Influence of Non-commercial Fuel Supply Systems on Small Engine SI Exhaust Emissions in Terms of European Approval Regulations

Łukasz Warguła (✉ lukasz.wargula@put.poznan.pl)

Politechnika Poznańska <https://orcid.org/0000-0002-3120-778X>

Piotr Lijewski

Politechnika Poznańska

Mateusz Kukla

Politechnika Poznańska

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Abstract

The development and operation of road infrastructure requires machines and equipment driven by low-powered internal combustion engines. The authors of this paper examined five small spark-ignition engines. They used the most popular commercial design on the market, the Lifan GX 390, with a carburettor power system, and another commercial power unit with the most innovative power system, the Honda iGX 390, characterised by an electronically controlled carburettor flap. The remaining three tested constructions are proprietary solutions modernising the design of the Lifan GX 390 engine. The first is the application of an electronic injection and ignition system powered by gasoline, the second and third are systems powered by alternative fuels. Emissions tests were conducted under identical operating conditions on an engine dynamometer coinciding with European Union guidelines (Regulation 2016/1628/EU). The results of the tests showed that innovative solutions in most cases reduced CO, CO₂, and HC emissions while increasing NO_x compounds.

1. 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 possibility to increase the mobility of people (Meekan et al. 2017) and the movement of goods (Gnap et al. 2019). However, this development is characterised by several negative impacts (Yu et al., 2013) e.g. an increase in air pollution (Ehrenberger et al. 2021; Cepeda et al. 2017; Colville et al. 2001) and a 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 is being conducted on the impact of air pollution on people's activity satisfaction, this research clearly indicates 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 groups of machines and vehicles for which acceptable limits of pollutant emissions from their propulsion engines are set, e.g. car and light truck (Regulation 715/2007 (Euro 5/6; Lijewski et al 2020; Ziółkowski et al. 2019), heavy-duty truck and bus (Regulation 595/2009; Rymaniak 2018; Merkisz et al. 2012b), 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 can 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 (compression-ignition CI engines or spark-ignition SI engines). The authors in the following study SI engines with a power output not exceeding 19 kW, which are called small engines by the legislators (Regulation 2016/1628/EU). These regulations are characterised by relatively liberal emission limit requirements relative to, for example, motor vehicles (Waluś et al. 2018). This translates into low technical sophistication of the fuel

supply systems of these engines (Warguła et al. 2018b). This is indicated by commercially available engine designs equipped with carburetor power systems (Warguła et al. 2018a), the use of which was abandoned in automotive vehicles as early as the 1990s. Among other things, they were withdrawn from widespread use in motor vehicles through stringent limits on allowable emissions that carburetor systems could not meet.

The main problem in the construction of fuel supply systems for SI small engine is the necessity of low weight of the whole construction, limited space for the engine and low cost of construction. 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 used in modern injection systems. Researchers around the world are studying the 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 of the described propulsion systems is to change the used fuel or alternative fuel admixtures (alternative fuel within the meaning of the European Union Directive (2014/94/EU), as it is an alternative for energy sources derived from crude oil (EU Directive 2014/94/EU) with respect to classical fuels i.e. gasoline to 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), biogas (Iyer 2020; Homdoun et. al. 2015; Surata et al. 2014). Other studies deal with design changes, e.g., valvetrain (Fontana and Galloni 2009) piston design (Iyer 2020) or intake manifold (Wahono et al. 2019). The main reason for developmental, simulation, experimental or real-world research is the aim to reduce air pollutant emissions and fuel consumption.

The problem of air pollution generated from these types of engines is important as these 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 Figure A.1 and include equipment used in construction and renovation such as circular saws, concrete trowels, rammers, soil drills or equipment used for cleaning and clearing snow from pavements. Another group is road marking machinery for painting road lanes. Another group is 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 will increase as the benefits of roadside trees are increasingly recognised. Roadside trees reduce the spread of road noise, absorb fine particles (Ozdemir 2019), harmful exhaust compounds from the air (Lahothi 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 confirm the pollutant absorption capacity (Kim et al. 2020). According to the public, residents of large cities appreciate the ecosystem properties of trees and other vegetation elements of roadside infrastructure. Even wild urban roadside vegetation has received high appreciation, 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 move and live

nearby (Weber et al. 2014). Another benefit of roadside trees is the protection of pedestrians, vehicles and roads from intense sunlight. 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. Researchers indicate that urban roadside trees are a source of stress relief and improved mental health for urban residents (Elsadek et al. 2019). Roadside studies in tropical areas have shown that trees with relatively large crowns reduced the mean radiant temperature (T_{mrt}) by 35% and the physiological equivalent temperature (PET) by 25% (Zaki et al. 2020). Contributing to improving the microclimate in the road infrastructure area by improving vehicle cooling and reducing heat build-up and improving pedestrian comfort. A final benefit is reducing the possibility of sun glare when moving on roads (Redweik et al. 2019). The disadvantages are the dangers associated with road collisions and damage to trees during adverse weather conditions. The average percentage of accidents, injured persons and fatalities related to collisions with a tree in Poland between 2003 and 2015 among the total road accidents, is at 6%, 6% and 14% (Rosłon-Szeryńska et al. 2019). They indicate that measures should be taken to reduce the risk of a road accident in a wooded area, as such events are characterised by a relatively high probability of a fatal event. According to the authors, it can be assumed that the demand for wood chipping machines in transport-related industries will increase due to the handling of trees in roadside areas but also as a result of their cutting due to the widening of road infrastructure (Lahothi et al. 2020).

Among the methods of limiting air pollution from non-road machinery, we can point to those related to policy, which by regulations allowing limits on exhaust gas emissions restricts the use of technologically older designs, or the search for innovative solutions in the studied group. The authors notice the research on small engines used in many industries, most often in real working conditions, these are 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. 2020c; 2020d; e), combustion scythes (Zardini et al. 2019).

However, there is also a perceived lack of research on a selected group of drives in identical operating conditions in order to compare them and assess the impact of applying innovative in this group of drives, design solutions. This paper presents tests of small engine emissions in laboratory conditions on an engine chassis dynamometer, the emissions of which were determined to coincide with European Union guidelines (Regulation 2016/1628/EU). Tests were carried out on a popular, commercially available propulsion unit with a carburettor Lifan GX 390 supply system and on the most innovative commercial propulsion unit on the market with an electronically controlled carburettor, Honda iGX 390. Then, three versions of the Lifan GX 390 engine, modernised by the authors, were tested. The modernisations concerned 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.

2. Materials And Methods

Propulsion units commonly used to drive non-road machinery were examined. Five designs were studied, two commercial and three innovative designs developed by the authors. The first propulsion unit tested was the SI Lifan GX390 spark-ignition engine (License: American Honda Motor Company, Inc., Torrance, CA, USA), a design with the most popular and cheapest fuel supply system. It is based on a classic carburettor system. The characteristics of the power unit are presented in Table A.1. The second power unit tested is the SI Honda iGX 390 internal combustion engine (Honda Motor Co., Ltd., Kumamoto Factory, Kumamoto, Japan) with the most innovative fuel supply system in this group of engines. The fuel supply system of this engine is characterised by an electronically controlled carburettor flap. The characteristics of this propulsion unit are also presented in Table A.1. The next tested propulsion units are based on the modernisation of the Lifan GX 390 engine. The modernisations concern the implementation of innovative fuel supply systems developed by the authors who are employees of the Poznań University of Technology, Poznań, Poland. The third engine tested is a Lifan GX 390 with a fuel supply system adapted to LPG, based on a carburettor adapted to gaseous fuels, engine characteristics are presented in Table A.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, the engine characteristics are presented in Table A.2 (Warguła et al. 2020c). The fifth and last engine was the Lifan GX 390 engine (also called the German GX 390 engine, depending on the engine distributor in the European market). It was characterised by the use of 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. The engine characteristics are shown in Table A.2 and design details are available in the referenced publications (Warguła et al. 2020a; 2020e; Warguła 2019). Commercial engines and fuel supply system diagrams of all tested systems are shown in Fig. 2.

The test methodology for the assessment of exhaust gas emissions was adopted in accordance with the European Union guidelines (Regulation 2016/1628/EU) for the testing of non-road mobile machinery equipped with low-power internal combustion engines. The Stage V engines tested fall into the NRS-v/vr-1b category (Table A.3) and are affected by the G2 test cycle (Table A.4), whose weighting factors of the ISO 8178 type B test cycle are shown in Table A.5 and emission limits in Table A.6.

The tests were carried out on an engine chassis dynamometer, adapted to be used with low-power internal combustion engines, the diagram of which is shown in Fig. 3. During the tests, the following values were recorded: rotational speed and torque, on the basis of which power output was determined. Simultaneously, the emission of exhaust gases was recorded: CO, HC, NO_x, CO₂. For each tested engine, the test was performed in ten repetitions, and the test results were subjected to statistical analysis. Axion RS +, a typical portable emission measurement system (PEMS) from Global MRV, was used for the exhaust emissions test. Table A.7 shows its technical specification. The emission tests analysed the levels of hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO₂) and nitrogen oxides (NO_x). The measuring instrument used in the experiments measured concentrations expressed in vol.% or ppmv. As a result, more measurable emissions were determined. Emissions were calculated on the basis of

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 A.8 presents the characteristics of the fuels used to power the engines during the tests. Commonly available composition of gaseous fuels (especially natural gas) varies in different geographical areas, the authors used gas available on the Central European market for the tests (Kuczyński et al. 2020).

3. Results And Discussion

The recorded test results cover a larger area of operating conditions than required by the European type approval regulations. The results of exemplary characteristics (torque, speed, power, CO, CO₂, HC, NO_x emissions and fuel consumption) during the research test are shown in Fig. 4, grey marking the area of operating conditions used for analysis according to ISO 8178 type B. The analysis was conducted under stable speed and torque conditions.

The average value of pollutant emissions at the operating points determined according to ISO 8178 Type B with consideration of weighting factors (Table A.5) is presented in Table A.9. The average value of the NRSC test emissions T_{NRSC} was determined according to Eq. (1), where W denotes the contribution of the selected operating conditions to the total test analysis and E denotes the pollutant emissions under the selected conditions, the assigned numerical subscripts denote the mode number according to Table A.5.

$$T_{NRSC} = W_1 \bullet E_1 + W_2 \bullet E_2 + W_3 \bullet E_3 + W_4 \bullet E_4 + W_5 \bullet E_5 + W_6 \bullet E_6$$

1

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

$$EU/T = \frac{X_{EU} - X_T}{X_{EU}} \bullet 100\%$$

2,

where: EU – reference to emission limits described in European Union regulations, T – emission test results of 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),

X – values from approval regulations or research tests according to the subscript (Fig. 5c).

The commercial design solutions (for the Lifan GX 390 and Honda iGX 390 engine, respectively) are characterised by lower CO emissions below the permissible standards by 33% and 8%, while HC + NO_x emissions by 43% and 51%. It may be noted that the most innovative commercial design (Honda iGX

390) is characterised by higher CO emissions, being close to the permissible limit, while the design reduces HC + NO_x emissions by almost half of the permissible standards. 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 innovative solutions developed by the authors are aimed at limiting the emission of pollutants through the use of electronic fuel injection (gasoline) or fuel switching while maintaining a carburettor adapted to gaseous fuels. The results of the research show that the use of LPG and CNG fuels may 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 is at the level of 10% and 60%. It may be noticed that the engine fuelled by LPG significantly reduces CO while having the highest HC + NO_x emission among the tested engines. The second tested construction adapted to gaseous fuels, i.e. the engine fuelled by CNG is characterised by the lowest emission of pollutants taken into account during the EU type approval tests; this emission is the lowest 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 is better than the commercial units, but is inferior to the CNG-fuelled engine.

The research was extended to the analysis of exhaust emissions beyond the components included in the approval tests used in the European Union. CO₂ emissions were measured, as well as HC and NO_x emissions independently. Controlling CO₂ emissions is also important as this gas contributes to the greenhouse effect, but is better recycled by the environment than the others. All the components tested (CO, CO₂, HC, NO_x) are plotted against each other in the figures (CO and CO₂ in Fig. 6 and HC and NO_x in Fig. 7). The results of these tests will make it possible to assess the impact of the retrofits carried out. For this purpose, the results of tests on commercial units (A - German GX 390 and B - Honda iGX 390) have been summed up and the arithmetic mean has been drawn, making it possible to relate the results of retrofitting (of the innovative designs tested: C - LPG-fuelled engine, D - CNG-fuelled engine, E - electronic fuel injection engine) in relation to commercial solutions, denoted further by the K index. Comparison of CO, CO₂, HC, NO_x emissions of innovative designs (C - LPG-fuelled engine, D - CNG-fuelled engine, E - electronic fuel injection engine) with commercial K designs reveals that the CNG-fuelled engine has the best results. Its emissions are sequentially lower than commercial designs by 96%, 72%, 50% and has the lowest increase in NO_x emissions by 9%. A common effect of fuel switching from gasoline to CNG, consistent with the findings of other authors, is the reduction, of CO (Usman and Hayat 2019; Yaser et al. 2013; Geok et al. 2009; Shamekhi et al. 2006), CO₂ (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; Merkisha et al. 2012a; Zhang et al. 2011; Jahirul et al. 2010; Shamekhi et al. 2006) and an increase in NO_x (Singh et al. 2016; Huang et al. 2016; Mohamed 2006). CNG is composed of lighter hydrocarbons and the hydrogen to carbon ratio in CNG is much higher than in gasoline. This affects the combustion process in the cylinder, reducing the proportion of incomplete combustion and thus lower CO and HC emissions, while it favours an increase in NO_x emissions which may be due to an

increase in combustion temperature. On the other hand, the reduction in CO₂ is mainly associated with a reduction in fuel consumption. The reduction of NO_x emissions after fuel switching is characteristic of diesel engines (Merkisz et al. 2015). The use of LPG fuel contributed to a 93% reduction in CO and 53% reduction in HC emissions, while a 485% increase in CO₂ and 234% increase in NO_x emissions is noticeable. A common effect of fuel switching from petrol to LPG, consistent with the findings of other authors, is a reduction of CO (Çinar et al. 2016; Myung et al. 2014; Gümüş 2009), HC (Duc and Duy 2018; Çinar et al. 2016; Myung et al. 2014; Gümüş 2009) and an increase in CO₂ (Myung et al. 2014), NO_x (Çinar et al. 2016; Duc and Duy 2018). The combustion of LPG fuel is characterised by a more homogeneous fuel input mixture. Thus, there is better combustion and lower HC and CO emissions are produced, which favours NO_x emissions. On the other hand, this fuel has a lower carbon content and is characterised by higher fuel consumption, which has a strong effect on CO₂ emissions. Merkisz and Radzimirski, 2006 show that emissions are significantly affected by the level of technical sophistication of the LPG and gasoline fuel supply system, while Dziwiatkowski et al. 2020 (Dziwiatkowski et al. 2020) indicate that emissions are also affected by the wear of fuel supply system components. The use of an electronically controlled gasoline injection system reduced CO emissions by 59%, CO₂ emissions by 71%, HC emissions by 18%, and increased NO_x emissions by 10% relative to commercial solutions based on carbureted fuel systems. The reduction of CO (Yao et al. 2017) and HC (Yao et al. 2017) and a slight increase in NO_x emissions (Yao et al. 2017) by using electronic fuel injection relative to a carbureted system are consistent with the findings of other researchers. 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 carbureted systems that operate on enriched mixtures (Warguła et al. 2020d). Lower HC and CO emissions, this promotes higher NO_x emissions, and reduced fuel consumption through better fuel-air mixture selection reduces fuel consumption and thus CO₂ emissions.

The research has shown that an advantageous direction of development in the studied group of engines is the use of electronically controlled fuel injection or remaining with a carburettor fuel supply system and extending it with the possibility of fueling with gaseous fuels, of which CNG was characterised by the best effects in terms of reducing pollutant emissions. The authors recognise that access to and popularity of gaseous fuels will increase as biogas plants (Wąs et al. 2020) (increase in types of biodegradable materials (Czarnecka-Komorowska and Wiszumirska, 2020; Knitter et al. 2019; Czarnecka-Komorowska et al. 2018) and backyard natural gas fueling stations (Kuczyński et al. 2019) become more common. In parallel, gas-fuelled designs can be developed with electronically controlled gaseous fuel injection systems. In addition, all designs can be investigated for the impact of the use of exhaust after-treatment systems (Merkisz and Siedlecki 2017), adaptive control systems (Irmesus et al. 2014) and fuel additives (Le Anh et al. 2014).

4. Conclusion

The results of the research presented in the paper show that small SI engines intended for non-road machines used e.g. in machines for the construction and maintenance of road infrastructure, irrespective

of the level of innovation of the fuel supply system, do not exceed the permissible pollutant emission limits provided for in the NRSC type-approval tests applied in the European Union. The limits of permissible emissions are relatively high in relation to other groups of engines, thus, the innovative constructional solutions limiting the emissions (CO, CO₂, HC and NO_x), developed and examined by the authors, may contribute to legislative actions towards their tightening. A gasoline-fuelled design with an innovative injection system reduces CO, CO₂, HC emissions, as does 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, which was the lowest for commercial engines (with a carburettor fuel supply system with 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 and an increase in CO₂ and NO_x emissions.

Small SI engine fuel supply systems for non-road machines should adapt to their design solutions found in other engine groups that meet more stringent emission requirements. However, if legislators do not restrict the use of technologically obsolete designs, innovative solutions will not be used as they are more expensive. Small engine emissions are relatively high and therefore constitute an important problem for the environment and human health, mainly for machine operators working, inter alia, in the sector of the maintenance and construction of transport infrastructure.

5. Declarations

Ethical Approval

Not applicable

Consent to Participate

Not applicable

Consent to Publish

Not applicable

Authors Contributions

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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Competing Interests

Not applicable

Availability of data and materials

Not applicable

6. References

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Figures

Figure 1

Examples of machinery with small engines used in the construction and maintenance of road infrastructure, where: (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, (k) wood chipper

Figure 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; where numbers on the diagrams 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 (from 1.5 MPa to 0.01 MPa), 6 – low pressure tank (1 MPa), 7 – second-stage regulator (from 0.6 MPa to 0.01 MPa), 8 – first-stage regulator (from 20 MPa to 0.6 MPa), 9 – gas heater, 10 – high-pressure tank (20 MPa), 11 – 12 V battery, 12 – DC converter from 12 V to 230 V AC, 13 – electronic control unit, 14 – injector, 15 – electric fuel pump, 16 – wideband sensor of oxygen contents

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

Figure 3

Diagram of an engine chassis dynamometer for low-power engines, where: 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

Figure 4

Characteristics of the Lifan GX 390 internal combustion engine with carburettor power system during testing, where: a) characteristics of power, torque and speed as a function of time and b) characteristics of CO, HC, NOx, CO2 exhaust emissions and fuel consumption.

Figure 5

Emission of CO, HC+NO_x from small engine related to the emission limits in the European Union, where EU - emission limits allowed in the European Union, 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

Figure 6

CO2 emission, CO from small engine, where K - is the average emission from commercial engines, 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

Figure 7

HC, NOx emission from small engine, where K - is the average emission from commercial engines, 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

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