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5. Smigins R., **Sondors K.**, Pirs V., Dukulis I., Birzietis G. (2023). Studies of engine performance and emissions at full-load mode using HVO, diesel fuel, and HVO5. *Energies*, 16(2), article number 4785. DOI: 10.3390/en16124785 (Scopus, Web of Science, AGRIS, CAB Abstracts, Chemical Abstracts, Current Contents – Engineering, Computing & Technology (Clarivate Analytics), DOAJ – Directory of Open Access Journals, EconPapers (RePEc), Ei Compendex / Engineering Village (Elsevier), ETDE – Energy Technology Data Exchange (IEA), Inspec (IET), https://www.mdpi.com/1996-1073/16/12/4785).

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CONTENT

INVESTIGATION IN TRACTOR CLAAS ARES 557ATX OPERATING PARAMETERS USING HYDROTREATED VEGETABLE OIL FUEL

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Abstract. Hydrotreating of vegetable oils, animal fats, waste cooking oils and algae is an alternative process to esterification for producing bio-based diesel fuels. Hydrotreated vegetable oil (HVO) belongs to the second generation BTL (biomass-to-liquid) biofuels group. Investigation of tractor *CLAAS ARES 557ATX* was carried out determining the engine power, torque, fuel consumption and exhaust gas content running the engine on two different fuels – hydrotreated vegetable oil and fossil diesel fuel. Power take-off dynamometer *MAHA ZW-500*, *AVL KMA MOBILE* fuel consumption meter, and *AVL SESAM FTIR* multi-component exhaust gas measurement system were used during these experiments. It was established that the average effective power and torque reduction using HVO fuel was about 5.0 % in comparison with fossil diesel fuel. The hourly fuel consumption using HVO was by about 1 % lower comparing to diesel fuel, but the increase of specific fuel consumption was in average by 4.1 % higher. Running the tractor on HVO the average reduction of NO_x in comparison with fossil diesel was 11.8 %. Decrease of total unburned hydrocarbons, CO and CO_2 was accordingly 26.4, 14.5 and 5.2 %.

Keywords: biofuels, hydrotreated vegetable oil, effective power, effective torque, fuel consumption.

Introduction

A lot of different EU directives and regulations are dedicated to decrease greenhouse gas emissions, to increase the share of renewable energy, and to improve energy efficiency. One of the latest documents – communication of the European Commission "A policy framework for climate and energy in the period from 2020 to 2030" states that greenhouse gas emissions in 2012 decreased by 18 % relative to emissions in 1990 and are expected to reduce further by 24 % in 2020, but the share of renewable energy has increased to 13 % in 2012 as a proportion of final energy consumed and is expected to rise to 21 % in 2020 [1]. The use of biofuels can promote to reach both of these targets.

Liquid biofuels commercially available today are mainly the so called first generation biofuels. The first generation biofuels are commonly derived from oil, starch or sugar containing plants that can be used in food. In order to mitigate against possible impacts of some biofuels, the European Commission has proposed to limit the amount of the first generation biofuels towards the 5 %, and to increase the incentives for advanced biofuels such as those made from ligno-cellulosic biomass, residues, waste, and other non-food biomass, including algae and microorganisms. After 2020 only the next, i.e., second, third and even fourth generation biofuels should receive public support. Communication of the European Commission "Clean power for transport: a European alternative fuels strategy" notes that there is no single fuel solution for the future of mobility and all main alternative fuel options have to be pursued, with a focus on the needs of each transport mode. A strategic approach for the EU must therefore build on a mix of alternative fuels without giving preference to any particular fuel [2].

Hydrotreated vegetable oil (HVO) that can be produced from triglycerides based biomass such as vegetable oil, animal fat, waste cooking oil and algae is one of the most perspective next generation biofuels in nearest future. Sometimes instead of the term "hydrotreated vegetable oil" researchers are using "hydrogenated vegetable oil", "hydroprocessed vegetable oil" etc. A number of manufacturers around the world, i.e., *Neste Oil* (Finland), *Conocophillips* (USA and Ireland), *Syntroleum* (USA), *Universal Oil Products (UOP)-Eni* (UK and Italy), *Nippon Oil* (Japan) and *SK Energy* (Korea) have developed HVO refining processes and tested them in commercial trials. Some of these fuels acquired their own trade names, for example, NExBTL (an acronym for "next generation bio-to-liquid") is the trade name of the HVO produced by *Neste Oil Corporation*, "Green Diesel" – produced by *UOP-Eni*, HBD (hydrogen-treating biodiesel) – produced by *SK Energy* [3].

During HVO processing three reactions take place – hydrogenation of double bonds present in unsaturated chains of bonded fatty acids, removal of oxygen atoms from carboxylic group in the form of water (hydrodeoxygenation), and elimination of carboxylic group in the form of carbon dioxide (hydrodecarboxylation) [4].

The main fossil diesel and HVO properties are compared in Table 1 [3-10].

Table 1

Fossil diesel fuel and HVO properties

Parameter	Fossil diesel fuel	HVO
Density, $kg \cdot m^{-3}$	820 … 850	775 … 785
Viscosity, $mm^2 \cdot s^{-1}$	2.2 … 3.5	2.5 … 3.5
Cloud point, ºC	-5 … -30	3 … -30
Lowest heating value (LHV_{mass}), $MJ \cdot kg^{-1}$	42.5 … 43.0	43.8 … 44.0
Lowest heating value (LHV_{volume}), $MJ \cdot l^{-1}$	34.9 … 36.6	33.9 … 34.5
Cetane number	51 … 60	80 … 99
Sulphur content, $mg \cdot kg^{-1}$	<12	≈0
Oxygen content, $mg \cdot kg^{-1}$	≈0	≈0

HVO like fossil diesel is not oxygenated fuel and density for it is lower than that of fossil diesel fuel. HVO has ultra-low sulphur content, high cetane number and heating value that is beneficial for use in compression ignition engines. Analysis of investigations of HVO application shows that most of the standard parameters are similar to or better than those of fossil diesel fuel, but low-temperature properties are worse [3; 4]. Most of the studies are devoted to determine the changes of physiochemical properties of HVO using different catalysts and reaction conditions (for example, temperatures and pressures) during fuel production. However, only few studies have been conducted on the engine power and torque measurement, and fuel consumption determination [3].

Testing a turbocharged 8.4 liter 6-cylinder 4-stroke direct injection heavy duty diesel engine in Finland it was established that the use of hydrotreated vegetable oil enables reductions in CO, total hydrocarbon, and NO_x emissions without any changes to the engine or its controls [5]. A 1.5 liter DOHC (double overhead camshaft) diesel engine was used in the Republic of Korea to evaluate the differences of performance using biodiesel and HVO blends with fossil diesel fuel. The investigation results show decreases in the power – the more biodiesel or HVO is blended, the more power decreased, for example, blending 2 % of biodiesel to fossil diesel the power loss was approximately 1.4 %, blending 20 % – about 2.5 %, but blending 50 % – more than 5 %. Blending the same volume of HVO to fossil diesel fuel the power loss was accordingly 0.7, 1.8 and 1.2 %. Biodiesel blended diesel shows the increase of fuel consumption when the blending ratio goes up (approximately from 1 to 8 %), but for HVO blends a small decrease of fuel consumption was observed (up to 1 %) [10].

Most of the studies investigating the use of HVO fuel are realized testing engines on the benches, but rarely – the car or tractor in general. Since agriculture is one of the main branches in Latvia, but tractors consume a great part of diesel fuel the aim of this research is to determine the main operating parameters (power, torque, fuel consumption, and emissions) of the tractor *CLAAS ARES 557ATX* running it on two different fuels – pure hydrotreated vegetable oil and fossil diesel fuel.

Materials and methods

The main fuel parameters were determined in an independent certified laboratory (See Table 2).

Table 2

Main parameters of tested fuels

Parameter	Fossil diesel fuel	HVO
Density at 15 ºC, kg m^{-3}	836.3	778.9
Viscosity at 40 ºC, mm^2 s^{-1}	2.6	2.9
Lowest heating value (LHV_{mass}), MJ kg^{-1}	43.5	44.2
Lowest heating value (LHV_{volume}), MJ l^{-1}	36.4*	34.4*
Cetane number	52.4	74.7

* – LHV_{volume} in MJ l^{-1} is calculated form measured LHV_{mass} in MJ kg^{-1} and density

The test object – tractor *CLAAS ARES 557ATX* – is equipped with a 4.5 liter 4-cylinder direct injection cooled turbo diesel engine (year of production – 2007, maximum engine power in accordance with ISO TR 14 396 – 77.5 kW at 2100 min^{-1}, maximum torque – 421 Nm at 1400 min^{-1}, specific fuel consumption – 218 g·kWh^{-1} at 1700 min^{-1}).

The tractor power was determined from the power take-off (PTO) using dynamometer *MAHA ZW-500* (See Fig. 1a). Simultaneously the hourly fuel consumption and exhaust emissions were measured, accordingly using *AVL KMA MOBILE* fuel consumption meter and *AVL SESAM FTIR* multi-component exhaust gas measurement system (See Fig. 1b and 1c).

b)

a)

c)

Fig. 1. **Test object and measuring equipment:** a – *CLAAS ARES 557ATX* and *MAHA ZW-500*; b – *AVL KMA MOBILE*; c – *AVL SESAM FTIR*

The maximum power to be measured from PTO using *MAHA ZW-500* is 500 kW, the maximum torque – 6600 N·m, the maximum PTO speed – 2500 min^{-1}, and the measurement accuracy ±2 %. The measured parameters can be determined at the entire revolution range, setting the measurement program (PTO revolutions range, step, and holding time) on the hand-held terminal. The *AVL KMA MOBILE* system measures the volumetric fuel consumption within very short measurement times. The measurement is possible up to 150 l·h^{-1} fuel flow with 0.1 % accuracy of reading. The *AVL SESAM* multicomponent exhaust gas measurement system is based on the FTIR (Fourier Transform Infrared Spectroscopy) optical measurement method that can diagnose up to 25 different exhaust gas components (for example, CO_2, CO, SO_2, NO, NO_2, CH_4 etc.) simultaneously. In addition, some collective components can be calculated, for example, NO_x and total hydrocarbons (THC).

Taking into account the nominal engine crankshaft frequency (2200 min^{-1}) of the test object and the PTO transmission ratio (3.67), the power determination was performed at PTO revolutions range from 300 to 625 min^{-1} with 25 min^{-1} step. The holding time at each measuring point was set to 15 seconds. Five repetitions were performed for each fuel. Examples of raw data – a printout from the *MAHA ZW-500* hand-held terminal and a fuel consumption graph – are shown in Figure 2.

To calculate the corresponding engine crankshaft revolutions n (min^{-1}), the following formula was used:

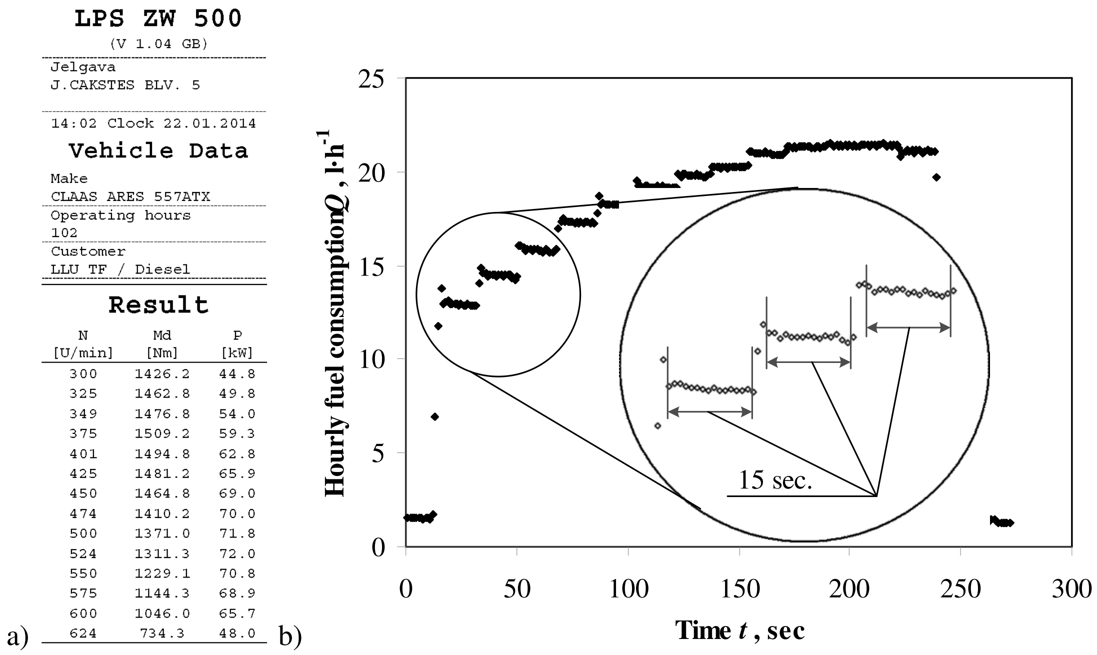
$$n = n_{PTO} \cdot i \,, \tag{1}$$

where i – PTO transmission ratio, 3.67;
n_{PTO} – PTO revolutions, min^{-1}.

The effective power of tractor engine N (kW) was calculated by formula:

$$N = \frac{N_{PTO}}{\eta} \,, \tag{2}$$

where η – PTO transmission efficiency, 0.95;
N_{PTO} – power measured from PTO, kW.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N [U/min]	Md [Nm]	P [kW]
300	1426.2	44.8
325	1462.8	49.8
349	1476.8	54.0
375	1509.2	59.3
401	1494.8	62.8
425	1481.2	65.9
450	1464.8	69.0
474	1410.2	70.0
500	1371.0	71.8
524	1311.3	72.0
550	1229.1	70.8
575	1144.3	68.9
600	1046.0	65.7
624	734.3	48.0

Fig. 2. **Examples of raw experiment data:** a – printout from the *MAHA ZW-500* hand-held terminal; b – raw fuel consumption graph

The effective torque of the tractor engine M (N m) was calculated using the relationship:

$$M = \frac{M_{PTO}}{i \cdot \eta}, \tag{3}$$

where M_{PTO} – torque measured from PTO, N m.

As the 15 seconds loading on certain PTO revolutions starts only when the revolutions become stable (after approximately 3 seconds) for further analysis the raw fuel consumption data have to be cut out (See Fig. 2b). Similarly to raw fuel consumption data look also individual exhaust emission components measuring graphs, but, due to the specifics of exhaust gases and the measuring device, stabilization of a certain component amount takes longer time and it is very difficult to cut out 15 seconds data intervals like for the fuel consumption. That is why it was decided to calculate an average amount of each emission component in all PTO revolutions range from 300 to 625 min^{-1}.

Since both diesel injection systems and fuel dispensing systems deliver fuel by volume, the specific fuel consumption g_e was calculated not in g·kW^{-1}·h^{-1} as usually, but in l kW^{-1}·h^{-1}:

$$g_e = \frac{Q_{(l \cdot h^{-1})}}{N_e}. \tag{4}$$

Results and discussion

The experimental results after data processing (confidence level – 95 %) are shown in Fig. 3-5.

The engine effective power and torque using HVO were decreased relatively to fossil diesel fuel – the average power and torque reduction in all PTO revolutions range was about 5.0 % (See Fig. 3). This value is close to the difference in the volume-based lowest heating values LHV_{volume} (accordingly 36.4 and 34.4 MJ l^{-1}), i.e., to 5.5 % (see Table 2).

Despite the fact that the hourly fuel consumption using HVO was approximately by 1 % decreased comparing to diesel fuel, lower developed engine effective power with this fuel is the reason for the increase of the specific fuel consumption in average by 4.1 % (See Fig. 4).

In comparison with fossil diesel, running engine on HVO the average reduction of NO_x was 11.8 %. The amount of other important components influencing environment – total unburned hydrocarbons (THC), CO and CO_2, using HVO was also decreased – accordingly by 26.4, 14.5 and 5.2 % (See Fig. 5).

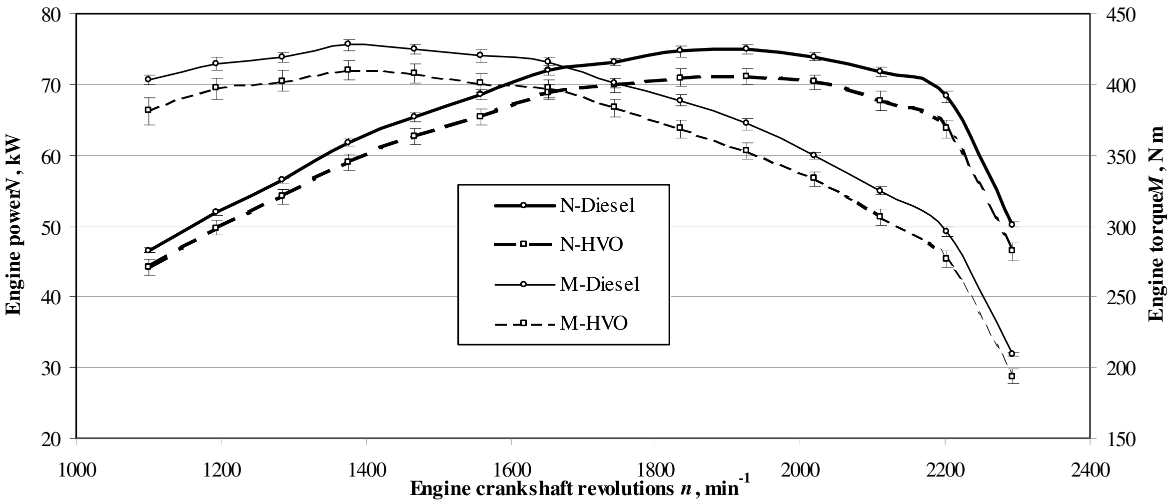

Fig. 3. **Engine effective power and torque characteristics**

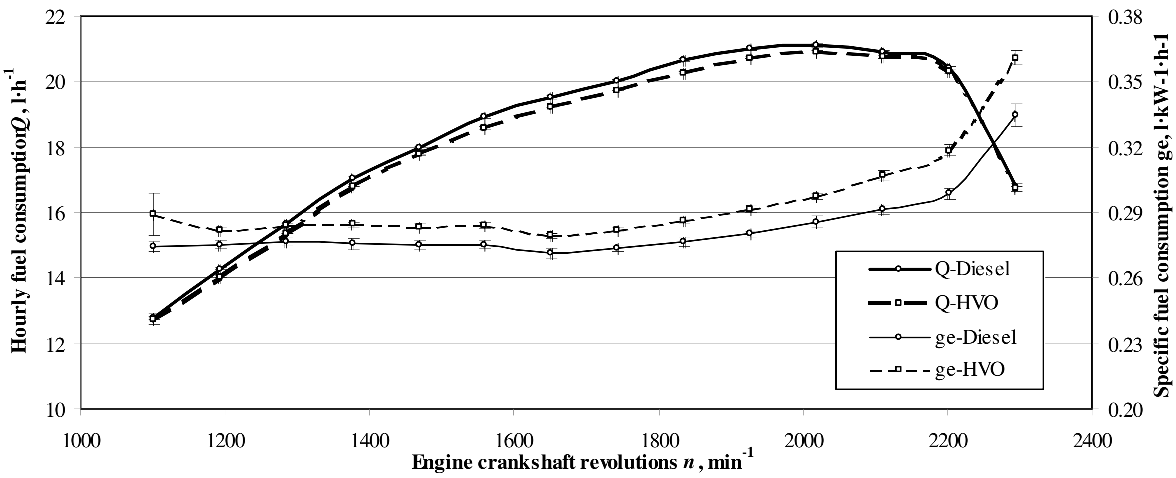

Fig. 4. **Fuel consumption characteristics**

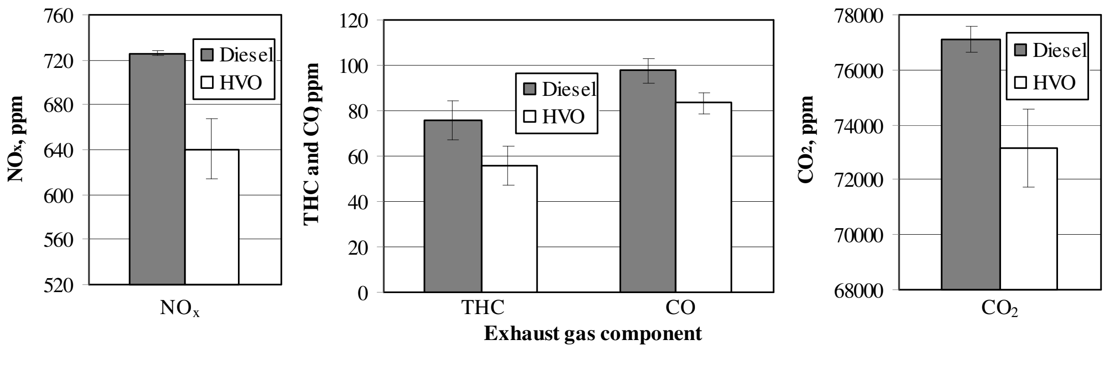

Fig. 5. **Content of NO_x, THC, CO and CO_2 in exhaust gases**

Summarizing the obtained data it can be concluded that HVO is environmentally friendly fuel with a small hourly fuel consumption economy, but the user has to be ready for power and torque reduction, close to the difference in HVO and fossil diesel fuel lowest volume-based heating values.

Since the results of the investigation "Key properties and blending strategies of hydrotreated vegetable oil as biofuel for diesel engines" carried out in Spain, Colombia and the USA show that a compromise between lubricity, cetane number, and cold flow properties, especially in colder regions, like in Latvia, leads to a recommendation for low or medium HVO concentrations, and blends with HVO content above 50 % are not recommended in unmodified diesel engines [7], the power and torque reduction using blends would not be so considerable. It is approved by studies performed in different countries, for example, in the Republic of Korea [10]. Of course, it has to be considered that testing biofuels the results are strongly dependant on the quality of fuel and raw materials used for their production, test vehicle and fuel injection system type, etc. That is why in future investigations it is necessary to test other type vehicles, for example, passenger cars and trucks, using HVO in pure form and in blends, especially in proportions that are most realistic implementation scenarios in nearest future, i.e., low content (up to 30 %) HVO blends with fossil diesel fuel.

Conclusions

1. Performing research of the tractor *CLAAS ARES 557ATX*, it was established that the engine effective power and torque using HVO fuel decreases relatively to fossil diesel fuel. The average power and torque reduction in PTO revolutions was about 5.0 %. It can be explained by the 5.5 % difference in the volume-based lowest heating values of both fuels.
2. The average hourly fuel consumption in PTO revolutions range from 300 to 625 min^{-1} using HVO was by about 1 % lower comparing to diesel fuel, but due to the lower developed engine power the increase of the specific fuel consumption was in average by 4.1 % higher.
3. Running the tractor on HVO the average reduction of NO_x in comparison with fossil diesel was 11.8 %. The amount of total unburned hydrocarbons (THC), CO and CO_2 was also decreased – accordingly by 26.4, 14.5 and 5.2 %.
4. In future studies it is necessary to test other vehicle types, for example, passenger cars and trucks, using HVO in pure form and in low content HVO blends with fossil diesel fuel, that are most realistic implementation scenarios in nearest future.

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THEORETICAL EVALUATION OF HYDROTREATED VEGETABLE OIL APPLICATION IN DIESEL ENGINES

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Abstract
A lot of different EU directives and regulations set the targets to decrease greenhouse gas emissions, to increase the share of renewable energy, and to improve energy efficiency. Biofuel usage is directly linked to all of these problems. Since the first generation food-based biofuels should not receive public support after 2020, investigations of next generation biofuels are topical. Hydrotreated vegetable oil (HVO) is one of the most promising next generation biofuels in the near future. This article deals with the results of mathematical modelling to determine the main diesel engine operating parameters (power, torque and fuel consumption) running them on HVO and its blends with fossil diesel fuel. The modelling results of the car *Opel Insignia 2.0 CDTi* show that every 5% of HVO in fuel blend reduces maximum power and torque of around 0.38% while raising specific fuel consumption by volume of around 0.10%. Analyzing the most realistic scenario in the near future – 7% HVO and 93% fossil diesel blend, the predicted fuel consumption increase (0.14%) and power and torque decrease (0.54%) is inconsiderable for vehicle exploitation, and HVO seems to be a promising biofuel to replace biodiesel in fuel blends and to promote reaching the EU targets.
Key words: biofuels, hydrotreated vegetable oil (HVO), mathematical modelling, power, torque, fuel consumption.

Introduction

A number of directives and regulations define biofuels use in the EU, for example, the Biofuels Directive, the Renewable Energy Directive, the Fuel Quality Directive etc. One of the latest documents – the Communication of the European Commission 'A policy framework for climate and energy in the period from 2020 to 2030' – was published on 23 January 2014.

Analyzing the EU targets 20/20/20 to be attained by 2020, i.e., greenhouse gas emissions reduction (20%), share of renewable energy (20%), and improvements in energy efficiency (20%), it was stated that the certain progress has been achieved (A policy framework …, 2014):

- greenhouse gas emissions in 2012 decreased by 18% relative to emissions in 1990 and are expected to reduce further by 24% and 32% in 2020 and 2030;
- the share of renewable energy has increased to 13% in 2012 as a proportion of final energy consumed and is expected to rise further to 21% in 2020 and 24% in 2030 respectively;
- the EU had installed about 44% of the world's renewable electricity (excluding hydro) at the end of 2012;
- the energy intensity of the EU economy has reduced by 24% between 1995 and 2011 whilst the improvement by industry was about 30%;
- the carbon intensity of the EU economy fell by 28% between 1995 and 2010.

The future of EU transport development should be based on alternative, sustainable fuels. The Commission has therefore not proposed new targets for the transport sector after 2020 (current target is 10% renewable energy). Based on the lessons of the existing target and on the assessment of how to minimise indirect land-use change emissions, it is clear that the first-generation biofuels have a limited role in decarbonising the transport sector (Biofuels Policy and Legislation, 2014) and the EU Commission has already indicated, that food-based biofuels should not receive public support after 2020 (A policy framework …, 2014).

At present the major part of the biofuels consumption in the world and in the European Union, including Latvia, is formed by the first-generation biofuels – biodiesel, bioethanol and rapeseed oil. Lately relatively little has been done to research the latest generation fuels and the results obtained are contradictory. The same inconsistency exists also in the classification of biofuels in the so-called generations (Carriquiry et al., 2011). The prevailing standpoint is that the first-generation biofuels commonly are derived from oil, starch or sugar containing plants that can be used in food. The second-generation biofuels are produced from non-food raw materials such as wood, straw, green grass, organic waste etc. Algae, microbes, cellulose and sea weed is a stock for the third-generation biofuels, but the fourth-generation biofuels in future will be produced from genetically modified plants (Carere et al., 2008; Scragg, 2009; Third and Fourth Generation ..., 2010; Demirbas, 2011a; Demirbas, 2011b; Nigam and Singh, 2011; Singh et al., 2011).

Hydrotreated vegetable oil (HVO) is one of the most promising next generation biofuels in the near future. It can be produced from the triglycerides based biomass such as vegetable oil, animal fat, waste cooking oil and algae (No, 2014).

Hydroprocessing of vegetable oils allows easy transformation of fatty acid triglycerides into

Table 1

Fossil diesel, biodiesel and HVO properties

Parameter	Fossil diesel	Biodiesel	HVO
Density, kg m^{-3}	820 … 850	860 … 900	775 … 785
Viscosity, mm^2 s^{-1}	2.2 … 3.5	3.5 … 5.0	2.5 … 3.5
Cloud point, °C	-5 … -30	-5 … 15	3 … -30
Distillation, °C	340 … 350	350 … 375	180 … 320
Lowest heating value, MJ kg^{-1}	42.5 … 43.0	37.5 … 38.0	43.8 … 44.0
Cetane number	51 … 60	50 … 65	80 … 99
Sulphur content, mg kg^{-1}	< 12	< 1	» 0
Oxygen content, mg kg^{-1}	» 0	» 11	» 0

hydrocarbons. Three most important reactions take place during processing (Šimáček et al., 2010):

- hydrogenation of double bonds present in unsaturated chains of bonded fatty acids;
- hydrodeoxygenation – removal of oxygen atoms from carboxylic group in the form of water;
- hydrodecarboxylation – elimination of carboxylic group in the form of carbon dioxide.

The main fossil diesel, biodiesel and HVO properties are summarized in Table 1 (Aatola et al., 2008; Šimáček et al., 2009; Arvidsson et al., 2011; Lapuerta et al., 2011; Bezergianni and Dimitriadis, 2013; Pinto et al., 2013; No, 2014; Kim et al., 2014).

It can be seen from the data of Table 1 that HVO is not oxygenated fuel and the density of it is lower than that of fossil diesel and biodiesel. HVO has ultra-low sulphur content, high cetane number and heating value which is very beneficial in fuel for combustion ignition (CI) engines.

Analysis of more than 50 different investigations of HVO application was performed in the Republic of Korea (No, 2014). It was concluded that HVO has a higher oxidation stability than biodiesel, but shows poorer low-temperature performance than fossil diesel.

Emission characteristics of neat HVO and blends of HVO with fossil diesel are widely investigated by many researchers. Most of these studies show that HVO generally reduces NO_x emissions compared to conventional diesel and biodiesel. Performing investigations in Finland (Aatola et al., 2008) the test engine was a turbocharged 8.4 liter 6-cylinder 4-stroke direct injection heavy duty diesel engine. The engine was equipped with a common-rail fuel injection system and a charge air cooler. No exhaust gas recirculation (EGR) or exhaust after treatment device was used. The nominal power of the engine was 225 kW at 2200 min^{-1}. The results of the investigations show that the use of hydrotreated vegetable oil enables reductions in CO, total hydrocarbons (THC), and NO_x emission, and in engine smoke without any changes to the engine or its controls.

However, only a few studies have been conducted on the spray and burn characteristics of neat HVO and blends of HVO with fossil diesel in CI engine conditions (No, 2014), as well as on the engine power and torque measurement, and fuel consumption determination.

Most of the studies investigating the use of HVO fuel are done by testing engines on the benches, but rarely – the car or tractor in general. For example, a 1.5 liter DOHC diesel engine was used for engine dynamometer test to evaluate the differences of performance using biodiesel and HVO blends with fossil diesel fuel (Kim et al., 2014). HVO and biodiesel blended diesel show decreases in the power – the more biodiesel or HVO is blended, the more power decreased, for example, blending 2% of biodiesel to fossil diesel the power loss was approximately 1.4%, blending 20% – approximately 2.5%, but blending 50% – more than 5%. Blending the same volume of HVO to fossil diesel the power loss was accordingly 0.7, 1.8 and 1.2%. Volume-based lowest heating values (LHVs) of biodiesel and HVO are less than that of fossil diesel. It is common that the maximum power decreases when lower caloric value fuels are used. Biodiesel blended diesel shows the increase of fuel consumption when the blending ratio goes up (approximately from 1 to 8%), but HVO show a slight decrease of fuel consumption while their blending ratios increase (up to 1%) (Kim et al., 2014).

The aim of this research is to perform mathematical modelling to determine the main diesel engine operating parameters (power, torque and fuel consumption) running them on HVO and its blends with fossil diesel fuel.

Materials and Methods

The first step to reach the aim of this investigation is creating the mathematical model to perform thermodynamic calculations of diesel engine operation, to construct engine's effective power and torque curves, and to calculate fuel consumption.

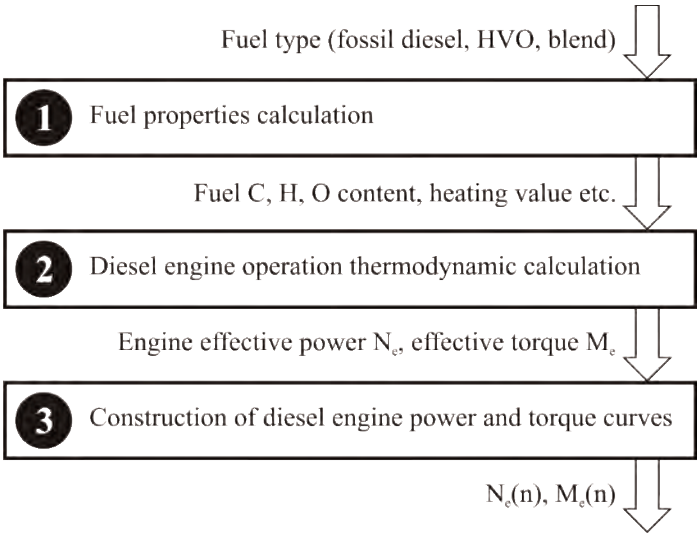

Figure 1. Model's block diagram.

Instead of creating a new model it was decided to modify an existing one that was developed in the doctoral thesis 'Rapeseed Oil Fuel Application in Diesel Engines and Logistics' (Dukulis, 2013) and described in the publication 'Development of the Model for Running the Diesel Engine on Rapeseed Oil Fuel and Its Blends with Fossil Diesel Fuel' (Dukulis and Birkavs, 2013).

This model was created in *ExtendSim* environment. Since the model is provided to evaluate the rapeseed oil fuel usage in diesel engines, the first module that calculates fuel's properties, for example, content of carbon (C), hydrogen (H) and oxygen (O) in fuel blend, heating value etc., have to be transformed substantially. The second module performs engine operation thermodynamic calculation, but the third one – constructs engine effective power and torque curves (Fig. 1). Last two modules do not need significant changes.

If the fuel blend percentage is known, the content of carbon (C), hydrogen (H) and oxygen (O) in fuel blend in fuel mass fractions can be calculated from the relationships (Šmigins, 2010):

$$C = \frac{\sum_{i=1}^{n} C_{cont-i} \cdot m_i}{\sum_{i=1}^{n} m_i}, \quad H = \frac{\sum_{i=1}^{n} H_{cont-i} \cdot m_i}{\sum_{i=1}^{n} m_i},$$

$$O = \frac{\sum_{i=1}^{n} O_{cont-i} \cdot m_i}{\sum_{i=1}^{n} m_i}, \qquad (1)$$

where
m_i – i_{th}-fuels content in blend, mass %;
C_{cont-i} – content of carbon in i_{th}-fuel, mass parts;
H_{cont-i} – content of hydrogen in i_{th}-fuel, mass parts;
O_{cont-i} – content of oxygen in i_{th}-fuel, mass parts.

The content of carbon, hydrogen, and oxygen in fossil diesel fuel is already known for a long time (the average values for modelling are assumed 0.870, 0.124, and 0.006 respectively). Since HVO is a relatively new fuel, a lot of researchers around the world investigate physicochemical properties of HVO depending on hydrotreatment temperature and catalysts. The average values are – 0.848 for carbon, 0.150 for hydrogen, and 0.002 for oxygen (Lapuerta et al., 2011; Pinto et al., 2013; Bezergianni et al., 2014).

The lower heating value Q_{lower} (J kg^{-1}) for any fuel can be calculated using classical relationship:

$$Q_{lower} = (33.91 \cdot C + 103.01 \cdot H - 10.89 \cdot O) \cdot 1000. \qquad (2)$$

The model blocks for determination of the fuel blend content and lower heating value are shown in Figure 2. Performing test simulations of these blocks, the calculated (theoretical) lower heating value for pure HVO is 44185 J kg^{-1}, but for fossil diesel fuel – 42209 J kg^{-1}. Comparing these values with the data from the Table 1, coincidence is close.

The second model's module 'Diesel engine operation thermodynamic calculation' determines engine's effective power and torque based on several fuel content sensitive parameters, for example, the theoretical amount of air required for combustion of 1 kg fuel, inlet pressure, temperature and pressure of fresh air-fuel mixture, residual gas pressure and coefficient, cylinder filling factor, pressure and temperature at the end of the compression stroke, the total and individual amount of combustion products, combustion products temperature etc. The

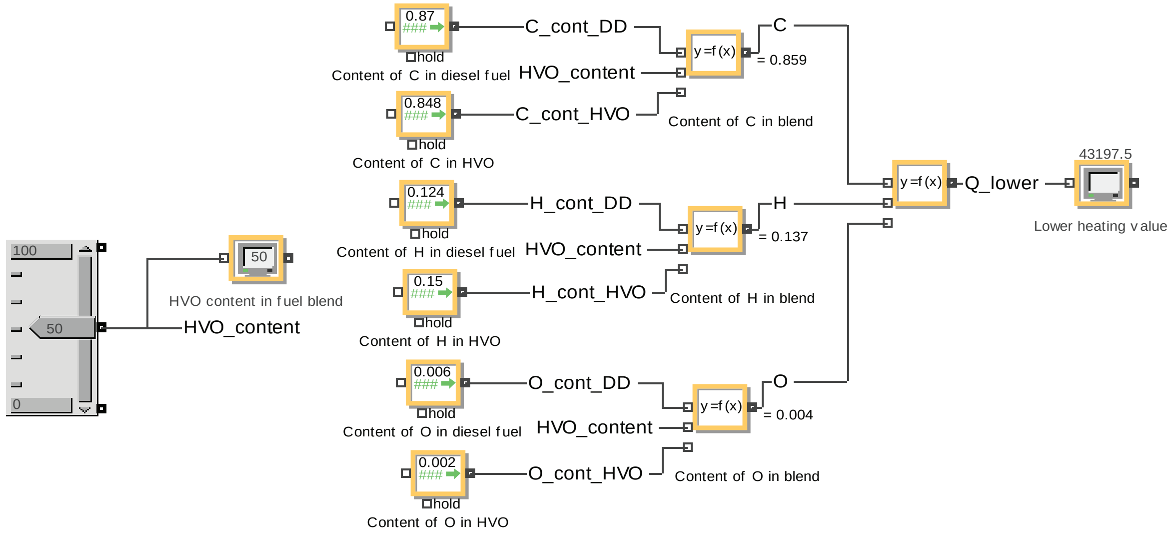

Figure 2. Fuel blend content and lower heating value determination blocks.

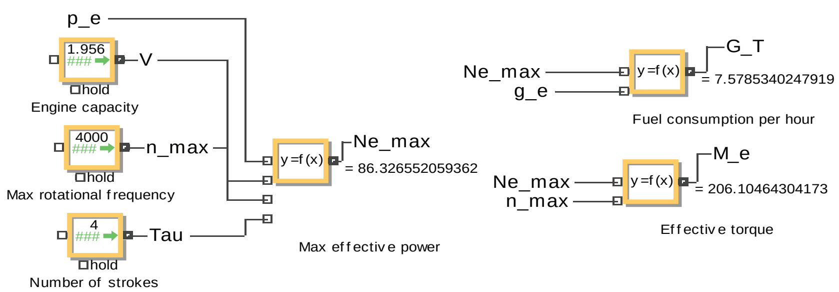

Figure 3. Engine power, fuel consumption and torque calculation blocks.

thermodynamic calculation of diesel engine operation is based on the classical relationships, given in the various sources of information (Internal Combustion Engine Handbook, 2004; Xin, 2011), but the existing model (Dukulis, 2013) was supplemented with a possibility to enter coefficients specific to the certain engine, depending on whether the engine is turbo-charged or not, with direct injection or precombustion chamber etc.

Since the diesel engine operation thermodynamic calculation module consists of about one hundred blocks only a few of them are shown in this article. The output parameters from the second module are: a maximum effective power N_{emax} (kW) at engine crankshaft rotational frequency n_{max} (min^{-1}), fuel consumption per hour G_T (kg h^{-1}), and an effective torque M_e (N m) at the same crankshaft rotational frequency n_{max} (Fig. 3).

If the maximum effective engine power N_{emax} and engine crankshaft rotational frequency n_{max} at which this power is developed are known, the engine effective power at any engine crankshaft rotational frequency can be determined according to the empirical relationship (Pommers and Liberts, 1985):

$$N_e = N_{e\max} \cdot \left[X \cdot \frac{n_e}{n_{\max}} + Y \cdot \left(\frac{n_e}{n_{\max}} \right)^2 - Z \cdot \left(\frac{n_e}{n_{\max}} \right)^3 \right] \cdot \quad (3)$$

where

N_e – engine effective power at engine crankshaft rotational frequency n_e, kW;

n_e – engine crankshaft rotational frequency at the point to be determined, min^{-1};

X,Y,Z – the empirical coefficients describing the engine type ($X + Y – Z = 1$).

If the value of the engine power in the full crankshaft rotational frequency range is known, the torque can be calculated using formula:

$$M_e = 9549 \cdot \frac{N_e}{n_e}. \quad (4)$$

Engine modelling studies are carried out for the same vehicle that is planned to be used later in the experimental studies, i.e., the passenger car *Opel Insignia 2.0 CDTi* (year of production – 2011, engine working capacity or volume – 1956 cm^3; compression ratio – 16.5).

Results and Discussion

In order to facilitate the input of variables and view the simulation results, a separate panel or window is set up. The essential elements of the model are 'cloned' in this window. Figure 4 shows an example of the car *Opel Insignia 2.0 CDTi* modelling.

The maximum power 94.49 kW for the car *Opel Insignia 2.0 CDTi* using diesel fuel is reached at 4000 min^{-1}, but maximum developed torque is 299.87 N m. Comparing acquired power and torque modelling values with the data given by motor vehicle manufacturers (128 hp or 96 kW and 300 N m respectively), differences do not exceed 2%. Such cut-off for modelling studies is permissible and does not interfere with the identification of differences among operating motor vehicles with various fuels.

The results of investigation 'Key properties and blending strategies of hydrotreated vegetable oil as biofuel for diesel engines' carried out in Spain, Colombia and USA (Lapuerta et al., 2011) show that a compromise between lubricity and cetane number would lead to a recommendation for low or medium HVO concentrations, and blends with concentrations above 50% would not be recommended in unmodified diesel engines. In colder regions, like in Latvia, especially in winter time cold flow properties of fuel blends also have to be considered. Every 10% of HVO in fuel blend deteriorate Cold Filter Plugging Point and Cloud Point temperatures accordingly by approximately 4.0 and 1.5 °C (Lapuerta et al., 2011). That is why in modelling studies blends of HVO with a diesel fuel in 5, 7, 10, 15, 20, and 25 vol.% are analysed. Additionally 7% blend is chosen because such amount of biofuel blend to fossil diesel is planned to be introduced in the fuel market in Latvia

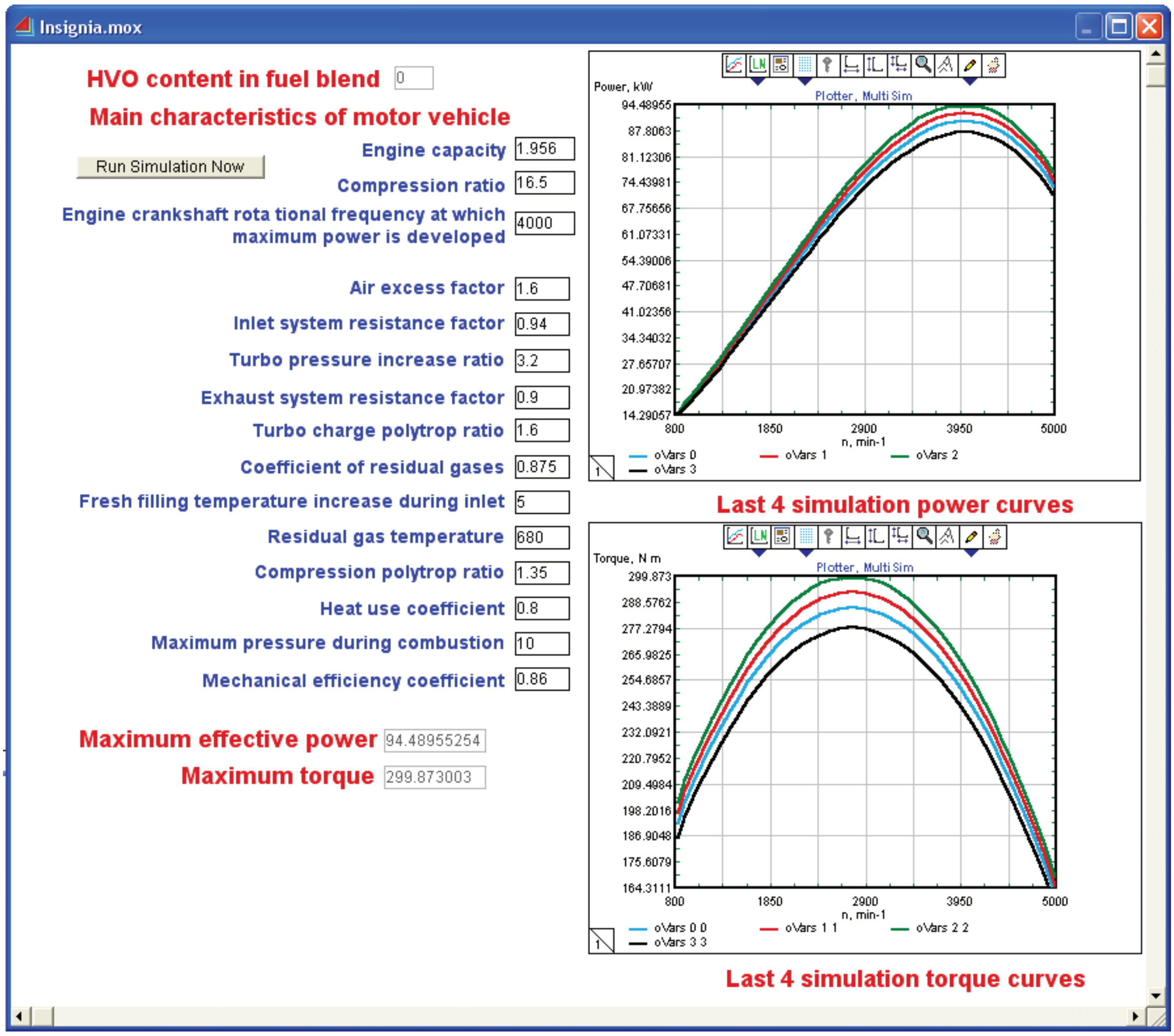

Figure 4. Example of the window for variables input and viewing of the simulation results.

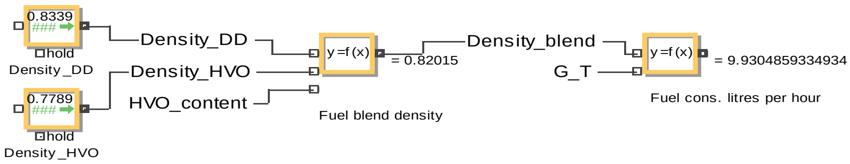

Figure 5. Fuel blend density and fuel consumption calculation blocks.

from 1 April 2014. Unfortunately, for now it could not yet be HVO because the Biofuel Law of Latvia, unlike many other countries, disclaim HVO as biofuel. But more than likely this problem legislatively will be solved in the near future.

Simulation results show, that the power and torque reduction for the car *Opel Insignia 2.0 CDTi* is linear – every 5% of HVO in fuel blend reduces maximum power and torque of around 0.38%, reaching the maximum power and torque difference for 25% HVO and 75% fossil diesel blend – 1.91%. Considering that 7% HVO and 93% fossil diesel blend is the most realistic scenario in the near future, predicted power and torque decrease (0.54%) is inconsiderable for vehicle exploitation.

Another important parameter is fuel consumption. In the case of HVO, the greater lower heating value (in modelling studies 4.5% higher than that of pure diesel fuel) makes reductions in specific fuel consumption when blends are used. Simulation shows that every 5% of HVO in fuel blend reduces specific fuel consumption of around 0.23%, reaching the maximum hourly consumption (kg h^{-1}) difference for 25% HVO and 75% fossil diesel blend – 1.15%. However, such interpretation on a mass basis is incorrect. The HVO fuel, despite having a greater heating value, has lower density. Since both diesel injection systems and fuel dispensing systems deliver fuel by volume, it is the volume-based heating value, and not the mass-based one which directly affects the engine specific fuel consumption. That is why additional blocks were added to the model recalculating hourly fuel consumption from kg h^{-1} to l h^{-1} (Fig. 5).

Recalculating hourly fuel consumption to l h^{-1} (at engine crankshaft rotational frequency n_{max} when the maximum effective engine power N_{emax} is developed) specific fuel consumption reduction transforms to the small increase – every 5% of HVO in fuel blend raises specific fuel consumption by volume of around 0.10%. For 25% HVO and 75% fossil diesel blend comparing with pure diesel fuel increase is 0.50%, but for pure HVO – 2.32%. Examining the most realistic scenario in the near future – 7% HVO and 93% fossil diesel blend, the predicted fuel consumption increase (0.14%) is inconsiderable for vehicle exploitation. It means that from both main operation viewpoints – dynamics and economy, HVO seems to be a promising biofuel to replace biodiesel in fuel blends and to promote reaching the targets estimated by EU directives and regulations.

Conclusions

1. An original mathematical model suitable to predict diesel engine operating parameters running them on HVO and its blends with fossil diesel fuel is developed using *ExtendSim* software.
2. Modelling results show that the reduction of engine power and torque, and the raise of specific fuel consumption for a car *Opel Insignia 2.0 CDTi* are linear – every 5% of HVO in fuel blend reduce the maximum power and torque of around 0.38%, at the same time raising specific fuel consumption by volume of around 0.10%. Using pure HVO the predicted fuel consumption increase is about 2.32% comparing with the diesel fuel.
3. Examining the most realistic scenario for the near future – 7% HVO and 93% fossil diesel blend, the predicted fuel consumption increase (0.14%) and power and torque decrease (0.54%) is inconsiderable for vehicle exploitation and from the theoretical point of view, HVO seems to be a promising biofuel to replace biodiesel in fuel blends and to promote reaching the targets estimated by EU directives and regulations.
4. In next studies it is necessary to carry out experimental investigations of vehicles to confirm the obtained modelling results.

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COMPARISON OF VEHICLE PERFORMANCE USING FOSSIL DIESEL FUEL BLENDS WITH BIODIESEL AND HVO FUEL

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Abstract. Biodiesel is increasingly used as an additive to fossil diesel fuel. For summer periods it is compulsorily in Latvia to use diesel fuel with 4.5-7 % biodiesel fuel mix. Some technical disadvantages of biodiesel/fossil diesel blends are mentioned by many researchers, for example, reduced energy density, and degradation of fuel under storage for prolonged periods. Therefore, one of the solutions might be blending of different biofuels instead of biodiesel. Hydrotreated vegetable oil (HVO) is one of the most promising next generation biofuels in the near future. An unmodified passenger car *Opel Insignia* 2.0 *CDTi* (manufactured in 2011) with a four-cylinder diesel engine (power 96 kW) has been investigated. Chassis dynamometer *Mustang MD*-1750, *AVL KMA MOBILE* fuel consumption meter, and *AVL SESAM FTIR* multi-component exhaust gas measurement system were used during the experiments. Running the car with diesel fuel mixed with 7 % of biodiesel, it developed 2.1 % less maximum power and 1.3 % less maximum torque compared with fossil diesel, and about 2.3 % less power and 1.5 % less torque compared to diesel fuel blended with 7 % HVO fuel. Diesel fuel l/7 % biodiesel blend fuel consumption is in average 3.1 % higher compared to pure fossil diesel, and in average 3.0 % higher in comparison with diesel fuel mixed with 7 % HVO fuel. Blend of 7 % HVO with fossil diesel fuel compared to diesel fuel mix with 7 % of biodiesel approximately by 4 % decreases the amount of NO_x, by 3 % CO_2, and about 3.5 times unburnt hydrocarbon content in exhaust gases, but CO increases by approximately 90 %.

Key words: diesel fuel, biodiesel, hydrotreated vegetable oil.

Introduction

The European Commission has proposed to limit the amount of first-generation biofuels up to 5 % and to increase incentives for modern biofuels, for example, for those produced from waste and other non-food biomass, including algae and microorganisms. After 2020 the state aid should be available only for the next generation, i.e. second, third and even fourth generation biofuels. The European Commission Communication "Clean Power for Transport: A European alternative fuels strategy" states that the future of mobility does not have a single fuel solution and that all major alternative fuels must be found, focusing on the needs of each mode of transport. A strategic approach for the EU should therefore be based on a combination of alternative fuels without favouring a specific fuel [1].

Hydrotreated vegetable oil (HVO) is one of the most promising next generation biofuels in the near future. Catalytic hydroprocessing technology can convert raw vegetable oils, waste cooking oils, animal fats and algae oils into biofuel with high calorific value, high cetane number, increased saturation level and oxidation stability [2].

HVO biofuels have been tested in several countries. For example, in South Korea a 1.5-liter DOHC diesel engine was used to measure power differences using blends of biodiesel and HVO with fossil diesel. The results of the study showed the reduction of power using fuel blends. For example, adding 2 % biodiesel to fossil diesel resulted in decrease of power for about 1.4 %, but 10 % blend showed decrease of power for about 2.0 %. Blending the same amount of HVO with fossil diesel, the power decrease was 0.7 % and 1.2 % accordingly. The fuel consumption of biodiesel blend with diesel fuel increases as the mixing factor increases (from about 0.5 % to 2 %), but HVO blends showed a slight increase in fuel consumption (from about 0.1 % to 0.3 %). Blending 10 % biodiesel to fossil diesel decreases unburned hydrocarbon (HC) content comparing with fossil diesel, while the content of CO, NO_x and CO_2 stays the same. 10 % HVO blend decreases CO, HC and CO_2 content comparing with both pure fossil diesel and biodiesel/diesel blend [3].

Emissions from two Euro 6b diesel passenger cars using different blends of HVO, fossil diesel and commercial diesel (Bio7) were investigated at 23 °C and −7 °C in Italy [4]. Overall, the use of different HVO blends did not lead to fuel related trends on the emissions of the tested vehicles in the laboratory nor on-road.

Another experimental result [5] proved that HVO blends give a benefit on both fuel consumption and CO_2 saving.

All these results, as well as HVO reviews [2; 6; 7], allow to conclude that the trends in power, fuel consumption and emissions are very different, depending on the type of the engine used, test conditions, and so on. Moreover, most of the experiments are carried out using engine test beds, but not by testing vehicles in general.

That is why in this experiment as a test car *Opel Insignia* 2.0 *CDTi* was used – a car is popular in Europe, and is produced at the time (2011) that roughly corresponds to the average age of passenger cars in European countries.

Materials and methods

Research has been carried out at the Alternative Fuel Research Laboratory of the Latvia University of Life Sciences and Technologies. The power, torque, fuel consumption and exhaust gas content of the car were measured using three different fuel samples:

- standard fossil diesel fuel (DF);
- fossil diesel fuel with 7 % (by volume) blend of biodiesel (Bio7);
- fossil diesel fuel with 7 % (by volume) blend of HVO (HVO7).

The main fuel parameters were determined at an independent certified laboratory (See Table 1).

Table 1

Main parameters of tested fuels

Parameter	DF	Bio7	HVO7
Density at 15 °C, $kg \cdot m^{-3}$	833.9	837.2	830.0
Viscosity at 40 °C, $mm^2 \cdot s^{-1}$	2.834	2.917	2.814
Lowest heating value (LHV_{mass}), $MJ \cdot kg^{-1}$	43.52	43.02	43.62
Lowest heating value (LHV_{volume}), $MJ \cdot l^{-1}$	36.29*	36.02*	36.21*
Cetane number	52.5	52.8	52.6
Water content, $mg \cdot kg^{-1}$	34	55	36

* – LHV_{volume} in MJ l^{-1} is calculated form measured LHV_{mass} in MJ kg^{-1} and density

The car *Opel Insignia* 2.0 *CDTi* (year of production – 2011, mileage – 56 580 km) with a four-cylinder diesel engine (engine displacement 1956 cm^3, maximum power of 96 kW at 4000 min^{-1}, and maximum torque 300 N·m at 1750 min^{-1}) was used as the test vehicle.

The chassis dynamometer *Mustang MD*-1750 was used for the power and torque measurement on the vehicle wheels. The main characteristic of the chassis dynamometer used in the test:

- maximum measuring capacity – 1750 hp;
- maximum absorption capacity – 400 hp;
- maximum measuring speed – 360 $km \cdot h^{-1}$;
- maximum axle load on rollers – 4500 kg.

Fuel consumption was measured by the *AVL KMA Mobile* measuring device, which is designed to measure fuel consumption in both laboratory and road conditions. The device is equipped with all the necessary components to measure the fuel consumption of diesel and gasoline engines. The *AVL KMA Mobile* measurement module is based on the high-precision flow meter *PLU*-121, using the world-wide proved PLU measurement principle.

The exhaust components of the vehicle were measured by the emission measurement system *AVL SESAM FTIR* (System for Emission Sampling and Measurement, *FTIR* – Fourier Transform Infra Red), which is designed for measurement of exhaust components for gasoline and diesel engines in different operating modes. With this system it is possible to measure up to 25 different exhaust components simultaneously, of which the main ones are: C_2H_2; C_2H_4; C_2H_6; C_3H_8; C_4H_6; C_4H_8; CH_4; CO_2; CO; H_2O; HCHO; HCN; HCOOH; HNCO; N_2O; NC_{10}; NC_8; NH_3; NO_2; NO; SO_2.

Schematic view of the experimental setup is shown in Figure 1.

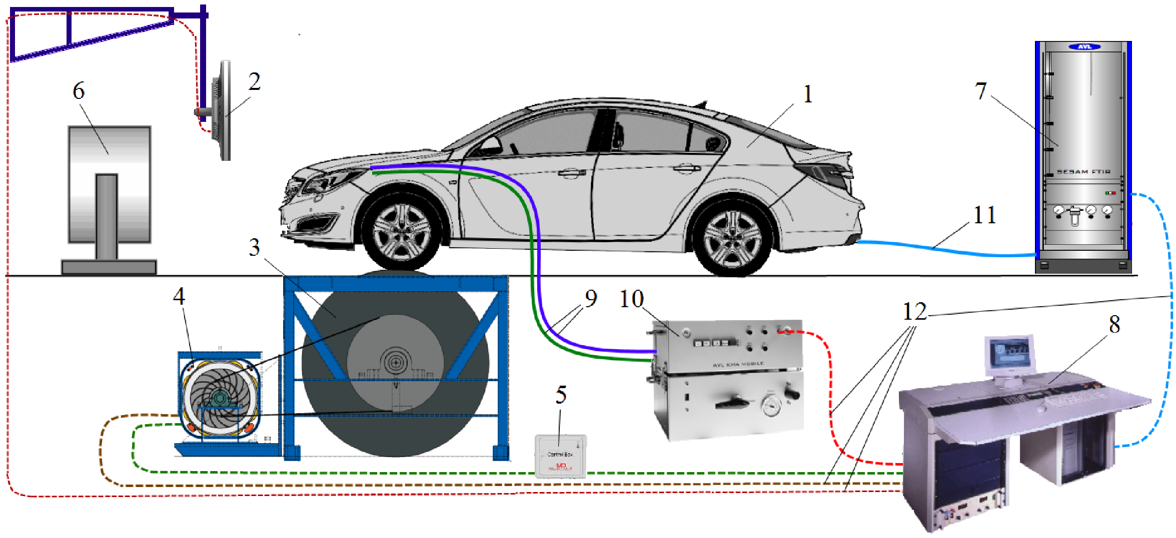

Fig. 1. **Schematic view of experimental setup:** 1 – experimental car; 2 – test cycle simulation screen; 3 – chassis dynamometer *Mustang MD*-1750; 4 – power absorber unit (PAU); 5 – dynamometer control box; 6 – air blower; 7 – multicomponent exhaust gas measurement system *AVL SESAM FTIR*; 8 – Mustang chassis dyno control module & PC with special software AVL & data recording; 9 – fuel lines; 10 – fuel measuring device *AVL KMA Mobile*; 11 – heated gas line for exhaust gas measurement from the exhaust tailpipe; 12 – AVL date communication cable & Mustang dyno date communication cable & dyno control circuit & screen communication cable

The experimental methodology included a series of tests with each of the fuel samples (primarily diesel fuel with a 7 % biodiesel blend, fossil diesel and, finally, diesel fuel with 7 % HVO fuel mix): power tests, idle tests, constant speed tests and driving cycle tests. The scheme of the experimental methodology and the logical sequence of tests are given in Figure 2. Each series of tests were performed with at least 3 repetitions. Each subsequent repetition was made when all the tests in the previous series were completed. The air temperature in the test room was maintained between + 18 °C and + 21 °C.

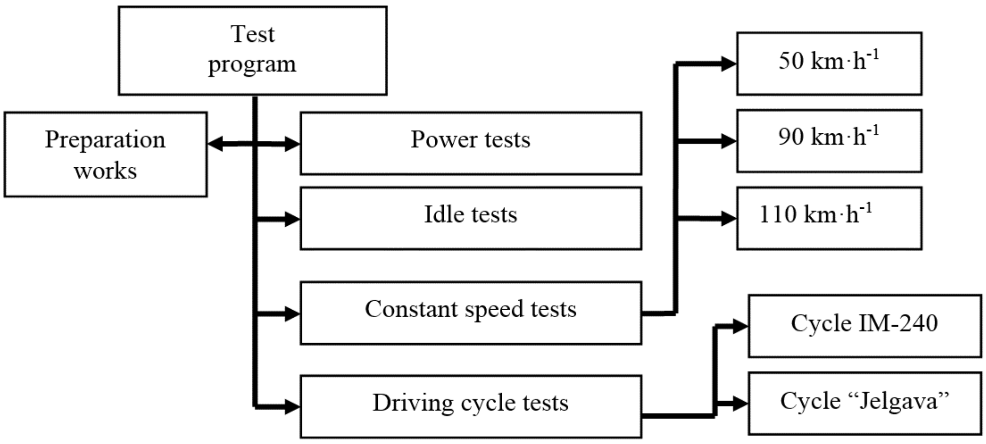

Fig. 2. **Scheme of experimental methodology and logical sequence of tests**

For determination the maximum power value, foremost the maximum power values were determined for each measurement repetition at the respective engine crankshaft rotation frequency. The final value was calculated as the average value from the repetitions of the particular measurements. The average fuel consumption (litres per 100 km) in constant speed mode was calculated from the instant fuel consumption ($l \cdot h^{-1}$), test time (s) and the speed ($km \cdot h^{-1}$) by the following relationship:

$$Q_{100} = \frac{1}{n} \cdot \sum_{i=1}^{n} \left(\frac{100}{v \cdot t} \cdot \sum_{i=1}^{k} Q_{inst} \right), \quad (1)$$

where Q_{100} – average fuel consumption, l per 100 km;
n – number of repetitions;
v – vehicle speed, km·h^{-1};
t – duration of one test repetition, s;
k – number of instant measurements;
Q_{inst} – instant fuel consumption, l·h^{-1}.

The average fuel consumption during the driving cycle (litres per 100 km) was determined by relationship:

$$Q_{100} = \frac{1}{n} \cdot \sum_{i=1}^{n} \left(\frac{100 \cdot t}{3600 \cdot s} \cdot \sum_{i=1}^{k} Q_{inst} \right), \tag{2}$$

where s – distance travelled during the repetition, km.

The relative quantity of each exhaust gas component in all test modes was determined by the relationship:

$$EGC = \frac{1}{n} \cdot \sum_{i=1}^{n} \left(\frac{1}{t} \cdot \sum_{i=1}^{k} EGC_{inst} \right), \tag{3}$$

where EGC – average relative quantity of the exhaust gas component, ppm or %;
EGC_{inst} – instant relative amount of the exhaust gas component, ppm or %.

The results of the tests are shown in Figures 3, 4 and 5.

Results and discussion

Comparing the average values of power and torque with the values of each individual repetition, the correlation for the torque data points exceeded 99.8 %, and for the power – 99.9 %. The power and torque curves were designed using the power and torque average values at specific speeds and operating the *Opel Insignia* with three different fuels (DF, Bio7 and HVO7) (see Fig. 3).

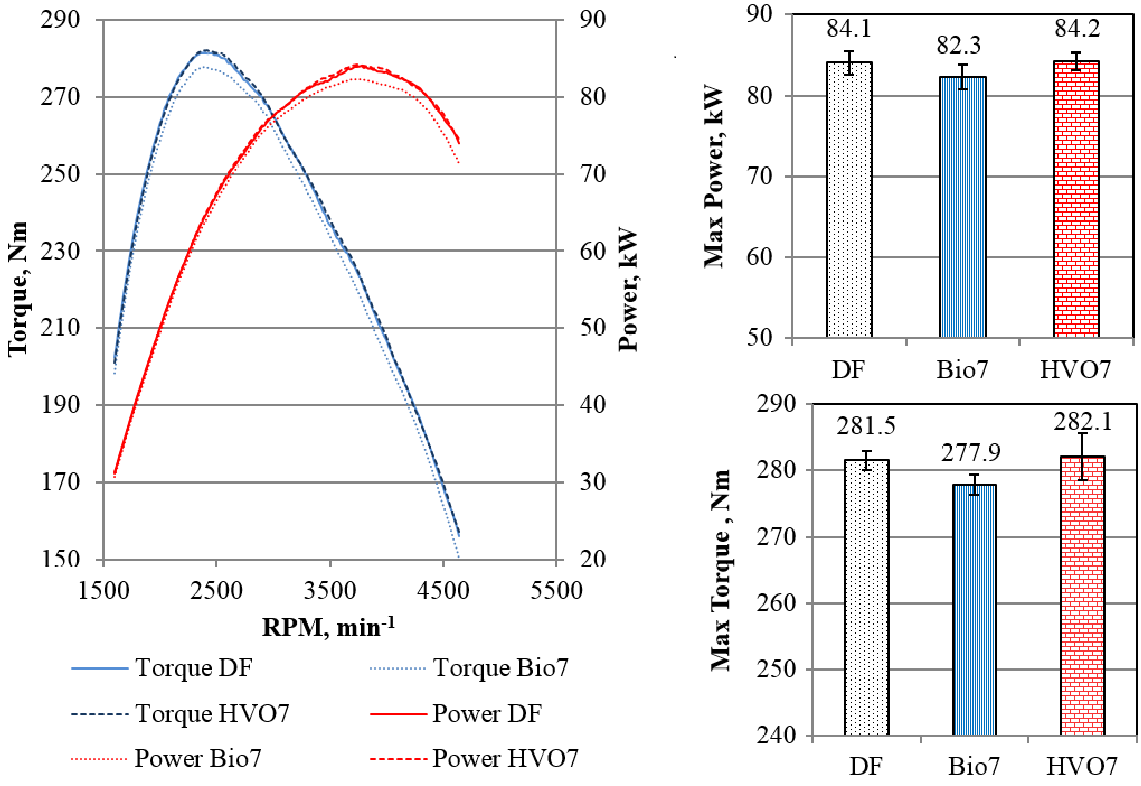

Fig. 3. **Power and torque measurement results for *Opel Insignia* car using three different fuels**

The experimental results showed that with fossil diesel and diesel fuel blended with 7 % of HVO fuel the car's power and torque curves in all range of the engine crankshaft rotation frequency were similar – the variation in power and torque values in all measured data points did not exceed 0.8 %.

The maximum car power with fossil diesel 84.1 kW was reached at 3780 min^{-1}, with diesel fuel blended with 7 % biodiesel – 82.3 kW at 3760 min^{-1}, but with diesel fuel blended with 7 % HVO fuel – 84.2 kW at 3740 min^{-1}.

The maximum power difference for fossil diesel and diesel fuel blended with 7 % HVO fuel was 0.16 %, which was considered as insignificant. Using 7 % biodiesel blend, the developed power was 2.12 % lower comparing with fossil diesel and 2.28 % lower than for diesel fuel blended with 7 % HVO fuel.

The maximum torque using fossil diesel 281.5 N m was reached at 2400 min^{-1}, with diesel fuel mixed with 7 % biodiesel – 277.9 N m at 2380 min^{-1}, but with diesel fuel blended with 7 % HVO fuel – 282.1 N m at 2380 min^{-1} (see Fig. 3).

The maximum torque difference for fossil diesel and diesel fuel blended with 7 % HVO fuel was 0.20 %, which was considered as insignificant. Using 7 % biodiesel blend the torque was 1.3 % less comparing with fossil diesel and 1.5 % less than for diesel fuel blended with 7 % HVO fuel.

The fuel consumption measurement errors were calculated at 95 % confidence level. The fuel consumption results are shown in Fig. 4.

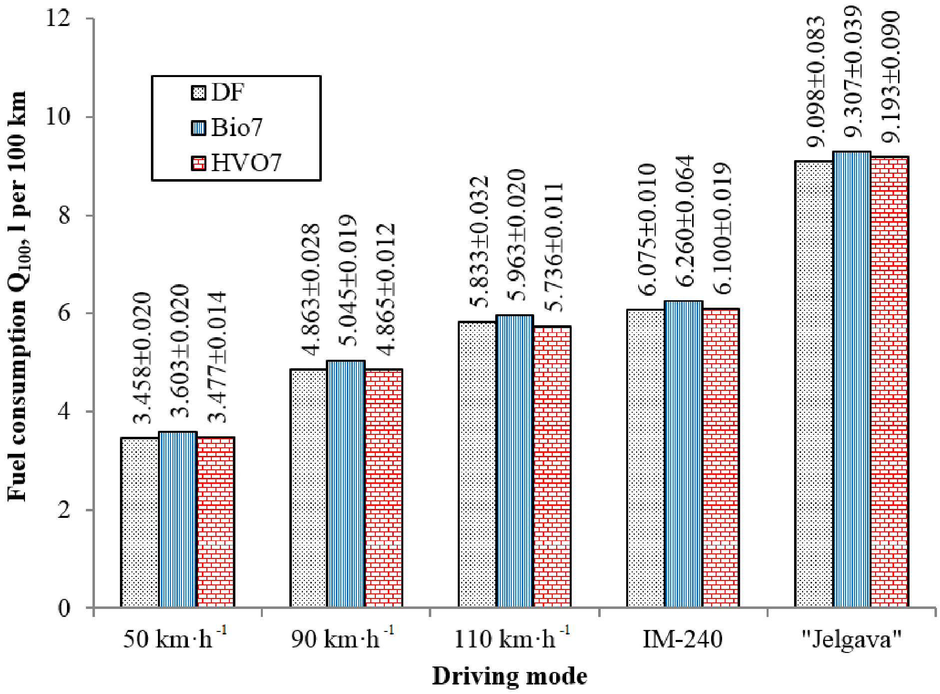

Fig. 4. **Fuel consumption in different driving modes operating *Opel Insignia* car on three different fuels**

The average idle fuel consumption for diesel fuel was 0.536±0.003 $l\cdot h^{-1}$, for diesel fuel blend with 7 % HVO – 0.531±0.003 $l\cdot h^{-1}$, and diesel fuel blend with 7 % biodiesel – 0.538±0.003 $l\cdot h^{-1}$. Considering that idle fuel consumption is most affected by various test conditions (e.g. engine temperature), these differences (within 1 % range) cannot be considered as significant. Therefore, exactly the different driving modes more objectively characterize the changes in fuel consumption.

The calculated mean values in three constant speed tests – 50, 90 and 110 $km\cdot h^{-1}$, as well as in two types of cycles – standardised IM-240 and self-designed cycle "Jelgava" [8] allowed to observe that the average fuel consumption for fossil diesel fuel and diesel fuel blend with 7 % HVO differs only by 0.07 %, which is considered to be an insignificant difference. Operating the car with the diesel fuel blend with 7 % biodiesel, the fuel consumption was in average 3.11 % higher than for fossil diesel fuel and in average 3.03 % higher than for diesel fuel blend with 7 % HVO fuel.

The changes of NO_x, unburned hydrocarbons (HC), CO_2 and CO content in exhaust gases operating the car on all three fuels are shown in Fig. 5. The content of all exhaust gases is given in ppm (parts per million). The same methodology as for fuel consumption was used for error calculation, only the exhaust gas component errors are not displayed as numerical values, but error bars at 95 % confidence level.

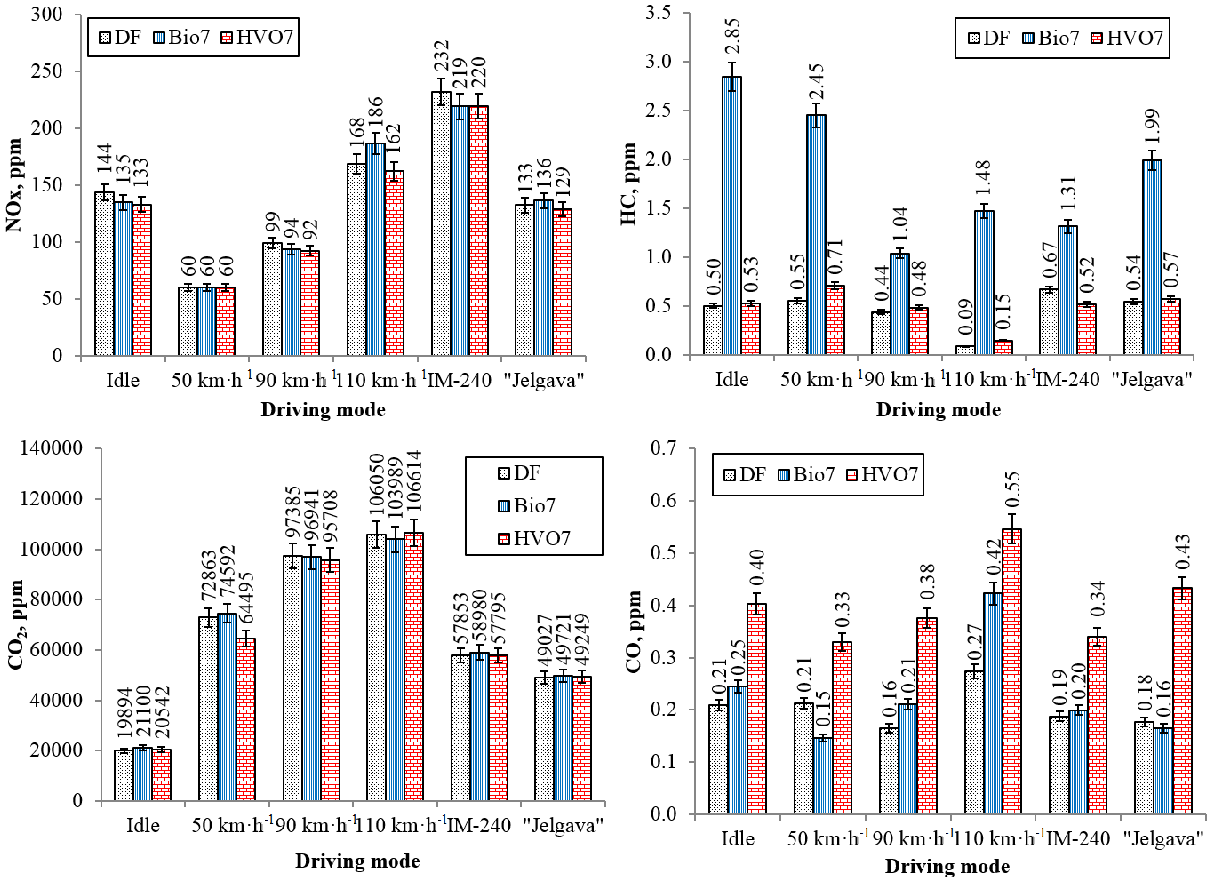

Fig. 5. **Changes in NOx, HC CO_2 and CO content in exhaust gases running *Opel Insignia* car on three different fuels**

The following evaluation of the results is based on the average value of measurements obtained by compiling all test modes used in this study.

The use of diesel fuel blended with 7 % biodiesel in comparison to fossil diesel fuel practically does not change the NO_x content in exhaust gases, but the CO_2 content rises insignificantly (~1.6 %). The CO content increases by about 9 % and the content of unburnt hydrocarbons increases by about 5 times.

Diesel fuel blended with 7 % HVO in comparison to fossil diesel practically does not change the CO_2 content in exhaust gases, and the NO_x content reduces by about 4.5 %. The unburnt hydrocarbon content increases by about 15 %, and CO – about 2 times.

The use of diesel fuel blended with 7 % HVO fuel in comparison to diesel fuel blended with 7 % biodiesel reduces NO_x by about 4 %, CO_2 by 3 %, and the HC content about 3.5 times, while CO increases by about 90 %.

Comparing these results with the results of other studies confirms mentioned in the introduction, i.e., the trends in changes of power, fuel consumption and emissions in different investigations are very various. For example, comparing with the results obtained in South Korea [3], there are similar trends in power reduction using biodiesel/diesel blends. But the reduction of power with HVO blends is not confirmed. Similar trends are in the changes of fuel consumption, HC and CO_2 content, but the trends in CO change are sharply different.

Conclusions

1. The study revealed that operating the *Opel Insignia* 2.0 *CDTi* car with fossil diesel fuel and diesel fuel blend with 7 % HVO fuel the power and torque curves in all engine crankshaft rotation frequency ranges were similar – the change of the power and torque values in all measured data points did not exceed 0.8 %.
2. The maximum power difference for fossil diesel fuel and diesel fuel blend with 7 % HVO was 0.16 %. Diesel fuel blend with 7 % biodiesel produced 2.12 % lower maximum power compared to fossil diesel fuel and 2.28 % less power than diesel fuel blend with 7 % HVO.
3. The maximum torque difference for fossil diesel fuel and diesel fuel blend with 7 % HVO was 0.20 %. Diesel fuel blend with 7 % biodiesel generated 1.3 % reduction in the maximum torque compared to fossil diesel fuel and 1.5 % lower torque compared to diesel fuel blend with 7 % HVO.
4. The difference in average fuel consumption for fossil diesel and diesel fuel blend with 7 % HVO was only 0.07 %. The diesel fuel blend with 7 % biodiesel consumed on average 3.11 % more than fossil diesel fuel and on average 3.03 % more than diesel fuel blend with 7 % HVO.
5. Running the car with the diesel fuel blend with 7 % biodiesel CO emissions increased by about 9 % and unburned hydrocarbons approximately 5 times compared to pure fossil diesel.
6. Using diesel fuel blend with 7 % HVO fuel, the NO_x content was reduced by 4.5 % compared to pure fossil diesel, the content of unburned hydrocarbons increased by about 15 % and CO – 2 times.
7. Using diesel fuel blend with 7 % HVO in comparison to diesel fuel blend with 7 % biodiesel, the NO_x emission was lower by 4 %, CO_2 and unburnt hydrocarbon emissions by 3 %, while CO was higher by 90 %.
8. The study showed that blending of 7 % HVO to fossil diesel was more effective from all evaluated aspects than admixing 7 % biodiesel fuel.

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COMPARISON OF CAR PERFORMANCE USING HVO FUEL AND DIESEL FUEL

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Abstract. All member states of the European Union are bound to the EU directives and regulations on the reduction of greenhouse gas emissions and the use of renewable energy sources in road transport. As the objectives defined in these documents cannot be achieved only by the mandatory blending of biofuels, opportunities to use new generation biofuels in pure form have to be investigated. One of the most promising fuel types in this matter could be hydrotreated vegetable oil (HVO), which can be produced from a variety of non-food raw materials. To determine the effect of fuel on the car's dynamic, economic and environmental performance, experimental studies were carried out using a car model *Opel Insignia* powered by pure HVO fuel (NExBTL manufactured by *Neste Oil*) and regular diesel fuel. The tests were performed on a power bench, but the AVL measuring equipment was used to determine the exhaust gas composition and fuel consumption. The experimental results show that the power and torque characteristics in the whole range of engine speed are similar when operated with NExBTL and fossil diesel. The average NExBTL fuel volumetric consumption is about 3% higher, fuel mass consumption 5.3% lower and fuel energy input 4.5% lower compared to diesel fuel. This can be explained by the differences between the physical properties of the tested fuels, such as density, lower heating value and compressibility. Exhaust components, which are usually compared in studies of different fuels, using NExBTL fuel tend to decrease compared to fossil diesel. A reduction was observed in most driving modes tested. Unburned hydrocarbons decreased on average by 44%, SO_2 – by 13.3%, NO_x by 5% and CO_2 – by 3.8%. Experimental studies show that NExBTL fuel might compete with fossil diesel in the future. It is confirmed by measurements of power, fuel consumption and exhaust gas content. An important drawback for the wider implementation of this fuel is its production cost.

Keywords: hydrotreated vegetable oil, renewable energy, power, torque, fuel consumption, exhaust emissions.

Introduction

Directive 2018/2001 of the European Parliament and the Council on the promotion of the use of energy from renewable sources determines that each Member State has to oblige fuel suppliers to ensure that the share of energy from renewable sources within the final energy consumption in the transport sector is at least 14% by 2030. Moreover, the contribution of advanced biofuels and biogas produced from the feedstock listed in Annex of the Directive (for example, algae, bio-waste, straw, palm oil mill effluent etc.) as a share of the final consumption of energy in the transport sector has to be at least 0.2% in 2022, at least 1% in 2025 and at least 3.5% in 2030 [1].

Current experience shows that these goals cannot be achieved only by the mandatory blending of biofuels. Consequently, the use of advanced or next-generation biofuels has to be investigated in their pure form. One of the most promising fuel types in this concern could be hydrotreated vegetable oil (HVO), which can be produced from a variety of non-food raw materials.

Most of the largest fuel manufacturers have developed HVO refining processes and even named their products. NExBTL (short for "next-generation bioliquid") is the trade name for HVO manufactured by *Neste Oil* (Finland). Product of *Universal Oil Products* (*UOP*)-*Eni* (UK, Italy) has the trade name "Green Diesel", but the HVO produced by *SK energy* (Korea) is called HBD (hydro-gen-treating biodiesel) [2].

HVO is a relatively new fuel, so it has been more widely studied only in the last decade. There are a few hundred serious publications and reviews that investigate the production, combustion, performance, fuel consumption, and exhaust emissions of this fuel type. Fuels with different physical properties, in pure form or in blends, on engine test stands and in whole vehicles have been examined. For these reasons, the obtained results and trends of individual parameters are different [3].

Eleven passenger cars with different exhaust gas after-treatment systems and emission standards (from Euro 3 to Euro 6), different injection systems and transmissions were tested at the Technology Transfer Centre Automotive of the Coburg University of Applied Sciences and Arts. The results showed that the emissions of passenger cars using HVO decreased from 35% to 90% of the unburned components (HC, CO) emissions, compared to diesel fuel. NO_x emissions increased between 5% and 14% versus diesel fuel, and the increase was independent of the exhaust treatment [4].

The effect of HVO fuel and blends with diesel fuel on the emissions and performance of a passenger car size diesel engine was investigated at the Czech Technical University in Prague. Using pure HVO increased the indicated power by 4.53%. Significant drops compared to diesel fuel in CO and HC emissions were obtained (61.8% and 64.3%). Emissions of CO_2 and NO_x slightly decreased (accordingly by 3.56% and 4.2%) [5].

Research on the combustion, energy and emission parameters of various concentration blends of NExBTL fuel and diesel fuel in a compression-ignition engine was performed in Lithuania and Hungary. The analysis of combustion rates did not show significant changes. The volumetric HVO fuel consumption was increased by 4% to 6% compared to diesel fuel. The variation in CO was insignificant. The decrease of CO_2 was up to 0.35%, and the maximum decrease was reached when the percentage of NExBTL increased up to 85-100%. The NO_x amount was reduced by up to 20% depending on the engine load. The HC concentration was reduced by 12% to 25% at different speed modes [6].

Two Euro 6b compliant diesel passenger cars were tested in real driving conditions using five different fuel blends including pure HVO fuel at different air temperatures in the Vehicle Emission Laboratory at the European Commission-Joint Research Centre Ispra, Italy. The use of different HVO blends and diesel did not lead to fuel-related trends on the emissions of the tested vehicles, not in the laboratory and not on road. The use of pure HVO resulted in 4% lower CO_2 emissions than the other fuel tested in all analysed conditions [7].

As more research has been done on engine test stands and using different fuel blends with HVO content from 5% to 80%, the aim of this study is to investigate using pure HVO in a non-adapted typical passenger car.

Materials and methods

The tests running the car *Opel Insignia* 2.0 *CDTi* on the chassis dynamometer *Mustang MD*-1750 have been carried out at the Alternative Fuel Research Laboratory of the Latvia University of Life Sciences and Technologies (See Figure 1).

Fig. 1. **Tested car on the chassis dynamometer**

Two different fuels were used in the experiments:

- fossil arctic diesel fuel, class 0 (Diesel);
- hydrotreated vegetable oil fuel produced by *Neste Oil* (NExBTL).

The main fuel parameters were determined at the certified laboratory of the Porvoo Refinery, Finland (See Table 1).

Table 1

Main parameters of tested fuels

Parameter	Test method	Diesel	NExBTL
Density (ρ) at 15 °C, $kg \cdot m^{-3}$	ENISO12185	836.3	778.9
Viscosity at 40 °C, $mm^2 \cdot s^{-1}$	ENISO3104	2.581	2.884
Lowest heating value (LHV_{mass}), $MJ \cdot kg^{-1}$	ASTMD4809	43.535	43.894
Lowest heating value (LHV_{volume}), $MJ \cdot l^{-1}$	–	36.408*	34.189*
Cetane number by IQT-analyser	ASTMD6890	52.4	74.7

* *Lowest heating value in $MJ \cdot l^{-1}$ is calculated from the measured lowest heating value in $MJ \cdot kg^{-1}$ and density*

The main parameters of the test vehicle *Opel Insignia* 2.0 *CDTi*:

- year of production – 2011;
- four-cylinder diesel engine with a displacement of 1956 cm^3;
- maximum power 96 kW at 4000 min^{-1};
- maximum torque 300 N·m at 1750-2500 min^{-1};
- engine compression ratio 16.5;
- common rail fuel injection.

The following facilities and systems were used for measurement:

- the chassis dynamometer *Mustang MD*-1750 for power and torque measurements on the vehicle wheels;
- the *AVL KMA Mobile* fuel consumption measuring device, using the zero resistance geared flow meter;
- the exhaust gas analytical system *AVL SESAM FTIR*.

The layout of the experimental equipment is shown in Figure 2.

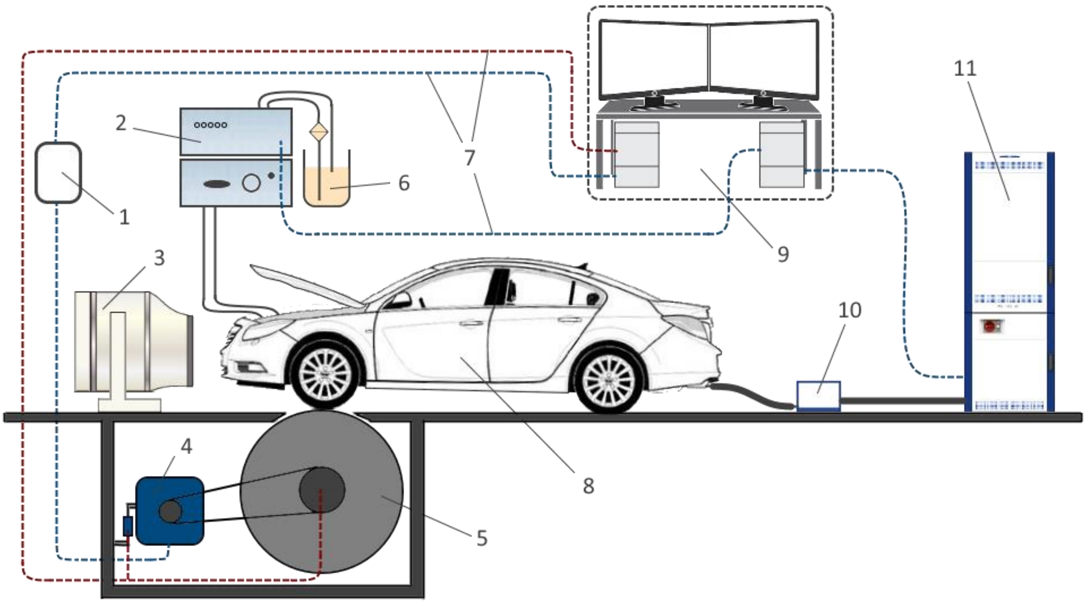

Fig. 2. **Layout of the experimental equipment:** 1 – dynamometer control box; 2 – fuel measuring device *AVL KMA Mobile*; 3 – air blower; 4 – power absorber unit; 5 – chassis dynamometer *Mustang MD*-1750; 6 – fuel tank; 7 – data communication cables; 8 – experimental car; 9 – PCs with special software; 10 – heated filter; 11 – multicomponent exhaust gas measurement system *AVL SESAM FTIR*

Exhaust gas analytical system software calculates NO_x concentration in a gas sample by the following equation [8]:

$$NO_x = NO + NO_2 , \quad (1)$$

where NO – concentration of nitrogen oxide;

NO_2 – concentration of nitrogen dioxide.

Another calculated parameter of the exhaust gas analytical system is the concentration of hydrocarbons, by the following equation [8]:

$$HC = CH_4 + 2 \cdot C_2H_2 + 2 \cdot C_2H_4 + 2 \cdot C_2H_6 + 3 \cdot C_3H_8 + 7.5 \cdot C_7H_8 + 10 \cdot C_8H_{18}, \quad (2)$$

where CH_4 – concentration of methane;
C_2H_2 – concentration of ethine;
C_2H_4 – concentration of ethene;
C_2H_6 – concentration of ethane;
C_3H_8 – concentration of propane;
C_7H_8 – concentration of toluene;
C_8H_{18} – concentration of n-octane.

The tests and the sequence of their execution have been approved in several previous studies, including experiments performed with the same car running on blends of 7% biodiesel and 7% hydrotreated vegetable oil with fossil diesel [9].

The following series of tests with each of the fuel samples were performed:

- maximal power and torque measurement tests;
- fuel consumption and exhaust emission analysis during idling and at constant driving speeds of 50 km·h^{-1}, 90 km·h^{-1} and 110 km·h^{-1};
- fuel consumption while performing two different driving cycles:
  - IM-240 – combined 240-second test representing a 3.1 km route with an average speed of 47.3 km·h^{-1} and a maximum speed of 91.2 km·h^{-1};
  - in-house developed Jelgava city cycle, based on real driving data – urban 360-second test representing a 2.36 km route with an average speed of 23.3 km·h^{-1} [10].

Each test series were performed with at least 3 repetitions. The air temperature in the laboratory was maintained between + 18 °C and + 22 °C.

The car's power and torque curves were obtained by operating it in fourth gear with the accelerator pedal fully pressed. These characteristics reflect the car's power and torque on the driven wheels.

The instant fuel consumption, test time and speed values were used to calculate the average fuel consumption at constant speed in litres per 100 km:

$$Q_{100} = \frac{1}{n} \cdot \sum_{i=1}^{n} \left(\frac{100}{v \cdot t} \cdot \sum_{i=1}^{k} Q_{inst} \right), \quad (3)$$

where Q_{100} – average fuel consumption, l per 100 km;
n – number of repetitions;
v – vehicle speed, km·h^{-1};
t – continuation of one test repetition, s;
k – number of instant determinations;
Q_{inst} – instant fuel consumption, l·h^{-1}.

The average fuel consumption performing driving cycles was calculated using the relationship:

$$Q_{100} = \frac{1}{n} \cdot \sum_{i=1}^{n} \left(\frac{100 \cdot t}{3600 \cdot s} \cdot \sum_{i=1}^{k} Q_{inst} \right), \quad (4)$$

where s – distance covered during the repetition, km.

The average relative amount of each exhaust gas component in all test modes was calculated using the relationship:

$$EGC = \frac{1}{n} \cdot \sum_{i=1}^{n} \left(\frac{1}{t} \cdot \sum_{i=1}^{k} EGC_{inst} \right), \quad (5)$$

where EGC – average relative amount of the exhaust gas component, ppm (parts per million);

EGC_{inst} – instant relative amount of the exhaust gas component, ppm.

Results and discussion

Comparing the average values of power and torque with the values of each repetition, the correlation of the torque and power data points exceeded 99.5%. Using the power and torque average values at particular crankshaft rotations, the power and torque curves were created (see Fig. 3).

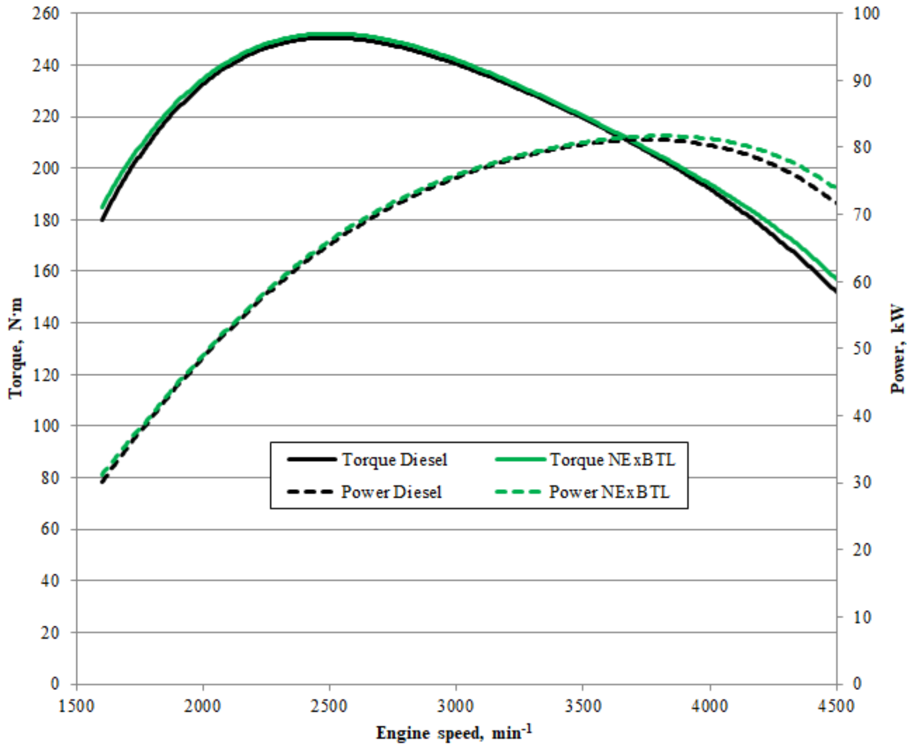

Fig. 3. **Power and torque measurement results**

The experimental results show that when working with both fuels, the car's power and torque characteristics in the entire range of the engine speed are similar. When running a car on NExBTL, the average increase in power and torque compared to fossil diesel is 1%. The maximum power of the car with NExBTL 82.1 kW is reached at 3760 min^{-1}, but with fossil diesel – 81.8 kW at 3700 min^{-1}. The maximum power difference is 0.34%. The maximum torque with NExBTL 252.8 N·m is reached at 2400 min^{-1}, but with fossil diesel – 250.9 N·m at 2360 min^{-1}. The maximum torque difference is 0.75%. As a common rail fuel system distributes fuel on a volumetric basis, and NExBTL has lower LHV per volume, one may expect a decrease of engine maximal torque when the engine runs on NExBTL. The observed increase of the torque and power can be explained by the following. It can be assumed that during the maximal power and torque test, the engine control unit (ECU) will respond to the driver's torque request by increasing the inlet air pressure, the fuel pressure in the common rail and injector opening timing similarly for both tested fuels. At particularly high fuel pressure (close and above 1000 bar), which is normally set by ECU when maximal torque is provided in such engines, the effects of fluid compressively must be evaluated. Boehman et al. reported that the bulk modulus of compressibility of regular diesel fuel and paraffinic distillate (which can represent NExBTL) is respectively 1477 MPa and 1318 MPa at temperature 27.8 °C and pressure 6.89 MPa [11]. The equation for calculation of the bulk modulus of compressibility is [11]:

$$B = \left(P - P_0\right) \cdot \frac{V_0}{V_0 - V}, \tag{6}$$

where B – bulk modulus of compressibility, MPa;
P – pressure after compression, MPa;
P_0 – pressure before compression, MPa;
V – initial volume of fluid, mm^3;

V_0 –volume of fluid after compression, mm^3.

The larger is the bulk modulus of compressibility, the smaller is the volume reduction during compression of the fluid. The bulk modulus is not constant and normally increases with the applied pressure, as the molecules of the fluid are compressed closer to each other. The authors calculated relative volume reduction of the two fuels of interest when compressed from 1 to 1000 bar, using equation (6) and the bulk modulus of compressibility from [11]:

- diesel fuel – volume reduction by 6.77%;
- NExBTL – volume reduction by 7.59%.

In the specific case of the fuel injection system, the actual volume of the fuel that is compressed is constant, and fuel mass increases according to the compressibility of the fluid.

By introducing the definitions of density and LHV, an equation for evaluation of fuel compressibility on energy amount is developed:

$$E_{fc} = V_0 + \frac{V_0 \cdot \left(P - P_0\right)}{B} \cdot \rho \cdot LHS_{mass}, \quad (7)$$

where ρ – fuel density, kg·mm^{-3};
E_{fc} – energy amount of injected volume of compressed fuel, MJ;
LHV_{mass} – lower heating value, MJ·kg^{-1};
V_c – compressed volume of fluid, mm^3.

Evaluation results of energy supplied in a combustion chamber at 1000 bar fuel pressure show that for a similar compressed volume of fuel, fuel energy ratio E_{NExBTL}/E_{Diesel} is 0.946 or in other words, there is 5.37% less energy in an equal volume of compressed fuel at 1000 bars, comparing NExBTL to diesel fuel.

The energy amount in each fuel and differences in compressibility cannot fully explain observed similarities of torque and power. The explanation why the torque or power curves are so close in this experiment lies in further analysis of fuel and energy use in other driving tests.

In contrary to maximal torque and power test, during constant engine speed (idle) and constant driving (50, 90 and 110 km·h^{-1}) speed tests, the fuel is supplied not at a constant volume but in just enough mass flow (or energy flow) to produce required torque. The same applies to the driving cycle (IM-240 and Jelgava) tests.

The average diesel fuel consumption in idling mode is 0.499±0.058 litres per hour and for NExBTL is 0.504±0.020 litres per hour. The difference in volumetric consumption is insignificant. Larger differences were observed in fuel mass consumption and energy use. Regarding that idling fuel consumption is most affected by engine auxiliaries, this difference cannot be considered significant. Additionally, the relatively large impact of pilot injection and short injection times increase the relative importance of premixed combustion on overall combustion during the engine cycle in idle mode.

Therefore, the changes in fuel consumption are more objectively characterized by the different driving modes. The experimental results were statistically evaluated by calculation of 95% confidence intervals that are also shown in Figs. 4 and 5. The fuel consumption results are shown in Fig. 4.

The difference in fuel consumption varies between driving modes. In the volumetric domain, NExBTL consumption is apparently higher by approximately 3%, but the differences are statistically insignificant. Quite an opposite situation is observed in the mass flow domain. The fuel mass consumption of NExBTL is 5.3% lower compared to diesel, but again in some test modes difference is statistically insignificant. To evaluate and compare the efficiency of different fuels, the analysis of energy supply and conversion can be the most meaningful. By looking at fuel consumption in the energy domain, the trend is like the one observed with fuel mass consumption. This time the average fuel energy that is supplied to the engine is 4.5% lower in the case of NExBTL. As driving in steady speed and driving cycles requires similar torque using both fuels, it can be assumed that energy conversion efficiency in conditions that are typical in tested vehicles engine is higher for paraffinic synthetic fuel NExBTL, compared to regular diesel fuel. These findings also explain why at assumed similar volumetric fuel consumption during maximal torque and power test runs the torque/power curves are so close to each other.

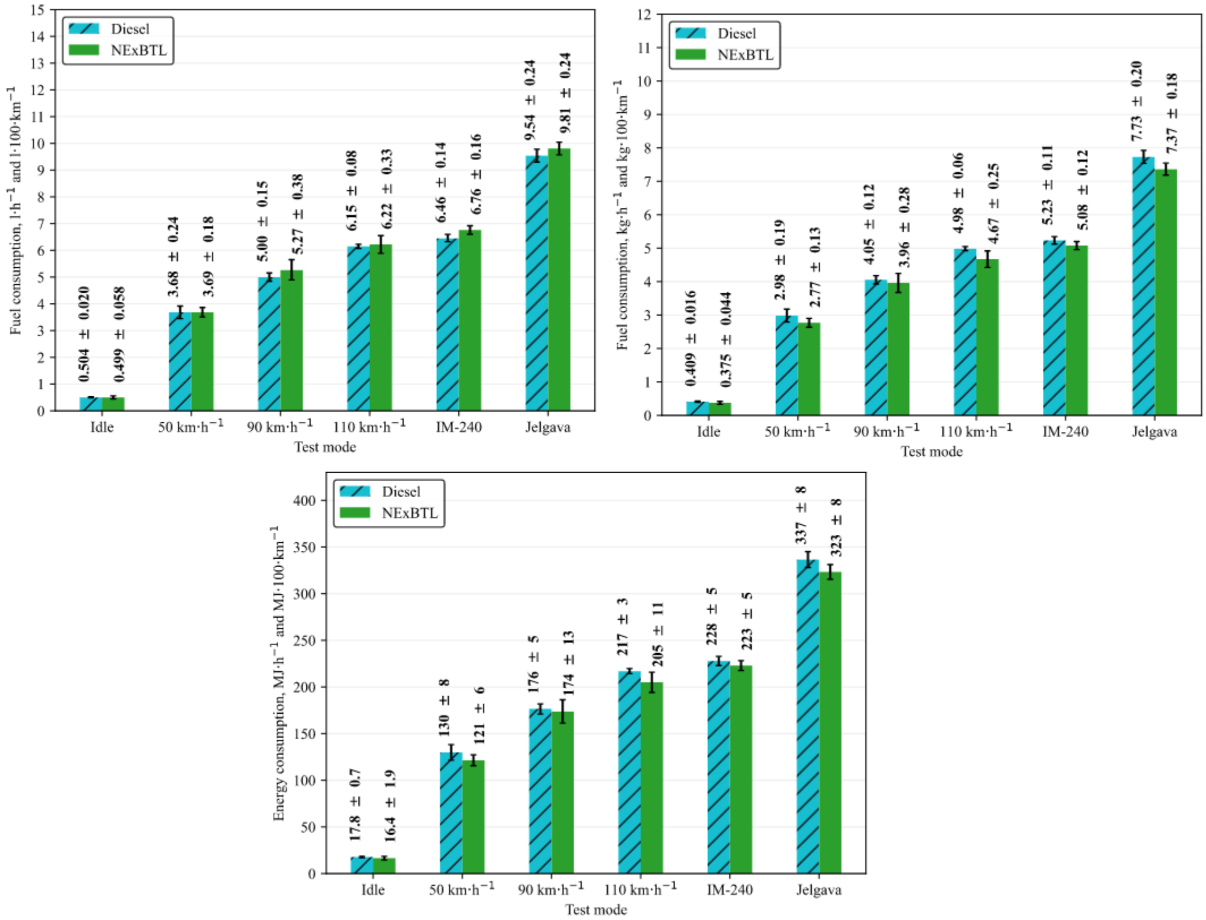

Fig. 4. **Fuel consumption, shown in volumetric, mass and energy domains**

The changes of NO_x, unburned hydrocarbons (HC), CO_2 and SO_2 concentration in exhaust gases running the car with both fuels are shown in Fig. 5. The concentration of all exhaust gases is given in ppm (parts per million), except CO_2, where it is shown in percent for better readability. Statistical evaluation is done using the same methodology as for fuel consumption and 95% confidence intervals are shown in bar plots. Only the results from constant engine speed test modes (idle, 50, 90 and 110 km h^{-1}) are shown, as the interpretation of driving cycle data requires the calculation of mass-specific emissions that are not included in this report.

Observed CO_2 concentration in the case of NExBTL is lower by approximately 3.8%. This result can be explained by the fact that the hydrogen to carbon ratio for NExBTL is 2.14, i.e., significantly higher, compared to the typical diesel fuel, 1.88 [12-13]. During complete combustion of NExBTL, relatively more H_2O and less CO_2 is produced, compared to diesel fuel.

The use of NExBTL instead of diesel fuel also led to a statistically insignificant reduction of SO_2 emissions. Oil derived products, such as diesel fuel, contain sulphur, which is removed during the fuel production to the level specified by the corresponding standard. On the other hand, synthetic fuel, such as NExBTL, which is made from biological sources, normally has very few sulphur compounds. According to analytic data by Sugiyama et al., diesel fuel has 6 ppm of sulphur, but NExBTL has only 3 ppm [12]. That explains the observed results of this research. Less sulphur in exhaust gases can prolong the useful service life of exhaust gas after-treatment devices. It can also reduce the emission of particle matter (PM) [14].

The effect of NExBTL on NO_x emissions was less pronounced, comparing to other gas species, analysed in this research. Only at the highest load conditions, steady driving at speed 110 km·h^{-1}, a statistically insignificant reduction was observed, compared to the use of diesel fuel. As NExBTL has a higher cetane number than diesel fuel, the combustion will start earlier in the engine cycle. Normally it can lead to increased pressure and temperature that further might lead to the increased NO formation.

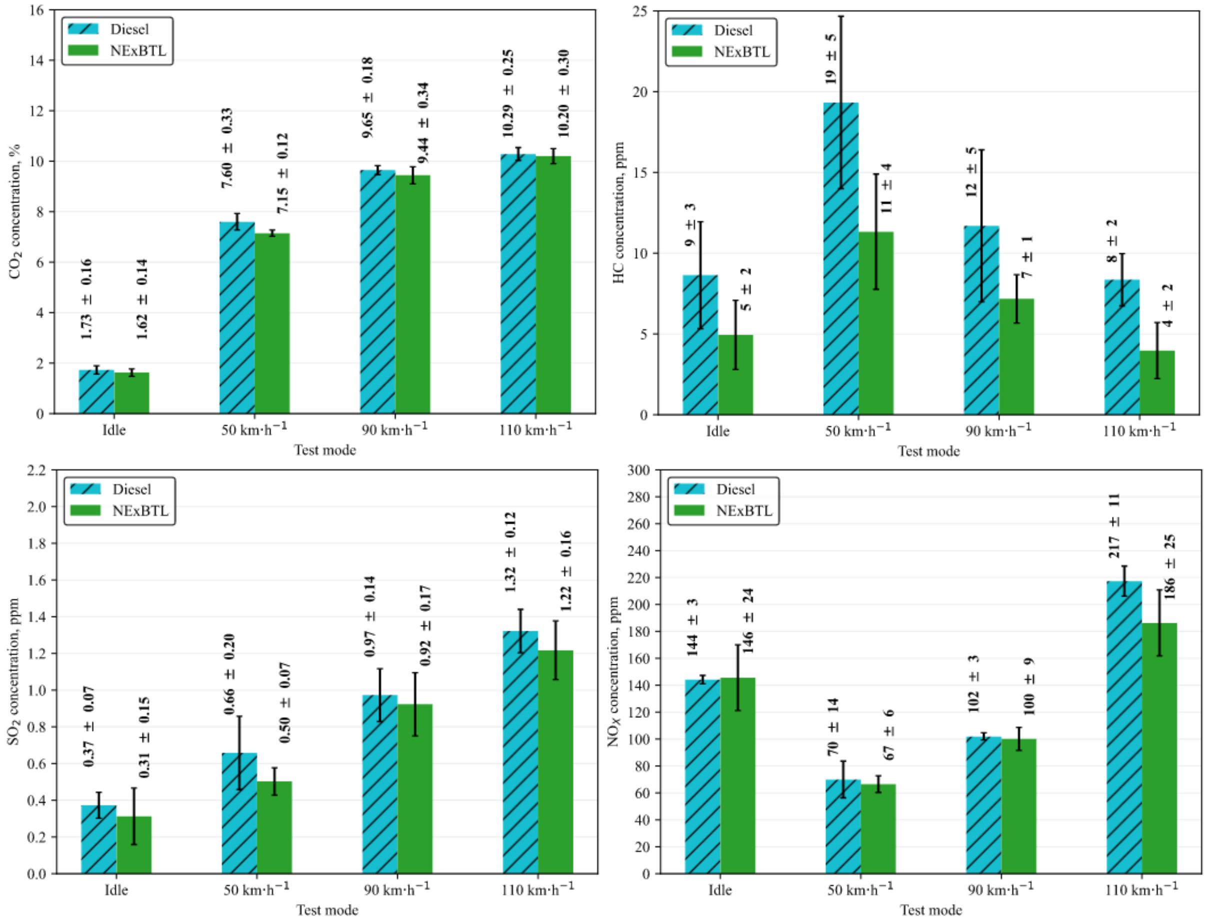

Fig. 5. **Concentration of CO_2, HC, SO_2 and NO_x in vehicle-out exhaust gases**

In low and middle engine speed pilot injection is typically used and it can be assumed so also for the engine in this study. The increase in fuel cetane number pronounces as a shorter ignition delay during combustion of the fuel injected during pilot injection and less so following the main injection. The described effect of pilot injection and comparison of apparent heat release rate curves between NExBTL and diesel fuel is shown in the work of Sugiyama et al. [12]. According to Heywood, the main source of NO production in a diesel engine is the diffusion combustion phase, which starts after pilot combustion and the premixed phase of following main injection is finished [15]. Additionally, higher compressibility of paraffinic fuel, compared to regular diesel fuel leads to delayed injection, which reduces pressure, temperature and NO formation [9]. The detailed results of NO_x composition, calculated by equation (1) are not included for the brevity of this paper, but NO_2 was approximately 55% and NO just 45% of the volumetric part of total nitrogen oxides for both tested fuels. Normally, NO_2 should be between 10 to 30% of nitrogen oxides diesel engine-out emissions [15]. That means that in this research the composition of nitrogen oxides in exhaust gases are affected by gas after-treatment systems.

Significant reductions of approximately 44% of HC emissions when NExBTL was used were observed. According to Heywood, there are two main pathways for hydrocarbons to escape compete combustion in diesel engines – fuel mixture becomes too lean to ignite during premixed combustion that follows ignition delay, and the fuel-air mixture becomes too rich to ignite during the diffusion-controlled combustion phase [15]. As NExBTL has a significantly higher cetane number, that leads to shorter ignition delay and less pronounced premixed combustion phase. That might lead to a reduction of HC emissions that might originate during the premixed combustion phase. The result of HC concentration is calculated by AVL SESAM FTIR gas analyser software, using equation (2). This parameter needs deeper investigation in future research, as some species of hydrocarbons might be not accounted.

Besides, it is important to note that gas samples were taken from the vehicle exhaust pipe, and the concentration of gas species is significantly altered by the catalytic converter and diesel particulate filter (DPF).

Comparing the obtained results with other studies, it is confirmed that was mentioned in the introduction, i.e., the tendencies of changes of various parameters differ depending on the used fuel properties and test objects. Similar to Singer et al. study [4], HC in the exhaust gas decrease, but no increase in NO_x is observed. Compared with Bortel et al. study [5], very similar results were obtained for the reduction of CO_2 and NO_x, but the reduction of HC is approximately twice as small. The increase in fuel consumption is very similar to that found by Rimkus et al. research [6]. However, there is a less significant reduction in NO_x and CO_2 concentrations. HC change trends are close. The changes in CO_2 are also very close compared to Suarez-Bertoa et al. study [7], but they did not identify significant changes in other exhaust components. The fact that no decrease in power and torque was observed with HVO is consistent with Sugiyama et al. investigation [12], which found that the injection quantity of HVO has to be 3% to 5% higher than diesel, but this results in no power loss with HVO in a common rail-equipped engine, even though the energy content on a volume basis is approximately less by 5%.

Conclusions

1. The trial results prove that the car's power and torque characteristics using both fuels, i.e., NExBTL and diesel fuel, in the whole range of the engine speed are similar. The difference in maximum power is 0.34%, but the maximum torque difference – 0.75%. Concerning the accuracy of the equipment, the differences in power and torque are considered insignificant.
2. The average fuel volumetric consumption of NExBTL fuel is about 3% higher than that of diesel. This can be explained by the differences in the physical properties of the two fuels. The calorific value of both fuels in MJ per kilogram is practically the same, but the density of fuels differs by more than 7%. It causes a 6.5% difference in calorific value per litre of fuel.
3. Running on NExBTL, the vehicle used relatively less fuel mass by approximately 5.3% and less fuel energy by 4.5%, compared to diesel fuel. Apparently more favourable mixture preparation and combustion occurred for NExBTL in tested engine and vehicle.
4. When analyzing the exhaust gases, the concentration of CO_2, SO_2, NO_x and HC species tend to decrease compared to fossil diesel. A reduction was observed in most tested modes. The largest reduction of NO_x concentration using NExBTL was observed at a higher engine load, at a steady speed of 110 km h^{-1}. The average observed reduction is for unburned hydrocarbons – by 44%, SO_2 – by 13.3%, NO_x by 5% and CO_2 – by 3.8%.
5. Experimental studies on the *Opel Insignia* 2.0 *CDTi* with NExBTL allow suggesting that this fuel could compete with fossil diesel in the future. It is confirmed by measurements of power, fuel consumption and exhaust gas content. An essential factor in the broader introduction of this fuel is its price.

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Article

Studies of Engine Performance and Emissions at Full-Load Mode Using HVO, Diesel Fuel, and HVO5

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Abstract: The aim of the study was to determine impact of commercially available hydrotreated vegetable oil (HVO) and its mixture (HVO5, where 5% (v/v) HVO and 95% (v/v) FDD) with diesel fuel (FDD) on the power, torque, fuel consumption, and exhaust gas composition of an atmospheric internal combustion diesel engine used in off-road applications. Diesel fuel was used as the comparative fuel. Testing was realized in a full-load mode on the KOHLER KDI 1903 M 3-cylinder diesel engine on a SIERRA CP-Engineering engine test bench. The AVL SESAM FTIR exhaust gas analytical system was used to determine exhaust gas emissions, while the AVL KMA Mobile fuel consumption measuring device was used to measure fuel consumption. Research showed that the lowest power and torque readings were obtained with FDD, while HVO showed a slightly higher result compared to the fossil diesel fuel. At the same time, the highest hourly fuel consumption was observed running on HVO5, while the lowest was observed with FDD. Increases in carbon monoxide (CO), carbon dioxide (CO_2), and nitrogen oxide (NO_x) emissions were observed for HVO5 compared to those of FDD. The CO content in emissions increased by an average of 3.0% using HVO and by an average of 36% using HVO5, but the NO_x content in the emissions increased by an average of 3.0% using HVO and by an average of 8.8% using HVO5. The reduction by an average of 60% using HVO in emissions was found in the case of hydrocarbons (HC). Research confirmed that the physicochemical properties of HVO could leave an impact on the main engine performance parameters and exhaust emissions.

Keywords: diesel engine; hydrotreated vegetable oil; testing; performance; emissions

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1. Introduction

In recent decades, Europe has been slowly and thoroughly moving in the direction of a European Green Deal, adopting a set of proposals to make the EU's policies fit for the reduction of greenhouse gas (GHG) emissions by at least 55% by 2030 in comparison to those in 1990 [1]. The desire to reduce CO_2 emissions is particularly strongly stimulated by the EU Directives, the main objective of which is the decarbonization of the European economy in most market sectors. Since road transport accounts for 77% of the total amount of emissions [2] and the stable increase in the number of vehicles in Europe will reach 246.3 million cars on the road in 2020 [3], the desire to introduce relevant regulatory standards is justified. In this regard, the often-mentioned European standards show a significant contribution to the reduction of air pollution levels over many years [4], taking into account that the long-term exposure of particulate matters of 2.5 µm diameter (PM2.5), nitrogen dioxide (NO_2) and ozone (O_3), contributed to over 400,000 premature deaths in EU [5]. In order to achieve better carbon dioxide (CO_2) targets in the transport sector, special attention has been paid both to the introduction of stricter test procedures and the development of new products (hybrids, electric vehicles), as well as to the adoption of appropriate laws, the last of which encourages that new cars that come on the market should be zero-emission and cannot emit any CO_2 [6].

At the moment, the automotive industry is intensively working on the electrification of vehicles and powertrains despite the domination of internal combustion engine vehicles in new registrations in the European market [7]. However, the complete electrification of transport, despite the deadlines set by the EU, is unpredictable due to the lack of purchasing possibility of customers and appropriate infrastructure, leaving only hybrids as a stable alternative in the road transport market [8]. It is also clear that the demand for liquid and gaseous fuels will remain relatively stable in the coming decade, despite the fact that significant developments in internal combustion engine technologies are unlikely to continue, at least in the light-duty vehicle sector. Therefore, newly manufactured cars will meet previously mentioned standards, but the large number of used cars will not just disappear from the roads and still will continue to emit significant amounts of pollutants. For this type of transport, the possibility of reducing emissions by fuel modifications without technical intervention could be a promising solution [9]. This alternative can be seen directly in the area of renewable fuel and meets the requirements of the Renewable Energy Directive (2009/28/EC). Based on the directive, each member state must ensure that the final energy use within the transport sector constitutes at least 14% in 2030, and biofuels based on food crops can represent only 7%. In this regard, the most well-known fuel is biodiesel (FAME), which is already used in a 7% mixture with fossil diesel named B7. However, the use of biodiesel is limited to the above-mentioned ratio due to its physicochemical properties. Directive 2009/28/EC also promotes so-called advanced biofuels, where one of the promising examples is hydrotreated vegetable oil (HVO) produced by a hydro-treating catalysis of a blend of different oils and waste materials. In this case, the conversion occurs through three reactions—hydrogenation, hydrodeoxygenation and hydrodecarboxylation—that create hydrocarbons similar to existing diesel fuel components [10]. There are significant advantages of hydroprocessing over esterification, which include lower processing cost, feedstock flexibility, and compatibility with existing fuel standards [11]. In addition, HVO has a higher energy content and superior thermal and storage stabilities than FAMEs and alcohols [12].

Its compatibility with conventional compression ignition engines and European standard EN 15940 for paraffinic fuels as well as its possibility to be blended with conventional diesel fuel (EN 590) without the labeling of biocomponents at the retail point [13] make HVO really attractive for retailers. Additionally, low risks for fuel system deposits and engine oil deterioration [10], improved exhaust emissions, and extension of the regeneration interval of the diesel particulate filter [14] make it also attractive for customers. HVO could be used without any change of the engine fueling system as it did not even significantly affect the degradation of elastomers, such as O-rings [15], which usually are not resistant to various types of biofuel used in the automotive industry.

A large part of the previously mentioned positive results obtained by HVO was achieved using the combination of the physicochemical properties of this fuel. HVO is a synthetic liquid biofuel free of aromatics and sulfur compounds [16]. It has a relatively high heating value and cetane number and a low viscosity, density, lubricity, and cloud point. It is made up of straight-chain paraffinic hydrocarbons [17]. Changes in each characteristics are interrelated. Increases in the heating value are connected with higher hydrogen content and lower density with the paraffinic nature of the fuel, while cloud point, highly dependent on the reaction conditions, may lead to a certain yield of triglycerides [18]. Reference [19] showed that the main restrictions for blending are imposed by the lubricity and the cetane number, where compromise should be found between those characteristics, while density and viscosity would not impose direct blending. Overall, the worsened low-temperature properties could be the only disadvantage in comparison with FAME-type fuel [18].

Additionally, HVO's similarities with fossil diesel in spray characteristics [13,20], air-fuel mixing [20], and combustion characteristics [21] allow it to achieve a positive impact on emissions in comparison to fossil diesel. Most of the studies confirm that HVO reduces carbon monoxide (CO), hydrocarbons (HC), and particulate matters (PM) dependent on the HVO shares in the mixture, while the effect of the HVO fuel on nitrogen oxide (NO_x) emissions is still not fully clear [17]. Studies concerning emission testing with HVO have been done with passenger cars [22], heavy-duty engines and city buses [23,24], tractors [25], and even underground mining machines [26].

The determination of emissions in different cycles, conditions, and in more advanced vehicles is becoming more and more relevant. For example, Di Blasio [7] confirmed that HVO significantly reduces regulated engine emissions, providing EU 6c NO_x emissions targets without changes in the efficiency. In the tests within the NEDC and WLTP homologation areas performed by the multicylinder reference engine, reductions of up to 0.5 $g \cdot kWh^{-1}$ for HC (50%) and 2.5 $g \cdot kWh^{-1}$ for CO (45%) were found.

Serrano [27] did not find significant differences considering the two homologation cycles, the oldest (NEDC) and the actual (WLTP), and the use of HVO15 (15% of HVO) in the case of the fuel consumption in comparison to B0 (pure diesel), B7 (7% biodiesel), B15 (15% biodiesel), B100 (pure biodiesel). Similar conclusions were also found considering the power of the engine obtained with the fuels, revealing variations smaller than 2%.

Pardhi [28], by calculating and comparing the optimal powertrain sizing of a plug-in hybrid coach, affirmed that switching from diesel to HVO could affect the optimal powertrain solutions, reducing the lifetime carbon footprint by 62% for around a 12.5% increase in overall costs across all sizing solutions.

A small amount of research with HVO was also conducted with agricultural machinery. For example, Sondors [29] performed research of the tractor CLAAS ARES 557ATX and found that the engine's effective power and torque using HVO fuel decreases by 5% compared to fossil diesel fuel. At the same time, he also observed an average reduction in NO_x of 11.8%, total unburned hydrocarbons (THC) of 26.4%, CO of 14.5%, and CO_2 of 5.2% in comparison with fossil diesel.

Similar results were also presented by Czech researchers [30] investigating the effect of HVO on the performance parameters of a Zetor Foretrra 8641 turbocharged internal combustion engine using an AW NEB 400 PTO dynamometer. They found a decrease in peak torque of approximately 0.9% and a decrease in peak power of approximately 6%.

Studies [31] in India with a direct-injection six-cylinder 5.9 l turbocharged diesel engine meeting Euro III norms showed a 26% increase in NO_x and a 16% decrease in CO and HC, which, in the case of HVO, was explained by a higher cetane number.

Pirjola [25] tested HVO in AGCO off-road diesel engine that meets the European Stage 3B emission standards. Exhaust emissions by a non-road mobile machine were studied chasing a tractor in real-world conditions and repeating the same transient tests with a similar engine on an engine dynamometer where, additionally, non-road steady state tests were carried out. By replacing diesel fuel with HVO, the on-road emissions of NO_x reduced by 20% and particle number by 44%. A similar trend was observed for NO_x in the laboratory, although the emissions were slightly lower than those on-road.

MacCaffery [32] tested HVO and two HVO-biodiesel blends on a John Deere 4.5L diesel engine that meets the Tier 3, 2004 emission standards. Extended testing was conducted over the non-road transient cycle (NRTC) and the 5-mode D2 ISO 8718 cycle. Authors observed NO_x, PM and solid particle number reduction with pure HVO compared to diesel, while low-molecular weight polycyclic aromatic hydrocarbons (PAHs) were the dominant components in the exhaust for all fuels showing lower concentration of these pollutants for HVO compared to diesel fuel.

Kumar [33] observed in his study with agricultural engine and blends of hydrotreated waste cooking oil with fossil diesel that HC, CO and smoke emissions for the test blends decrease up to 30%, but for larger blends the emissions start increasing. At the same time, NO_x emissions were lower than diesel for all the test samples.

Extensive studies with engines of different Euro emission norms were carried out in Finland. Tests with 11 buses, starting from older vehicles that comply with Euro II emission norms, up to EVV (Enhanced Environmentally-friendly Vehicles), i.e., vehicles whose emission level is lower than the current regulations, showed a lower energy consumption of about 0.5%, but an increase in fuel volume consumption of 5.2 and 3.5%, respectively, for pure HVO compared to summer and winter class diesel [34]. Another study with 17 buses, ranging from older vehicles that meet Euro II emission standards to EVVs, showed average reduction of NO_x emissions by 10%, PM by 30%, CO by 29% and HC by 39%, for pure HVO compared to FDD. A consistent reduction in emissions was observed for Euro II and Euro III buses, but no such trends were observed for the newer buses [35].

Additionally, it should be noted that lower lubricity could require the use of special additives, the correct selection of which will not have a negative impact on emission reduction. For example, the author of [9] in studying different additives to existing B7 fuel, including ferrocene nanoparticles and cerium dioxide, as well as HVO biofuel and its mixtures with 10 and 30% HVO by volume with nanomodifiers, showed a significant reduction in carbon monoxide and hydrocarbon emission in relation to the base fuel (B7).

As was mentioned before, HVO's effect on NO_x is still unclear. For example, Demuynck [22] did not find specific fuel effects for NO_x between market diesel fuel B7, diesel fuel with 30% FAME, and 100% HVO using a vehicle with an advanced emission control system and Euro 6b diesel engine, while differences explained by the impact of the driver, traffic, ambient temperature, etc. were obtained within the expected test-to-test variability. Kuronen [24], in the tests with heavy-duty engines using HVO, observed reductions in NO_x of 7–14% in comparison to that with EN 590 fuel. At the same time, Happonen [36] reported that NO_x can be reduced at different loads (50%, 75%, and 100%) over 25% and higher by engine parameter adjustments, concluding that the full advantage of HVO cannot be realized unless the engine is optimized for the new fuel. Overall, it should be noted that the final NO_x concentration is a delicate balance among different factors—fuel properties, spray characteristics, air-to-fuel ratio, compression ratio, injection strategy, etc. [17]—therefore, replacing conventional diesel with HVO does not guarantee a reduced NO_x emission [37]. Considering all the above, it could be concluded that HVO has great potential and could be an appropriate solution for achieving emission targets for the existing fleet as well as new vehicles without improvements of the existing fueling infrastructure.

Overall, there is still limited knowledge on the effect of HVO on engine performance, fuel consumption, and emissions from agricultural engines, and it should be investigated more deeply. Considering the growing demand for low-emission vehicles, the current research was conducted on a modern internal combustion engine using an advanced test bench, fuel consumption, and exhaust equipment. The dynamic, economic, and ecological parameters of the compression ignition engine were analyzed within the scope of this study.

2. Materials and Methods

Research was carried out at the Alternative Fuels Research Laboratory of Latvia University of Life Sciences and Technologies in December 2021. Commercially available fuels Neste Futura Diesel (denoted as FDD), Neste MY (denoted as HVO), and Neste Pro Diesel (denoted as HVO5; containing 5% (v/v) HVO and 95% (v/v) FDD) were used in the study. All fuels used in the tests were purchased from one fuel distributor (Neste Latvija Ltd., Riga, Latvia), which also provided the physicochemical properties of those fuels; the main characteristics of the fuels are given in the Table 1.

Table 1. Selected physicochemical properties of tested fuels.

Property	Method	Fuel		
		FDD	**HVO**	**HVO5**
Density at 15 °C, $g{\cdot}m^{-3}$	EN ISO 12185	816.1	780.8	807.4
Viscosity at 40 °C, $mm^2{\cdot}s^{-1}$	IN ISO 3104	1.853	3.025	1.797
CFPP, °C	EN 116	−40	−38	−42
CP, °C	EN 23015	−28	−34	−33
Cetane number	EN ISO 5165	53.8	74.5	55.0

The study was performed on the KOHLER KDI 1903 M 3-cylinder internal combustion atmospheric diesel engine, mostly used as agricultural engine and an engine for generator sets. The engine is equipped with a mechanical rotor high-pressure pump and complies with EUR STAGE 3 A emission standards. The main technical characteristics of this engine are listed in Table 2.

Table 2. Technical data of the KOHLER KDI 1903 M diesel engine.

Parameter	Value
Engine capacity, cm^3	1861
Cylinder number	3
Top power, kW	31 at 2600 min^{-1}
Maximum torque, Nm	133 at 1500 min^{-1}
Compression ratio	17
Bore, mm	88
Stroke, mm	102
Fuel injection system	Direct injection

The research engine was connected to the SIERRA CP-Engineering engine test bench, which consists of an AC dynamometer capable of operating in both absorption and motor modes. When operating in absorption mode, the absorbed energy is converted into electricity and fed into the public grid. The maximum absorption power of the dynamometer is 50 kW; maximum revolutions—7000 min^{-1}; maximum absorption torque—140 Nm. The ABB 4 drive system, which is controlled by the CADET control system, is responsible for the correct operation of the loading equipment. The engine test bench setup is given in Figure 1.

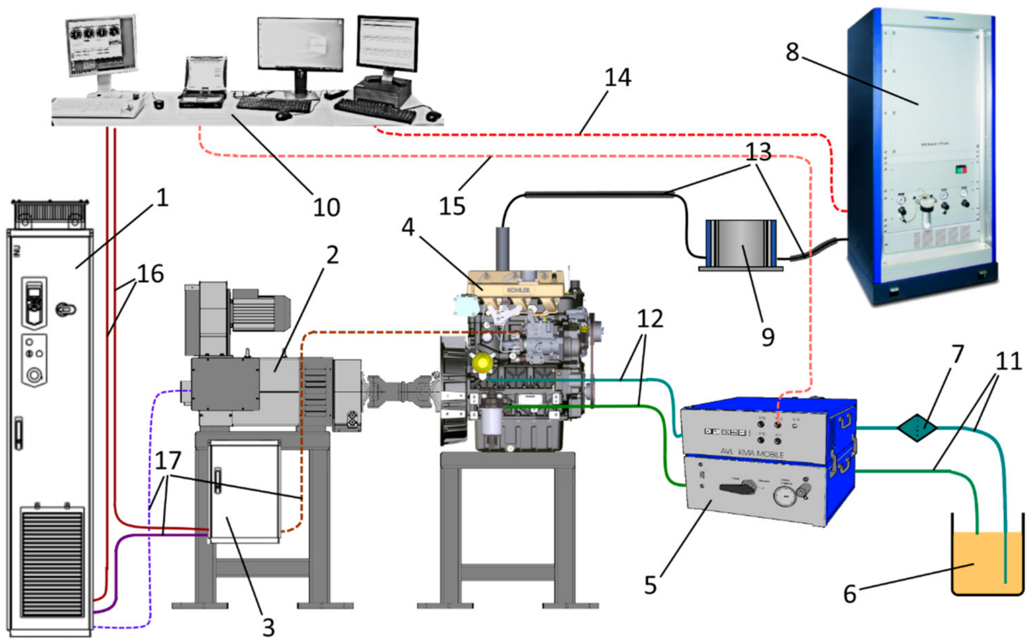

Figure 1. Engine test bench setup: 1—regenerative drive; 2—AC dynamometer; 3—test engine control box with throttle actuator; 4—Kohler engine; 5—fuel measuring device AVL KMA Mobile; 6—fuel tank; 7—fuel filter; 8—multicomponent exhaust gas measurement system AVL SESAM FTIR; 9—heated filter; 10—operator interface with data recording and measuring device control computers; 11, 12—fuel lines; 13—heated gas line for exhaust gas measurement from the exhaust tailpipe; 14—AVL SESAM FTIR data communication cable; 15—AVL KMA Mobile data communication cable; 16, 17—dynamometer and test engine communication cable.

The AVL KMA Mobile fuel consumption measuring device was used to measure fuel consumption. The measuring range of the device is from 0.35–150 l h^{-1}; measurement error—0.1%; data recording step, 1 s. The device is connected between the fuel system of the test engine and the fuel tank.

The AVL SESAM FTIR exhaust gas analytical system was used to determine the exhaust gas emissions. In this system, the composition of exhaust gases is determined by an infrared spectrometer. This system is able to measure 24–27 different exhaust gas components.

The aim of the study was to determine the impact of commercially available hydrotreated vegetable oil (HVO) and its mixture (HVO5, where 5% (v/v) HVO and 95% (v/v) FDD) with diesel fuel (FDD) on the power, torque, fuel consumption, and exhaust gas composition of the atmospheric diesel engine used in off-road applications. Testing was realized in a full-load mode. Since all the mentioned fuels are commercially available at Neste Latvia Ltd. (Riga, Latvija) fueling stations in Latvia, it was important to understand within the framework of the study whether the changes in the dynamic and economic parameters found will be significant enough for the end-users. The test program was based on a pre-developed loading cycle that ensures the operation of the test engine in the speed range from 1000 min^{-1} to 2700 min^{-1}. Loading was carried out with a step of 100 min^{-1} that makes 18 loading steps in the given engine speed range. The fuel supply lever was set to the maximum fuel supply position. The duration of each loading step was 10 s. When the test was activated, the dynamometer automatically maintained the set engine speed, simultaneously recording the developed power and torque of the test engine, while the additionally connected fuel consumption and exhaust gas emission measuring devices recorded the instantaneous fuel consumption and exhaust gas composition data.

In total, 5–7 measurement repetitions were performed with each test fuel. Initially, the stable ranges of each measurement step (i.e., ~10 s) were selected from each experimental repetition, from which the average values of the measurement step were calculated. After mathematical processing of the data, the results were presented as average values of all repetitions for each fuel type.

3. Results

The characteristic curves of engine power and torque after data processing (confidence level—95%) are given in Figure 2. Comparing the values of power and torque of each individual repetition at certain revolutions, the correlation for FDD values exceeds 98.1%, HVO—99.6%, and HVO5—98.0% (from 5–7 repetitions performed with each fuel, at least four with the highest mutual power; correlations of rpm and torque data points were left for data processing). It can be seen that the highest power and torque were obtained when the experimental engine was operated with HVO5, which is a mixture of HVO and fossil diesel fuel. The lowest power and torque readings were obtained with FDD, while HVO showed a slightly higher result compared to the fossil diesel fuel. Since fuels have different properties (fuel density, heating value, etc.), power changes should be viewed together with changes in fuel consumption.

Operating an engine with HVO5, the maximum power was obtained at 2600 min^{-1} (26.2 kW) and the maximum torque was obtained at 1600 min^{-1} (120.9 Nm). The increase in maximum power was 2% and the increase in maximum torque was 2.4% compared to FDD (25.7 kW at 2600 min^{-1} and 118.1 Nm at 1600 min^{-1}). In the case of HVO, the maximum power was obtained at 2600 min^{-1} (26.0 kW) and the maximum torque was obtained at 1600 min^{-1} (119.5 Nm). Therefore, the increase in maximum power was 1.4% and the increase in maximum torque was 1.2% compared to the operation of the engine using FDD. Overall, the differences are very small and practically would not be noticeable by an end-user.

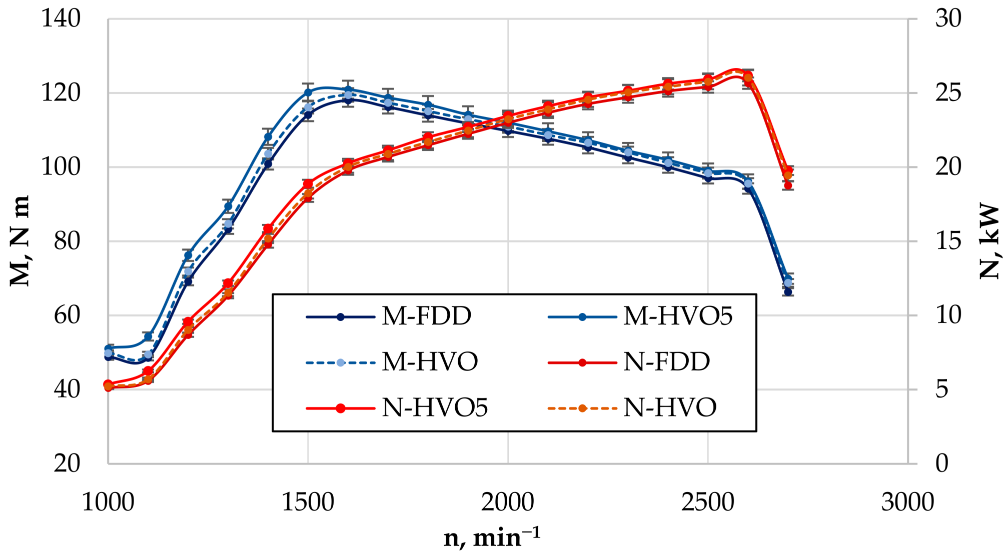

Figure 2. Power and torque of the experimental engine on three different fuels.

The curves of hourly fuel consumption (Q) and specific fuel consumption (g_e) after data processing (confidence level—95%) are given in Figure 3. Comparing the fuel consumption values of each individual repetition at certain revolutions, the correlation for all fuels was at least 99.8% (from 5–7 repetitions performed with each fuel, at least four were left—the same as for the power and torque analysis). The trend of instantaneous fuel consumption for all three test fuels was similar to that of the power data. The lowest hourly fuel consumption was obtained by the engine running on diesel fuel, while the highest was obtained when it was running on HVO5. At the same time, HVO5 usage resulted in a 2.34% increase in the maximum average hourly fuel consumption over the entire crankshaft speed range compared to FDD, while for HVO, the increase was only 1.00% more than for FDD.

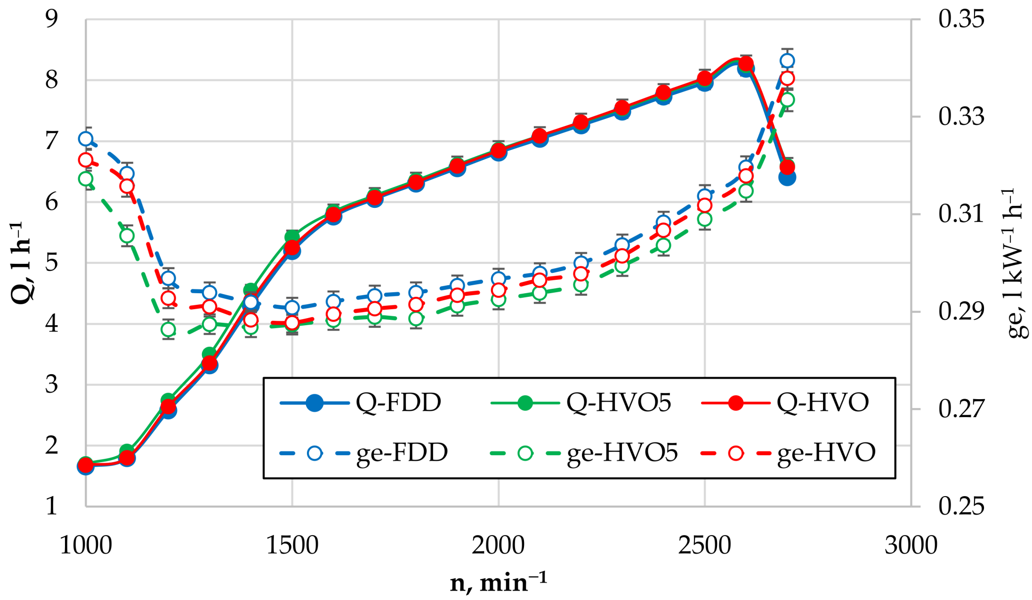

Figure 3. Fuel hourly consumption Q ($l \cdot h^{-1}$) and specific fuel consumption g_e ($l \cdot kW^{-1}\ h^{-1}$) data for all three test fuels based on crankshaft revolutions of the engine.

However, it is more objective to compare the specific fuel consumption data, which are obtained by calculation, dividing the instantaneous fuel consumption at a specific turning point by the power developed at this point. Despite the fact that the engine running with HVO5 obtained the highest hourly fuel consumption, at the same time, it showed the lowest specific fuel consumption. This means that less fuel is needed to develop one unit of power than is the case with FDD or HVO. On average, in the entire range of engine revolutions, the reductions of specific fuel consumption were 1.88% using HVO5 and 0.86% using HVO in comparison to FDD.

Variations in the content of CO, CO_2, HC, and NO_x in exhaust gases engine operating with three different fuels after data processing (confidence level—95%) are given in Figures 4–7. In total, from 5–7 repetitions performed with each fuel, at least four were left for data processing, similarly as for the analysis of power, torque, and fuel consumption data.

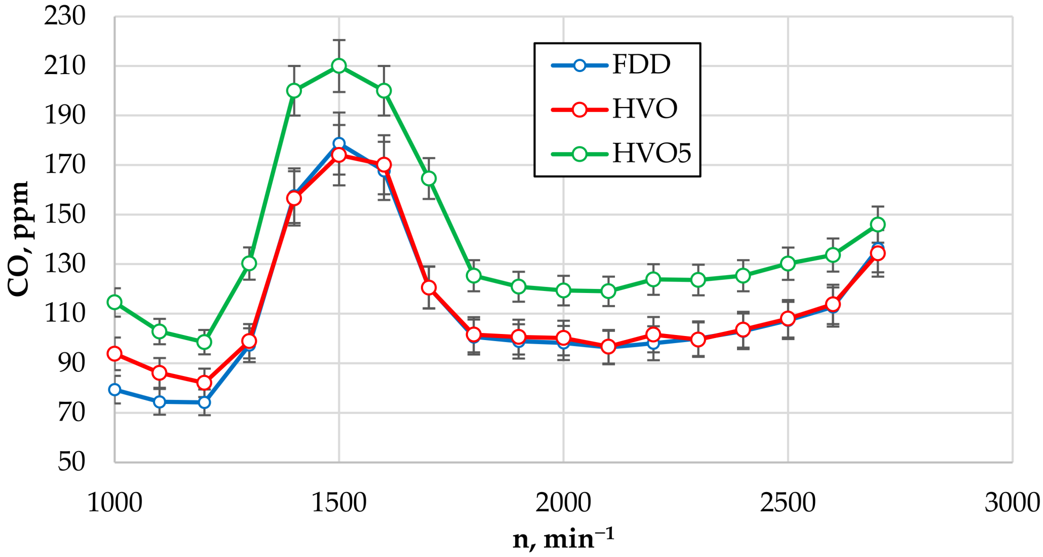

Figure 4. Carbon monoxide emissions from the engine running on three different fuels.

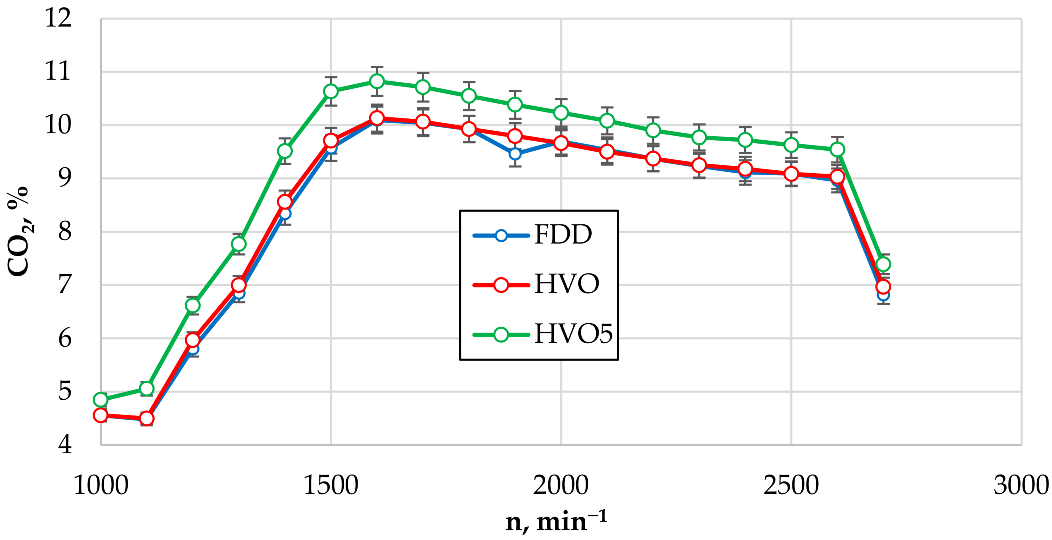

Figure 5. Carbon dioxide emissions from the engine running on three different fuels.

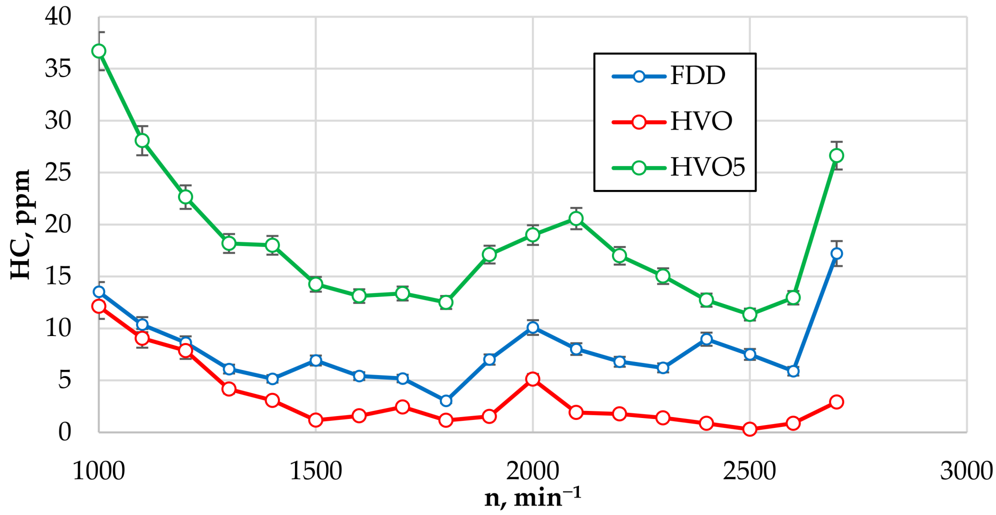

Figure 6. Hydrocarbon emissions from the engine running on three different fuels.

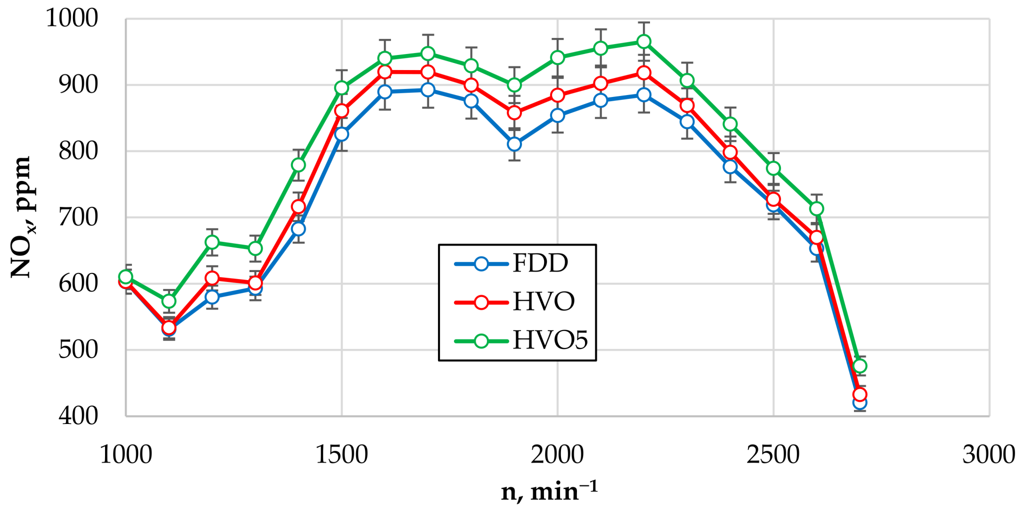

Figure 7. Nitrogen oxide emissions from the engine running on three different fuels.

Overall, the emissions data show a peculiar trend. The lowest emissions of nitrogen oxides (NO_x) are achieved using FDD, while HVO5 has a clear advantage in terms of the other investigated emissions. In addition, a similar trend of emission changes was observed for all three fuels in the entire range of engine crankshaft revolutions, occasionally decreasing or increasing the difference in the step values.

Pure HVO usage resulted with an increase in CO emissions by an average of 3.0% in the entire engine crankshaft speed range compared to FDD, while HVO5 usage increased them by an average of 36%. Moreover, it was observed that CO emission content has a direct relationship with the torque characteristic curve; the maximum of this emission component using all fuels was formed at the revolutions that coincide with the maximum torque.

In the case of pure HVO, the content of CO_2 emissions in the entire range of engine crankshaft revolutions in comparison to FDD increased by an average of 0.9%, and this difference is considered insignificant, but using HVO5, it increased by an average of 8.4% (see Figure 5).

Comparing the graph of CO_2 emissions with the power and torque characteristics, it can be seen that the content of this emission component directly “follows” the torque developed by the engine.

In the case of using pure HVO, the content of HC in emissions in the entire range of engine crankshaft revolutions decreased by 60% on average in comparison to FDD, but using HVO5, it increased by an average 1.45 times (see Figure 6).

If the NO_x content is taken as a reference point operating the engine with FDD, then using pure HVO, the NO_x content in the emissions increased by an average of 3.0% over the entire range of engine crankshaft revolutions and by an average of 8.8% using HVO5 (see Figure 7). Peak NO_x emissions for all fuels occur at revs coinciding with the peak torque and 300 min^{-1} before peak power revs.

4. Discussion

The composition of fuel nowadays is subject to change, especially when there are also different alternatives in the range of choices that can be used to create different mixtures. The physicochemical properties of HVO and diesel fuel are very similar, which means that the creation of mixtures will not cause significant changes in the fuel injection process nor in evaporation At the same time, some changes in results were observed. Looking at the overall results, it can be concluded that there was not always such an unequivocal trend in the results between the types of fuel that would be expected in the case of mixed fuels when the increase in the biofuel additive contributed to the increase or decrease of some specific physicochemical properties of the fuel or engine operating parameters. In the given case, this was due to the fact that in the experiments, the mixed fuel HVO5 (or Pro Diesel at fueling stations) was taken from a public fueling station and not mixed from the two pure fuels themselves. Therefore, it cannot be guaranteed that the physicochemical properties of such mixtures would be equivalent to what they would be when mixing the two pure fuels used in the experiments. This could accordingly explain why HVO5 sometimes shows a better effect than pure HVO.

Fuel properties such as the higher heating value of HVO may contribute to the reduction in fuel consumption expectable using blends [19], and it was also observed in this study. The increase in hourly fuel consumption that was found in the given study is natural because HVO, despite a higher lower heating value (LHV), still has a lower energy per unit volume as a consequence of the lower density. Since the fuel supply is provided by volume, it is clearly that it is a volume-based calorific value. Therefore, it is not a mass-based calorific value, which already directly affects the specific fuel consumption, as a result of which, specific fuel consumption would already be lower. The results of this study are also confirmed by another study [38], where it was found that specific fuel consumption reduces with an increasing blend ratio, saving 2.3%, and such reduction corresponds to the higher mass-based heating value of HVO, which is 2.4%.

This insight can even be applied to power; maximum power decreases with the reduction of lower heating values of the fuels used in research. If an insignificant increase in power was found in this study, then the previously mentioned study [38] confirms no significant power loss with HVO. In comparison with the results obtained by other researchers, where the studies were carried out on the engine test bench, sometimes a decrease in power is also observed. For example, in a study conducted in Korea [39], blending a similar amount of HVO with fossil diesel produced about a 1% power reduction compared to FDD, but more than a 2% power reduction with pure HVO fuel.

At the same time, the reduction in fuel consumption is explained by the difference in carbon chains [39], as HVO consists of C15-C18 of the carbon chain while fossil diesel consists of C6-C30, in such way improving the combustion efficiency of HVO compared to FDD due to the absence of a heavy-tail carbon chain. In theory, combustion efficiency should also have a positive effect on emissions, but this will not always be the case. Both an increase and decrease in emissions with HVO was found both in this study as well as in others. A slight increase in NO_x was found in light-duty and heavy-duty engine tests [40]. Larger NO_x emissions were found in [39] at the higher loads than in other conditions regardless of the differences of blending ratios of HVO with fossil diesel, while in the same research, lower HC emissions were observed. Rantanen [41], during tests with several HVO blends, pointed out reductions of HC and CO emissions, while clear reduction of NO_x was not observed. Chau [42] observed NO_x and soot concentrations decrease with HVO percentage increases, testing HVO and different blends by mass of HVO with commercial diesel fuel (mixed 7% FAME). Overall, vast differences in emissions with HVO and its blends could be explained by many reasons, including the fuel properties of the benchmark EN590 diesel fuel and especially the aromatics content, viscosity, and cetane number [38]. Bohl [38] explained variations in NO_x emissions with the lower fuel injection rate of HVO resulting in improved air–fuel mixing and a higher heat release rate at the start of combustion, which could be offset using fuel with a higher cetane number, correspondingly earlier ignition, and reduced heat release rates. Therefore, the ignition delay and injection control strategy must be monitored during such tests to get the most precise results of NO_x emissions and find out their explanation. This was also iterated by Dimitriadis [43], who explained that engines are designed for optimum operation with fossil diesel fuel and significant reductions in exhaust emissions are possible with favorable fuel characteristics and proper engine control.

Looking at the emission graphs shown in the study, the initially obtained results seem to be contrary to logic, i.e., two fuels were mixed, and the content of all emission components was practically the same (3% difference in emission studies is not considered significant in practice), but the blended fuel obtained significantly worse emissions indicators. However, looking at another study [27] studying fuel with a small admixture of biocomponents, the emission results obtained were equally contradictory. Furthermore, voluminous research summaries [37,44–46] have highlighted that the full benefits of HVO are not being utilized when using HVO–fossil diesel blends, and emission trends are very different depending on the type of engine used, the test conditions, and the characteristics of the specific fuels. In this regard, it is important to note that CO_2 reduction is mostly explained by lower C/H ratios, which shift to a slightly higher production of H_2O instead of CO_2 [12], while HC could be reduced by shortening the ignition delay [43]. Therefore, future studies should concentrate on the effect of HVO on emissions analyses of combustion characteristics. This will give a much more accurate explanation of the increase in emissions in each specific situation.

Unfortunately, the price of pure HVO, which is approximately 1.5–2 times higher than the price of fossil diesel fuel in Latvia, cannot motivate vehicle users to use it either in its pure form or in mixtures for only the environmental protection if no other benefits are given, for example, the significant fuel economy, power increase. or beneficial effect on vehicle systems. That is why currently, from an economic point of view, there are partially sufficient arguments for the use of only low-level blends because 6–9% price increases could be compensated by the fact that the HVO admixture is much more friendly in cases of power and fuel consumption changes than the first-generation biodiesel admixture, especially during periods when it is mandatory for fuel dealers.

5. Conclusions

1. Studies have shown that there are benefits in using HVO fuel and its admixture, namely, power increases slightly and fuel consumption and hydrocarbons in the exhaust gases decrease. At the same time, no additional effect can be observed from increasing the mixture concentration; HVO5 showed better power and torque indicators than HVO compared to FDD.
2. The full desired ecological effect found by other researchers has not been achieved. The carbon monoxide content in emissions increased by an average of 3.0% using HVO and by an average of 36% using HVO5, while the NO_x content in the emissions increased by an average of 3.0% using HVO and by an average of 8.8% using HVO5.
3. To achieve significant improvements in results, more attention should be paid to research the impact of other different factors, such as the fuel composition, spray characteristics, air-to-fuel ratio, compression ratio, injection strategy, engine parameter adjustments, etc., which can further affect the combustion process and, accordingly,

the exhaust gas composition. This means that achieving the benefits of HVO cannot be fully realized with the existing internal combustion engine adapted to work with diesel fuel, but only after optimal adaptation to work with HVO.

4. Considering society's desire for low-emission and zero-emission vehicles, the ecological effect could be the most important driver of the use of this fuel in the latest generation of diesel engines. In addition, the slight increase in power in the case of using pure HVO will not be felt by the end-user, which will therefore hinder the full evaluation of this fuel. In that case, some more extensive outdoor studies using portable emission measurement systems (PEMSs) and high-precision fuel consumption measurement systems (AVL KMA Mobile) for fuel consumption and emission detection would be recommended and probably will be realized in future research.

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