

Article

Influence of the Use of Liquefied Petroleum Gas (LPG) Systems in Woodchippers Powered by Small Engines on Exhaust Emissions and Operating Costs

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Abstract: The use of alternative fuels is a contemporary trend in science aimed at the protection of non-renewable resources, reducing the negative impact on people and reducing the negative impact on the natural environment. Liquefied petroleum gas (LPG) is an alternative fuel within the meaning of the European Union Directive (2014/94/UE), as it is an alternative for energy sources derived from crude oil. The use of LPG fuel in low-power internal combustion engines is one of the currently developed scientific research directions. It results from the possibility of limiting air pollutant emissions compared to the commonly used gasoline and the lower cost of this fuel in many countries. By “gasoline 95” the Authors mean non-lead petrol as a flammable liquid that is used primarily as a fuel in most spark-ignited internal combustion engines, whereas 95 is an octane rating (octane number). This article presents the results of research on fuel consumption, toxic exhaust gas emission, and operating costs of a woodchipper used for shredding branches with a diameter of up to 100 mm in real working conditions. The woodchipper, powered by a 9.5 kW internal combustion engine, fueled by gasoline and LPG was tested. Liberal regulations of the European Union (Regulation 2016/1628/EU) on the emission of harmful exhaust compounds from small spark-ignition engines (up to 19 kW) and non-road applications contribute to the low technical advancement level of these engines. The authors researched a relatively simple and cheap LPG fueling system, as in their opinion, such a system has the best chance of being implemented for use. In the study, the branches of cherry plum were shredded (*Prunus cerasifera* Ehrh. Beitr. Naturk. 4:17. 1789 (Gartenkalender 4:189-204. 1784)). Their diameter was ca. 80 mm, length 3 m, and moisture content ca. 25%. The system was tested during the shredding of the branches in real working conditions (the frequency of supplying the branches about 4 min⁻¹ and the mass productivity of about 0.73 t/h). Based on the recorded results, it was found that the LPG fueled engine was characterized by higher carbon monoxide (CO) and nitrogen oxides (NO_x) emissions by 22% and 27%, respectively. A positive effect of using LPG was the reduction of fuel consumption by 28% and carbon dioxide (CO₂) and hydrocarbons (HC) emissions by 37% and 83%, respectively. The results of the research show that the use of alternative fuels can bring benefits in terms of CO₂ and HC emissions, but at the same time be characterized by an increase in CO and NO_x emissions. Further research should be conducted on innovative alternative fuel supply systems, such as in the automotive industry. At the same time, legislators should limit the use of low-quality fuel supply systems with the limits of pollutant emissions in exhaust gases, contributing to the development and economic competitiveness of new fuel injection systems.

Keywords: small engine; woodchipper; liquefied petroleum gas LPG; alternative fuels; toxic exhaust gases emission

1. Introduction

Air pollution in urban areas is a serious environmental problem in many cities around the world (e.g., Europe [1], Asia [2], North America [3], South America [4], Australia [5], and Africa [6]). Green infrastructure has been lost in many urban areas as a result of population growth and urbanization. One way to improve air quality is to increase green areas (for example parks) in cities [7]. The most important problem of modern cities is the loss of urban green areas [7]. Reducing their surface increases air pollution [8], and above all its dustiness [9]. Considering that scientists are working on determining the species of plants that will be used in urban areas, the increase in the demand for machinery and equipment necessary for the care of these plants is noticeable. Different equipment and machines are used for wood chipping and shredding after the pruning or felling in urban areas (home gardens, parks, or roadsides) than in forests or industrial biomass production areas. As indicated in the literature [10] on the subject the industrial woodchippers are characterized by a drive unit ranging in mechanical power from 130 kW up to 900 kW. Chippers used for works in urbanized areas are mainly driven by spark-ignition internal combustion engines, whose power usually does not exceed 19 kW [11]. These machines are characterized by relatively small parameters of wood chips production efficiency [12] and are not intended for biomass processing on an industrial scale. Woodchippers are classified as non-road machines. For this reason, they are subject to quite liberal legal regulations as compared to the provisions on internal combustion engines used in motor vehicles [13]. They are associated with the emission of toxic exhaust gases, and thus directly affect the technical advancement of the engine fuel supply system. As a result of the lack of appropriate regulations, internal combustion engines used in chippers are characterized by high toxicity of the emitted exhaust fumes and contribute significantly to air pollution. This problem is noticed by the authors and other researchers, which is why development is currently underway towards fuel injection systems, [14–16] systems adapting the drive to the conditions of use [17–19], improving durability [20], and alternative fuels (e.g., liquefied petroleum gas (LPG) [21–25], ethanol [26,27]) for small spark-ignition engines; however, no regulations limit the use of outdated technologies. The relatively high cost of drives with the injection system is the result of their low popularity in the industry [28].

Fuel supply systems in spark-ignition engines have been developing dynamically since the use of electronic control. In motor vehicles, carburetor fuel supply systems using hydrodynamic Bernoulli equations for fuel dosing were superseded in the 1990s. The development of injection systems led to electronic fuel injection integration with the ignition timing system. The expansion of these systems with an oxygen content sensor in the exhaust gas made it possible to regulate the fuel mixtures in terms of stoichiometric mixtures. In turn, the injection systems in the processes of regulating the composition of the air–fuel mixture took into account the need to select the optimal mixture for the correct operation of exhaust gas treatment systems, e.g., three-way catalytic reactors. Currently, the best injection systems feature a multiphase direct injection into the combustion chamber. The same trend is developed for LPG; however, for this fuel, differences in systems can be distinguished due to its phase. The first LPG systems provided the fuel in the combustion chamber in the gaseous phase by indirect injection into the intake manifold; however, the latest systems with direct injection into the combustion chamber are characterized by the use of LPG in the liquid phase. Vehicles powered by such fuel supply systems meet the highest emission standards [13]. On the other hand, in non-road machines with small engines, the carburetor systems are acceptable and commonly used. Their technical advancement is at a lower level than the available solutions used in, for example, transport, and despite this, they comply with the European regulations on exhaust emissions

In order to successfully become a large part of the fuel market, alternative fuels must be widely available for sale. One of the alternative fuels to gasoline 95, commonly used all over the world, is LPG. It is characterized by relatively easy availability (and a competitive price). The breakdown of

LPG and gasoline prices in Europe and Asia are presented in Figures 1 and 2, respectively. The same comparison for America and Oceania is shown in Figure 3. There is a trend associated with attempts to use LPG as an alternative fuel to gasoline. This has economic benefits, as LPG is cheaper than gasoline in the vast majority of countries around the world. There are also possible ecological effects related to the comparison of the toxicity of gases resulting from the combustion of LPG and gasoline; however, it depends on the degree of technical advancement as well as the settings and parameters of the drive system of machines and vehicles [29]. It is possible to indicate the conditions for which the results of the toxicity of gases generated as a result of LPG combustion will be worse than during gasoline combustion [29] and vice versa [30]. Despite this fact, research works aimed at adapting gasoline engines to the combustion of gaseous fuels (e.g., LPG or compressed natural gas (CNG)) is an important direction of development, because in the future they can be replaced with more environmentally beneficial biogas, e.g., from wastewater treatment [31].

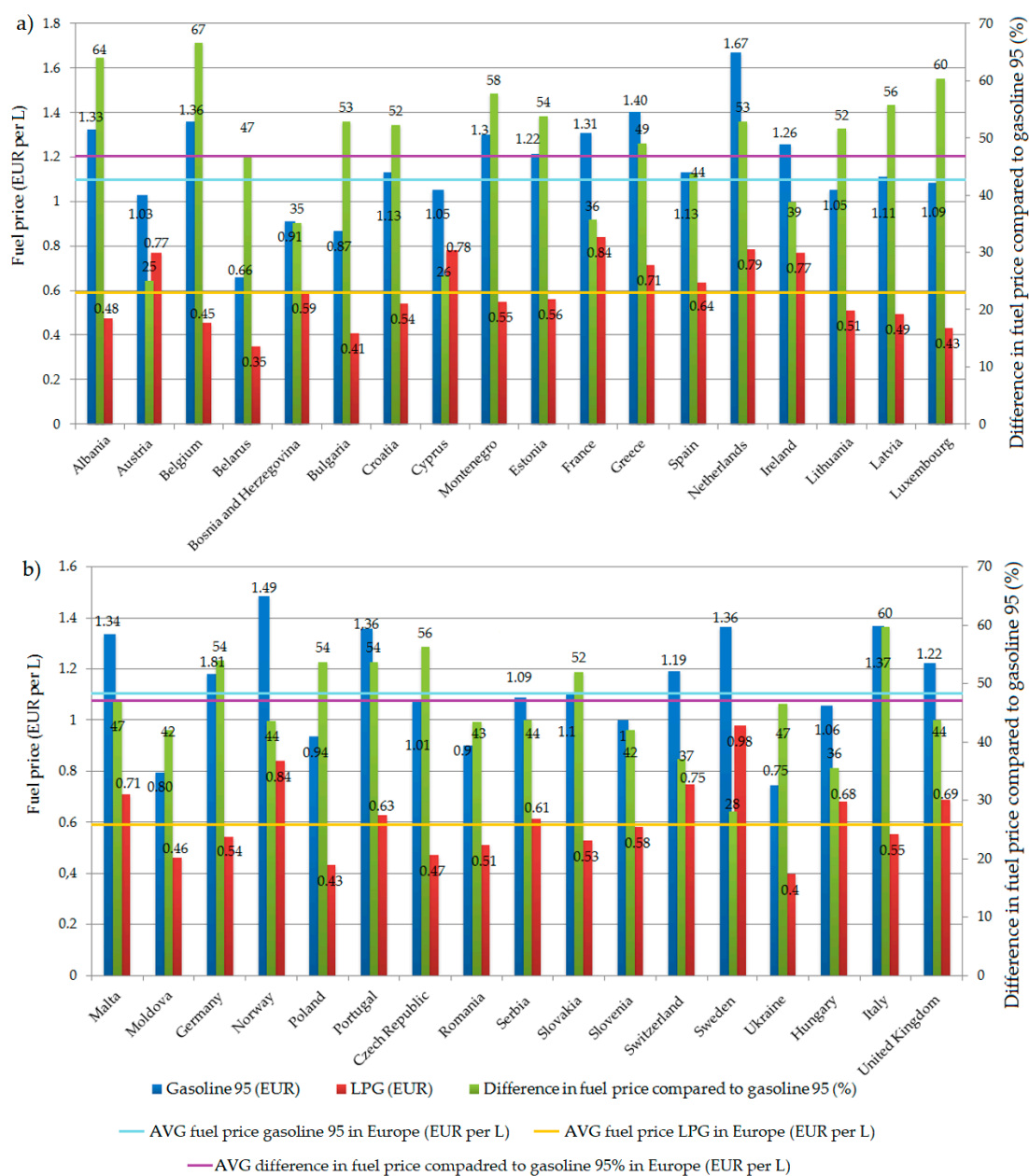


Figure 1. Price of gasoline 95 and liquefied petroleum gas (LPG) in selected European countries from 20 July 2020, where (a) part 1, (b) part 2 [32,33].

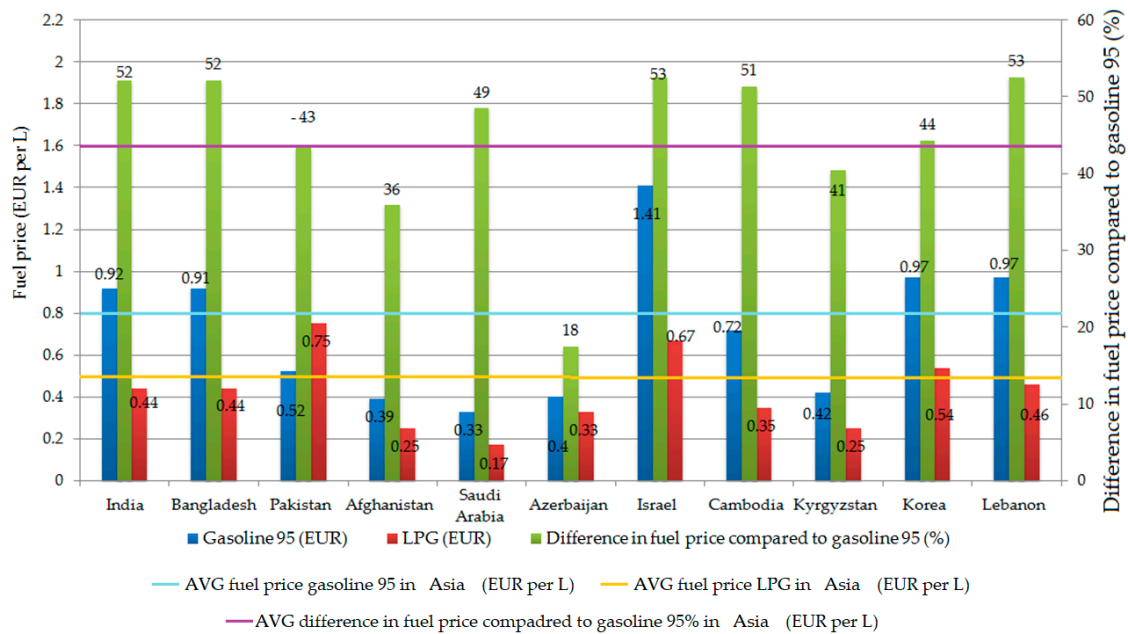


Figure 2. Price of gasoline 95 and LPG in selected Asian countries from 20 July 2020 [32,33].

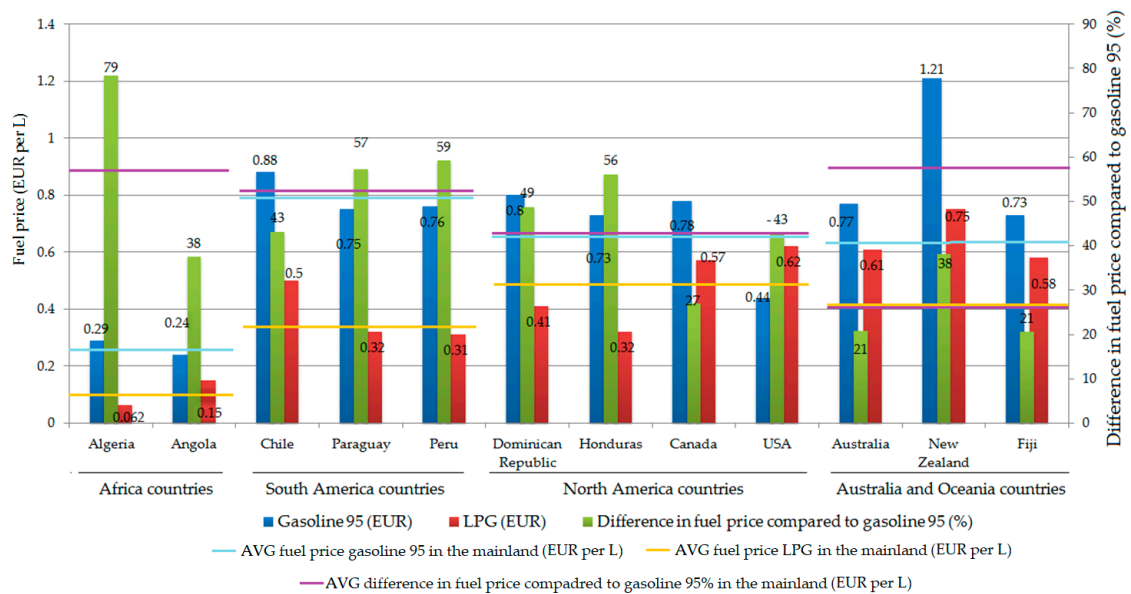


Figure 3. Price of gasoline 95 and LPG in selected African, South American, North American, and Oceanic countries from 20 July 2020 [32,33].

Research on the use of LPG fuel in internal combustion engines shows different conclusions as to the effects of their application. The authors of [34] presented the results of tests of a compression-ignition internal combustion engine (cylinder capacity 296 cm³ and 5.59 kW) powered by two types of fuel (diesel and LPG in different ratios), showing that the use of LPG injected in the liquid phase to the fuel may reduce CO and HC emissions by about 20–30% and increase NO_x emissions by 6% [34]. A comparative study of the energy and ecological parameters of dual-fuel engines (diesel– natural gas (NG) and hydrotreated vegetable oil (HVO)–biogas) and conventional diesel oil in a compression-ignition engine showed that the use of methane in the dual-fuel mixture reduced the CO₂ volume in the exhaust by 17–20%, and biomethane increased the CO₂ volume by 10–14%. Using two fuels significantly increased the emissions of CO (by about 24 times) and HC (by about 28 times), but the NO_x volume decreased by 67–82%, and the smoke emitted by the engine decreased by 23–39% [35]. Efficient and

ecological indicators of a compression-ignition engine powered by various mixtures of diesel oil and LPG indicate that additional LPG reduces the volume of diesel fuel injected into the cylinder and causes a delay in the start of injection, thus affecting the combustion process of the fuel mixture and reducing the efficiency of the engine. Increasing the share of LPG causes an increase in the concentrations of incomplete fuel combustion products, such as CO and HC as well as smoke; however, NO_x and CO₂ emissions are decreasing [36]. The observed trend suggests that alternative fuels for internal combustion engines can reduce the negative environmental impact of those engines [37]; however, research results are showing that LPG-powered internal combustion engines are characterized by a higher emission of harmful exhaust gas compounds compared to gasoline-powered engines [29]. These studies have shown that the level of emission of harmful exhaust gas compounds is dependent on the type, or rather a generation, of the gas installation used. Older generation installations may have less favorable effects of using alternative fuel [29]. The competitive design of fuel supply systems in terms of installation costs for small engines is the first-generation installations, which are now ready for implementation. In order to evaluate the available structures in terms of the emission of harmful exhaust compounds and fuel consumption, tests were performed in the actual operating conditions of the machines. Such measurements are possible thanks to portable emission measurement systems (PEMS) which, according to scientists, should be used for road approval and homologation in the future [38].

The article presents research that is a part of the global trend of research on machines and vehicles in real operating conditions. The study was carried out on a small engine driving woodchipper created for use in urban areas. The engine was powered by gasoline 95 and after the modernization of the fuel supply system, by LPG. A commercial power supply system was used, and the modernization cost was EUR 105. The research aimed to show the differences in the emission of harmful exhaust gas compounds and the operating costs of the machine by comparing the combustion engine when fueled by either gasoline 95 or LPG.

2. Materials and Methods

The subject of performed research was a Red Dragon RS-100 (Remet CNC Technology Sp. Z O.O., Kamień, Poland) woodchipper presented in Figure 4a. This is a commonly used machine for chipping branches in urbanized areas. The specification of the chipper is shown in Table 1. The chipper with the factory settings (A) was driven by the spark-ignition engine Lifan GX390 (License: American Honda Motor Company, Inc., Torrance, CA, United States), 9.5 kW (Figure 4b). The specification of the drive is shown in Table 1. The tested drive unit characteristics in terms of power, torque, and fuel consumption are shown in Figure 5a. The efficiency characteristics of engines determined based on the input and output energy are shown in Figure 5b. Then, the original design (A) was modernized to the second version (B). In version (B) the carburetor powered by gasoline 95 was replaced by a carburetor system adapted to use a mixture of propane and butane as fuel. The modified carburetor powered by LPG is presented in Figure 4c. It is an innovative system in this group of engines, and it is commercially available as an upgrade system. The modernization of the gasoline 95 engine and its most essential components and cost are presented in Table 2. A modernized engine with an LPG fuel system was installed in a woodchipper with a branch logger mechanism. The designs (A) and (B) were adjusted before the tests following the rules of regulating the tested carburetors for stoichiometric mixtures (AFR). For design (A) that used gasoline 95 this value was equal to 14.7: 1; for design (B) that used LPG fuel this value was equal to 15.5: 1. Tests were performed to compare the emission of harmful exhaust gas compounds: CO₂, CO, HC, and NO_x emitted by the chipper powered by gasoline 95 and LPG engine. The tests were carried out in real operating conditions. During the tests, the chipper shredded branches with a diameter of up to 100 mm, for which its cutting mechanism was designed. The characteristic of the fuels used during the tests is presented in Table 3.

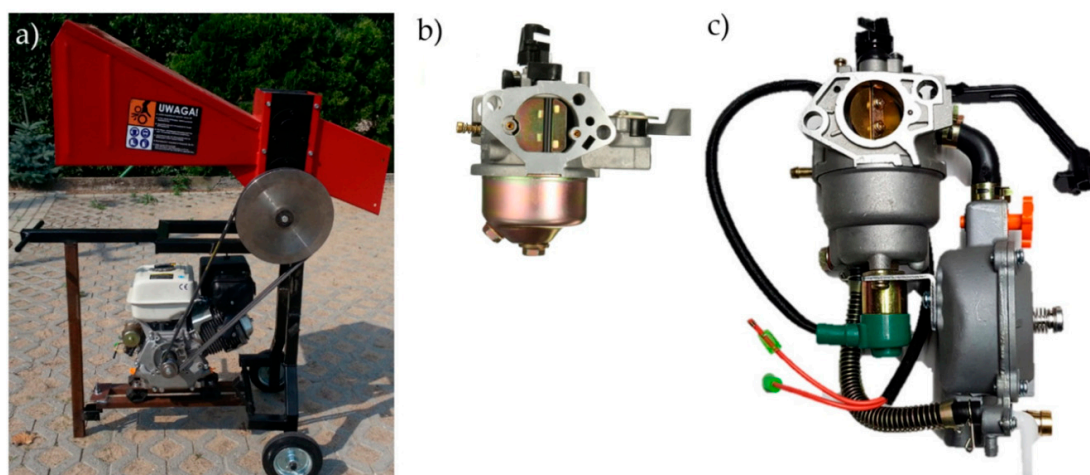


Figure 4. The tests were carried out on (a) woodchipper with branch logger mechanism, (b) carburetor system adapted to gasoline 95, (c) carburetor system adapted to LPG.

Table 1. Technical specification of woodchipper Red Dragon RS-100 and Lifan GX390 engine.

Woodchipper Red Dragon RS-100	
Parameter	Characteristic
Cutting mechanism type	Cylindrical
Cut branches maximal diameter	100 mm
Cut branches length (mechanism has 4 knives)	140 ± 50 mm
Average mass flow rate [12]	0.66 t/h
Average volumetric flow rate [12]	3.5 m ³ /h
Lifan GX390 Engine	
Parameter	Characteristic
Swept volume	389 cm ³
Engine maximal power at 3600 rpm	9.56 kW/13 HP
Engine maximal torque at 2500 rpm	26.5 Nm
Bore/Stroke	88 mm/64 mm
Engine Type	Four-stroke, OHV (Over Head Valve)
Number of cylinders	1
Ignition	Electronic, without ignition timing adjustment [39]
Weight	31 kg
Average cost	270 EUR

Table 2. Cost of components and services for modernizing a small engine to be powered by LPG.

System Components and Service	Cost
Carburetor	46 €
LPG gas reducer with pressure gauge	7 €
Installation hose	6 €
11 kg gas tank	23 €
Working time spent on the modernization of the structure and system regulation 1 h	23 €

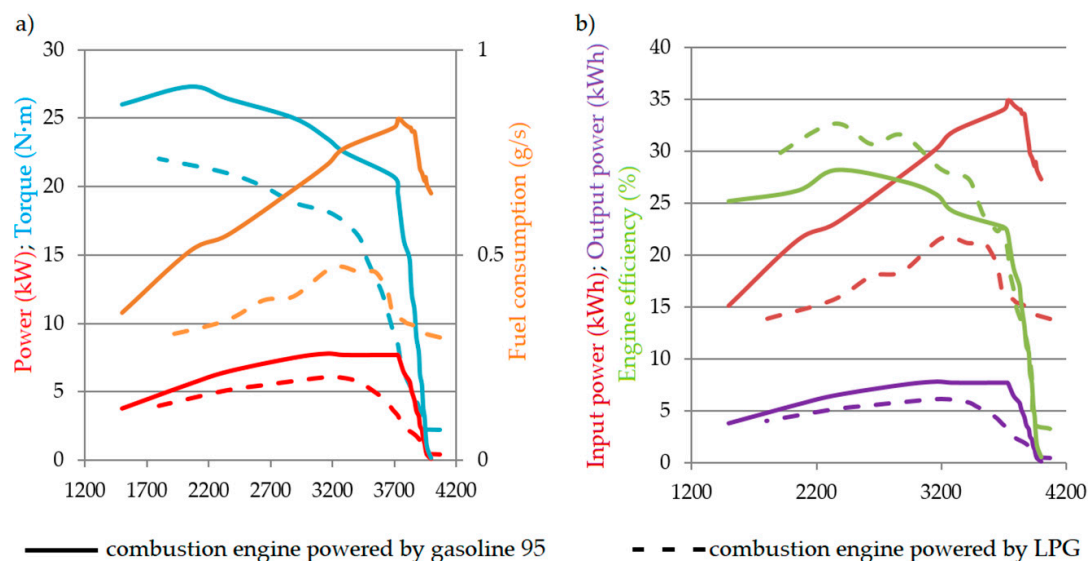


Figure 5. Characteristics of the German iGX engine powered by gasoline and LPG, in terms of (a) power, torque, fuel consumption, and efficiency; (b) efficiency, energy input, and energy output. The colors correspond to the individual physical quantities, and the line type to the type of fuel.

Table 3. Properties of tested fuels, where MON = motor octane number; RON = research octane number [40].

Fuel	Gasoline 95	Liquefied Petroleum Gas Propane–Butane 50%/50%
Density under reference conditions (liquid phase) (kg/m ³)	720–775	520
Fuel calorific value (MJ/kg)	42.6	46
Boiling temperature (°C)	40–210	–30
Excess air coefficient λ up to the ignitability boundaries	0.4–1.4	0.4–1.7
Octane number MON (RON)	85 (95)	95 (100)
Air fuel ratio (AFR) for stoichiometric mix (mass)	14.7:1	15.5:1

The branches of cherry plum (*Prunus cerasifera* Ehrh. Beitr. Naturk. 4:17. 1789 (Gartenkalender 4: 189–204. 1784)) were shredded. Their diameter was ca. 80 mm, length 3 m, and moisture content ca. about 25%. The moisture content of selected branches was checked before and during the tests; the branches came from different places in the branch pile. The moisture test was carried out using a METTLER TOLEDO HR83 moisture analyzer (Mettler Toledo, Columbus, OH, United States). Branches with such parameters take about 4.5 s to be chipped in a cylindrical chipper [17]. Branches of similar diameters and lengths generated a similar machine load, which translated into a more uniform chipping time. Such branches should be considered typical. They put a heavy load on the machine. The tested specimens were representative of hardwood species in accordance with the Janka classification [41]. The Janka hardness test measures the resistance of a sample of wood to denting and wear. It measures the force required to drive a steel drive of an 11.28 mm (0.444 in) diameter halfway into a sample of wood [42,43]. The branches were stashed at a distance of 2 m from the chipper and were fed by one experienced operator. During the test, based on signals from the optical system in the feed channel, the branch feeding frequency was recorded. The recorded results are presented in Table 4. The branch feeding frequency in all samples was close to 4 min^{−1}. The second parameter characterizing the chipping machines' working conditions is the average mass flow rate of the shredded material. This value was determined based on shredded branches' mass measurements as a time function using a portable scale (Radlastplattform up to 1500 kg, meeting the requirements of ISO 9001). The mass flow rate measurement results depending on the different configurations of the machine are presented in Table 4. The average mass productivity of the chipper during the tests was 0.73 t/h. The results of

measurements of the frequency of branch delivery and mass productivity during the research were determined as being at a similar level, which allows concluding that the machines in both tests were subject to comparable operating conditions.

Table 4. Branch feeding frequency in measurement samples and cylindrical chipper mass flow rate during tests, where a: Gasoline supply system; B: LPG supply system.

Tested Design	A	B
Average branch feeding frequency	3.9 min ⁻¹	4.1 min ⁻¹
Cylindrical chipper mass flow rate	0.75 t/h	0.71 t/h

Exhaust emissions were tested using Axion RS+, a typical portable emissions measurement system (PEMS) from Global MRV. Table 5 presents its technical specification. In the research emission levels of CO₂, hydrocarbon (HC), carbon monoxide (CO), carbon dioxide (CO₂), and nitrogen oxides (NO_x) were analyzed. Based on the carbon balance, we determined fuel consumption according to Equation (1) [44]:

$$FC = 1.153 [(0.866 \cdot HC) + (0.429 \cdot CO) + (0.273 \cdot CO_2)], \quad (1)$$

where *FC* is the fuel consumption (g/s); *HC*, *CO*, and *CO₂* are the emission of harmful ingredients (g/s).

Table 5. Characteristics of Axion RS, a portable exhaust emissions analyzer [44].

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.%

The device used measured the concentrations expressed in vol.% or ppmv. As a result, more measurable emissions are determined.

3. Results

The results of the hourly emissions of harmful exhaust gas compounds and fuel consumption for the chipper powered by a gasoline 95 and LPG engine are shown in the figures: CO (Figure 6), CO₂ (Figure 7), HC (Figure 8), NO_x (Figure 9) together with the fuel consumption during the shredding process (Figure 10) as a function of time. The presented descriptions show greater changes in the instantaneous emission value for an LPG-powered engine, and this applies to all harmful compounds. These instantaneous changes (peaks), both for the gasoline 95 and LPG engine, result from changes in the engine load, which is the result of supplying branches to the chipper. It follows that the emission from the LPG-powered engine shows a greater susceptibility to load changes. Average values of hourly emissions of harmful exhaust gas compounds: CO and NO_x (Figure 11) are higher, whereas CO₂ and HC emissions are lower for the LPG-powered engine. The description of CO emissions as a function of time shows that the LPG-powered engine is characterized by higher emissions, which is related to the control of the fuel–air mixture composition in the scope of lean mixtures. Constructions powered by LPG was characterized by lower fuel consumption. For nitrogen oxides (NO_x) to be created, the combustion temperature must be high, and there must be free oxygen molecules. Hence, NO_x emissions are most often associated with the combustion of a lean mixture, i.e., with an excess of air over fuel compared to a stoichiometric mixture. This parameter is also unfavorable for the LPG-powered design. One positive aspect of the LPG-powered design is the reduction in HC emissions. The HC emissions are due to the unburnt fuel particles in the exhaust gas. The lower HC emission indicates that the LPG-powered engine under the periodically variable loading conditions was characterized by a less rich mixture than

the gasoline-powered design (Figure 12) [10,45]. The air–fuel ratio (AFR) characteristics during the chopping processes are also presented. A direct comparison of the characteristics of the engine fueled by gasoline and LPG fuel is not justified as the AFR value for the stoichiometric mixtures of these fuels is different (14.7 for gasoline and 15.5 for LPG); however, the individual nature of the work of the tested engines can be observed. The gasoline-powered engine has a rich mixture under the tested operating conditions (avg $\approx 13.2 \pm 0.03$) and maintains it relatively stable. The average AFR value differs from the stoichiometric mixture by about 10%. On the other hand, the LPG-powered engine has a rich mixture (avg $\approx 15.1 \pm 0.3$), but its operation is less stable and is characterized by much greater fluctuations of the AFR value. In this case, the average AFR value deviates from the stoichiometric mixture by about 2.5%. This indirectly contributes to the higher efficiency of this engine, as shown in Figure 5b. As the supplied fuel is largely completely burned and converted into energy.

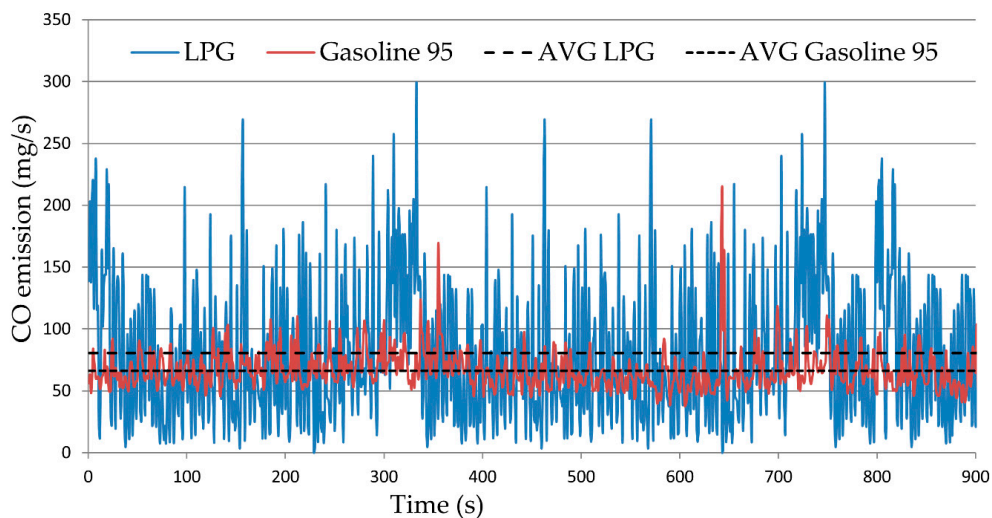


Figure 6. CO emission as a time function during the chipping process.

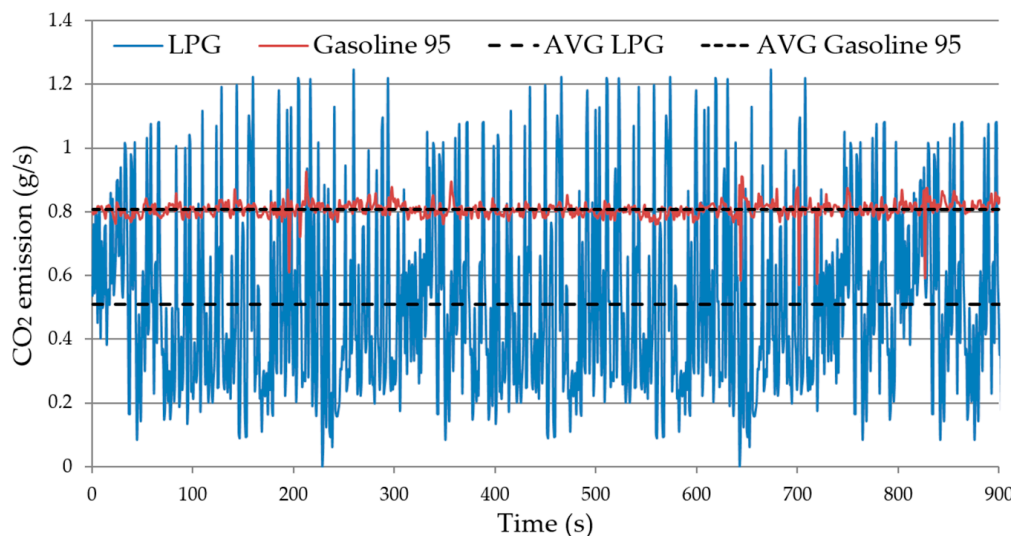


Figure 7. CO₂ emission as a time function during the chipping process.

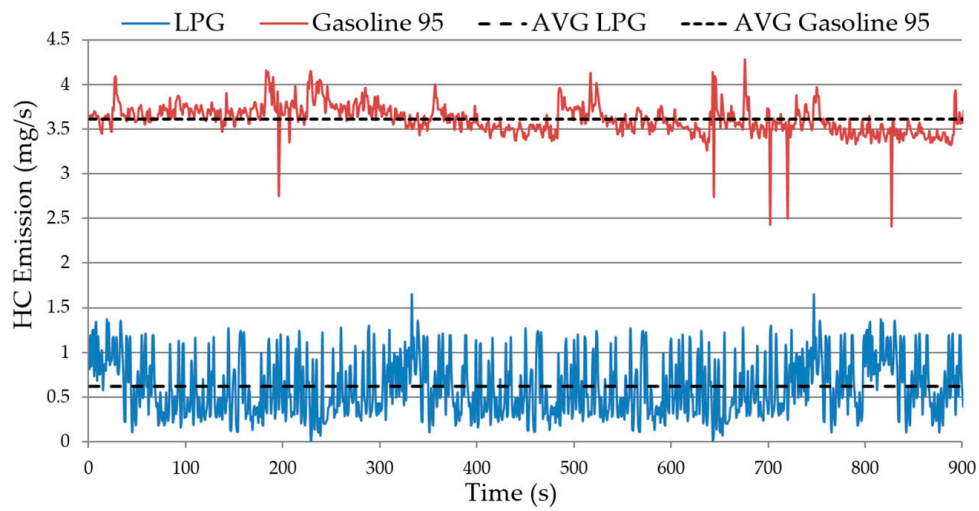


Figure 8. HC emission as a time function during the chipping process.

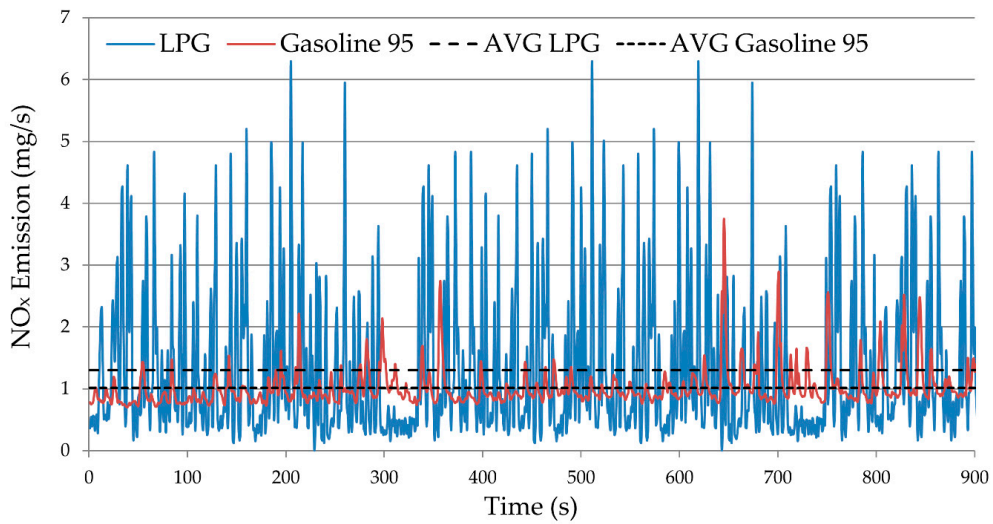


Figure 9. NO_x emission as a time function during the chipping process.

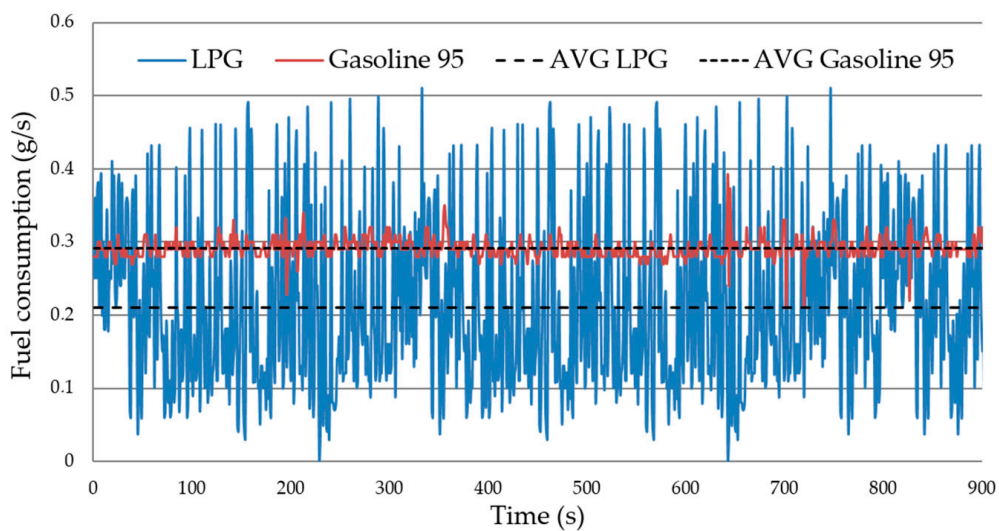


Figure 10. Fuel consumption as a time function during the chipping process.

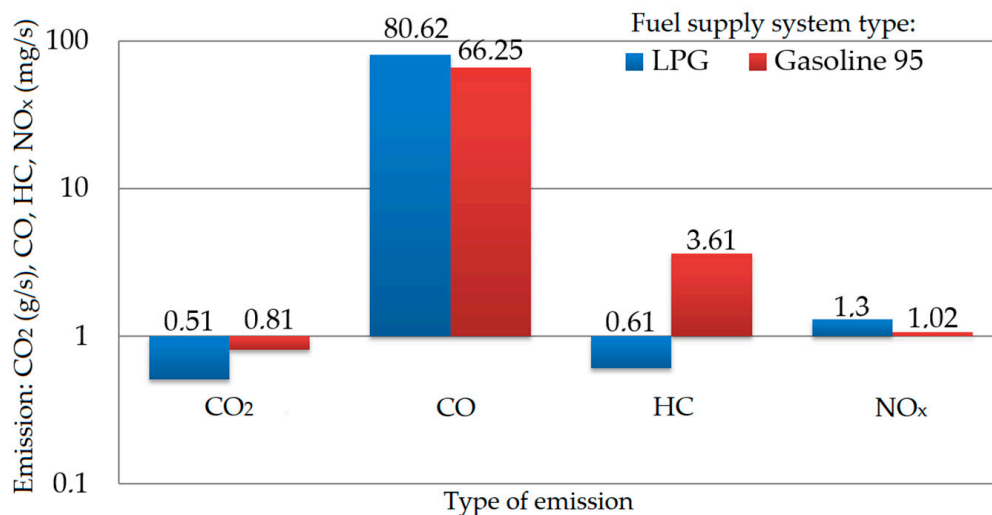


Figure 11. Comparison of emissions from engine fueled by gasoline 95 and LPG.

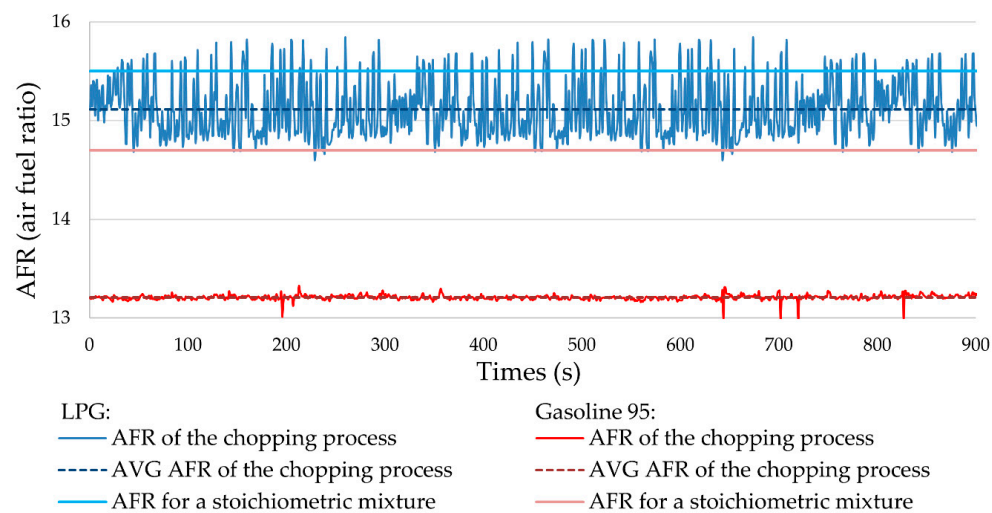


Figure 12. Air–fuel ratio (AFR) characteristics for the engine powered by gasoline and LPG.

4. Discussion

For efficient control of the drive unit and to evaluate the reaction of the tested design to changes in the operating conditions, it is important to measure the emission of the generated exhaust gas compounds as a function of time. The results may indicate areas that require improvements in the design. The results of the exhaust emission tests with their average values per specific time interval are equally important (Figure 11). They enable a comparison of the data on selected designs and provide information on the impact of selected machines on global or local exhaust emissions. Comparison of the tested designs are presented (gasoline 95 and LPG) in Figure 13, with the percentage comparison calculated according to Equation (2):

$$A/B = -\frac{x_A - x_B}{x_A} \cdot 100\%, \quad (2)$$

where x_A is the selected value for the gasoline 95 fuel supply system, x_B is the selected value for the LPG fuel supply system. Equation (2) is written in such a form that drops in the value are negative and increases in the value are positive.

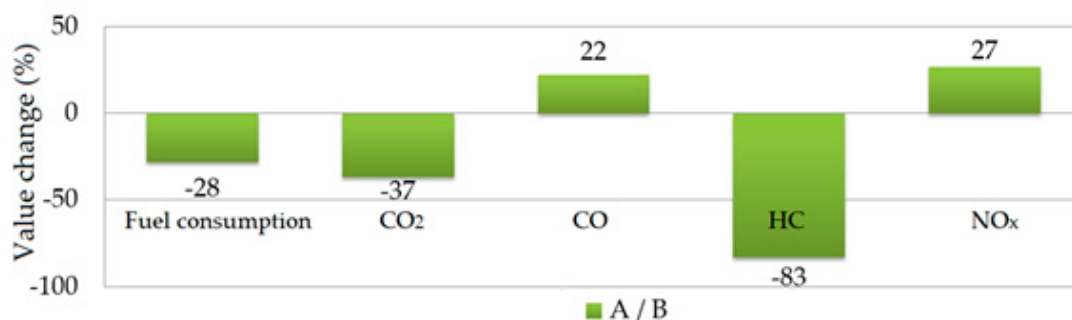


Figure 13. Influence of the fuel supply system on selected values of exhaust emissions and fuel consumption, where: A—gasoline 95 fuel supply system, B—LPG fuel supply system.

The use of the LPG system increased the emissions of, CO by 22%, and NO_x by 27% compared to the engine with the classic gasoline 95 carburetor system. On the other hand, the beneficial effect of using the LPG system was the reduction of HC emissions by 83% and CO₂ emissions by 37%. The use of an LPG system allowed to reduce fuel consumption by 28%, which is a good result.

Exhaust gas emission is most often expressed in g/km or g/kWh. The data collected in the literature review refer to various physical quantities. To make them comparable, it is necessary to transform them. Thus, exhaust emissions (*EE*) expressed in (g/h) were determined based on the nominal power of the machine *P* given in kW and the exhaust emissions depending on the power of the machine *E* expressed in g/kWh. For this purpose, we used the relationship defined by Equation (3):

$$EE = E \cdot P. \quad (3)$$

In other words, the procedure described for determining the value *EE* assumes an hour of machine operation at full power.

The permissible limits for the harmful compounds in exhaust gas emission for the tested group of propulsion units according to the provisions in force in the European Union from 2019 are presented in Table 6 [11]. These engines are subject to the NRS-vr/vi-1b category, according to Stage V emission standards for non-handheld spark ignition SI engines below 56 kW (NRS).

Table 6. Stage V emission standards for non-handheld SI engines below 19 kW (NRS), an engine displacement greater than or equal to 225 cm³ (A), and theoretically permitted exhaust emissions in the European Union for 10 kW engines during an hour of operation (B).

	Category	Power (<i>P</i>)	Engine Displacement (<i>V</i>)	Date	Permitted Emission	
					CO	HC + NO _x
A	NRS-vr/vi-1b	<i>P</i> < 19 kW	<i>V</i> ≥ 225 cm ³	2019	610 g/kWh	8 g/kWh
B	NRS-vr/vi-1b	≈10 kW	390 cm ³	2019	6100 g/h	80 g/h

Therefore, a comparison of permissible emissions and approximate emissions from the tested engines was made (Table 6). The results indicate that the drives in question do not exceed the limits allowed in the European Union during one hour of operation (Figure 14). However, it should be borne in mind that the engines tested in real operating conditions were not characterized by the maximum load. The comparisons presented in Figures 13 and 14 show the emissions from gasoline and LPG engines and the exhaust emissions of the tested constructions with exhaust emission limits in Europe. The absolute number of measurements for consumption and emissions are for comparison purposes only.

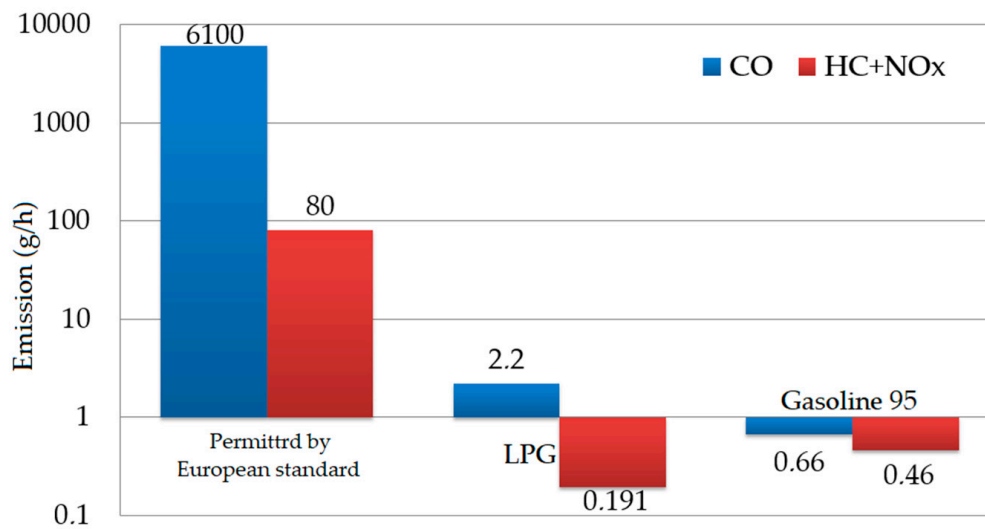


Figure 14. Comparison of the exhaust emissions of the tested designs with the exhaust emission limits in Europe.

The results of air pollutant emission tests during LPG combustion are characterized by higher emissions of harmful compounds in terms of CO and NO_x emissions and lower in terms of CO₂ and HC emissions compared to gasoline 95. Such results partially coincide with the studies presented in the literature [29], which indicate that higher emissions might characterize low-tech gas installations in vehicles. On the other hand, studies in which the use of LPG fuel and the injection system, i.e., a system with a higher technical advancement level, may be characterized by favorable results of harmful emissions, as shown by other studies presented in the literature [30]. Good ecological and economical properties characterize technologies of LPG installations used in modern motor vehicle engines, however, the transfer of these systems to small power engines is difficult. Modern LPG systems require cooling with the coolant from the internal combustion engine and require a permanent battery power supply system. This contributes to the basic problems of using these components in small engines. Most of these engines are air-cooled and have no battery. Further, technologically advanced LPG systems require, among others, the measurement of crankshaft rotational speed, camshaft position, engine load, oxygen content in exhaust gases, and engine temperature. Engines equipped with gasoline 95 injection systems already have such elements; hence their modernization with LPG systems is simpler and cheaper. The most technically advanced small commercial engine in the 390 cm³ capacity range is the Honda iGX390. Of the above-mentioned elements and sensors that are beneficial in the application of LPG systems dedicated to car engines, the Honda iGX390 has rotational speed measuring sensors and a battery. The introduction of changes necessary in the use of car components in small engines is associated with design changes resulting from the introduction of measuring sensors. Besides, all components necessary to run this type of construction may exceed the cost of purchasing a small engine without an LPG installation. In order to implement the technology of powering small engines with alternative fuels such as LPG, it is necessary to search for cheap and simple design solutions adapted to the characteristics of the tested engines.

5. Conclusions

Researching innovative solutions that are ready for implementation is as important as developing solutions that are still clearly far from implementation for various reasons, e.g., production costs, availability of components, or materials. The authors tested a small, gasoline 95 powered engine (with a carburetor fuel system). Later, they modernized the system to power the same engine (also with carburetor) with an LPG. The test was carried out in real working conditions, and the drives were mounted in a cylindrical chipper designed for branches with a diameter of up to 80 mm.

Chipper equipped with an LPG system was characterized by a higher emission of harmful exhaust compounds: CO by 22%, NO_x by 27% compared to the engine with the classic gasoline 95 carburetor system during the actual operation of the machine (while shredding branches). The engine after modernization enabling the use of LPG fuel, showed an 83% lower HC emission and reduction in CO₂ emission by 37% as well as lower fuel consumption by 28%. It should be emphasized that the performed tests are one of the first concerning small engine measurements in real operating conditions, using PEMS equipment. Increased fuel consumption when using LPG over gasoline 95 is common [46], however, the developed structure showed lower LPG fuel consumption despite its lower calorific value. This is due to the mixture composition control characteristic, where the gasoline-powered engine during loading was characterized by a rich mixture (avg AFR $\approx 13.2 \pm 0.03$), whereas the LPG engine operated on a slightly enriched mixture (avg AFR $\approx 15.1 \pm 0.3$). A positive aspect of the decreased LPG consumption and its lower price is the operating cost reduction. This is particularly important in Europe as the difference in gasoline 95 and LPG prices on this continent is on average around 0.2 EUR/h. The LPG fuel system, despite the increased emission of selected exhaust gas components compared to the gasoline 95 carburetor system, does not exceed the European exhaust standards for small engines for non-road applications. This proves that carburetor fuel supply systems can meet the applicable standards in the European Union, even though in other industries, e.g., transport, such systems did not meet the emission requirements. Further research and work should be carried out in the direction of the technical development of fuel supply systems and tightening the regulations that will prevent the use of simple fuel supply systems and will enable the introduction to the market competitive and more advanced fuel injection systems [10,47].

The authors researched systems that adapt the character of low-power motors operation to the real work conditions [19,47]. The results of their work show a reduction in fuel consumption and exhaust emissions of CO, CO₂, and NO_x; however, the developed system is characterized by increased HC emissions when running on gasoline. The research presented in this paper shows that the use of LPG fuel can reduce HC emissions by about 83%, which may suggest that LPG is the recommended fuel for use in adaptive systems. This statement is supported by the fact that LPG is a fuel with a lower carbon content than gasoline 95 and may contribute to lower HC emissions in the described systems, the increased emission of which is caused by unburned fuel particles.

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