Effects of biodiesel and Hydrotreated Vegetable Oil on the performance and exhaust emissions of a stationary diesel engine

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Abstract: *The increasing use of renewable fuels in transportation is a prime environmental target so much for the European member states, as much for the rest of the world, in order to reduce the dependency on fossil oil, as well as the pollutant emissions. Renewable biofuels, such as Hydrotreated Vegetable Oil (HVO) and Fatty Acid Methyl Esters (Biodiesel) are promising substitutes of conventional diesel fuel for compression ignition (CI) engines. In this study the physicochemical properties of biodiesel from used cooking oils and HVO were examined, when blended in different concentrations with an ultra-low-sulfur diesel. Four blends for each biofuel (up to 40% v/v) were evaluated according to EN 590. The effects of the biofuels and the eight mixtures on engine performance and exhaust emissions were studied in a stationary diesel engine, operating under various loads. The results of the present research showed that HVO displayed reductions up to 14.8% in low and medium loads for nitrogen oxides (NO_x) emissions and decreased carbon monoxide (CO) in all engine loads, compared to conventional diesel. Biodiesel produced less CO than diesel only in high loads, but increased nitrogen oxides (NO_x) by almost 15% in high engine loads. Significant decreases were observed with both biofuels in particulate matter (PM) emissions.*
Keywords: biodiesel, HVO, paraffinic diesel, exhaust emissions

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I. Introduction

Diesel engines have for many decades dominated the medium and medium-large transportation sector. In recent years, the number of diesel engines in the automotive market has significantly increased, particularly in Europe. In 2017, diesels' market share was 44,8% of total passenger car registrations in the EU-15 [1]. Despite theiradvantages, reliability, fuel efficiency and turbocharging capability, diesel engines also exhibit drawbacks, regarding the exhaust emissions [2]. Their levels of particulate matter (PM) and nitrogen oxides (NOx), due to the high flame temperature and the diffusive combustion, are considerable and are raising awareness [3].

The increasing concerns about the depletion of fossil fuel resources and their negative environmental impact have triggered interest on the potential benefits of biofuels. Biodiesel (FAME) has been well accepted as a renewable alternative to diesel fuel globally. It is an environmentally friendly, free of sulfur, non-toxic biofuel, which can be produced from the transesterification of edible or non-edible vegetable oils, waste vegetable oils and animal fats. Its usage in diesel engines, as a substitute of diesel, can reduce harmful tailpipe combustion emissions (CO, PM and unburned hydrocarbons), as well as the greenhouse gas emissions [4]–[8]. The quality of biodiesel is known to depend on feedstock [9]–[11]. Although biodiesel is an environmentally attractive fuel, it is characterized by several disadvantages, such as poor oxidation stability, deposit formation, lower calorific value, high feedstock cost and microorganism degradation [12]–[15]. Another factor that makes the use of biodiesel less attractive is the increase of NO_x emissions, as has been reported by numerous researchers. This increase is more significant as the content of biodiesel rises in diesel fuel [16]–[20]. It was noticed that the greater increase of NO_x emissions occurred during high engine loads, due to the higher combustion temperatures. The most important mechanism for the production of NO_x is the formation of thermal NO_x described by the so-called Zeldovich mechanism. Thermal NO_x is believed to be the predominant contributor to total NO_x [21].

Hydrotreating of vegetable oils is a modern and promising way to produce very high-quality biobased diesel fuels (HVO) without compromising fuel logistics, engines, exhaust after treatment devices, or exhaust emissions [22], [23]. In this process hydrogen is used to remove oxygen from the triglyceride vegetable oil molecules and to split the triglyceride into three separate chains, thus creating hydrocarbons similar to existing diesel fuel components. HVO can be produced from various feedstocks, such as vegetable oils, animal fats and waste oils, without affecting the properties of the final product [24]. HVO is a mixture of straight chain and branched paraffins, without any aromatics. Consequently, it has a very high cetane number (75-95) and lower

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density compared to fossil diesel fuel [13], [25]. Its lower density could impose blending restrictions with diesel fuels. However the refineries could take advantage of it, by upgrading heavy oil fraction, which typically are denser, and keeping their density within the limits established in the standards [23], [24]. The properties of HVO have much more similarities with high quality sulfur free fossil diesel fuel than FAME. The energy content of HVO is higher than biodiesel's and its cold properties can be adjusted by isomerization. Sulfur content, ash and metals content are very low. Like sulfur free diesel fuels, pure HVO requires lubricity additive. According to several researchers, the fuel does not present the detrimental effects of biodiesel, like deposit formation, storage stability problems, rapid aging of engine oil and poor cold properties [13], [25]–[27]. HVO shows a positive potential in terms of greenhouse gas emissions [13], [28]. Regarding the harmful tailpipe emissions, substantial reductions in PM, CO and HC emissions have been reported, while NO_x were either slightly decreased, or remained on the same levels as the fossil diesel [29]–[31]. The majority of the researchers has observed that the reduction of PM emissions caused by HVO, or HVO mixture with diesel fuel, is less than the reduction caused by biodiesel fuels [24], [32], [33].

The aim of this research was to evaluate comprehensively the engine performance and emission characteristics of HVO and biodiesel (BD), compared to fossil diesel. Both renewable fuels were mixed in 10, 20, 30 and 40 percent by volume with conventional ultra-low sulfur diesel (ULSD). Initially, the physicochemical properties of fuels were measured and evaluated according to EN 590 for standard automotive diesel fuels, EN 14214 for FAME and EN 15940 for paraffinic diesel fuels from synthesis or hydrotreatment. The blends were evaluated in accordance with EN 590. All fuels were examined in a stationary diesel engine, where their impact on engine operation and exhaust emissions was evaluated in comparison to ULSD fuel.

II. Materials And Methods

The diesel fuel was supplied by Hellenic Petroleum S.A. ULSD's measured physicochemical properties are displayed in Table 1, alongside the properties of the renewable fuels. Biodiesel fuel was supplied by ELIN Biofuels S.A., a Greek biodiesel production plant. The biodiesel was produced through transesterification of used cooking oils and contained 9,895 % (m/m) oxygen. The fatty acid composition of biodiesel, presented in Table 2, was measured according to the EN 14103 method. The HVO was supplied by Neste Oil Corporation. The fuel was an isomerized high cetane number product meeting EN 15940 Class A requirements. The derived cetane number (DCN) was measured according to the ASTM D7170 method, which measures the ignition delay by utilizing a constant volume combustion chamber with direct fuel injection into heated, compressed air.

Two series of binary mixtures were prepared and examined. The first series consisted of diesel blends with 10%, 20%, 30% and 40% v/v biodiesel, and the second series of diesel blends with HVO in the same proportions. The blends were labelled as Bxx and Hyy, where B denotes Biodiesel and H is HVO.

Table 1. Physicochemical properties of ULSD, biodiesel and HVO

Properties	Units	ULSD	B100	H100	Test method
Density	kg/m³	825.2	881.3	778.9	EN ISO 12185
Viscosity	mm²/s	2.5598	4.2215	2.8208	ASTM D7042
DCN	-	56.5	52.9	77.8	ASTM D7170
Sulfur	mg/kg	7.4	<1	1.9	EN ISO 20846
CFPP	°C	-5	2	-37	EN 116
IBP	°C	171	285	177	EN ISO 3405
T10	°C	200	324	257	EN ISO 3405
T50	°C	271	334	279	EN ISO 3405
T90	°C	335	338	291	EN ISO 3405
T95	°C	352	340	294	EN ISO 3405
FBP	°C	361	349	301	EN ISO 3405
Gross calorific value	MJ/kg	45.5	40.1	47.1	ASTM D240
Net calorific value	MJ/kg	42.5	37.5	43.8	ASTM D240

Exhaust emissions experimental setup

The study of the exhaust emissions was conducted using a typical stationary diesel engine by Lister Petter, where all fuels and mixtures were tested. No after treatment devices were used, as well as no modifications were applied in the engine operating parameters. Table 3 presents the technical specifications of the engine. The engine operated with a compression ratio of 18,5:1 and was connected to an electric generator. The load was controlled manually through a resistive load bank, Avrton K490.

The engine was connected to the portable Quintox, KANE 9206 exhaust gas analyzer, through a heated stainless-steel probe and a heated line. The probe was positioned just after the exhaust manifold. The exhaust gases were transferred to a dehydrator and a water trap, to avoid water condensation, and resulted in electro-

chemical sensors to monitor NO_x, CO, CO_2 and HC emissions. The resolution, the measurement range and the accuracy of the gas analyser are provided in Table 4.

Particulate matter was measured in mass through a Whatman glass microfiber filter. The probe containing the filter was mounted on the exhaust line and was connected to a Ritter BG6 gas meter to measure the volume of the exhaust gases. The filters were dried and weighed, before and after their use, in order to determine the mass of particulate matter. A high-accuracy analytical balance was used for the measurement of the filter mass, with 0.1 mg resolution.

The temperature of the exhaust gases was measured using a k-type thermocouple fitted in the exhaust manifold. Also, fuel consumption was measured and the Brake Specific Fuel Consumption (BSFC) was calculated. The experimental set- up is shown schematically in Figure 1.

Table 2. Fatty acid composition of biodiesel

Fatty acids	Composition
C14:0	0,73
C14:1	0,10
C16:0	14,32
C16:1	1,15
C18:0	7,66
C18:1	32,26
C18:2	35,62
C18:3	0,83
C20:0	0,34
C20:1	0,24
C22:0	1,22

Experimental procedure

The engine loads examined in the study were idle, 1.5, 3, 4.5 and 5.5 kW. Each fuel was tested sequentially on all engine loads, under steady-state operating conditions. Before starting the measurements, the steady-state conditions were verified by checking the exhaust gas temperature. The engine was running on a specific load and readings were taken only after the temperature was stabilized.

The measurements of fuel consumption and mass of particulate matter were obtained after the completion of the gas measurements. For the determination of particulate matter, different sampling durations were taken, depending on the studied load of the engine. At low loads, the sampling duration was long enough, in order for the filter to retain sufficiency quantity of the soot and avoid to reach the accuracy limits of the analytical balance. Consequently, at high loads the sampling duration was quite short, to avoid PM accumulation on the filter. All measurements of each fuel resulted from the average of at least 3 engine cycles.

Table 3. Technical specifications of the diesel engine

Engine type	Lister Petter, LPW2
General	4 stroke, water cooled diesel engine
Type of fuel injection	Direct
Number of cylinders	2 in line
Aspiration	Natural
Nominal cylinder bore	86.0mm
Stroke	80.0 mm
Displacement	0.93 lt
Compression ratio	18.5:1
Engine speed	1500 RPM
Alternator	Brushless
Electrical output power	5.6 kW, 50 Hz

Table 4. Specifications of the gas analyzer

Parameter	Resolution	Measurement range	Accuracy
HC	1ppm	0-5000 ppm	±5 %
CO_2	0.1 %	0-10 %	± 5%
CO	1 ppm	0-10000 ppm	±5 ppm (<100 ppm)
			±5 % (>100 ppm and <2000 ppm)
			±10 % (>2000 ppm)
NO	1 ppm	0-5000 ppm	±5 ppm (<100 ppm)
			±5 % (>100 ppm)
NO_2	1 ppm	0-1000 ppm	±5 ppm (<100 ppm)
			±10 ppm (>100ppm and <500ppm)
			±5% (>500 ppm)
Exhaust gas temperature	0.1 °C	0-1100 °C	1,0 °C ± 0,3%
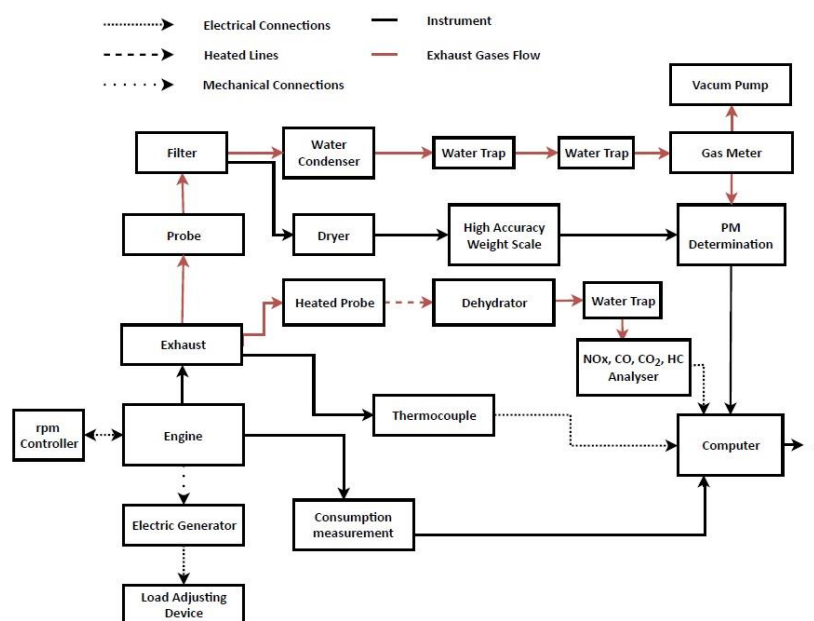
Figure 1. Experimental setup

III. Results And Discussion

Physicochemical properties

The physicochemical properties of all samples were measured and evaluated. As demonstrated in Table 1, ULSD, biodiesel and HVO fully complied with the relative European standards, EN 590, EN 14214 and EN 15940, respectively. It should be mentioned that the biodiesel was a summer grade fuel, which falls under grade A for temperate climates. Thus, the CFPP value of 2°C complies with the limits of EN 14214.

HVO had lower density when compared to ULSD and biodiesel, due to its paraffinic nature. The low density of HVO imposes blending restrictions, particularly when blended with diesel fuels with low densities, like the studied ULSD. Figure 2 shows the linear correlation of the density with the increased percentage of biodiesel and HVO in the blends. It was observed that the only mixture of HVO which complied with the lower limit requirement set by EN 590, regarding the density, was H10. However, the reductions in density could provide some economic saving and some flexibility to refineries, by upgrading heavier oil distillation fractions [23], [24]. On the other hand, no limitations were observed regarding the viscosity of the blends, Figure 3. Pure HVO had significantly lower viscosity than biodiesel and slightly higher than diesel. The viscosity of the blends was increased slightly with the addition of larger proportions of HVO in ULSD, while in biodiesel blends the increase was more significant. The density and viscosity are important parameters among fuel properties because of the effect on the amount of injected fuel, the engine performance and emission characteristics [34]. The viscosity of a fuel affects the quality of the atomization process, the size of fuel droplets and the in-cylinder penetration of the fuel spray [9], [35], [36].
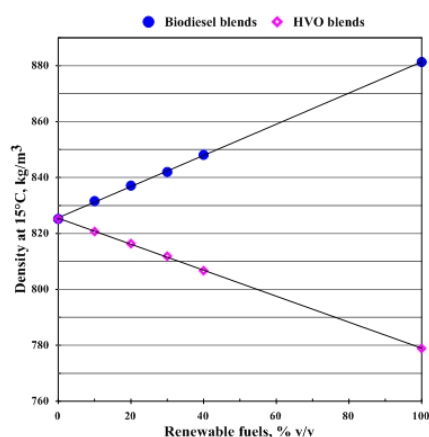
Figure 3. Density at 15°C of ULSD, biodiesel, HVO and their blends
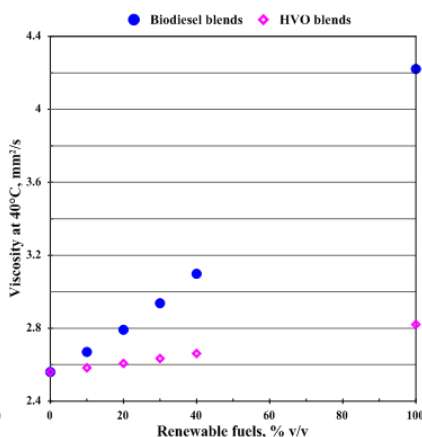
Figure 2. Viscosity at 40°C of ULSD, biodiesel, HVO and their blends

Distillation curves of ULSD, B100 and H100 are presented in Figures 4 and 5, alongside the distillation curves of the blends. HVO had fewer low-boiling components since it distills in the range of 260-290°C. For this reason the distillation curve of paraffinic diesel was almost flat for about 60% of the distillation region. HVO consists mainly of C_{15}-C_{18} n-parafins and iso-parafins [26], [37]. The same level of narrow boiling points was observed during the distillation of biodiesel. However, biodiesel's distillation curve was almost flat in higher temperatures, around 330-340°C, due to the common boiling temperatures of the majority of methyl esters. Although the addition of both renewable fuels in ULSD did not affect significantly the initial boiling point (IBP) and the final boiling point (FBP), the distillation curves were gradually flattened out the curve of ULSD. The addition of continuously larger proportions of biofuels affected the same way the distillation point T10, which was found to be higher by around 2.5%, 3.5%, 6% and 8% for the blends containing 10%, 20%, 30% and 40% biofuels, respectively. A high value of T10 could cause problems related to the cold start of the engine [38]. T50 was increased in higher levels with the addition of larger biodiesel percentages in the mixture, compared to HVO. B30 and B40 caused a 6.3% and 9.6% raise of T50, while H30 and H40 caused increases around 1,5%. In addition, HVO blends reduced T90 boiling points by 1.4-6.4%. The reduction of tail-end volatility could lead to fewer carbon deposits on the engine [38].

The ignition quality of HVO, expressed as derived cetane number DCN, was higher than ULSD and biodiesel. On the contrary biodiesel presented lower DCN than ULSD. These specific fuels were chosen in order to investigate the effect of cetane number on the engine operation and exhaust emissions. Thus, a high cetane number fuel (HVO) and a low cetane number fuel (biodiesel) were mixed with ULSD, producing mixtures covering a wide range of cetane numbers, i.e about 53-78 [3]. The results of the DCN are provided in Figure 6, where an almost linear correlation in both blended series was observed [30]. The increase of the percentage of biodiesel in blends led to a slight reduction of the cetane number, while HVO blends presented a significant increase of DCN.
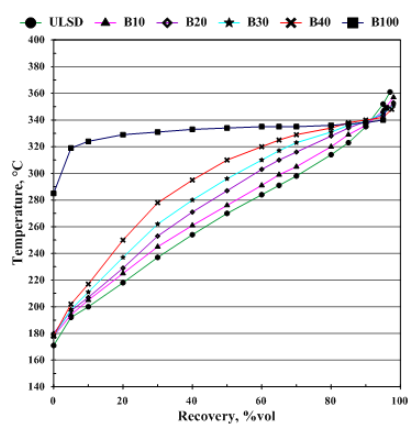

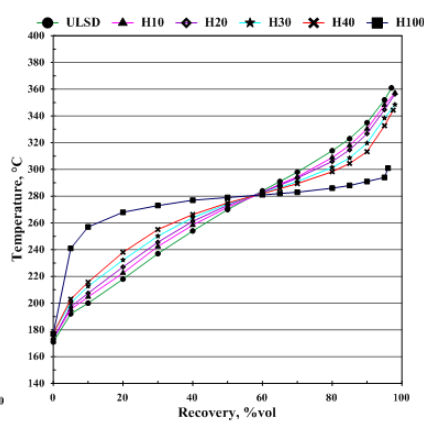**Figure 5.** Distillation curves of ULSD, biodiesel and their blends

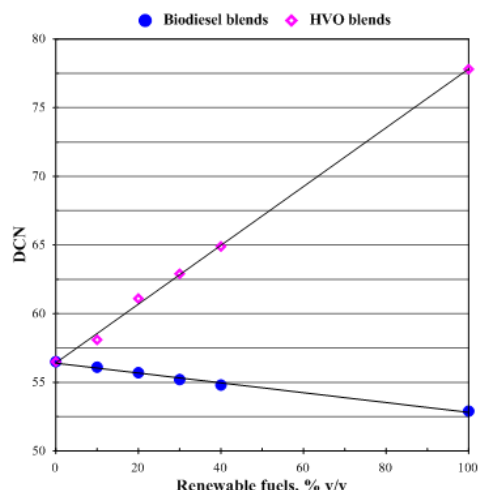**Figure 4.** Distillation curves of ULSD, HVO and their blends

Figure 2. Cetane number values of ULSD, biodiesel, HVO and their blends

Engine results

Fuel consumption was measured by mass per unit of time. As seen in Figure 7, B100 displayed higher fuel consumption than ULSD on all examined engine loads, due to the lower net calorific value of biodiesel in comparison with ULSD. The loss of heating value was compensated with higher fuel consumption [39]–[41]. As expected, fuel consumption of biodiesel blends was higher than ULSD's, as a result of the reduction of calorific value as the biodiesel percentage in the blend increased. These results are in agreement with the results of other researchers, who observed similar reductions with pure biodiesel, or diesel-biodiesel blends [42]–[44].

As Figure 8 demonstrates, the use of HVO in the engine resulted to lower fuel consumption on all engine loads, compared to ULSD. The reductions varied from 3.2% to 6.5%, depending on the load. A decrease was also observed as HVO concentrations in the blends increases. A maximum reduction of 3.4% was obtained by H40, while H10 reduced fuel consumption by 0.4-1.2%. This was attributed to high calorific value of HVO [13], [23], [30], [33], [45], [46].

Table 5 shows the variations of exhaust gas temperatures (EGT) of the pure fuelswith respect to applied loads, provided by the thermocouple which was fitted on the exhaust manifold of the engine. EGT values increased with the increase of engine load. The main reason that can be attributed for the EGT increase of biodiesel is the fuel's oxygen content, which leads to improved combustion [47]. The higher combustion temperatures of biodiesel are associated with the increase in NO_x emissions. In comparison with ULSD, EGT of biodiesel was increased by 16°C in low loads and by 32°C during full engine load. On the other hand, HVO exhibited lower EGT than ULSD by 2 to 7°C on all loads, except for the full load, where the EGT was reduced by 16°C.
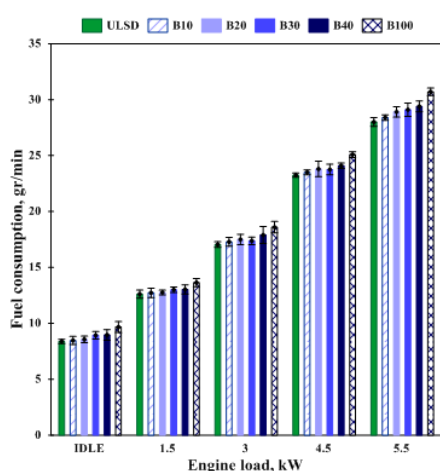

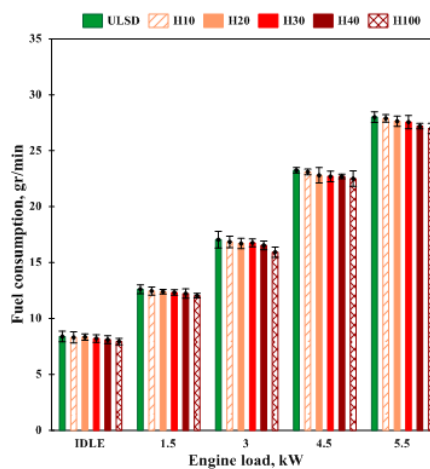**Figure 8.** Mass fuel consumption for ULSD, biodiesel and their blends

Figure 7. Mass fuel consumption for ULSD, HVO and their blends

Table 5. Exhaust gas temperature of pure fuels

Engine load	Exhaust gas temperature (°C)		
	ULSD	B100	H100
IDLE	140	149	134
1,5 kW	187	203	180
3 kW	246	262	243
4,5 kW	333	358	331
5,5 kW	407	439	391

Carbon monoxide is a product of incomplete combustion and is one of the most harmful pollutants. CO is formed in regions of the cylinder with insufficient oxygen concentration, especially in fuel rich zones. Another factor enhancing CO formation is the low cylinder temperatures [48], [49]. In this study, CO emissions remained in low levels during IDLE, 1.5 kW and 3 kW and displayed rapid growth during the high and full loads. By increasing the load, air-fuel ratio decreases and cylinder temperature increases. Consequently, failure of combustion or partial combustion may occur, resulting to higher CO emissions. Figures 9 and 10 show the percentage increase or decrease of CO that was produced by the pure biofuels and their blends, in comparison with diesel emissions. It was observed that in low and medium loads CO concentration tended to increase as biodiesel concentration increases. In these loads, pure biodiesel produced around 9% more CO than ULSD. Meanwhile, in 4.5 kW load and full load, biodiesel produced less CO than ULSD by 4.6% and 3.3%, respectively. Although the accuracy of the exhaust gas analyzer sets the observed reduction statistically insignificant, a trend was observed. The same trend was followed also by diesel-biodiesel blends. These reductions were attributed to the oxygen content of biodiesel, which improves combustion and enhances CO oxidation. In high engine loads the oxygen promotes the oxidation mechanisms of CO [50]. It should be mentioned that the majority of researchers have observed reductions with the use of biodiesel in comparison with the examined diesel fuel. They attributed these decreases to the oxygen content of the fuel, as well as to the higher cetane number of biodiesel, compared to diesel [3], [20]. However, in the present study, the biodiesel sample exhibited lower cetane number than diesel, which could lead to higher CO emissions in low and medium loads.

Regarding the CO emissions of HVO and ULSD-HVO blends, Figure 10, significant reductions were observed. Pure HVO produced less CO by 23.5-30.9% during all loads, except full engine load, where the reduction obtained was 10.3%, in comparison with ULSD. As the concentration of HVO in the mixtures was increased, CO production followed a declining trend [51]. These decreases occurred due to the low viscosity and high cetane number of HVO, properties that enhance fuel atomization and promote complete combustion [52]. Also, the lower boiling points of HVO were beneficial for a complete evaporation in the combustion chamber at low loads [23].Similar trends observed in this study were reported by other researchers, where the use of HVO resulted in CO reductions [32], [53], [54].
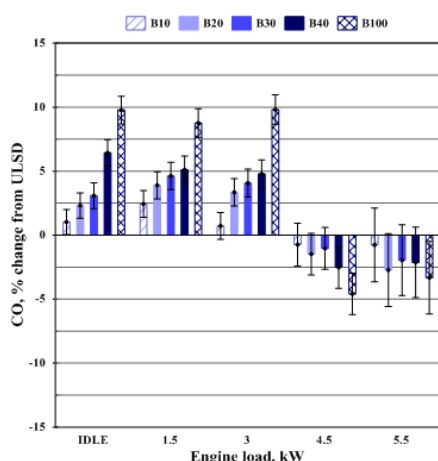
Figure 9. Carbon monoxide emissions of biodiesel and its blends with ULSD, expressed as percentage change from ULSD
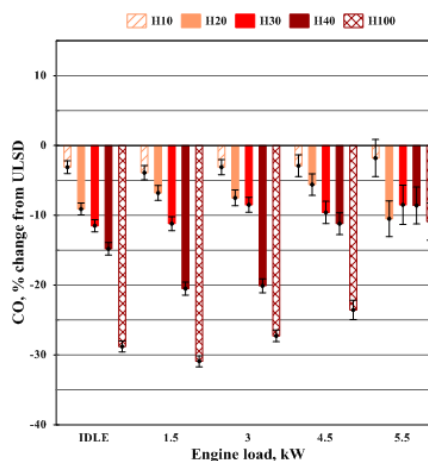
Figure 10. Carbon monoxide emissions of HVO and its blends with ULSD, expressed as percentage change from ULSD

Hydrocarbon (HC) emissions were at very low levels, approaching the determination limits of the exhaust gas analyzer. Regarding carbon dioxide (CO_2) emissions, no statistically significant changes were observed among the studied fuels and mixtures.

Nitrogen oxides emissions increased following the engine load, since higher cylinder temperatures promote NO_x formation. Thermal NO_x is believed to be the predominant contributor to total NO_x. At high

temperatures, such as those occurring within the combustion chamber of a diesel engine, N_2 and O_2 can react through a series of chemical steps known as the Zeldovich mechanism. NO_x formation, as well as the rate of formation increases rapidly with increasing temperatures [21], [55]. As depicted in Figure 11, NO_x formation was promoted with the use of biodiesel and its blends. Pure biodiesel demonstrated a 3.4-4.9% increase of NO_x in low and medium loads, whereas in high loads an increase of 14% and 15.1% was observed, compared to ULSD's emissions. These results were consistent with the increased values of EGT of biodiesel, which is an indication of the higher cylinder's temperature. As biodiesel concentration in blends increased, the production of NO_x was also increased. This was attributed to the increase of oxygen content in blends, which promotes more complete combustion and raises the adiabatic flame temperature [56]. Slight increases, lower than 3.5%, were found in low and medium loads, which could be considered statistically insignificant. Although, all blends presented higher NO_x than ULSD in 4.5 kW and 5.5 kW loads. In these loads, the use of B10 led to 3% and 5.2% more NO_x, while B20 presented 6.1% and 10.6% increases, respectively. The mixture with 30% and 40% v/v biodiesel displayed 7.7-9.2% higher NO_x in 4.5 kW load and around 11.5% in full load. This can be explained by the presence of oxygen in biodiesel samples, which results in higher heat release during pre-combustion, leads to the predominance of higher temperatures in the combustion chamber and consequently to the increase in NO_x [57]. Another factor that may affects the higher NO_x emissions of biodiesel is the lower cetane number of the fuel, compared with ULSD. An increase in ignition delay leads to a sharp and higher increase of temperature and pressure during premixed combustion, which favors NO_x formation [58]. Previous studies have shown similar increases in NO_x emissions with biodiesel and diesel-biodiesel blends [59], [60]. Also, the low cetane number of biodiesel has been reported to be associated with the increase of NO_x emissions [32], [61].

The percentage changes of NO_x emissions obtained by the use of HVO and its blends, compared to ULSD, are presented in Figure 12. Pure HVO demonstrated a significant drop in NO_x (12.4-14.8%), in low and medium loads. Also in 1.5 kW and 3 kW loads, H20, H30 and H40 blends produced less NO_x by 5.2-8.1%. On the other hand, a slight increase was observed by pure HVO in high loads, of the order of magnitude of 1.5%. Regarding the blends, in high loads, no significant change was found. The reductions of NO_x emissions are consistent with the findings of previous studies, which have generally shown reductions in NO_x with HVO relative to diesel fuels [13], [62]–[64] These reductions could be the result of the absence of aromatics and the higher H/C ration in HVO [24]. The combustion of aromatic hydrocarbons leads to higher adiabatic flame temperatures and higher NO_x emissions, compared to paraffins. Also, some researchers associate the reduction on NO_x emissions with the high cetane number of HVO [2], [56].
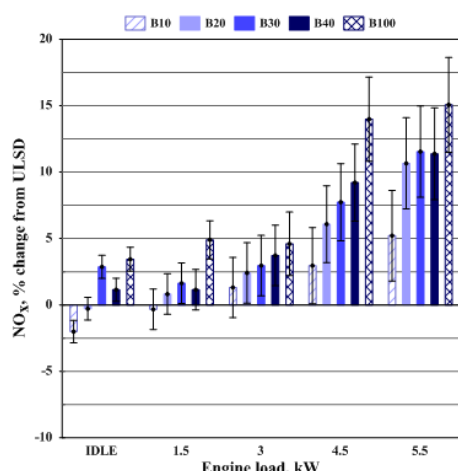
Figure 11. Nitrogen oxides emissions of biodiesel and its blends with ULSD, expressed as percentage change from ULSD
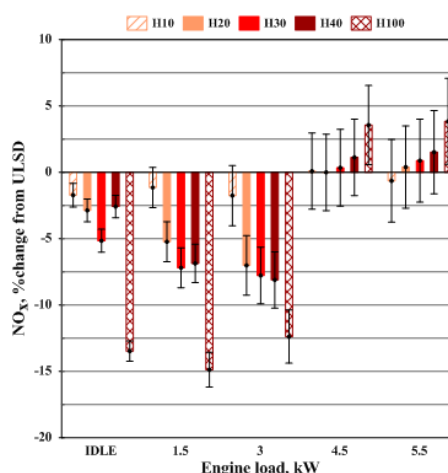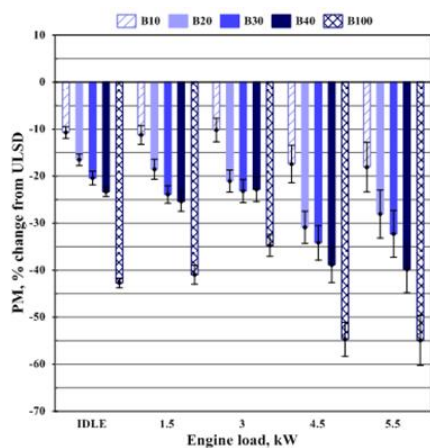
Figure 12. Nitrogen oxides emissions of HVO and its blends with ULSD, expressed as percentage change from ULSD

Particulate matter (PM) emissions, combined with high NO_x emissions of diesel engines, consists of the major problems of diesel engines. Numerous efforts have been made to achieve simultaneous reduction of both pollutants. Figure 13 demonstrates PM emissions of biodiesel and ULSD-biodiesel blends, expressed as percentage change from the emissions of ULSD. Pure biodiesel displayed significant reduction in all examined loads. PM production was decreased by more than 35% in low and medium loads, whereas greater reductions (around 55%) were observed in high and full loads. The same trend of biodiesel was followed by its mixtures, where B10 showed almost 11% and 18% reductions in low and high loads, respectively. As the biodiesel content of the blends was increased, further decrease was found. B40 reduced PM by 23.3-25.4% during the

operation of the engine in low loads, and by 38.8-39.8% in high loads. Similar reductions occurred with the increase of biodiesel concentration in blends were reported also by other researchers [3], [65]. These reductions were consistent with the results of other studies, which have shown larger reductions with the use of biodiesel during the examination of high engine loads. It was noted that the oxygen content of biodiesel has a greater impact to combustion during high loads, where diffusion flame predominates. In these conditions, oxygen promotes further oxidation of the formed soot [66]–[68]. Another factor that has been stated to affect high biodiesel's NO_x emissions and is consistent with this study's results is the reduction of heat absorption by radiation, due to the reduction of the emitted particulate matter [69].

As depicted in Figure 14, HVO displayed significant PM reductions, around 31%, during low and medium loads. In high loads the decreases were lower, but still statistically important. Its blends with ULSD did not show graduate reductions, associated with the increasing content of HVO. Particularly, in IDLE, H30 and H40 were as effective as pure HVO. Furthermore, H40 reduced PM emissions in 3 kW load in similar levels as HVO. Apparently, the increase of the cetane number, which causes a reduction in fuel ignition delay, may lead to the formation of less soot during the premix stage and help to further reduce particulate matter [33]. The reduction rates observed in low and medium load operations are in agreement with other researches that detect 30% reductions using HVO [70], [71]. Because of the similarity between CO and PM emissions of HVO and its mixtures, it could be concluded that the positive impact of its high cetane number was more detectable during the engine operation in low and medium loads.

Figure 13. Particulate matter emissions of HVO and its blends with ULSD, expressed as percentage change from ULSD
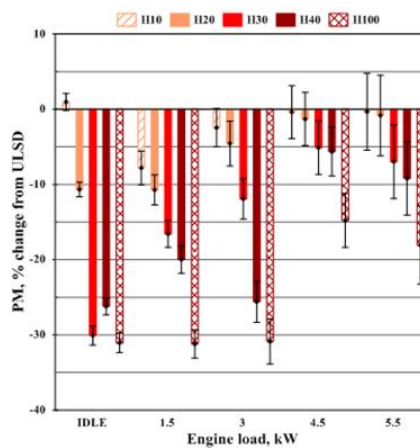
Figure 14. Particulate matter emissions of biodiesel and its blends with ULSD, expressed as percentage change from ULSD

IV. Conclusion

In this study, results are presented for the performance of two biofuels (biodiesel and HVO) when used on a small diesel engine. The fuels were compared with ULSD base diesel, and a series of binary mixtures ULSD-Biodiesel/ULSD-HVO were used, varying in proportions from 0-40% v/v. Their physicochemical characteristics were measured and found to satisfy the technical specification EN 590.

The engine tests included measurements of fuel consumption and some of the most important emissions, i.e. CO, HC, NO_x, CO_2 and particulate emissions. Gravimetric fuel consumption and exhaust gas temperature were increased with the use of biodiesel and its blends, while HVO displayed lower consumption in all engine loads, due to its high net calorific value. For high engine loads, biodiesel produced less CO than ULSD, whereas an increase in CO emissions was observed with biodiesel during the low and medium operating loads of the engine. HVO and H20, H30 and H40 blends displayed a significant reduction of CO during all tested loads, except for full load where the reductions were lower. This behavior could be the result of HVO's improved ignition delay, which also led also to reductions of up to 30% of particulate matter emissions during low and medium loads. In general, HVO's high cetane number, had a greater impact in promoting more complete combustion in low and medium loads, in comparison with the high loads of the engine. The reductions occurred by the use of biodiesel and its blends were attributed to their oxygen content and were more significant than those of HVO, as a 55% decrease was detected while testing biodiesel in high loads. Regarding NO_x emissions, biodiesel blends displayed increases as the concentration of biodiesel in the mixtures was increased, particularly in high engine operating conditions. Pure biodiesel produced more NO_x that ULSD by almost 15% in high loads, due to its oxygen which raises the adiabatic flame temperatures. These increases were in agreement with the higher EGT value of biodiesel. On the other hand, HVO presented a significant drop in NO_x, up to 14.8% in low and medium loads, while in high loads NOx were found slightly increased. Hydrocarbon

(HC) emissions were at very low levels, approaching the determination limits of the exhaust gas analyzer, while CO_2 emissions did not display any significant change among the tested fuels and blends.

Acknowledgments

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