THEORETICAL EVALUATION OF HYDROTREATED VEGETABLE OIL APPLICATION IN DIESEL ENGINES

Kristaps Sondors, **Ilmars Dukulis**
Latvia University of Agriculture
kristaps.sondors@gmail.com; ilmars.dukulis@llu.lv

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.

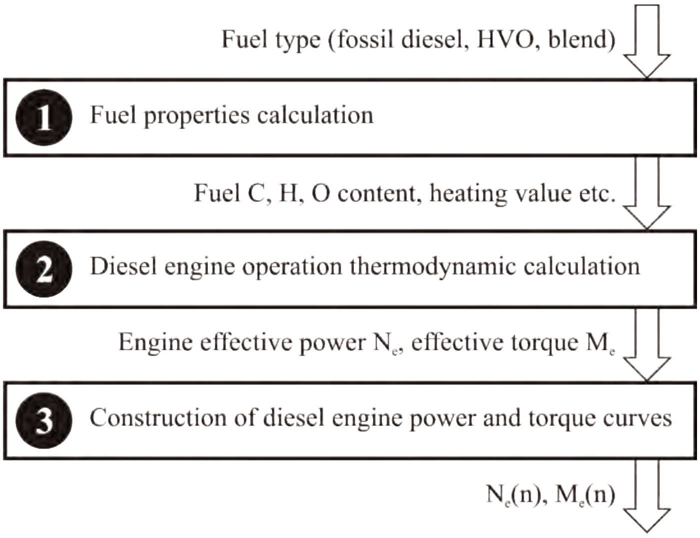

Figure 1. Model's block diagram.

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):

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

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

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:

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

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

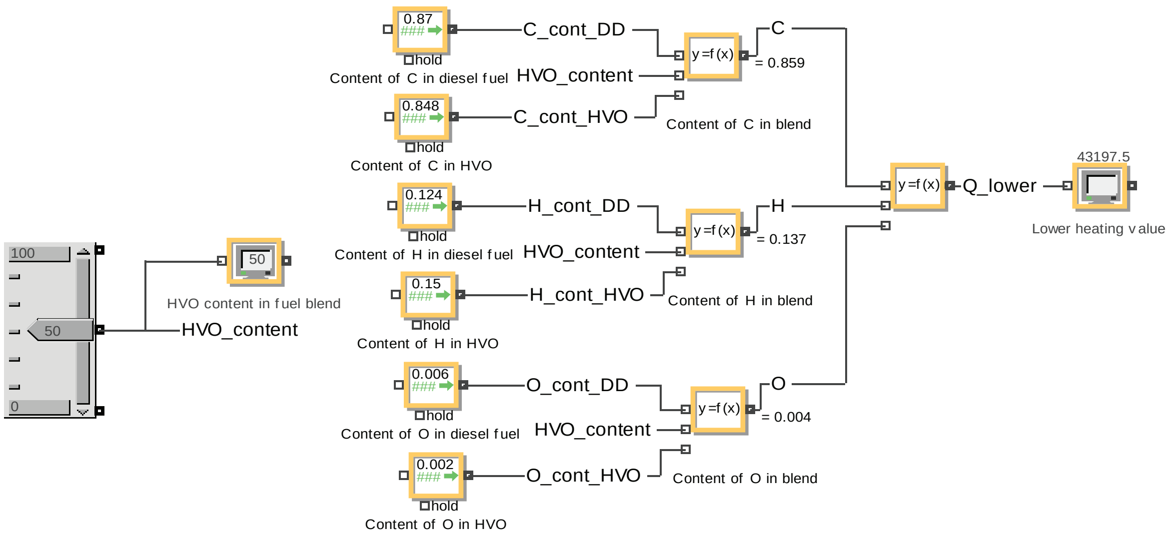

Figure 2. Fuel blend content and lower heating value determination blocks.

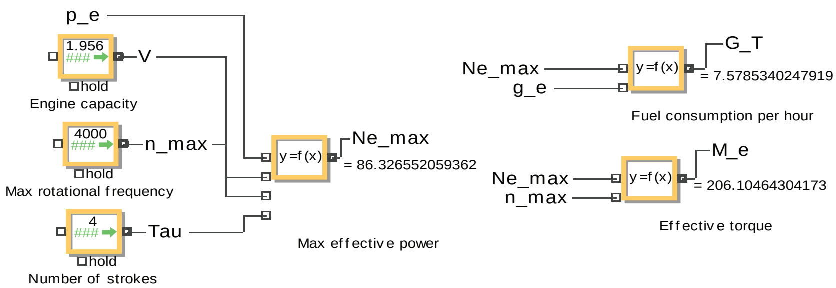

Figure 3. Engine power, fuel consumption and torque calculation blocks.

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):

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

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

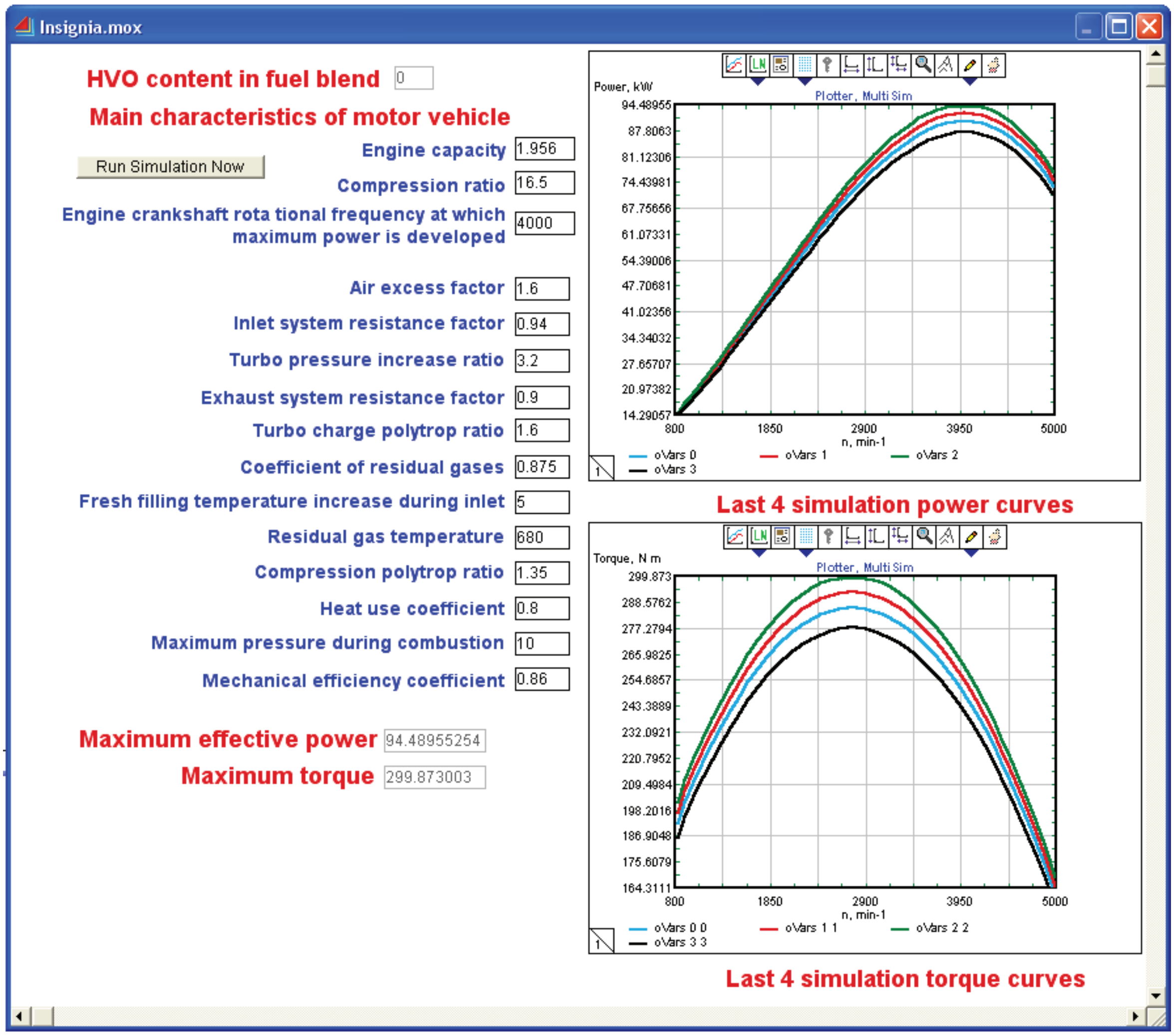

Figure 4. Example of the window for variables input and viewing of the simulation results.

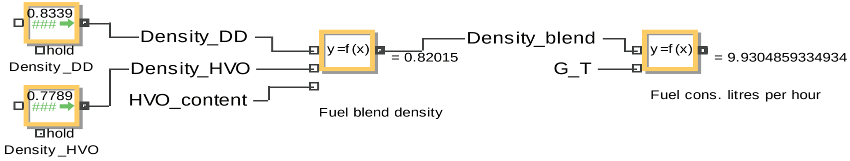

Figure 5. Fuel blend density and fuel consumption calculation blocks.

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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