energies

MDPI

Article

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

Ruslans Smigins *, Kristaps Sondors, Vilnis Pirs, Ilmars Dukulis and Gints Birzietis

Faculty of Engineering, Latvia University of Life Sciences and Technologies, 5 J. Cakstes Blvd., LV 3001 Jelgava, Latvia
* Correspondence: ruslans.smigins@lbtu.lv; Tel.: +371-28228222

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

Citation: Smigins, R.; Sondors, K.; Pirs, V.; Dukulis, I.; Birzietis, G. Studies of Engine Performance and Emissions at Full-Load Mode Using HVO, Diesel Fuel, and HVO5. *Energies* **2023**, *16*, 4785. https://doi.org/10.3390/en16124785

Academic Editor: Anastassios M. Stamatelos

Received: 16 May 2023
Revised: 9 June 2023
Accepted: 15 June 2023
Published: 18 June 2023

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.

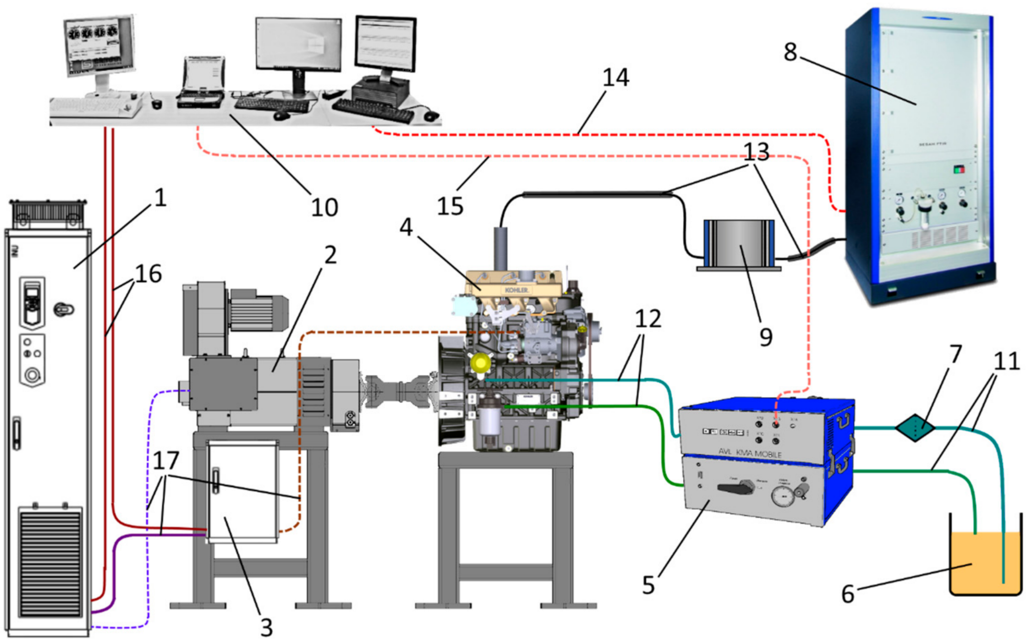

Figure 1. Engine test bench setup: 1—regenerative drive; 2—AC dynamometer; 3—test engine control box with throttle actuator; 4—Kohler engine; 5—fuel measuring device AVL KMA Mobile; 6—fuel tank; 7—fuel filter; 8—multicomponent exhaust gas measurement system AVL SESAM FTIR; 9—heated filter; 10—operator 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.

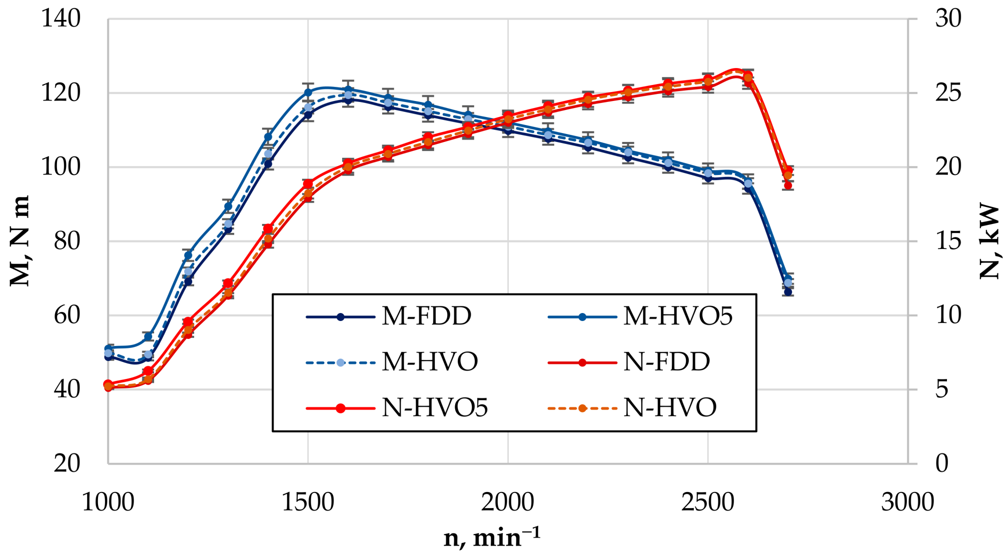

Figure 2. Power and torque of the experimental engine on three different fuels.

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.

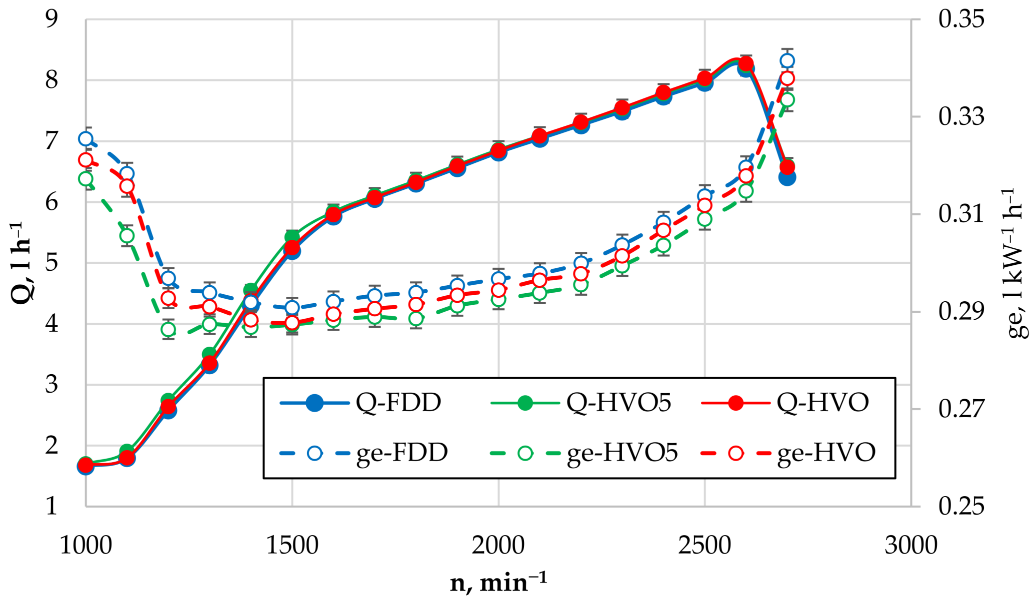

Figure 3. Fuel hourly consumption Q ($l \cdot h^{-1}$) and specific fuel consumption g_e ($l \cdot kW^{-1}\ h^{-1}$) data for all three test fuels based on crankshaft revolutions of the engine.

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.

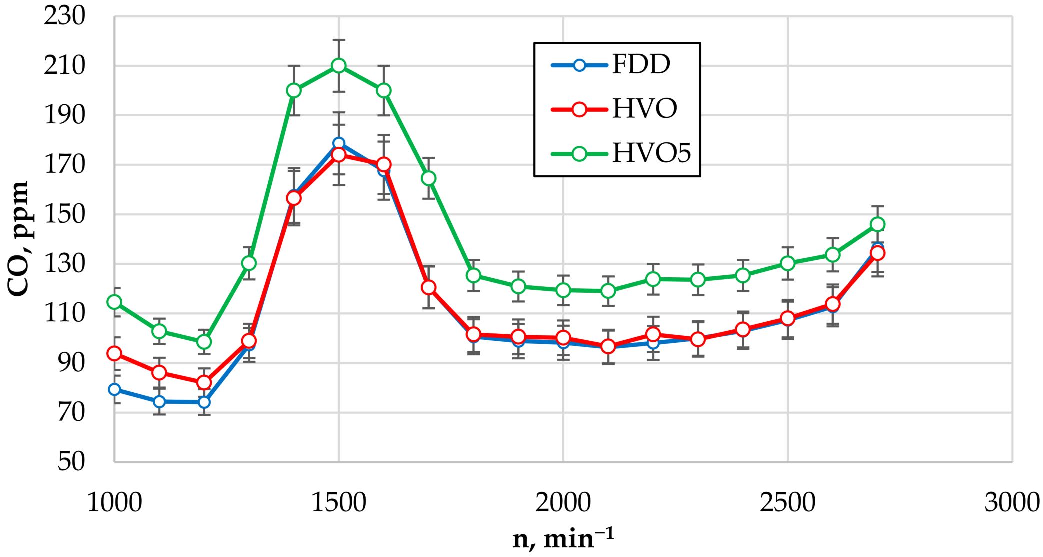

Figure 4. Carbon monoxide emissions from the engine running on three different fuels.

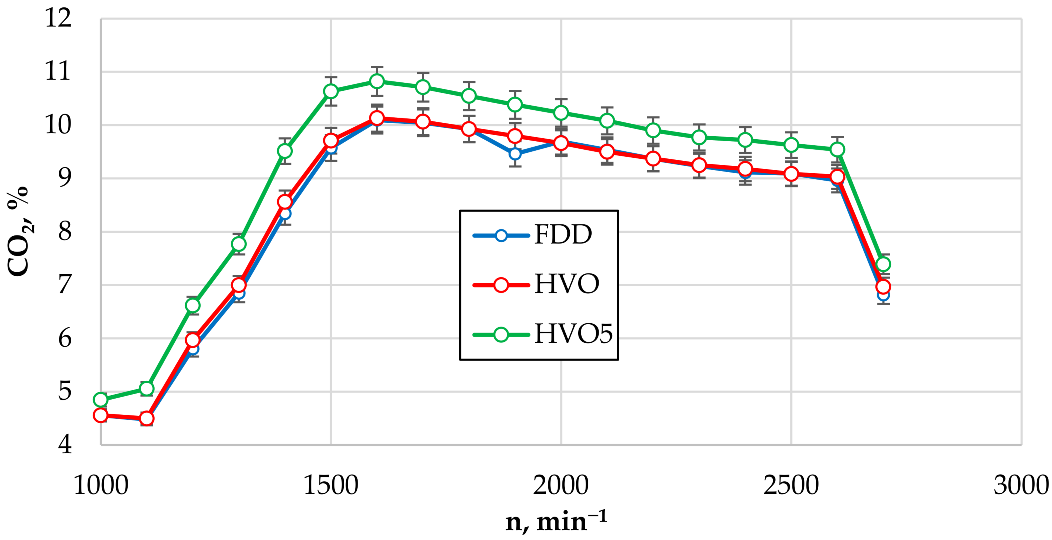

Figure 5. Carbon dioxide emissions from the engine running on three different fuels.

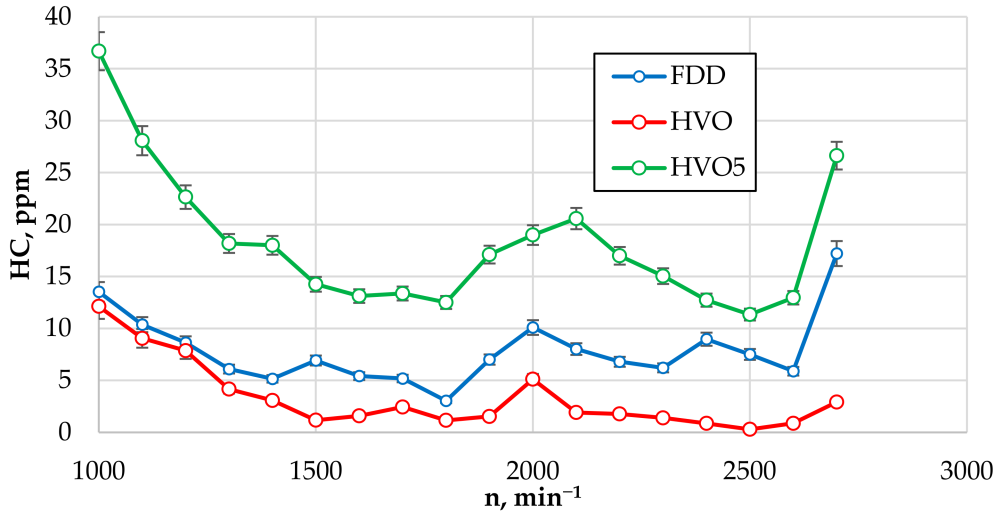

Figure 6. Hydrocarbon emissions from the engine running on three different fuels.

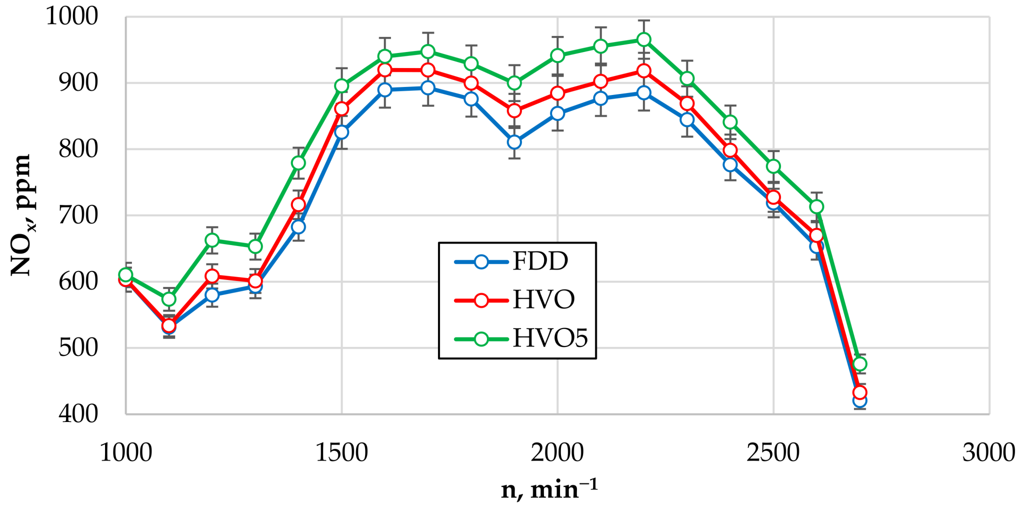

Figure 7. Nitrogen oxide emissions from the engine running on three different fuels.

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.

Author Contributions: Conceptualization, R.S., K.S. and I.D.; methodology, I.D. and V.P.; software, V.P.; validation, K.S., I.D. and G.B.; formal analysis, G.B.; investigation, R.S. and V.P.; resources, R.S. and K.S.; data curation, K.S. and V.P.; writing—original draft preparation, R.S. and K.S.; writing—review and editing, I.D. and G.B.; visualization, R.S., I.D. and V.P.; supervision, R.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data will be made available upon request.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. European Green Deal. Available online: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en (accessed on 24 November 2022).
2. Greenhouse Gas Emissions from Transport in Europe. Available online: https://www.eea.europa.eu/ims/greenhouse-gas-emissions-from-transport (accessed on 24 November 2022).
3. Report—Vehicles in Use, Europe. 2022. Available online: https://www.acea.auto/publication/report-vehicles-in-use-europe-2022/ (accessed on 24 November 2022).
4. Mulholland, E.; Miller, J.; Braun, C.; Jin, L.; Rodríguez, F. *Quantifying the Long-Term Air Quality and Health Benefits from Euro 7/VII Standards in Europe*; International Council on Clean Transportation: Washington, DC, USA, 2021. Available online: https://theicct.org/publication/quantifying-the-long-term-air-quality-and-health-benefits-from-euro-7-vii-standards-in-europe/ (accessed on 24 November 2022).
5. EEA. Air Quality in Europe 2022. Report No. 05/2022. Available online: https://www.eea.europa.eu//publications/air-quality-in-europe-2022 (accessed on 24 November 2022).
6. EU Ban on the Sale of New Petrol and Diesel Cars from 2035 Explained. Available online: https://www.europarl.europa.eu/news/en/headlines/economy/20221019STO44572/eu-ban-on-sale-of-new-petrol-and-diesel-cars-from-2035-explained (accessed on 24 November 2022).
7. Di Blasio, G.; Ianniello, R.; Beatrice, C. Hydrotreated vegetable oil as enabler for high-efficient and ultra-low emission vehicles in the view of 2030 targets. *Fuel* **2022**, *310*, 122206. [CrossRef]
8. Andersson, Ö.; Börjesson, P. The greenhouse gas emissions of an electrified vehicle combined with renewable fuels: Life cycle assessment and policy implications. *Appl. Energy* **2021**, *289*, 116621. [CrossRef]
9. Dobrzynska, E.; Szewczynska, M.; Posniak, M.; Szczotka, A.; Puchalka, B.; Woodburn, J. Exhaust emissions from diesel engines fueled by different blends with the addition of nanomodifiers and hydrotreated vegetable oil HVO. *Environ. Pollut.* **2020**, *259*, 113772. [CrossRef]
10. Mikkonen, S.; Honkanen, M.; Kuronen, M. HVO, hydrotreated vegetable oil. A premium renewable biofuel for diesel engines. Germany. In Proceedings of the Conference: 9. International Colloquium Fuels: Conventional and Future Energy for Automobiles, Ostfildern, Germany, 15–17 January 2013; pp. 281–291. Available online: https://www.osti.gov/etdeweb/biblio/22114203 (accessed on 24 November 2022).
11. Stumborg, M.; Wong, A.; Hogan, E. Hydroprocessed vegetable oils for diesel fuel improvement. *Bioresour. Technol.* **1996**, *56*, 13–18. [CrossRef]
12. Suarez-Bertoa, R.; Kousoulidou, M.; Clairotte, M.; Giechaskiel, B.; Nuottimaki, J.; Sarjovaara, T.; Lonza, L. Impact of HVO blends on modern diesel passenger cars emissions during real world operation. *Fuel* **2019**, *235*, 1427–1435. [CrossRef]
13. Bjorgen, K.O.P.; Emberson, D.R.; Lovas, T. Combustion and soot characteristics of hydrotreated vegetable oil compression-ignited spray flames. *Fuel* **2020**, *266*, 116942. [CrossRef]
14. Rodriguez-Fernandez, J.; Lapuerta, M.; Sanchez-Valdepenas, J. Regeneration of diesel particulate filters: Effect of renewable fuels. *Renew. Energy* **2017**, *104*, 30–39. [CrossRef]

15. Müller, M.; Šleger, V.; Čedík, J.; Pexa, M. Research on the Material Compatibility of Elastomer Sealing O-Rings. *Polymers* **2022**, *14*, 3323. [CrossRef]
16. Singh, D.; Subramanian, K.A.; Garg, M.O. Comprehensive review of combustion, performance and emissions characteristics of a compression ignition engine fueled with hydroprocessed renewable diesel. *Renew. Sustain. Energy Rev.* **2018**, *81*, 2947–2954. [CrossRef]
17. Dimitriadis, A.; Natsios, I.; Dimaratos, A.; Katsaounis, D.; Samaras, Z.; Bezergianni, S.; Lehto, K. Evaluation of a Hydrotreated Vegetable Oil (HVO) and effects on emissions of a passenger car diesel engine. *Front. Mech. Eng.* **2018**, *4*, 7. [CrossRef]
18. Simacek, P.; Kubicka, D.; Sebor, G.; Pospisil, M. Fuel properties of hydroprocessed rapeseed oil. *Fuel* **2010**, *89*, 611–615. [CrossRef]
19. Lapuerta, M.; Villajos, M.; Agudelo, J.R.; Boehman, A.L. Key properties and blending strategies of hydrotreated vegetable oil as biofuel for diesel engines. *Fuel Process. Technol.* **2011**, *92*, 2406–2411. [CrossRef]
20. Cheng, Q.; Tuomo, H.; Kaario, O.T.; Martti, L. Spray dynamics of HVO and EN590 diesel fuels. *Fuel* **2019**, *245*, 198–211. [CrossRef]
21. Zhang, T.; Andersson, M.; Munch, K.; Denbratt, I. *Optical Diagnostics of Spray Characteristics and Soot Volume Fractions of N-Butanol, N-Octanol, Diesel, and Hydrotreated Vegetable Oil Blends in a Constant Volume Combustion Chamber*; SAE Technical Paper Series 2019-01-0019; SAE International: Warrendale, PA, USA, 2019. [CrossRef]
22. Demuynck, J.; Dauphin, R.; Yugo, M.; Mendoza Villafuerte, P.; Bosteels, D. Advanced Emission Controls and Sustainable Renewable Fuels for Low Pollutant and CO_2 Emissions on a Diesel Passenger Car. *Sustainability* **2021**, *13*, 12711. [CrossRef]
23. Aatola, H.; Larmi, M.; Sarjovaara, T.; Mikkonen, S. Hydrotreated Vegetable Oil (HVO) as a renewable diesel fuel: Trade-off between NO_x, particulate emission, and fuel consumption of a heavy duty engine. *SAE Int. J. Engines* **2008**, *1*, 1251–1262. [CrossRef]
24. Kuronen, M.; Mikkonen, S.; Aakko, P.; Murtonen, T. *Hydrotreated Vegetable Oil as Fuel for Heavy Duty Diesel Engines*; SAE Technical Paper 2007-01-4031; SAE International: Warrendale, PA, USA, 2007. [CrossRef]
25. Pirjola, L.; Ronkko, T.; Saukko, E.; Parviainen, H.; Malinen, A.; Alanen, J.; Saveljeff, H. Exhaust emissions of non-road mobile machine: Real-world and laboratory studies with diesel and HVO fuels. *Fuel* **2017**, *202*, 154–164. [CrossRef]
26. Bugarski, A.D.; Hummer, J.A.; Vanderslice, S. Effects of hydrotreated vegetable oil on emissions of aerosols and gases from light-duty and medium-duty older technology engines. *J. Occup. Environ. Hyg.* **2016**, *13*, 297–306. [CrossRef]
27. Serrano, L.; Santana, B.; Pires, N.; Correia, C. Performance, Emissions, and Efficiency of Biodiesel versus Hydrotreated Vegetable Oils (HVO), Considering Different Driving Cycles Sensitivity Analysis (NEDC and WLTP). *Fuels* **2021**, *2*, 448–470. [CrossRef]
28. Pardhi, S.; El Baghdadi, M.; Hulsebos, O.; Hegazy, O. Optimal Powertrain Sizing of Series Hybrid Coach Running on Diesel and HVO for Lifetime Carbon Footprint and Total Cost Minimisation. *Energies* **2022**, *15*, 6974. [CrossRef]
29. Sondors, K.; Birkavs, A.; Dukulis, I.; Pirs, V.; Jesko, Z. Investigation in tractor Claas Ares 557ATX operating parameters using hydrotreated vegetable oil fuel. In Proceedings of the 13th International Scientific Conference "Engineering for Rural Development", Jelgava, Latvia, 29–30 May 2014; pp. 63–68.
30. Pexa, M.; Čedík, J.; Mařík, J.; Hönig, V.; Horníčková, Š.; Kubín, K. Comparison of the operating characteristics of the internal combustion engine using rapeseed oil methyl ester and hydrogenated oil. *Agron. Res.* **2015**, *13*, 613–620.
31. Singh, D.; Subramanian, K.A.; Singal, S.K. Emissions and fuel consumption characteristics of a heavy duty diesel engine fueled with Hydroprocessed Renewable Diesel and Biodiesel. *Appl. Energy* **2015**, *155*, 440–446. [CrossRef]
32. McCaffery, C.; Zhu, H.; Ahmed, C.M.S.; Canchola, A.; Chen, J.Y.; Li, C.; Johnson, K.C.; Durbin, T.D.; Lin, Y.-H.; Karavalakis, G. Effects of hydrogenated vegetable oil (HVO) and HVO/biodiesel blends on the physicochemical and toxicological properties of emissions from an off-road heavy-duty diesel engine. *Fuel* **2022**, *323*, 124283. [CrossRef]
33. Kumar, N.; Sonthalia, A.; Tomar, M.; Koul, R. An experimental investigation on spray, performance and emission of hydrotreated waste cooking oil blends in an agricultural engine. *Int. J. Engine Res.* **2021**, *22*, 2305–2317. [CrossRef]
34. Makinen, R.; Nylund, N.O.; Erkkila, K.; Saikkonen, P.; Amerla, A. *Bus Fleet Operation on Renewable Paraffinic Diesel Fuel*; SAE Technical Paper 2011-01-1965; SAE International: Warrendale, PA, USA, 2011. [CrossRef]
35. Erkkilam, K.; Nylund, N.O.; Hulkkonen, T.; Tilli, A.; Mikkonen, S.; Saikkonen, P.; Mamkinen, R.; Amberla, A. *Emission Performance of Paraffinic HVO Diesel Fuel in Heavy Duty Vehicles*; SAE Technical Paper 2011-01-1966; SAE International: Warrendale, PA, USA, 2011. [CrossRef]
36. Happonen, M.; Heikkila, J.; Murtonen, T.; Lehto, K.; Sarjovaara, T.; Larmi, M.; Keskinen, J.; Virtanen, A. Reductions in particulate and NO_x emissions by diesel engine parameter adjustments with HVO fuel. *Environ. Sci. Technol.* **2012**, *46*, 6198–6204. [CrossRef] [PubMed]
37. Szeto, W.; Leung, D.Y.C. Is hydrotreated vegetable oil a superior substitute for fossil diesel? A comprehensive review on physicochemical properties, engine performance and emissions. *Fuel* **2022**, *327*, 125065. [CrossRef]
38. Bohl, T.; Smallbone, A.; Tian, G.; Roskilly, A.P. Particulate number and NO_x trade-off comparisons between HVO and mineral diesel in HD applications. *Fuel* **2018**, *215*, 90–101. [CrossRef]
39. Kim, D.; Kim, S.; Oh, S.; No, S.Y. Engine performance and emission characteristics of hydrotreated vegetable oil in light duty diesel engines. *Fuel* **2014**, *125*, 36–43. [CrossRef]
40. Preuß, J.; Munch, K.; Denbratt, I. Performance and emissions of renewable blends with OME3–5 and HVO in heavy duty and light duty compression ignition engines. *Fuel* **2021**, *303*, 121275. [CrossRef]
41. Rantanen, L.R.; Linnaila, P.; Aakko, P.; Harju, T. *NExBTL-Biodiesel Fuel of the Second Generation*; SAE Technical Paper 2005–01-3771; SAE International: Warrendale, PA, USA, 2005. [CrossRef]

42. Chau, V.T.; Chinda, C.; Preechar, K.; Sato, S.; Kosaka, H. Optical study on combustion characteristics of hydrotreated vegetable oil and blends under simulated CI engine conditions and various EGR. *J. Mech. Sci. Technol.* **2017**, *31*, 4521–4531. [CrossRef]
43. Dimitriadis, A.; Seljak, T.; Vihar, R.; Baskovic, U.Z.; Dimaratos, A.; Bezergianni, S.; Samaras, Z.; Katrasnik, T. Improving PM-NO_x trade-off with paraffinic fuels: A study towards diesel engine optimization with HVO. *Fuel* **2020**, *265*, 116921. [CrossRef]
44. No, S.-Y. Application of hydrotreated vegetable oil from triglyceride based biomass to CI engines—A review. *Fuel* **2014**, *115*, 88–96. [CrossRef]
45. Sonthalia, A.; Kumar, N. Hydroprocessed vegetable oil as a fuel for transportation sector: A review. *J. Energy Inst.* **2019**, *92*, 1–17. [CrossRef]
46. Sunde, K.; Brekke, A.; Solberg, B. Environmental impacts and costs of hydrotreated vegetable oils, transesterified lipids and woody BTL—A review. *Energies* **2011**, *4*, 845–877. [CrossRef]