhu korišteni analizatori emisija ispušnih plinova PEMS (prijenosni sustav za mjerenje emisija). Za mjerenje plinova korišten je SEMTECH DS, a za mjerenje količine čestica čađe korišten je LAM (oba proizvođača SENSORS). Navedeni analizator može mjeriti koncentraciju komponenti ispušnih plinova u on-line modu tijekom rada motora u terenskim uvjetima. Predstavljena je metodologija novo rješenje koje bi u budućnosti moglo poslužiti kao osnova za rad na razvoju smanjenja emisija ispušnih plinova motora. Tijekom istraživanja autori su mjerili i količinu proizvedenoga drva, stoga su rezultati emisija mogli biti dovedeni u vezu s količinom proizvoda (jednoga kubnoga metra izrađene oblovine).

Ključne riječi: emisije ispušnih plinova, harvester, motorna pila, mjerenje na vozilima

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