Analysis of Hazardous Emissions of Hand-Operated Forestry Machines Fuelled with Standard Mix or Alkylate Gasoline

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Abstract

In addition to safety, small hand-operated forestry machines can be criticised for affecting the operators' health, especially because of high levels of exhaust gas emissions, noise and vibrations. In this study, gas emissions, noise and hand-arm vibrations (HAV) levels have been measured on chainsaws, hedge cutters and blowers fuelled with two different types of fuel: a commercial RON 95 gasoline with the addition of 2% of synthetic oil suitable for two-stroke engines and, as an alternative, a specific advanced mixture available on the market, based on alkylate gasoline. For two different running conditions, i.e. with the engine at idle speed and when executing a typical working routine (maximum speed with load), tests were carried out for:

⇒ *gas emissions, using a gas analyser, for measuring the volatile organic compounds (VOC) values*

⇒ *noise, using a sound level meter, to record the levels at both of the operator's ears*

⇒ *HAV, using a tri-axial accelerometer fixed on the handgrip(s) of the machines.*

The results demonstrated that, when using the alkylate fuel, the VOC emissions were reduced, in the considered machines, from 23 to over 77%, while for noise and HAV, the differences in level were not statistically significant. The present study confirms that the reduction in the amount of emissions can be remarkably improved by adopting advanced fuels that lead to a more efficient combustion process.

Keywords: alkylate fuel, blower, chainsaw, hedge cutter, exhaust gas emission, noise, hand-arm vibrations

1. Introduction

In forestry, but also in green maintenance and even more in hobby-oriented fields, the use of small hand-operated machines is widespread. This category of machines is widely diffused at a worldwide level; in the Italian market alone, in 2014 more than 700,000 small hand-operated machines were purchased for professional and hobby use (Comagarden/Morgan 2015).

The internal combustion engine of specialised machines for forestry and green maintenance (i.e. chain saws, lawn mowers, hedge cutters, blowers, etc.) is typically a two-stroke spark ignition, fuelled by gasoline with synthetic oil added to provide suitable engine lubrication. This simplifies manufacturing, as it is necessary to provide reduced mass, a small size and a relatively low production cost. For example, the engines of chain saws typically have a very high specific power, up to 45 W/cm^3, but at the same time, they have a reduced mass, even less than 115 g/cm^3 (Wòjcik 2002). The two-stroke internal combustion engine offers a heat efficiency that is lower than a four-stroke internal combustion engine, due to the incomplete combustion of the air-fuel mixture into the cylinder. The main consequences are higher fuel consumption and higher emission of exhaust gas, with damaging effects on the environment and human health (Bünger et al. 1997, Magnusson et al. 2000, Skoupi et al. 2010).

In detail, the representative pollutants emitted are carbon monoxide (CO), nitrogen oxides (NOx), unburned hydrocarbons (HC), sulphur compounds (SO_2 and H_2S) and particulate matter (PM) (Wòjcik and Skarżyński 2006, Volckens et al. 2007, Nilsson et al. 2010). Moreover, the exhaust emission includes other gases (not dangerous for the operator but sometimes harmful for the climate), such as nitrogen (N_2), oxygen (O_2) and carbon dioxide (CO_2) (Wòjcik and Skarżyński 2006).

In the statement »Trend of Emissions in 2002«, the US Environmental Protection Agency (EPA) (EPA 2005) underlined that the emissions of HC and CO from this type of engine represented approximately 10.5% and 4.8%, respectively, of total emissions in the USA. In order to reduce harmful compounds in the exhaust gas of small hand-operated machines, with Directives 97/42/CE and 99/38/CE, the European Commission established the limits for toxic pollutants by introducing the European Emission Standards and the contextual duty of the manufacturers to install catalytic converters for these particular categories of machines.

Besides the accomplishment of the EU Directive, in order to reduce the pollution due to the exhaust gas, alternative fuels specifically developed for hand-operated small machines are available on the market. These fuels are a mix of alkylate gasoline and synthetic oil, produced with the goal of reducing drastically the impact on operators' health and environment. Alkylate gasoline is a fuel characterised by highly branched alkanes and only very small amounts of arenes and alkenes, derived from the residual gas of petroleum refining. This fuel is practically lacking in sulphur, benzene, aromatics and ethanol. Alkylate gasoline is also a desirable fuel due to its high octane number in comparison with unleaded gasoline (Ostermark 1996, Ostermark and Petersson 1993). Nowadays, the main limitation to the wide diffusion of this alternative fuel is its high cost (about 2–2.5 times the price of normal fuel, based on unleaded gasoline).

To reduce the health risk for the operator, besides the use of alkylate gasoline, it is important to evaluate carefully the performance of small hand-operated forestry machines from further points of view. Apart from personal protective devices and systems created to reduce injuries, other factors affecting the onset of occupational diseases are noise pollution and vibrations transmitted to the hand and arm of the operator (Davis 1978, Groves and Lyons 2013).

In fact, these machines typically generate noise levels that can be dangerous for the operator's hearing (Fonseca et al. 2015). In particular, considering chain saws, Tunay and Melemez (2008) executed an audiometric test on 114 forest loggers to ascertain whether they were experiencing hearing loss, finding a dramatic loss (hearing threshold) reaching the range of 40–50 dB.

Moreover, concerning hand-arm vibrations (HAV), small hand-operated forestry machines are characterised by high acceleration levels, often exceeding the limits specified by the national and international standards. Unfortunately, technological progress has not improved this factor in recent years (Monarca et al. 2003).

The aim of this work was to study the behaviour of some important parameters influencing the health of operators arising from the use of hand-operated forestry machines (chain saws, hedge cutters and blowers). These machines were fuelled with a commercial RON 95 gasoline (EN 228 2013) with addition of 2% of synthetic oil suitable for two-stroke engines and, as an alternative, a specific advanced mixture available on the market, based on alkylate gasoline (Swedish Standard SS 155461 2008). In particular, field tests were carried out to evaluate the influence of this alternative fuel on pollutant emissions, in terms of VOC (Volatile Organic Compounds, particularly dangerous for the operator's health and environment), due to fuel combustion.

Furthermore, alkylate gasoline leads to a more efficient combustion process due to a higher Motor Octane Number (MON) than conventional gasoline (Stratiev 2011). In fact, conventional gasoline has MON usually equal to 85, whilst the MON value of alkylate gasoline is higher than 90; so it was interesting – as a secondary hypothesis – to verify if the use of alkylate fuel could influence the noise and HAV levels emitted by hand-operated machines. With this aim, field tests were also carried out to measure the noise at the operator's ear and the HAV affecting the operator's hand-arm area. All the field tests (VOC, noise and HAV) were carried out considering different engine loads, to simulate the real working conditions in which these machines are typically used.

2. Materials and method

The research involved eleven machines: six chain saws, two hedge cutters and three blowers, all equipped with a two-stroke engine, except for one blower equipped with a four-stroke engine, alternatively fuelled with conventional gasoline and alkylate gasoline. The investigated machines show different technical characteristics in terms of displacement, engine power, emission stage, and year of production (Table 1). The characteristics of the two fuels used during the tests are reported in Table 2.

Table 1 Main technical characteristics of machines tested

Category	Machine ID	Manufacturing year	Strokes n	Emission stage	Displacement cm^3	Engine power kW
Chain saw	CS1	1997	2	n.a. *	40.2	1.9
	CS2	2004	2	Euro 1	30.1	1.2
	CS3	2010	2	Euro 1	55.5	2.8
	CS4	2012	2	Euro 1	45.6	2.2
	CS5	2014	2	Euro 2	31.8	1.5
	CS6	2015	2	Euro 2	35.2	1.8
Hedge cutter	HC1	2010	2	Euro 1	41.6	2.0
	HC2	2013	2	Euro 2	45.0	2.2
Blower	B1	2011	4	Euro 1	64.8	2.8
	B2	2012	2	Euro 2	36.3	1.4
	B3	2014	2	Euro 2	27.2	0.8

* n.a. – Not applicable

Table 2 Characteristics of conventional and alkylate gasoline used in tests

Fuel characteristic	Conventional gasoline	Alkylate gasoline
Octane number RON	95	>95
Octane number MON	85	>90
Sulphur, ppm	<10	<1
Aromatic content, % vol.	≤35	<0.5
Benzene content, % vol.	≤1	<0.05
Olefins content, % vol.	≤18	<0.1

Concerning gas emissions, only the VOC levels were measured, while the noise and HAV values were respectively obtained in accordance with the ISO 22868:2011 and ISO 22867:2011 Standards.

The tests involved the use of the following instrumentation:

⇒ for gas emission: a gas analyser MultiRAE Plus model PGM 50 (Rae Systems, San Jose, USA)

⇒ for the noise: a noise level meter Cesva mod. SC–30 (CESVA Instruments s.l.u, Barcelona, Spain) equipped with Cesva C–130 ½" condenser microphone, to measure the overall level (in dB(A)), with a sampling rate of 1 s

⇒ for HAV: a four-channel analyser Quest mod. HAVPro (Ashtead Technologies, Letchworth Garden City, UK), equipped with a tri-axial accelerometer of make Dytran, model 3023A2 (Dytran Instruments, Chatsworth, USA), with a sensitivity of approximately 11 mV/g on each axis. According to the UNI EN ISO 5349-1 (2004), the acceleration values on the x, y and z axes were recorded in real time, as well as the RMS value (the square root of the sum of the single squared values) calculated over each single trial duration of 1 min.

From the operating point of view, the tests were carried out by the same operator, outdoors in an experimental field. The hand-operated machines were set in both idle and working conditions. In particular, the working conditions considered the maximum engine speed under load or a typical operating condition of use. In detail, the working conditions were as follows:

⇒ for chain saws: complete cutting of a trunk section of a tree (*Robinia Pseudoacacia* L.), Ø approximately 400 mm

⇒ for hedge cutters: to simulate the load produced by the cutting of vegetation, the length of the cutting nylon string was doubled with respect to the one normally used

⇒ for blowers: the air flow was oriented towards the soil, maintaining the output approximately 0.2 m away from the soil surface.

The duration of each trial for measurement of VOC, noise and HAV, was exactly 1 minute in all operating conditions apart from the cutting with chain saws of the trunk of *Robinia Pseudoacacia* L. In this case, as the single task was completed in a few seconds (depending on the chain saw engine power and the sharpening of the chain), the duration of 1 minute was obtained by consecutive cuttings. Before each test with alkylate and 2% mix gasoline, the engine was warmed for around 5 minutes to burn off all the residues of the fuel previously used.

For executing the VOC emission measurements, the probe sensor was located in proximity to the output of the muffler (Fig. 1A). It was not possible to insert the probe sensor directly inside the muffler because in this condition the pump of the analyser, used to capture a given amount of gas to perform the analysis, caused an immediate overflow of the pressure sensor. However, this arrangement did not influence the test results; in fact, the goal was to compare the gas emission composition and amounts in two different and real working conditions, and not to obtain absolute

values. The gas analyser was set for a sampling rate recording of 1 Hz; as each trial lasted approximately 1 min, the VOC values (expressed as µg/g) are the average of about 60 data.

For the noise measurements, in all the investigated working conditions, the sensor of the noise level meter (the microphone) was placed or held by another operator very close to both ears of the operator using the hand-operated machine (1 minute near to the right ear, 1 minute near to the left ear) (Fig. 1B). According to ISO 22868:2011, the A-weighted sound pressure was measured for each trial, in terms of Equivalent Level, in dB(A).

For HAV, the tri-axial accelerometer was fixed to the machines in accordance with ISO 22867:2011. Specifically, it was rigidly fixed with cable ties to the handgrip(s) of the machines. In particular, for chain saws and edge cutters, the HAV values were measured on both the right (driving) and left (transporting/grasping) handgrips, while for blowers, just the single handgrip (drive/grasping) was taken into account (Fig. 1C).

The recorded data were then stored and elaborated using a commercial spreadsheet (Microsoft Excel 2013). The statistical analysis, aimed at studying the possible influence of alkylate gasoline on VOC emission, noise levels and HAV, has been carried out using XLSTAT software v. 7.5.2 (Addinsoft, Paris, FR).

3. Results and discussion

Hereinafter, the results of VOC emissions, noise and HAV measured during the experimental tests carried out on the selected machines (six chain saws, two hedge cutters and three blowers) are described. Each value (VOC, noise, HAV) is the average, provided by each instrument, of about 60 raw data recorded during a single experimental test.

3.1 Gas emissions

In general, when fuelled with alkylate gasoline, the machines had a remarkable reduction in VOC emissions (Table 3). This behaviour is confirmed by the Mann-Whitney test of two populations – VOC values obtained using conventional gasoline and alkylate gasoline. This non-parametric test was applied because the measured values of VOC did not follow a normal distribution according to the_Shapiro-Wilk test. The result of the Mann-Whitney test rejected the null hypothesis (p=0.010, α>0.05); therefore, the observed differences can be considered significant.

Specifically, in all conditions investigated, when using the alkylate gasoline, the VOC levels were lower than VOC levels recorded using the 2% mix fuel, with a decrease ranging from 23 to over 77%. This is in accordance with the results obtained by other studies conducted on small two-stroke engines (Tsai et al. 2003, Alander et al. 2005, Neri et al. 2016). Moreover, the blower B1 showed the lowest values of VOC; in fact, this is the only model equipped with a four-stroke engine. On the contrary, the most polluting machine is the chain saw CS1, which produced a VOC amount exceeding the gas-analyser's full scale (2000 µg/g) in all conditions.

Fig. 1 A) VOC emission measurement on a blower, placing the sensor probe as close as possible to the gas output; B) operator's ear noise measurement; C) detail of the tri-axial accelerometer fixed on the chain saw driving handgrip

Table 3 Test results for gas emissions

Category	Machine ID	Engine speed	Fuel type		Mean difference %
			2 % Mix	Alkylate fuel	
			VOC, μg/g		
Chain saw	CS1	idle	>2000*	1030	–40*
		max	>2000*	1371	
	CS2	idle	1600	730	–61
		max	1350	450	
	CS3	idle	1831	750	–58
		max	1870	795	
	CS4	idle	470	314	–26
		max	800	650	
	CS5	idle	460	200	–48
		max	485	290	
	CS6	idle	1950	350	–64
		max	1200	650	
Hedge cutter	HC1	idle	1000	540	–33
		max	680	550	
	HC2	idle	1116	185	–77*
		max	>2000*	570	
Blower	B1	idle	120	51	–56
		max	120	55	
	B2	idle	380	250	–23
		max	410	362	
	B3	idle	205	80	–59
		max	200	85	

* Value exceeding the instrument's full scale

Furthermore, the behaviour of the tested machines is not homogeneous: some models fuelled with 2% mix (CS2, HC1 and B3) emitted a higher quantity of VOC at the engine idling speed in respect to the working speed, while the rest showed the opposite results.

Only the chain saw CS2 (the oldest Euro 1 machine) showed VOC levels higher at engine idling compared to the maximum speed, for both fuels. This behaviour is not unusual for this engine type, due to the less efficient removal of the unburned fuel from the cylinder, resulting from the slower piston movement at idle speed than working speed (Wòjcik and Skarżyński 2006). This can cause high emission of VOC especially with 2% mix, which, having a low octane number, tends to burn worse than alkylate fuel. In any case, in most of considered forestry machines, using either 2% mix or alkylate fuel, the values of VOC measured at working conditions are quite similar to those measured at idle speed. It can be concluded that leaving the hand operated forestry machine engine working on idle running is undesirable for the health of operators and, if moving from one workplace to another is necessary, it is recommended to switch off the machine (Wòjcik and Skarżyński 2006).

Concerning the chain saws, the decrease of VOC emissions is mainly due to the use of alkylate gasoline and to the improvement of the engines, passing from Euro 1 to Euro 2. In fact, the most modern machines (CS5 and CS6) produce low VOC levels both when idling and at the max engine speed. On the contrary, when the same machines were fuelled with 2% mix, this trend was not observed. Even in this case, the chain saw CS6 (Euro 2, manufactured in 2015) showed an emission level similar to CS2 (Euro 1), manufactured 10 years earlier.

This confirms the evident improvement, in terms of VOC emissions, when passing from Euro 1 to Euro 2.

The chain saw CS1, produced in 1994 (before the introduction of the emission regulations), dramatically reduced the VOC emissions passing from the traditional mix to the alkylate fuel, from over 2000 to around 1000 μg/g, in all the running conditions. As an old machine, designed to work with a traditional oil-gasoline mixture and not subject to anti-pollution regulation, it can reduce its VOC emissions by using alkylate fuel.

3.2 Noise

In general, the average noise level at the right ear is higher than that measured at the left ear (Table 4), because the tested machines were mainly operated by a right-handed worker. The average difference ranges from approximately 2 (for blowers) to 6 dB(A) (for hedge cutters). Furthermore, the use of alkylate fuel seems to reduce the noise levels in respect of the 2% mix. A statistical analysis was then conducted to ascertain if this difference is significant. The measured values of noise did not follow a normal distribution according to the Shapiro-Wilk test, so the Mann-Whitney test was applied to verify the differences between the two data populations. The result between medians did not reject the null hypothesis (p=0.957, α>0.05). As a consequence, the observed differences cannot be considered significant.

In any case, except for those obtained at idle speed on most machines, all the levels greatly exceeded the limits provided by the national standards (i.e. for Italy Ministero del Lavoro D. L. 81/2008), and, therefore, the use of a hearing protector (i.e. earmuff or earplug) should be provided.

3.3 Hand-arm vibrations

For chain saws and hedge blowers, HAV measured at the right (rear) handle exceeded those of the left (front) handle, according to Rottensteiner and Stampfer (2013). Similarly to noise, also in this case the average levels (right and left hand for chain saws and hedge trimmers, only right hand for blowers) were lower when using machines fuelled with alkylate gasoline (Table 4). The average decrease was of 11.4% (9.8% for the right hand, 13.6% for the left hand), with a maximum of 40% recorded for the B3 blower handgrip at maximum engine speed.

Similarly to the noise, the distribution of the studied variables was not normal according to the Shapiro-Wilk test. Again, the application of the Mann-Whitney test to the HAV dataset showed that the observed differences were not statistically significant (p=0.222, α>0.05). Therefore, the two fuels did not significantly influence the HAV.

Table 4 Test results for noise at the operator's ears and HAV at the front (left hand) and rear (right hand) handgrips, except for blowers, which are operated only with the right hand. Each value is the average of 60 data recorded during each experimental test

Category	Machine ID	Engine speed	Noise, dB(A)				Hand-arm vibrations (HAV), m/s^2			
			Alkylate fuel		2% Mix		Alkylate fuel		2% Mix	
			Right ear	Left ear	Right ear	Left ear	Right hand	Left hand	Right hand	Left hand
Chain saw	CS1	idle	88.7	87.0	86.8	86.5	4.3	2.9	4.9	3.5
		max	107.5	108.3	107.1	107.0	3.9	3.8	5.2	4.0
	CS2	idle	83.6	78.5	82.0	78.4	3.8	2.1	4.1	2.7
		max	106.2	102.7	106.6	101.5	9.6	7.8	10.1	8.6
	CS3	idle	82.6	77.1	83.2	79.9	3.2	2.8	3.3	3.2
		max	107.2	104.7	106.1	103.8	1.5	3.5	1.7	3.9
	CS4	idle	79.5	78.7	80.4	77.0	6.0	3.6	7.6	4.8
		max	109.5	107.3	109.8	105.5	4.7	7.3	4.8	8.6
	CS5	idle	82.9	80.6	85.5	84.0	2.6	2.0	3.3	3.0
		max	104.8	103.3	104.6	103.0	3.7	3.6	4.0	3.7
	CS6	idle	81.8	79.2	80.2	74.9	4.8	3.6	4.9	3.7
		max	103.8	102.7	103.0	98.8	6.1	3.2	6.7	4.1
	Average		85.4*	82.3*	85.4*	81.6*	4.5**	3.9**	5.1**	4.5**
Hedge cutter	HC1	idle	76.6	71.3	78.5	72.9	2.2	1.2	2.3	1.6
		max	99.3	90.7	100.3	90.9	10.0	7.8	10.3	8.2
	HC2	idle	85.1	78.9	85.0	79.0	4.7	3.0	5.2	3.7
		max	98.1	95.0	99.5	96.6	8.0	6.2	8.9	7.2
	Average		82.0*	76.6*	83.6*	77.9*	6.2**	4.6**	6.7**	5.2**
Blower	B1	idle	73.8	73.3	76.5	76.6	1.6	–	1.8	–
		max	97.6	98.1	96.8	97.6	1.3	–	1.6	–
	B2	idle	76.8	72.2	76.6	73.4	2.3	–	2.5	–
		max	98.4	98.0	98.1	97.0	2.1	–	2.3	–
	B3	min	71.8	70.5	72.3	71.3	2.3	–	2.0	–
		max	84.9	83.2	85.0	82.7	1.5	–	2.5	–
	Average		76.6*	74.7*	77.5*	76.1*	1.9**	–	2.1**	–

* Logarithmic average; ** Arithmetic average

If the obtained results are theoretically compared to the 8-hour limits provided by the 44/2002/EC Directive (2.5 m/s² action value, 5.0 m/s² limit value), a different behaviour for the eleven machines could be observed. For many chain saws (in the working condition) and hedge cutters (at max engine speed), the levels often exceed 9–10 m/s². Thus, to respect the limit value of 5 m/s², a reduction in the working time must be considered. On the contrary, the blowers showed HAV levels always below the action values of 2.5 m/s² (mainly due to the absence of rotating working parts), thus also respecting the lowest value provided by the Directive.

4. Conclusions

In the last two decades, the standards finalised to reduce the exhaust gas emissions of on-road and off-road vehicles have dramatically affected the technological progress of internal combustion engines (Punov et al. 2017), including those fitted on forestry and agricultural machinery.

Manufacturers have made a great effort to ensure the compliance of their production with the rigorous requirements provided. Although with a certain delay in respect to medium-high power engines, those fitted on small hand-operated machines used in the agriculture and forestry sectors must also now respect the limits provided by the relevant standards. The present survey confirms that the reduction in the amount of emissions can be remarkably improved not only with the technological progress of the engine design, but above all by adopting advanced fuels that lead to a more efficient combustion process. In fact, the experimental results demonstrated that alkylate fuel is able to reduce VOC pollution more than 77% compared to the use of the traditional 2% mix. On the other hand, the use of alkylate gasoline has no effect on noise and HAV, even though this fuel has a higher octane number.

In any case, a generalised evolution from two-stroke to four-stroke engines could lead to a further, considerable reduction in the pollutant gas emissions (Jüttner et al. 1995, Tsai et al. 2000, Tsai et al. 2003). Along these lines, the performance of hand-operated machines will also be improved, in order also to assure better working conditions for the operators.

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