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RESEARCH ARTICLE

Influence of non-commercial fuel supply systems on small engine SI exhaust emissions in relation to European approval regulations

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Abstract
The development and operation of road infrastructure require machines and equipment driven by low-powered internal combustion engines. In this study, we conducted emission tests on five small spark-ignition engines. We used the most popular commercial design on the market, the Lifan GX 390, with a carburettor power system, and another commercial power unit, the Honda iGX 390, with an innovative power system characterised by an electronically controlled carburettor flap. The remaining three tested constructions were proprietary solutions modernising the design of the Lifan GX 390 engine: one had an electronic injection and ignition system powered by gasoline, whereas the other two had systems powered by alternative fuels. Emission tests were conducted under identical operating conditions on an engine dynamometer complying with European Union guidelines (Regulation 2016/1628/EU). The results of the tests showed that the innovative solutions in most cases reduced CO, CO_2 and hydrocarbon emissions but increased NO_x compounds.

Keywords Small SI engine · Exhaust emissions · Non-road · Fuel injection · LPG · CNG

Introduction

The dynamic development of road infrastructure and vehicular transport has undeniable benefits related to economic development (Liu and Chao 2020; Said and Hammami 2017) and the increased mobility of people (Meekan et al. 2017) and movement of goods (Gnap et al. 2019). However, such development may also have negative impacts (Yu et al. 2013), e.g. increased air pollution (Ehrenberger et al. 2021; Cepeda et al. 2017; Colvile et al. 2001) and reduction of natural green areas (Ren et al. 2019) and residential areas (Lin et al. 2015) at the expense of transport infrastructure sprawl.

There is a perceived link between human health, green spaces and pollution from transport (Nieuwenhuijsen 2018). Research conducted on the impact of air pollution on people's activity satisfaction has shown the need to improve air quality in urban areas (Ma et al. 2020). The problem is well known, and one of the countermeasures is the introduction of increasingly stringent standards for toxic emissions from vehicles and machinery on a global level. Legislators distinguish different groups of machines and vehicles when setting acceptable limits of pollutant emissions from their propulsion engines, e.g. car and light truck (Regulation (EC) 715/2007; Lijewski et al. 2020; Ziółkowski et al. 2019), heavy-duty truck and bus (Regulation 595/2009; Rymaniak 2018; Merkisz et al. 2012a), heavy-duty vehicles (Regulation (EU) 2019/1242; Yasar et al. 2013) and non-road machinery and vehicles (Directive 97/68/EC; Rymaniak et al. 2020; Kamińska et al. 2019). The last group of machines may be used during the construction and operation of road infrastructure, and thus, the emissions they generate can be linked to transport. Of the above-mentioned groups affected by the permissible limits of pollutant emissions in the European Union, non-road machinery and vehicles have been characterised by different directives since 2002 depending on the type of internal combustion engine used, i.e. compression-ignition (CI) engines or spark-ignition (SI) engines.

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The present study considered SI engines with a power output not exceeding 19 kW, which are known as small engines in the legislation (Regulation 2016/1628/EU). These regulations are characterised by relatively liberal emission limit requirements relative to, e.g. motor vehicles (Waluś et al. 2018). This translates into low technical sophistication of the fuel supply systems of these engines (Warguła et al. 2018a), as demonstrated by commercially available engine designs equipped with carburettor power systems (Warguła et al. 2018b), the use of which was abandoned in automotive vehicles as early as the 1990s partly owing to increasingly stringent limits on emissions.

The main problems in the construction of fuel supply systems for SI small engines are the necessity for a low weight and low cost of construction and the limited space available for the engine. One of the many problems of using modern injection systems in small engines is the lack of space for an energy generator (e.g. alternator) necessary to power the controller, sensors and actuators. Researchers around the world are studying development of these drive units towards the use of innovative injection systems, mainly indirect injection into the intake manifold with electronic control (Niinikoski et al. 2016) or direct injection (Darzi et al. 2018; Andwari et al. 2018; Tartakovsky et al. 2015). Another direction of development is to change the fuel or use alternative fuel admixtures (alternative fuel within the meaning of the European Union Directive 2014/94/EU), e.g. ethanol (Ribeiro et al. 2018; Schirmer et al. 2017; Lin et al. 2010), methanol (Ravi et al. 2021; Tartakovsky et al. 2015; Celik et al. 2011; Arapatsakos et al. 2003), LPG (bin Mohd Zain et al. 2019; Sabariah et al. 2018; Sulaiman et al. 2013; Li et al. 2003), CNG (Subramanian 2011; Mikulski et al. 2015) and biogas (Iyer 2020; Homdoung et al. 2015; Surata et al. 2014), as alternatives to energy sources derived from crude oil (EU Directive 2014/94/EU), e.g. gasoline. Other studies have considered design changes of, e.g. the valvetrain (Fontana and Galloni 2009), piston (Iyer 2020) and intake manifold (Wahono et al. 2019). The main aim of developmental, simulation, experimental and real-world research is to reduce air pollutant emissions and fuel consumption.

Fuel supply systems commonly and commercially fitted in non-road small engines use carburettor systems, in which fuel in the liquid phase is sucked into the intake manifold according to Bernoulli's law. At the point of narrowing of the channel through which the air flows across the carburettor (Venturi tube), a pressure difference is created (hydrodynamic paradox). This causes the fuel supplied through the nozzle to be sucked into the intake manifold (Barbosa 2012). Over the years, systems have been developed to improve the precision of fuel dosing, e.g. depending on the engine load. For this purpose, various types of regulation mechanisms are used, e.g. centrifugal or vacuum, which most often change the position of the throttle valve, increasing or reducing the amount of fuel–air mixture supplied to the cylinder (Warguła et al. 2017). Most of the adjustments in carburettor systems are mechanical and require control, as their settings may change as a result of wear or large changes in the surrounding environment, e.g. temperature, atmospheric pressure or air density (Czarska-Klisz et al. 2010; Afonina 2005). These designs are also replaced in many applications because they do not have the ability to automatically adjust the mixture composition based on the results of the exhaust gas composition. In addition, during engine braking processes, injection systems can cut off the fuel supplied to the cylinder, whereas most carburettor designs continue to supply fuel to the engine, increasing fuel consumption and emissions of unburned fuel particles in the exhaust gas. For this reason, in machines and devices where it is possible to use injection fuel systems, carburettor systems are replaced. An injection system for control purposes requires electric power for the electronics, sensors and actuators. Therefore, the engine structures must also be expanded with energy generation systems (Warguła et al. 2016). The simplest system to meet the electricity demands of a fuel injection system comprises an alternator and a battery. On the other hand, the simplest fuel injection system requires a signal form sensors carrying information about the engine load, which could be in form of vacuum in the intake manifold or information about the throttle angle, rotational speed and camshaft position. In addition, such a system requires electricity to power the injectors and fuel pump. Moreover, it is advantageous to measure the temperature of the engine and intake air supplied to the intake manifold. Regarding the control precision, feedback information on the amount of oxygen in the exhaust gas is also important. Recent innovations in small combustion engines (with a power of about 10 kW) have led to the development of carburettor systems with an electronic controllable throttle flap. An example of such an engine is the Honda iGX 390. On the other hand, in motor vehicles, the standard is the implementation of multiphase direct injection into the combustion chamber, which requires a high pressure fuel system, most often with a mechanical pump (Nocivelli et al. 2020; Li et al. 2019). This type of injection is also characteristic of the newest alternative fuel injection systems, such as LPG and CNG (Kim et al. 2017; Choi et al. 2016). However, non-commercial innovations in small energy non-road engines adapted to LPG and CNG fuels have mainly been based on older solutions used in motor vehicles. Such systems are characterized by the supply of fuel to the combustion chamber in the gaseous phase. In basic designs, this is accomplished by gas expansion regulated by a gas pressure reducer. In motor vehicles, where liquid cooling of engines is common, the fuel is additionally heated, improving transition to the gaseous phase of the liquid fuel stored in the tank. However, non-road small engines are most often air-cooled. Hence, non-commercial fuel supply systems are based on gas expansion using gas reducers. LPG fuel is stored in tanks at a pressure of about 1 MPa, whereas CNG is stored at a higher pressure (20 MPa) due to the lower calorific value of the gas (Demirbas 2002). Expanding the gas from such a high pressure usually causes the pressure reducer to freeze up. Therefore, it is advantageous to supply these types of engines from a stationary installation characterized by a lower natural gas pressure of about 0.01 MPa, avoiding the problem of freezing of the reducer. Alternatively, CNG systems may be equipped with an electric heater, but this requires an additional electricity supply system.

The problem of air pollution generated from these types of engines is important as such drives are applied in machinery used in the construction or maintenance of road infrastructure, and very often, the operator is in direct contact with the exhaust gases. Examples of such machinery are shown in Fig. 1 and include equipment used in construction and renovation, such as circular saws, concrete trowels, rammers, soil drills and equipment used for cleaning and clearing snow from pavements. Other groups include road marking machinery for painting road lanes and machinery related to the maintenance of green infrastructure in the lane area, e.g. combustion scythes, chain saws and wood chippers. Demand for the last group is expected to increase as the benefits of roadside trees are increasingly recognised. Roadside trees reduce the spread of road noise and absorb fine particles (Ozdemir 2019), harmful exhaust compounds from the air (Lahoti et al. 2020; Amorim et al. 2013) and de-icing salts from the soil (Ju et al. 2020; Gałuszka et al. 2011). Studies of metal concentrations in tree rings in industrial and roadside areas have demonstrated their pollutant absorption capacity (Kim et al. 2020). According to public opinion, residents of large cities appreciate the ecosystem properties of trees and other vegetation elements of roadside infrastructure. Even wild urban roadside vegetation is highly appreciated, although planted and maintained vegetation is preferred. Since many cities lack public green areas, enhancing cultivated and wild roadside vegetation can help provide ecosystem services in areas where people travel and live nearby (Weber et al. 2014). Another benefit of roadside trees is the protection of pedestrians, vehicles and roads from intense sunlight. Roadside studies in tropical areas have shown that trees with relatively large crowns reduce the mean radiant temperature (Tmrt) by 35% and the physiological equivalent temperature (PET) by 25% (Zaki et al. 2020), helping to improve the microclimate of road infrastructure areas by increasing vehicle cooling, reducing heat build-up and improving pedestrian comfort. Another benefit is reducing the possibility of sun glare when travelling on roads (Redweik et al. 2019). In addition to thermal comfort for pedestrians, walking on urban roads surrounded by trees has the potential to significantly reduce negative psychological states, such as tension, fatigue, disorientation and anxiety, compared to roads without them. Research has indicated that urban roadside trees can help to relieve stress and improve mental health for urban residents (Elsadek et al. 2019). However, disadvantages include dangers associated with road collisions and damage to trees during adverse weather conditions. The average percentages of accidents, injured persons and fatalities related to collisions with a tree among total road accidents in Poland between 2003 and 2015 were 6%, 6% and 14%, respectively (Rosłon-Szeryńska et al. 2019). Thus, measures should be taken to reduce the risk of road

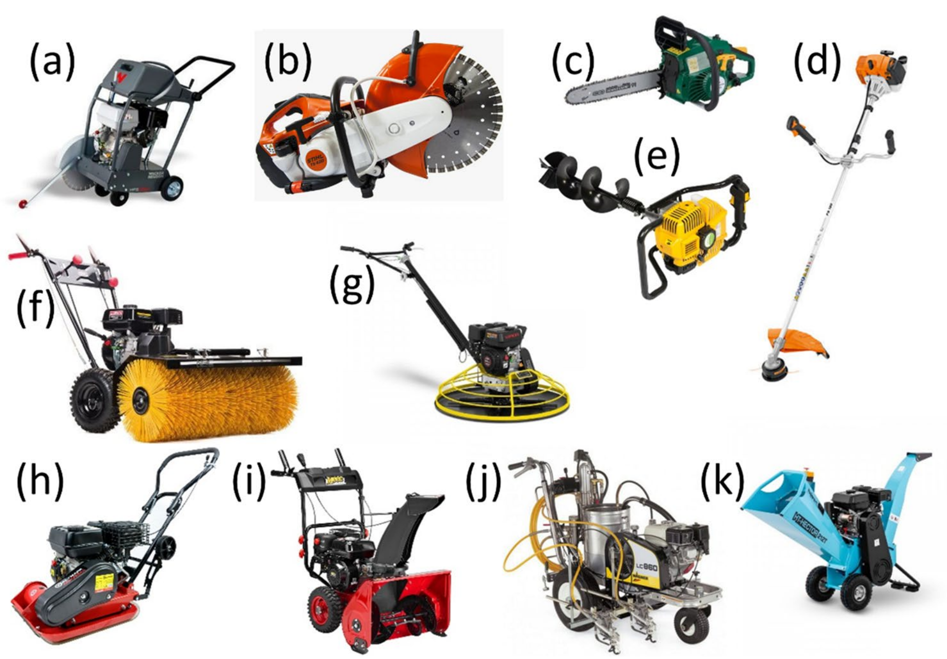

Fig. 1 Examples of machinery with small engines used in the construction and maintenance of road infrastructure: **a** concrete and asphalt cutter, **b** circular saw, **c** chain saw, **d** combustion scythe, **f** pavement and car park rotary broom, **g** concrete trowel, **e** soil drill, **h** soil compactor, **i** snowblower, **j** road marking machine and **k** wood chipper

accidents in wooded areas, as such events are characterised by a relatively high probability of a fatal event. The demand for wood chipping machines in transport-related industries is likely to increase due to not only increased handling of trees in roadside areas but also their cutting in widening road infrastructure (Lahoti et al. 2020).

The main aim of the present study was to evaluate exhaust emissions from small engines (power ~ 10 kW) commercially available in the European Union market, taking into account the level of technical advancement of the fuel supply system (classic carburettor, electronic carburettor). The values of the tested emissions were compared to limits in force in the EU from 2019. Such results can be used as a reference for developing other innovative solutions for this group of engines related to the fuel supply system in order to reduce fuel consumption and exhaust emissions. Such changes are likely to be the next stage implemented in commercial power units, as direct injection solutions require extensive alterations to the engine design, extending the time and cost of commercialization of such solutions. Recent studies of non-commercial fuel supply systems have mainly concerned carburettor fuel supply systems adapted to fuels such as LPG and CNG, which, owing to their simple and cheap design, have a high potential for commercialization in the coming years. The present study investigated how different changes, e.g. innovations in control or variation of the type of fuel, can enable a reduction of pollutant emissions. It was important to compare the results of tests of modifications on the same drive unit under identical, standardized operating conditions. In addition, this paper provides information on emissions related to the construction or operation of transport infrastructure.

Among the methods used to limit air pollution from non-road machinery, regulations setting out limits on permissible exhaust gas emissions restrict the use of technologically older designs and motivate the search for innovative solutions. Several studies have been conducted on small engines used in a wide range of industries, often under real working conditions, e.g. combustion chain saws (Lijewski et al. 2017), energy generators (Lijewski et al. 2017), scooters (Lijewski et al. 2021), wood chippers (Warguła et al. 2020a; 2020b; 2020c) and combustion scythes (Zardini et al. 2019). However, there is a lack of research on this group of drives under identical operating conditions, which is needed to compare them and assess the impact of applying different innovative design solutions. This paper presents test results of small engine emissions under laboratory conditions on an engine chassis dynamometer, the emissions of which were determined to comply with European Union guidelines (Regulation 2016/1628/EU). Tests were carried out on a popular, commercially available propulsion unit with a Lifan GX 390 carburettor supply system and the most innovative commercial propulsion unit on the market, Honda iGX 390, with an electronically controlled carburettor. Three versions of the Lifan GX 390 engine modernised by the authors were tested. The modernisations involved changing the fuel supply system from a carburettor to an electronic ignition and injection system or changing the fuel used to alternative gaseous fuels LPG and CNG using a design based on a carburettor adapted to gaseous fuels.

Materials and methods

Five different designs of propulsion units commonly used to drive non-road machinery were examined: two commercial and three innovative designs developed by our group. The first propulsion unit tested was a Lifan GX390 SI engine (license: American Honda Motor Company, Inc., Torrance, CA, USA), a design with the most popular and cheapest fuel supply system. It was based on a classic carburettor system. The characteristics of the power unit are presented in Table 1. The second power unit tested was a Honda iGX 390 SI internal combustion engine (Honda Motor Co., Ltd., Kumamoto Factory, Kumamoto, Japan) equipped with the most innovative fuel supply system available for this group of engines. The fuel supply system of this engine was characterised by an electronically controlled carburettor flap. The characteristics of this propulsion unit are also presented in Table 1. The remaining three propulsion units were modernisations of the Lifan GX 390 engine with innovative fuel supply systems developed by our group at the Poznań University of Technology, Poznań, Poland. The third engine tested was a Lifan GX 390 with a fuel supply system adapted to LPG based on a carburettor adapted to gaseous fuel (engine characteristics are presented in Table 2) (Warguła et al. 2020b; 2020d). The fourth engine tested was a Lifan GX 390 with a fuel supply system adapted for CNG based on a carburettor adapted for gaseous fuels (Table 2) (Warguła et al. 2020a). The fifth and final engine was a Lifan GX 390 engine (also called German GX 390 engine depending on the engine distributor in the European market) equipped with an innovative fuel supply system based on an electronically controlled integrated injection and ignition system operating in feedback through the use of a wideband oxygen sensor in the exhaust gases (Table 2) (Warguła et al. 2020c; 2020e; Warguła 2019). Photos of the commercial engines and fuel supply system diagrams of all the tested systems are shown in Fig. 2.

The test methodology for assessment of exhaust gas emissions was in accordance with European Union guidelines (Regulation 2016/1628/EU) for testing non-road mobile machinery equipped with low-power internal combustion engines. The stage V engines tested belong to the NRS-v/vr-1b subcategory (Table 3) and are affected by the G2 test cycle (Table 4), whose weighting factors of the ISO 8178

Table 1 Characteristics of small, commercial, non-road Lifan GX390 and Honda iGX390 engines

Low-power internal combustion engines		
Parameters	Characteristics	
	Lifan GX390	Honda iGX390
Displacement	389 cm^3	389 cm^3
Maximum power at 3600 rpm	9.56 kW/13 HP	8.72 kW/11.7 HP
Maximum torque at 2500 rpm	26.5 Nm	26.5 Nm
Diameter/stroke	88 mm/64 mm	88 mm/64 mm
Engine type	Four-stroke, OHV (overhead valve)	Four-stroke, OHV (overhead valve)
Number of cylinders	1	1
Ignition system	Electronic, without ignition timing adjustment	Electronic, without ignition timing adjustment
Weight	31 kg	37 kg

type B test cycle are shown in Table 5 and emission limits in Table 6.

Tests were carried out on an engine chassis dynamometer adapted for use with low-power internal combustion engines (Fig. 3). During the tests, the rotational speed and torque were recorded, on the basis of which the power output was determined. Simultaneously, emissions of different exhaust gases, i.e. hydrocarbons (HCs), carbon monoxide (CO), carbon dioxide (CO_2) and nitrogen oxides NO_x, were measured. For each engine, the test was performed with ten repetitions, and the test results were subjected to statistical analysis. An Axion RS + portable emission measurement system (PEMS) from Global MRV was used for the exhaust emission tests (Table 7 shows its technical specifications). The emission tests analysed levels of hydrocarbons (HCs), carbon monoxide (CO), carbon dioxide (CO_2) and nitrogen oxides (NO_x). Measured concentrations were expressed in vol.% or ppmv. As a result, more measurable emissions were determined. Emissions were calculated from the measured concentrations of the tested compounds and the mass of air delivered to the combustion chamber by measuring the pressure in the intake manifold.

Table 8 presents the characteristics of the fuels used to power the engines during the tests. The composition of gaseous fuels (especially natural gas) varies in different geographical areas. We used gas available on the Central European market for the tests (Kuczyński et al. 2019).

The main test results provided average values from 10 trials ($N = 10$), for which confidence intervals were determined at a confidence level of 95% ($p = 0.05$). Significant statistical differences were analysed using Student's t-test.

Results and discussion

The recorded test results spanned a larger range of operating conditions than required by the European type approval regulations. Results (torque, speed, power, CO, CO_2, HC, NO_x emissions and fuel consumption) obtained during the research test are shown in Fig. 4 (grey indicated the range of operating conditions used for analysis according to ISO 8178 type B). The analysis was conducted under stable speed and torque conditions.

Average values of pollutant emissions at the operating points determined according to ISO 8178 type B with consideration of weighting factors (Table 5) are presented in Table 9. The average values of non-road steady cycle (NRSC) test emissions T_{NRSC} were determined according to Eq. (1):

$$T_{NRSC} = W_1 \cdot E_1 + W_2 \cdot E_2 + W_3 \cdot E_3 + W_4 \cdot E_4 + W_5 \cdot E_5 + W_6 \cdot E_6 \quad (1)$$

where W denotes the contribution of the selected operating conditions to the total test analysis, E denotes the pollutant emissions under the selected conditions and the numerical subscripts denote the mode number according to Table 5.

Exhaust gas emissions from small SI engines analysed in the European Union during type approval tests concern CO and HC + NO_x. All the power units tested did not exceed the permissible emission limits (CO in Fig. 5a and HC + NO_x in Fig. 5b). We calculated the percentage comparison of emissions during the engine dynamometer tests and the permissible emission limits according to Eq. (2):

Table 2 Characteristics of upgraded Lifan GX390 engines with LPG, CNG and gasoline fuel injection systems

Upgraded Lifan GX390 low-powered internal combustion engines			
Parameters	Characteristics		
	LPG	**CNG**	Fuel injection system
Maximum power	5.8 kW/6.8 HP at 2800 rpm	5.5 kW/6.8 HP at 2700 rpm	8.6 kW/11.5 HP at 3480 rpm
Maximum torque	22 Nm at 2100 rpm	23 Nm at 2100 rpm	30 Nm at 1500 rpm

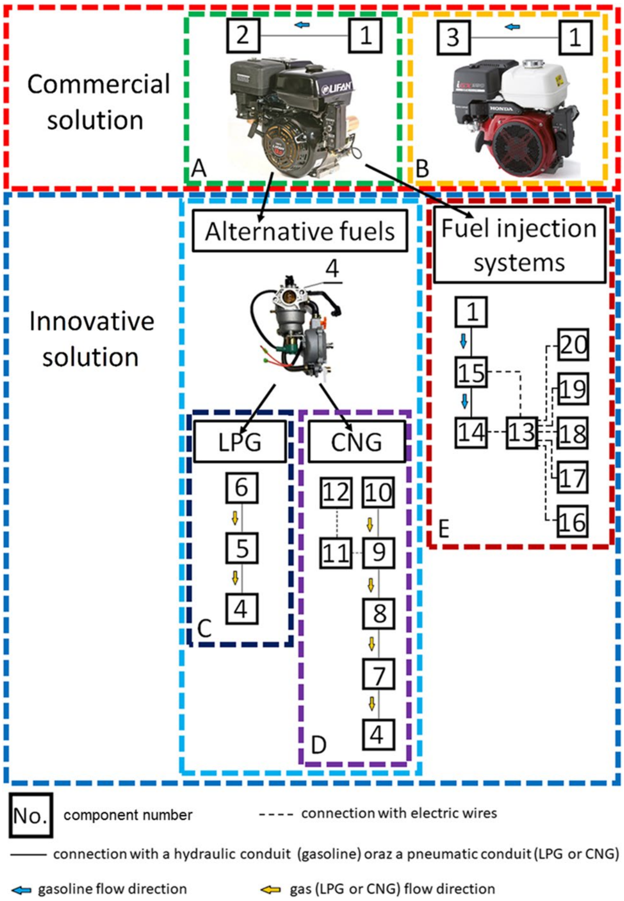

Fig. 2 Tested drive units. Commercial engines: **A**, German GX 390; **B**, Honda iGX 390; innovative designs: **C**, LPG fuelled engine; **D**, CNG fuelled engine; **E**, engine with electronic fuel injection. Numbers in the diagram represent the basic components of the fuel supply system: 1, fuel tank; 2, gasoline carburettor; 3, gasoline carburettor with electronically controlled flap; 4, carburettor for gaseous fuels (LPG and CNG); 5, regulator (1.5 to 0.01 MPa); 6, low pressure tank (1 MPa); 7, second-stage regulator (0.6 to 0.01 MPa); 8, first-stage regulator (20 to 0. 6 MPa); 9, gas heater; 10, high-pressure tank (20 MPa); 11, 12 V battery; 12, DC converter (12 to 230 V AC); 13, electronic control unit; 14, injector; 15, electric fuel pump 16, wide-band sensor of oxygen content in exhaust gases; 17, intake air temperature sensor; 18, engine temperature sensor; 19, engine rotational speed and crankshaft angular position sensor; 20, throttle position sensor

$$\frac{EU}{T} = \frac{X_{EU} - X_T}{X_{EU}} \bullet 100\%, \tag{2}$$

where EU is the emission limit described in European Union regulations, T is the emission test result of the tested designs (commercial engines: A, German GX 390, B, Honda iGX 390; innovative designs: C, LPG-fuelled engine, D, CNG-fuelled engine, E, engine with electronic fuel injection), and X is the value from approval regulations or research tests according to the subscript (Fig. 5c).

Table 3 Category of NRS internal combustion engines as defined in Regulation (EU) on Requirements for Emission Limit Values of Gaseous and Particulate Pollutants and Type-Approval with Respect to Internal Combustion Engines for Mobile Machines Non-road, Amending Regulations (EU) No. 1024/2012 and (EU) No. 167/2013 and Amending and Repealing Directive 97/68/WE. No. 2016/1628 of the European Parliament and of the Council of 14 September 2016. Off. J. Eur. Union. 2016, 252, 53–117

Category	NRS
Ignition type	SI
Speed characteristics	Variable ≥ 3600 rpm or constant
Power range (kW)	$0 < P < 19$
Displacement (cm^3)	SV ≥ 225
Subcategory	NRS-vr-1b
Reference power	Maximum net power
Date of the regulation	1 February 2018

The commercial design solutions (for the Lifan GX 390 and Honda iGX 390 engines) were characterised by lower CO emissions than the permissible standards by 33% and 8%, respectively, whereas HC + NO_x emissions were lower by 43% and 51%, respectively. It should be noted that the most innovative commercial design (Honda iGX 390) was characterised by higher CO emissions close to the permissible limit, whereas the design reduced HC + NO_x emissions by almost half of the permissible standard. When setting emission limits, legislators consult with scientists and manufacturers on the feasibility of meeting the requirements. The set limits are met by classically used designs with a carburettor supply system and innovative ones with an electronically controlled carburettor throttle flap. The values of harmful exhaust compounds emitted during gasoline combustion were consistent with other tests results for this group of engines carried out under real conditions, i.e. 408 ± 2.3–561 ± 3.1 g/kW for CO and 3.90 ± 0.2–4.53 ± 0.2 g/kW for HC + NO_x versus results available in the literature from tests of wood shredding machines of 346 g/kW and 4 g/kW, respectively (Warguła et al. 2020a). CO emissions for a similar engine have also been measured in laboratory tests at 381 g/kW (Bin et al. 2003) and for 2-stroke engines at 603 g/kW (Volckens et al. 2007). In addition, tests on an engine with similar design and power and fuelled by gasoline showed that depending on the composition of the air–fuel mixture, emission values were in the range CO 250–550 g/kW, HC 4–10 g/kW and NO_x 1–4 g/kW (Murillo et al. 2005).

The innovative solutions developed in the present study were aimed at limiting the emission of pollutants by using electronic fuel injection (gasoline) or changing the fuel coupled with use of a carburettor adapted to gaseous fuels. The results showed that the use of LPG and CNG fuels may

Table 4 NRSC test cycle for NRS category engines

Category	NRS
Speed characteristics	Variable ≥ 3600 rpm or constant
Purpose	Variable speed engine with reference power not exceeding 19 kW designed to operate at ≥ 3600 rpm; constant speed engine with reference power not exceeding 19 kW
Subcategory	NRS-vr-1b
NRSC	G2

Table 5 Weighting factors of ISO 8178 type B test cycles

Mode number	1	2	3	4	5	6	7	8	9	10	11
Torque %	100	75	50	25	10	100	75	50	25	10	0
Speed	Rated speed					Intermediate speed					Low idle
G2	0.09	0.20	0.29	0.30	0.07	-	-	-	-	-	0.05

Engine torque is expressed as a percentage of the maximum available torque at a given engine speed. Rated speed is the speed at which the manufacturer specifies the rated engine power. Intermediate speed is the speed corresponding to the peak engine torque.

Table 6 Emission limits for stage V for engines of NRS category

Emission stage	Engine subcategory	Power range [kW]	Ignition type	CO [g/kWh]	$HC + NO_x$ [g/kWh]
Stage V	NRS-vr-1b	$0 < P < 19$	SI	610	8

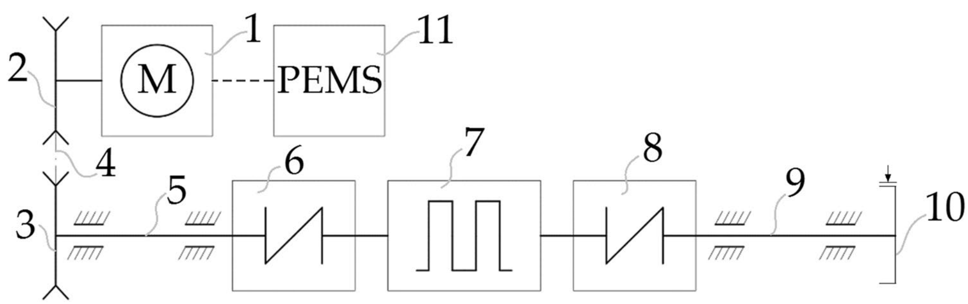

Fig. 3 Diagram of an engine chassis dynamometer for low-power engines, where the numbers denote the different components: 1, internal combustion engine; 2, driving pulley; 3, driven pulley; 4, belt transmission (ratio 1:1); 5 and 9, layshaft; 6 and 8, clutch with elastic insert; 7, torque meter with speed measurement; 10, brake with control of braking torque value; 11, PEMS

Table 7 Characteristics of Axion RS+, a portable exhaust emissions analyser (Lijewski et al. 2019)

Gas	Measurement range	Sensitivity	Characteristic
HC propane	0–4000 ppm	±3%	1 ppm
CO	0–10%	±3%	0.01 vol.%
CO_2	0–16%	±3%	0.01 vol.%
NO_x	0–4000 ppm	±4%	1 ppm
O_2	0–25%	±3%	0.01 vol.%

reduce CO emission by 94% and 97%, respectively, with respect to the limits allowed in the European Union. On the other hand, the reduction of $HC + NO_x$ was 10% and 60% for LPG and CNG, respectively. Thus, the engine fuelled by LPG significantly reduced CO emissions but had the highest $HC + NO_x$ emissions among the tested engines. In contrast, the engine fuelled by CNG was characterised by the lowest emission of pollutants during the EU type approval tests among the tested engines. The use of an electronic fuel supply system with gasoline reduced CO emissions by 67% and $HC + NO_x$ by 50%. This result was better than those of the commercial units but was inferior to that of the CNG-fuelled engine. The values of harmful exhaust compounds emitted during CNG and LPG combustion were consistent with previous test results for this group of engines. The results of the emission tests during the combustion of CNG were 19 ± 0.3 g/kW for CO and 3.20 ± 0.2 g/kW for $HC + NO_x$. These values are comparable to those reported in the literature for wood shredding machines of 31 g/kW and 1 g/kW, respectively (Warguła et al. 2020a). Tests on CNG-fuelled engines have shown CO emissions of 30 g/kW and

Table 8 Properties of tested fuels. MON, motor octane number; RON, research octane number (Dorosz 2018; Merkisz et al. 2016; Wołowsz 2003; Warowny and Tkacz 2001)

Properties	Gasoline	Liquefied petroleum gas	Compressed natural gas
Density under reference conditions (liquid phase) (kg/m^3)	720–775	520	450
Density under reference conditions (gas phase) (kg/m^3)	0.74	2.36	0.72
Fuel calorific value (MJ/kg)	42.6	46	48
Boiling temperature (°C)	40–210	− 30	− 161
Excess air coefficient λ up to the ignitability boundaries	0.4–1.4	0.4–1.7	0.7–2.1
Octane number MON (RON)	85 (95)	95 (100)	105(110)
Air fuel ratio (AFR) for stoichiometric mixture (mass)	14.7:1	15.5:1	17.2:1
Composition of LPG and CNG fuels at Polish filling stations (% by volume)	-	C_3H_8 50%	CH_4 96.6%
			N_2 2.1%
		C_4H_{10} 50%	O_2 0.1%
			CO_2 0.1%
			C_2H_6 1.1%

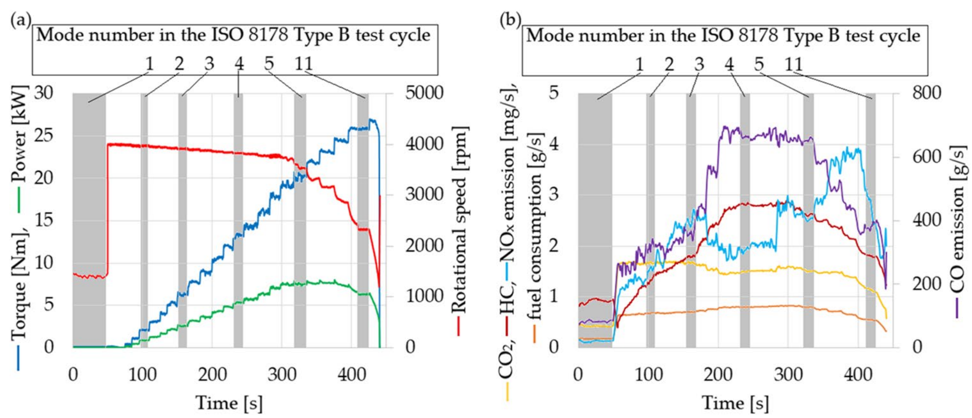

Fig. 4 Characteristics of the Lifan GX 390 internal combustion engine with carburettor power system during testing as a function of time: **a** power, torque and speed and **b** CO, HC, NO_x and CO_2 exhaust emissions and fuel consumption

6 g/kW (Johnson 2014) and a range of values of 26–34 g/kW (Srivastava and Agarwal 2014). On the other hand, the emission values of different exhaust gases during LPG combustion were CO 35 ± 0.4 g/kW, CO_2 9544 ± 56.6 g/kW, NO_x 6.08 ± 0.3 g/kW, HC 1.14 ± 0.1 g/kW and HC + NO_x 7.23 ± 0.4 g/kW. For comparison, previous tests of an engine of similar design and power fuelled by LPG fuel showed that, depending on the composition of the fuel–air mixture, emission values were CO 1–300 g/kW, HC 3–7 g/kW and NO_x 1–20 g/kW (Murillo et al. 2005). Emission results of a LPG-powered energy generator under a heavy load have been reported as CO 18 g/kW, CO_2 701 g/kW and NO_x 9 g/kW (Romero-Piedrahita and Mejía-Calderón 2022).

We next extended the analysis of exhaust emissions beyond the components included in the approval tests used in the European Union. CO_2 emissions were measured, as well as HC and NO_x emissions independently. Controlling CO_2 emissions is important as it contributes to the greenhouse effect, but it is better recycled by the environment than other pollutants. All the components tested are plotted in Fig. 6 and 7 (CO and CO_2 in Fig. 6 and HC and NO_x in Fig. 7). The results of these tests allowed assessment of the impact of the retrofits carried out. For this purpose, the results for the commercial units (A, German GX 390, and B, Honda iGX 390) were summed and the arithmetic mean calculated, making it possible to relate the results of retrofitting (innovative design: C, LPG-fuelled engine; D, CNG-fuelled engine; E, electronic fuel injection engine) to those of the commercial solutions, denoted further by the *K* index. Comparison of CO, CO_2, HC and NO_x emissions of the innovative designs with those of the commercial designs revealed that the CNG-fuelled engine gave the best results. Its emissions were lower than those of the commercial designs by 96%, 72% and 50% for CO, CO_2 and HC, respectively, and showed the lowest increase in NO_x emissions by 9%. These results are consistent with other studies showing that switching fuel from gasoline to CN helps to reduce emissions of CO (Usman and Hayat 2019; Yaser et al. 2013; Geok et al. 2009; Shamekhi et al. 2006), CO_2 (Usman and Hayat 2019; Jahirul et al. 2010; Geok et al. 2009; Shamekhi et al. 2006) and HC (Quintili and Castellani 2020; Usman and Hayat 2019; Bielaczyc et al. 2016; Yaser et al. 2013; Merkisz et al.

Table 9 Values of air pollutant emissions from small engines of different designs and under different operating conditions

Mode number	NRSC test				Other measured values					
	Average emissions at selected operating conditions in g/kWh and confidence interval ($p=0.05$)									
	CO	$p=0.05$	$HC+NO_x$	$p=0.05$	CO_2	$p=0.05$	HC	$p=0.05$	NO_x	$p=0.05$
Lifan GX390 engine — commercial design										
1	218	1.1	2.57	0.1	628	3.2	1.03	0.1	1.54	0.1
2	313	1.4	2.43	0.1	739	3.3	1.22	0.1	1.21	0.1
3	231	1.2	3.23	0.2	1018	5.5	1.90	0.1	1.33	0.1
4	503	2.5	6.15	0.3	2305	11.7	2.55	0.1	3.60	0.2
5	1324	6.1	12.04	0.6	12,857	59.0	5.37	0.2	6.69	0.3
11	290	1.4	3.78	0.2	1440	7.1	3.31	0.1	0.46	0.1
T_{NRSC}	408	2.3	4.53	0.2	2163	15.0	2.19	0.1	2.34	0.2
Honda iGX390 engine — commercial design										
1	237	1.2	1.87	0.1	468	2.4	1.15	0.1	0.73	0.1
2	371	1.7	1.99	0.1	537	2.4	1.28	0.1	0.71	0.1
3	376	2.0	3.34	0.2	842	4.5	1.80	0.1	1.54	0.1
4	681	3.4	4.73	0.2	1276	6.5	3.26	0.2	1.48	0.1
5	1967	9.0	10.76	0.5	3558	16.3	8.12	0.4	2.64	0.1
11	289	1.4	3.67	0.2	1330	6.5	3.23	0.1	0.56	0.1
T_{NRSC}	561	3.1	3.90	0.2	1098	6.4	2.60	0.2	1.30	0.1
Lifan GX390 engine — fuelled by LPG										
1	2.93	0.1	9.32	0.5	753	3.9	2.51	0.1	3.39	0.2
2	2.73	0.1	11.21	0.5	868	3.9	1.19	0.1	3.28	0.1
3	5.05	0.3	7.61	0.4	1096	5.9	0.81	0.1	6.80	0.4
4	18.4	0.9	4.47	0.2	18,383	92.9	0.57	0.1	10.64	0.5
5	186	0.9	5.89	0.3	48,539	222.6	1.09	0.1	8.23	0.4
11	276	1.4	3.78	0.2	1440	7.8	3.23	0.1	0.56	0.1
T_{NRSC}	35	0.4	7.23	0.4	9544	56.4	1.14	0.1	6.08	0.3
Lifan GX390 engine — fuelled by CNG										
1	0.68	0.1	2.09	0.1	109	0.6	0.32	0.1	1.78	0.1
2	2.2	0.1	3.60	0.1	366.8	1.6	0.88	0.1	2.74	0.1
3	3.6	0.2	4.17	0.2	540	2.9	1.02	0.1	3.15	0.2
4	4.8	0.2	1.44	0.1	320	1.6	0.56	0.1	0.88	0.1
5	26.4	0.2	6.42	0.3	793	3.6	5.2	0.2	1.23	0.1
11	270	1.3	3.62	0.2	1300	6.4	2.9	0.1	0.45	0.1
T_{NRSC}	19	0.3	3.20	0.2	463	2.8	1.20	0.1	1.99	0.1
Lifan GX390 engine with fuel injection system										
1	124	0.6	2.21	0.1	331	1.7	1.06	0.1	1.15	0.1
2	99	0.4	1.55	0.1	227	1.0	0.73	0.1	0.82	0.1

Table 9 (continued)

Mode number	NRSC test									
	Average emissions at selected operating conditions in g/kWh and confidence interval ($p=0.05$)				Other measured values					
	CO	$p=0.05$	HC + NO_x	$p=0.05$	CO_2	$p=0.05$	HC	$p=0.05$	NO_x	$p=0.05$
3	19	0.1	5.90	0.3	378	2.0	0.98	0.1	4.92	0.3
4	281	1.4	3.34	0.2	472	2.4	2.58	0.1	0.753	0.1
5	921	4.2	8.03	0.4	1037	4.8	7.20	0.3	0.835	0.1
11	190	0.9	3.50	0.2	1440	7.1	3.30	0.1	0.468	0.1
T_{NRSC}	199	1.3	3.97	0.2	471	3.2	1.97	0.2	2.00	0.1

2012b; Zhang et al. 2011; Jahirul et al. 2010; Shamekhi et al. 2006) but increases NO_x emissions (Singh et al. 2016; Huang et al. 2016; Mohamed 2006). CNG is composed of lighter hydrocarbons and has a much higher hydrogen-to-carbon ratio than in gasoline. This affects the combustion process in the cylinder, reducing the proportion of incomplete combustion and lowering CO and HC emissions. However, it also increases NO_x emissions, which may be due to an increase in combustion temperature. On the other hand, the reduction in CO_2 is mainly associated with a reduction in fuel consumption. A reduction of NO_x emissions after fuel switching is characteristic of diesel engines (Merkisz et al. 2015). In the present study, the use of LPG fuel contributed to a 93% reduction in CO and 53% reduction in HC emissions but a 485% increase in CO_2 and 234% increase in NO_x emissions. HC emissions from the LPG-fuelled engine were the lowest, in agreement with previous results for gasoline-LPG blends showing that 100% LPG had the lowest HC emissions (Simsek et al. 2021a). The latter study also considered a mixture of gasoline and biogas with a composition similar to that of LPG and CNG and showed that 100% biogas had lower HC emissions than mixtures with gasoline (Simsek et al. 2021b). A reduction of CO (Çinar et al. 2016; Myung et al. 2014; Gümüş 2009) and HC (Duc and Duy 2018; Çinar et al. 2016; Myung et al. 2014; Gümüş 2009) emissions and an increase of CO_2 (Myung et al. 2014) and NO_x (Çinar et al. 2016; Duc and Duy 2018) emissions has been observed previously after switching fuel from petrol to LPG. The combustion of LPG fuel is characterised by a more homogeneous fuel input mixture than gasoline, resulting in better combustion and lower HC and CO emissions but higher NO_x emissions. On the other hand, LPG has a lower carbon content and is characterised by higher fuel consumption, which has a strong effect on CO_2 emissions. Merkisz and Radzimirski (2006) showed that emissions were significantly affected by the level of technical sophistication of the LPG and gasoline fuel supply systems, while Dziewiatkowski et al. (2020) demonstrated that emissions were also affected by wear of the fuel supply system components. In the present study, the use of an electronically controlled gasoline injection system reduced CO emissions by 59%, CO_2 emissions by 71%, HC emissions by 18% and increased NO_x emissions by 10% relative to commercial solutions based on carburettor fuel systems. These findings are similar to those of other studies showing a reduction of CO and HC emissions and a slight increase in NO_x emissions when using electronic fuel injection compared to a carburettor system (Yao et al. 2017). Electronic fuel injection with mixture control promotes better matching of the fuel–air mixture composition to the operating conditions and ensures operation close to stoichiometric mixtures, unlike carburettor systems that operate on enriched mixtures (Warguła et al. 2020b). With lower HC and CO emissions, this promotes higher NO_x emissions, and

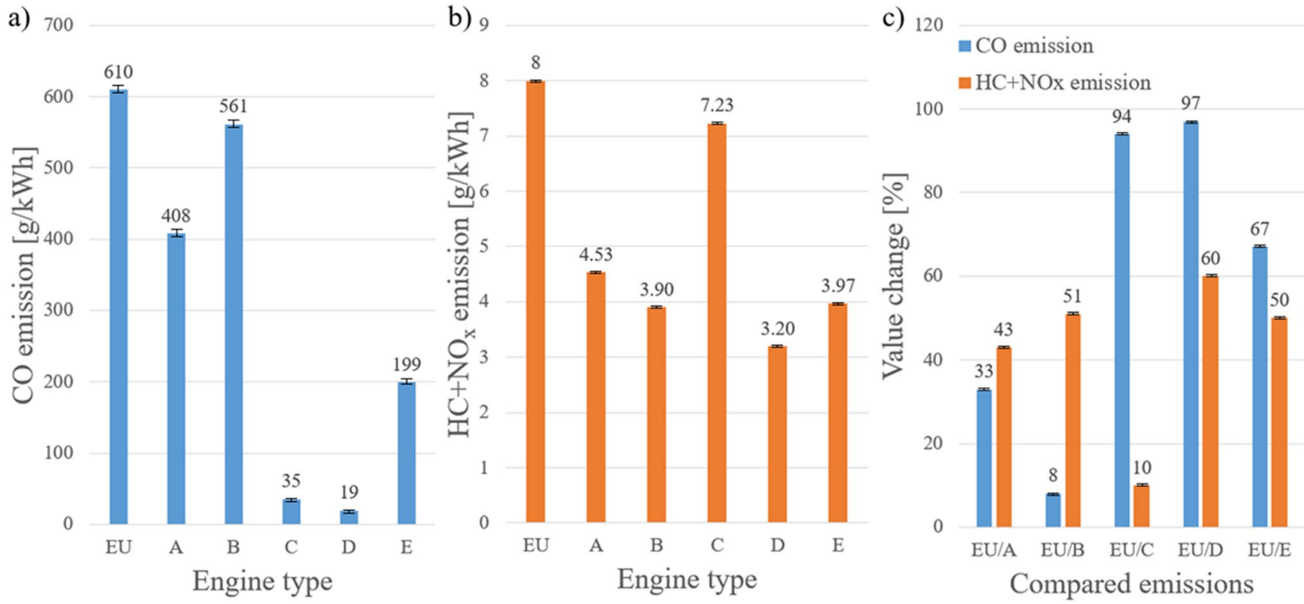

Fig. 5 Emissions of **a** CO and **b** HC + NO_x from small engines and **c** comparison to emission limits in the European Union (EU). Commercial engines: A, German GX 390; B, Honda iGX 390; innovative designs: C, engine fuelled by LPG; D, engine fuelled by CNG; E, engine with electronic fuelinjection

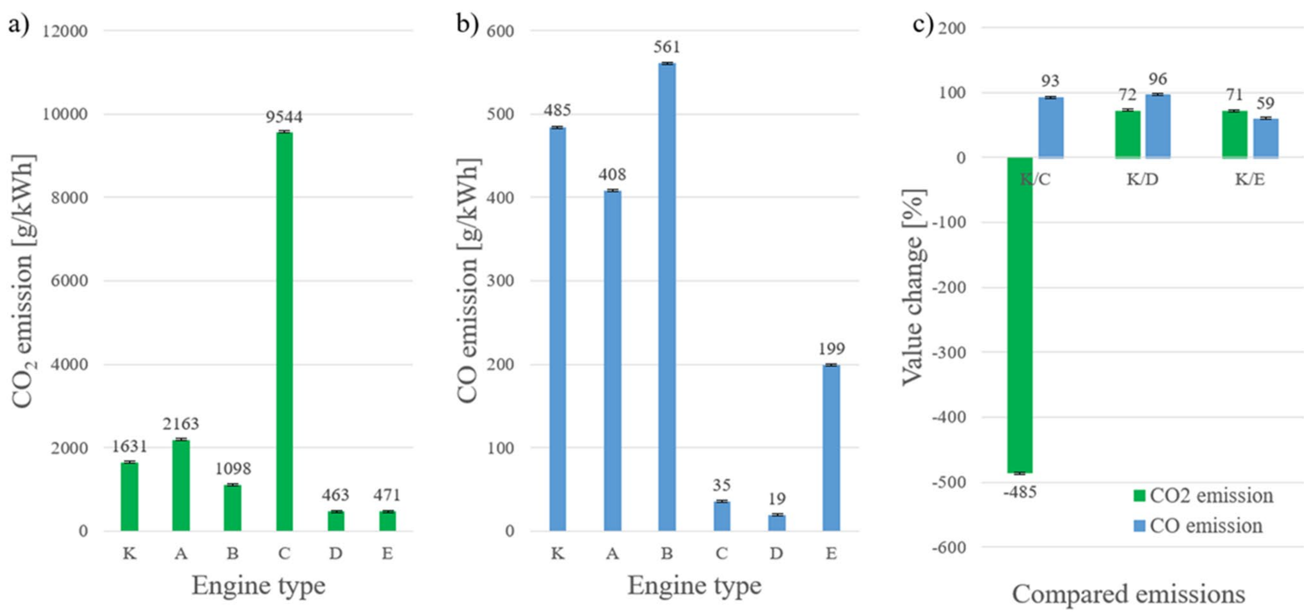

Fig. 6 **a** CO_2 and **b** CO emissions from small engines and **c** comparison of average emissions from commercial engines (*K*) to those of the innovative designs. Commercial engines: A, German GX 390; B, Honda iGX 390; innovative designs: C, engine fuelled by LPG; D, engine fuelled by CNG; E, engine with electronic fuel injection

reduced fuel consumption through better fuel–air mixture selection reduces fuel consumption and thus CO_2 emissions.

Our results show the opportunities for development of these types of small engines and the possibility of using gaseous fuels. In particular, CNG gave the best effects in terms of reducing pollutant emissions. We expect that access to and the popularity of gaseous fuels will increase as biogas plants (Wąs et al. 2020), different types of biodegradable materials (Czarnecka-Komorowska and Wiszumirska 2020; Knitter et al. 2019; Czarnecka-Komorowska et al.

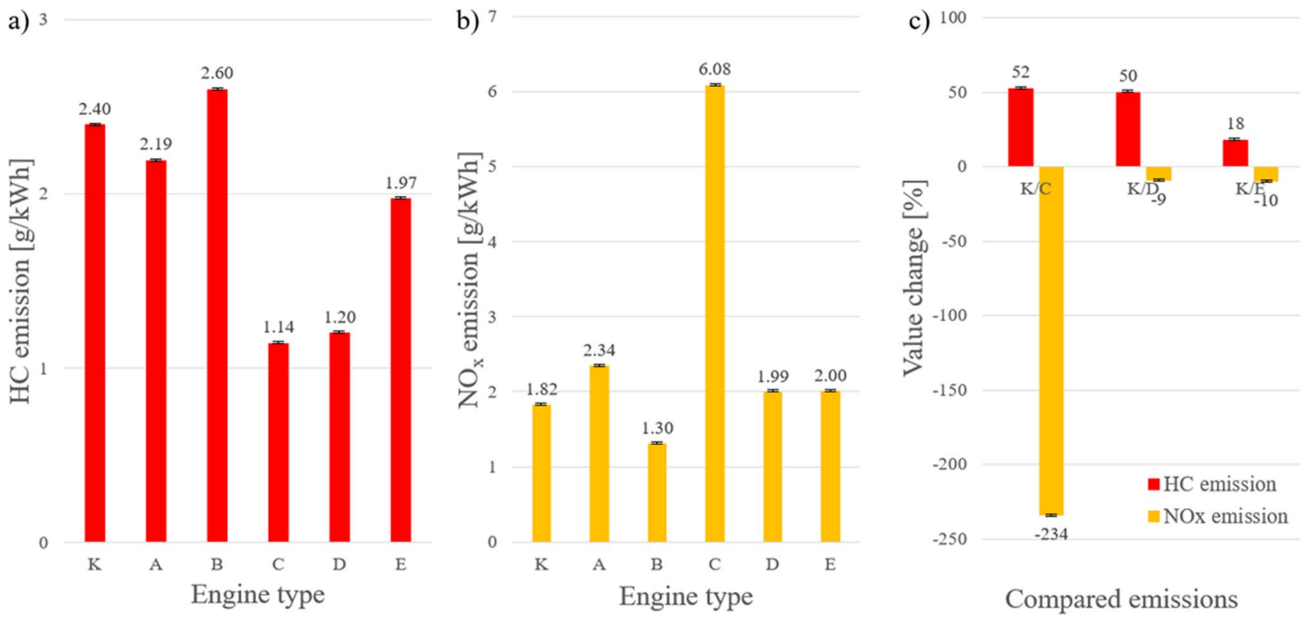

Fig. 7 **a** HC and **b** NO_x emissions from small engines and **c** comparison of average emissions from commercial engines (*K*) to those of the innovative designs. Commercial engines: A, German GX 390; B, Honda iGX 390; innovative designs: C, engine fuelled by LPG; D, engine fuelled by CNG; E, engine with electronic fuel injection

2018) and backyard natural gas fuelling stations (Kuczyński et al. 2019) become more common. In parallel, gas-fuelled designs could be developed with electronically controlled gaseous fuel injection systems. Such designs should be investigated to assess the impact of using exhaust aftertreatment systems (Merkisz and Siedlecki 2017), adaptive control systems (Irimescu et al. 2014) and fuel additives (Le Anh et al. 2014).

Conclusion

The results of this study showed that small SI engines intended for non-road machines, e.g. in machines for the construction and maintenance of road infrastructure, irrespective of the level of innovation of the fuel supply system, did not exceed the permissible pollutant emission limits provided in NRSC type-approval tests applied in the European Union. However, these limits are relatively high compared to those of other groups of engines. The non-commercial solutions, developed and examined by the authors, may contribute to future legislative efforts to limit emissions (CO, CO_2, HC and NO_x) from this type of engine. The use of a gasoline-fuelled design with an innovative injection system reduced CO, CO_2 and HC emissions, as did an engine with a carburettor supply system adapted to CNG gas fuel. The CNG-fuelled engine had the highest pollutant emissions, except for NO_x emissions. NO_x emissions were lowest for the commercial engines (with a carburettor fuel supply system and mechanical or electrical throttle flap control) fuelled with gasoline. The LPG-fuelled engine with a carburettor system was characterised by a reduction in CO and HC emissions by an increase in CO_2 and NO_x emissions. Our research shows that a reduction of pollutants can be achieved by introducing innovations in fuel supply systems and by changing the type of fuel used. However, the best results are expected when the two measures are combined. Small SI engine fuel supply systems for non-road machine designs could be adapted to include similar solutions to those utilised in other engine groups that meet more stringent emission requirements. Thus, in these small SI engines, efforts should be made to develop systems that enable the use of alternative fuels with a lower environmental impact and electronic systems for controlling the operation of the internal combustion engine. Developments in the design of electricity generating systems and high pressure fuel injection systems are also needed to produce a low weight and compact design. However, commercialization of such solutions will require significant reconstruction of production lines and higher product costs. Thus, the implementation of such solutions on the market will require legal regulations limiting the use of technologically old designs characterized by higher emissions of air pollutants.

Author contribution Validation, Ł.W.; resources, Ł.W., P.L. and M.K.; methodology, Ł.W., P.L.; writing—original draft preparation, Ł.W., M.K. and P.L.; conceptualization, Ł.W.; data curation, Ł.W.; software,

Ł.W.; investigation, Ł.W. and P.L.; formal analysis, Ł.W.; visualization, Ł.W.; writing—review and editing, M.K., Ł.W.; supervision, Ł.W.; project administration, Ł.W.; funding acquisition, Ł.W. All authors have read and agreed to the published version of the manuscript.

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Declarations

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Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests Not applicable.

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