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Hydrotreated Vegetable Oil (HVO) as a Renewable Diesel Fuel: Trade-off between NO_x, Particulate Emission, and Fuel Consumption of a Heavy Duty Engine

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ABSTRACT

Hydrotreating of vegetable oils or animal fats is an alternative process to esterification for producing biobased diesel fuels. Hydrotreated products are also called renewable diesel fuels.

Hydrotreated vegetable oils (HVO) do not have the detrimental effects of ester-type biodiesel fuels, like increased NO_x emission, deposit formation, storage stability problems, more rapid aging of engine oil or poor cold properties. HVOs are straight chain paraffinic hydrocarbons that are free of aromatics, oxygen and sulfur and have high cetane numbers.

In this paper, NO_x – particulate emission trade-off and NO_x – fuel consumption trade-off are studied using different fuel injection timings in a turbocharged charge air cooled common rail heavy duty diesel engine. Tested fuels were sulfur free diesel fuel, neat HVO, and a 30% HVO + 70% diesel fuel blend.

The study shows that there is potential for optimizing engine settings together with enhanced fuel composition. HVO could be used in optimized low emission diesel power trains in captive fleet applications like city buses, indoor fork-lift trucks, or mine vehicles.

INTRODUCTION

Vehicle owners in the developed countries have had the privilege of using high-quality fuels: ash free fuels with ultra-low or zero sulfur content and which are free of heavy fractions. For engines and emission control systems, this has resulted in longer life times, fewer repairs, less maintenance and extended oil-change intervals compared to the situation a decade or more ago.

In addition to the fuel requirements set by legislation and fuel standards, “fit for purpose” has risen as an essential requirement for fuels. Thus the addition of certain “bio components” is opposed as they are seen to reduce fuel quality from the point of view of engines, engine cleanliness, cold operability, emission control systems, or regulated and unregulated emissions. Fuel requirements are in fact becoming more stringent due to new regulations for exhaust emissions, fuel economy, and on-board diagnostics. The mileage requirements for emission control are also being extended.

Fuel distributors must also take into consideration the storage stability and water tolerance when introducing biofuels. Dedicated solutions that are not compatible with the existing fuel logistics involve significant extra costs.

HVO – HYDROTREATED VEGETABLE OIL

Hydrotreating of vegetable oils is a modern way to produce very high-quality biobased diesel fuels without compromising fuel logistics, engines, exhaust aftertreatment devices, or exhaust emissions. These fuels are now also referred to as “renewable diesel fuels” instead of “biodiesel” which is reserved for the fatty acid methyl esters (FAME).

Chemically hydrotreated vegetable oils (HVOs) are mixtures of paraffinic hydrocarbons and are free of sulfur and aromatics. Cold properties of HVO can be adjusted to meet the local requirements by adjusting the severity of the process or by additional catalytic processing. Cetane number of HVO is very high, and other properties are very similar to the gas-to-liquid (GTL) and biomass-to-liquid (BTL) diesel fuels produced by Fischer-Tropsch (FT) synthesis (see Table 1 and Table 2).

Since HVOs are hydrocarbons, they meet conventional diesel fuel requirements (EN 590, ASTM D 975, World-wide Fuel Charter category 4) except for low limit of density in some specifications. The FAME ester specifications (EN 14214, ASTM D 6751) do not apply for HVO.

The lower heating value of HVO (34.4MJ/liter) is substantially higher than that of ethanol (21.2MJ/liter). When the better efficiency of compression ignition engines compared with spark ignition engines is also taken into account, one liter or gallon of HVO can power a vehicle about double the distance compared to an ethanol based fuel such as E85.

Table 1. Typical properties of HVO, European EN 590:2004 diesel fuel, GTL and FAME. [1]

	HVO	EN 590 (summer grade)	GTL	FAME (from rape seed oil)
Density at 15 °C (kg/m^3)	775 ... 785	≈ 835	770 ... 785	≈ 885
Viscosity at 40 °C (mm^2/s)	2.5 ... 3.5	≈ 3.5	3.2 ... 4.5	≈ 4.5
Cetane number	≈ 80 ... 99	≈ 53	≈ 73 ... 81	≈ 51
Distillation range (°C)	≈ 180 ... 320	≈ 180 ... 360	≈ 190 ... 330	≈ 350 ... 370
Cloud point (°C)	−5 ... −25	≈ −5	−0 ... −25	≈ −5
Heating value, lower (MJ/kg)	≈ 44.0	≈ 42.7	≈ 43.0	≈ 37.5
Heating value, lower (MJ/l)	≈ 34.4	≈ 35.7	≈ 34.0	≈ 33.2
Total aromatics (wt-%)	0	≈ 30	0	0
Polyaromatics (wt-%)(1)	0	≈ 4	0	0
Oxygen content (wt-%)	0	0	0	≈ 11
Sulfur content (mg/kg)	< 10	< 10	< 10	< 10
Lubricity HFRR at 60 °C (µm)	< 460(2)	< 460(2)	< 460(2)	< 460
Storage stability	Good	Good	Good	Very challenging

(1) European definition including di- and tri+ -aromatics
(2) With lubricity additive

Table 2. Different technologies for biobased diesel fuels. [1]

Large scale production	Process	Product	Feedstocks: Volume availability and price	Product quality	Production plant investments
≈ 1995 …	Esterification	Biodiesel Ester FAME	-	-	+
2007 …	Hydrotreating	Renewable diesel C_nH_{2n+2} HVO	+	+ + +	-
≈ 2015 …	Gasification + Fischer-Tropsch	Renewable diesel C_nH_{2n+2} FT-BTL	+ + +	+ + +	- - -

C_nH_{2n+2} is a general formula for paraffinic hydrocarbons. + sign indicates benefit, - sign indicates disadvantage

The quality of FAME is known to depend on the properties of the feedstock used and this limits what feedstocks may be used in cold climates. HVOs can be produced from many kind of vegetable oil without compromising fuel quality. Existing farm based feedstocks such as rapeseed, sunflower, and soybean oil can be used, as well as palm oil. However, as these feedstocks compete with food production, alternative non-food oils such as jatropha and algae oil must be available in the future in large cost-effective volumes in order to be able to replace a significant portion of fossil based diesel. Waste animal fats can also be used as a feedstock for HVO process.

In the HVO production process, hydrogen is used to remove the oxygen from the triglyceride (vegetable oil) and integration to an existing oil refinery is preferred for small plants. Stand alone units may become competitive as scale increases. Additional chemicals, like methanol for FAME-production, are not needed. HVO production process does not produce any glycerol as a side product. LPG produced as a side product is used on site to fulfill the heat and energy requirements (see Figure 1).

The first commercial scale HVO plant with a capacity of 170 000 tons per year (3 800bbl per day) was started up in summer 2007 at Neste Oil's Porvoo oil refinery in Finland. This technology, branded "NExBTL", is based on a separate unit at an oil refinery site while at the same time using existing logistics, quality-control laboratories, and energy plant. A separate unit like this can be optimized and run without risking the refinery units, which may be a problem if bio-oils are fed into existing refinery units as blended with fossil feeds.

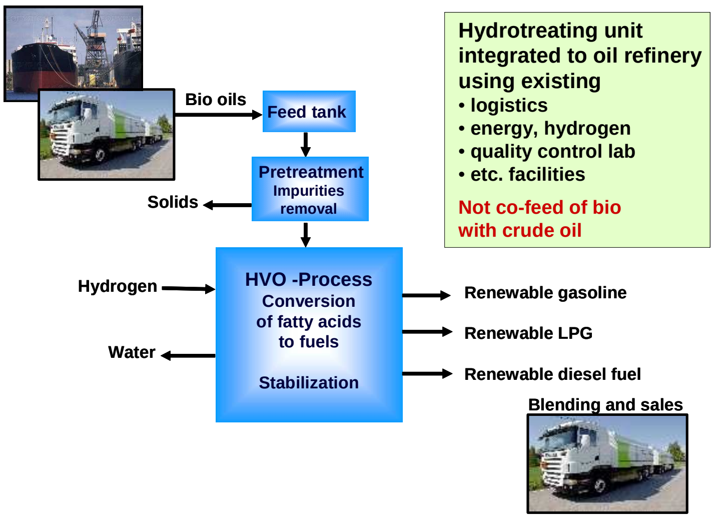

Figure 1. HVO-unit. In addition to the renewable diesel fuel also some biobased hydrocarbon-type gasoline and gases are produced.

Several HVO-units are under consideration around the world by many oil companies and process technology suppliers up to a scale of 800 000 tons per year (18 000bbl per day) per unit [1, 2]. Fischer-Tropsch plants for producing BTL fuels from biomass like wood and residues are estimated to be in commercial scale during the next decade (see Figure 2).

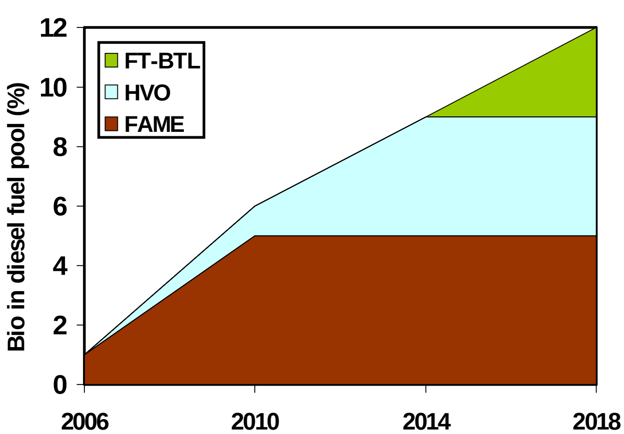

Figure 2. An illustrative market penetration estimate for biobased diesel fuels. [1]

USE OF BIOCOMPONENTS IN DIESEL FUEL

In principle, biobased diesel fuel component can be used in three ways:

1. To add a couple percent of biocomponent into diesel fuels. This is a common approach with ester-type biodiesel fuels (FAME), and the amount is currently limited to maximum 5vol-% by the EN 590:2004 standard. Higher amounts, like 7%, 10% or even 30%, are considered but they need extra precautions because of fuel stability, engine oil dilution, and deposit formation in fuel injection systems.

2. To blend tens of percents of biocomponent into diesel fuels. This is possible with hydrotreated vegetable oils (HVO) without compromising fuel quality, exhaust emissions and engine operation. In fact, the fuel blend will be premium grade since cetane number is increased and aromatic content is decreased resulting in reduced exhaust emissions and better cold-start performance. These blends are able to meet diesel fuel standards like EN 590 and ASTM D 975.

3. To use HVO as a pure fuel in fleet operations like city buses and mine vehicles in order to reduce exhaust emissions and improve local air quality. This will reduce emissions of all vehicles concerned, including old high-emitters. Also tasks of exhaust aftertreatment devices will be easier when engine-out emissions are lower. To attain full benefits of the fuel and engine, fuel injection system may need re-calibration due to the lower density and higher cetane number of HVO.

Green house gas (GHG) emissions are a global issue and depend on a combination of the total amount of biocomponents used and the overall life cycle emissions of the fuel. Therefore the biobenefit or reduction of green house gases in a country or quota area is the same in all three cases mentioned above when equal amounts of biocomponent are utilized.

The effect of HVO on regulated and unregulated exhaust emissions without changing engine parameters have already been reported in [3] for passenger cars and in [4] for heavy duty engines and vehicles (see Table 3).

A large three-year field trial with HVO has also commenced in co-operation with Helsinki City Transport, Helsinki Metropolitan Area Council, and Neste Oil in 2007. City buses and refuse trucks run with a blend of 25vol-% HVO and 75vol-% diesel fuel (blend meets EN 590), and also with 100% HVO from 2008 onwards. Exhaust emissions will be measured in a heavy-duty vehicle dynamometer for verifying regulated and unregulated exhaust emissions. Some old vehicles will be equipped with a retrofit exhaust aftertreatment device. The first priority is to reduce local emissions like particulates, NO_x, and PAHs. The use of biofuels and reduction of GHG is only a second priority in this trial.

A study concerning enhanced diesel fuel quality in order to reduce exhaust emissions locally has been reported in reference [5], and when vehicles were used in confined spaces is reported in reference [6]. Today only sulfur-free automotive diesel fuel is used in Finland and majority of non-road diesel fuel is also sulfur-free.

Table 3. The effect of 100% HVO on exhaust emissions compared to sulfur-free EN 590 diesel fuel in heavy duty applications. [4]

Emission	Effect of HVO
Particulate mass	−28 … −46 %
NO_x	−7 … −14 %
THC	0 … −48 %(1)
CO	−5 … −78 %(1)

(1) Due to low absolute values (g/kWh, g/km) reduction for THC and CO is not as relevant and reliable as for particulates and NO_x.

The targets of this study were to add sufficiently large amounts of HVO to diesel fuel and use HVO as such to determine the potential for emission reduction as a function of diesel fuel quality and optimized engine settings for reduced exhaust emissions and improved fuel economy. The effect of fuel injection timing on engine performance and emissions with GTL diesel fuel has been studied in [7, 8, 9] and with FT-BTL fuel in [10]. For comparison, the chemistry and properties of HVO are very similar to GTL and BTL, and quite similar results could be expected.

In this paper, the effect of injection timing on engine emissions and fuel consumption with HVO and a 30vol-% HVO + 70vol-% diesel fuel blend is studied. The objectives were to find out the effect of HVO on engine emissions with different injection timings and to increase understanding for the observed effects.

EXPERIMENTAL SETUP

The experimental setup consisted of a heavy duty diesel engine, eddy current dynamometer, emission measurement equipment, cylinder pressure sensor, measurement PC, and various other measurement devices.

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 EGR or exhaust aftertreatment device was used. Nominal power of the engine was 225kW at 2200r/min.

Measured emissions were CO, THC, NO_x, and smoke in filter smoke number (FSN). CO was measured using H&B Uras 3G analyzer, THC using J.U.M. Engineering Model VE 7, and NO_x using Eco Physics CLD 822 Sh analyzer. FSN was measured using AVL-415S variable sampling smoke meter.

Fuel consumption was measured using AVL 733 dynamic fuel meter with AVL balance control 7030-A04.1 and AVL fuel calculator 7030-A05.

Temperature of the test cell, and thus intake air, was approximately 30°C. All tests were performed with engine warmed to normal running temperature. Fuel temperature was held at 35°C.

TEST FUELS

Fuels used in the tests were prepared by Neste Oil. Tested fuels were 100% HVO and a blend, which contained 30vol-% HVO and 70vol-% base fuel (EN 590-30 diesel fuel). The base fuel was a sulfur free (S < 10mg/kg) commercial summer grade diesel fuel meeting EN590:2004 standard. Base fuel (EN 590 diesel fuel) was also used as a reference fuel. The most important properties of the fuels can be seen from Table 4 and distillation curves in Figure 3. The very high cetane number of 100 % HVO can not be measured with the standard cetane engine but it can be measured by the IQT-method.

As it can be seen from Table 4, on world-wide bases EN 590 diesel fuel was of a high quality (cetane number 54.6, total aromatics 18.9%, polyaromatics 1.6%) meaning that compared with some other diesel fuels benefits of HVO might have been even more remarkable.

HVO was produced at the 1st commercial HVO-unit at Neste Oil's Porvoo refinery in Finland during a period when process optimization for cold operability was not yet conducted. Fuel analyses were made by Neste Oil.

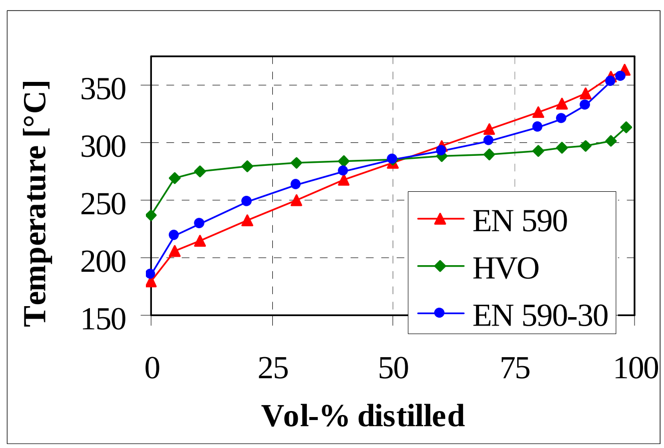

Figure 3. Distillation curves of the test fuels.

Table 4. Analyses of the test fuels.

Quantity	Unit	EN 590	HVO	EN 590-30
EN 590 diesel fuel	vol-%	100	0	70
HVO	vol-%	0	100	30
Carbon	wt-%	85.9	84.8	85.8
Hydrogen	wt-%	13.5	15.2	14.0
C/H-ratio (1)		6.4	5.6	6.1
Sulfur	mg/kg	5	<3	3
Nitrogen	mg/kg	28	1.5	20
Total aromatics	wt-%	18.9	0.2	13.6 (2)
Monoaromatics	wt-%	17.2	<0.2	12.4 (2)
Diaromatics	wt-%	1.5	<0.1	1.1 (2)
Triaromatics	wt-%	0.20	<0.10	0.17 (2)
Polyaromatics (3)	wt-%	1.6	<0.1	1.2 (2)
Paraffins	wt-%	29	100	49 (2)
Naphthenics	wt-%	52	0	37 (2)
Ash	wt-%	<0.001	<0.001	<0.001 (2)
Water	mg/kg	20	7	18
Density (at 15℃)	kg/m^3	843.0	779.7	824.0
Flash point	℃	68	99	74
Cloud point	℃	−5	7 (4)	−6
Viscosity (at 40℃)	mm^2/s	3.208	3.087	3.165
Lubricity (HFRR)	µm	324	360	300
Cal. heating value	MJ/kg	45.99	47.27	46.35 (2)
Eff. heating value	MJ/kg	43.13	44.04	43.38 (2)
	MJ/l	36.35	34.34	35.75 (2)
Cetane number		54.6	>70	>65
Cetane number (IQT™)		57	95	71.9
Cetane index		52.1	>56.5	>56.5
Distillation				
5 vol-%	℃	206	269	219
50 vol-%	℃	282	286	285
90 vol-%	℃	343	298	332
95 vol-%	℃	358	302	352
Final boiling point	℃	363	313	358

(1) Calculated from carbon and hydrogen content
(2) Calculated from the analysis of components (EN 590 and HVO)
(3) Sum of di- and tri+ aromatics according to the European regulation
(4) Can be adjusted from -5 to -25 ℃ for different climate zones

TEST MATRIX

During the tests, performance and emissions of the test engine were recorded under steady-state conditions with a warmed engine. The engine was run at three speeds of 2200r/min, 1500r/min, and 1000r/min, and at two loads corresponding to 50% and 100% load. 1000r/min was only run with 50% load. Main injection timing was changed from the default setting of the engine (D) to six crank angle degrees (°CA) earlier (D-6°CA) and to six °CA later than the default setting (D+6°CA) with two °CA intervals.

Pilot injection was in use at engine speed of 1500r/min at 50% load and at 1000r/min at 50% load. Post injection was in use at 1000r/min at 50% load. Timing of pilot and post injection was constant in time units in relation to main injection timing. At 1500r/min the start of pilot injection was 5°CA earlier than the start of main injection. At 1000r/min the start of pilot injection was 4°CA earlier than the start main injection. The start of post injection was 6.5°CA later than the end of main injection.

To achieve equal brake power of the engine with the test fuels, injected fuel amount needed to be adjusted. With HVO and EN 590-30 diesel fuel duration of the main injection was increased because of the lower densities of these two fuels compared to EN 590 diesel fuel. Injected fuel mass was still lower with HVO and EN 590-30 diesel fuel due to their higher effective heating value (see Table 4).

RESULTS AND ANALYSES

RESULTS WITH DEFAULT SETTINGS OF THE ENGINE - An average relative change of the measured emissions (CO, HC, NO_x, smoke), and volumetric and mass based fuel consumption of the test engine ran with default injection timings is presented in Figure 4. Results are averaged results calculated without any weighting factors from absolute emission values (g/kWh, FSN) of all measured engine speed and load configurations. At each speed, the test engine is run under same load with all test fuels. This is achieved by modifying the injected fuel amount until same load is obtained.

As it can be seen from Figure 4, average reductions of all emissions are clear with 100% HVO. The most significant reduction of about 35% is measured in smoke. With 100% HVO NO_x emission is reduced about 5%. With the EN 590-30 diesel fuel smoke is reduced about 11% but NO_x is found to be approximately the same as with the reference fuel (EN 590 diesel fuel). The changes in THC and CO emission are not very significant in absolute terms because of the already quite low absolute values.

Compared with the reference fuel, gravimetric specific fuel consumption (SFC) is reduced with 100% HVO and with EN 590-30 diesel fuel because of the higher mass based effective heating value of the HVO (see Table 4). Volumetric fuel consumption is increased with 100% HVO and with EN 590-30 diesel fuel because of the lower volumetric effective heating value of the HVO.

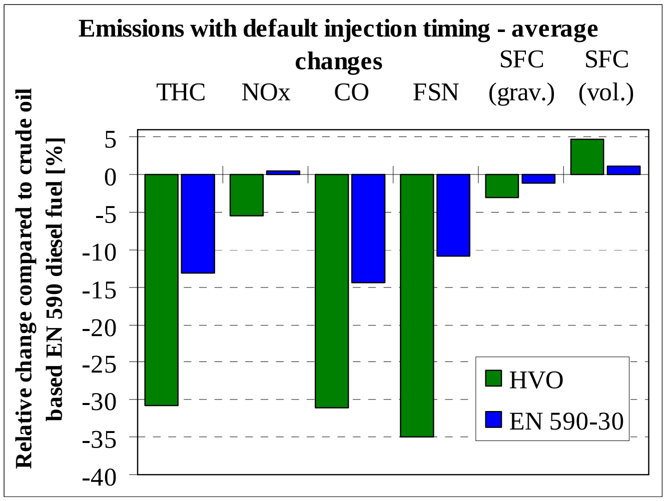

Figure 4. Emissions of HVO and EN 590-30 compared with EN 590 fuel. Average of all speeds and loads with default injection timing.

TRADE-OFF CURVES - Trade-off between specific NO_x emission and engine smoke with test fuels is shown in Figure 5. In Figure 6, trade-off between specific NO_x emission and specific fuel consumption (SFC) is shown. At 1000r/min with 50% load main injection timing D-6°CA could not be measured. The error bars in the figures represent, in case of NO_x emission and SFC, calculated uncertainty of the measurement and in case of engine smoke, deviation of three repeated measurements.

NO_x - smoke trade-off - Trade-off between specific NO_x emission and engine smoke is shown in Figure 5. As it can be seen, compared with EN 590 diesel fuel the use of 100% HVO lowers both NO_x and smoke at all engine speeds and loads on each measured injection timing. Especially engine smoke decreases significantly but there is also a clear reduction in NO_x emission.

With EN 590-30 diesel fuel, the changes in engine smoke or NO_x emission compared with EN 590 diesel fuel are not that apparent. At some early injection timings NO_x emission seems to increase when using the EN 590-30 diesel fuel. At 1000r/min with 50% load NO_x emission has increased at each injection timing point, but the uncertainty of the measurement is larger than the difference of results between the EN 590 and EN 590-30 diesel fuels (see Figure 5).

As it can be seen from Figure 5, at 2200r/min with both tested loads curves are not, in fact, trade-offs between NO_x and smoke. This is due to the fact that charge air pressure increased as main injection timing was retarded. This resulted in increased air-fuel ratio of the engine. As the air-fuel ratio increased, the FSN decreased. Same kind of phenomenon can also be seen at 1500r/min with 50% load at early main injection timings.

Figure 5 shows also that the curve of HVO and EN 590-30 is smoother than the curve of EN 590 diesel fuel. In most of the measured injection timing points, the deviation of smoke measurements (error bars in Figure 5) is smaller with HVO than with the two other test fuels. This might indicate more stable behavior of engine when running with the HVO or EN 590-30 diesel fuel.

The main reason for the low engine smoke when using HVO is the very low total aromatic hydrocarbon and poly-aromatic content of the fuel. Also a high cetane number of HVO might have an impact on engine smoke.

With HVO, a lower amount of heat is released in the pre-mixed combustion phase because of the shorter ignition lag (very high cetane number). Because of the lower volumetric heating value of the HVO (see Table 4), the fuel injection lasts longer than with the other two fuels at a same engine brake power. Because of this and the shorter ignition lag, the combustion time might be higher resulting to lower temperature and eventually lower NO_x emission.

NO_x - SFC trade-off - Trade-off between specific NO_x emission and specific fuel consumption (SFC) is presented in Figure 6. As it can be seen, the use of 100% HVO decreases the SFC of the engine at all engine speeds and loads at each measured injection timing when comparing with EN 590 and EN 590-30 diesel fuels. With EN 590-30 diesel fuel, the decrease of SFC compared to EN 590 diesel fuel is, of course, not that clear (see Figure 6). The specific NO_x emission is, as already mentioned earlier, also decreased. The decrease of the SFC of the engine is mainly due to the higher effective heating value of the HVO (see Table 4). Also a slight increase in total efficiency of the engine was observed with HVO and EN 590-30 diesel fuel, but this result is not very significant because of measurement uncertainties. The possible increase in engine efficiency might be because of the higher cetane number of the HVO and therefore shorter ignition delay.

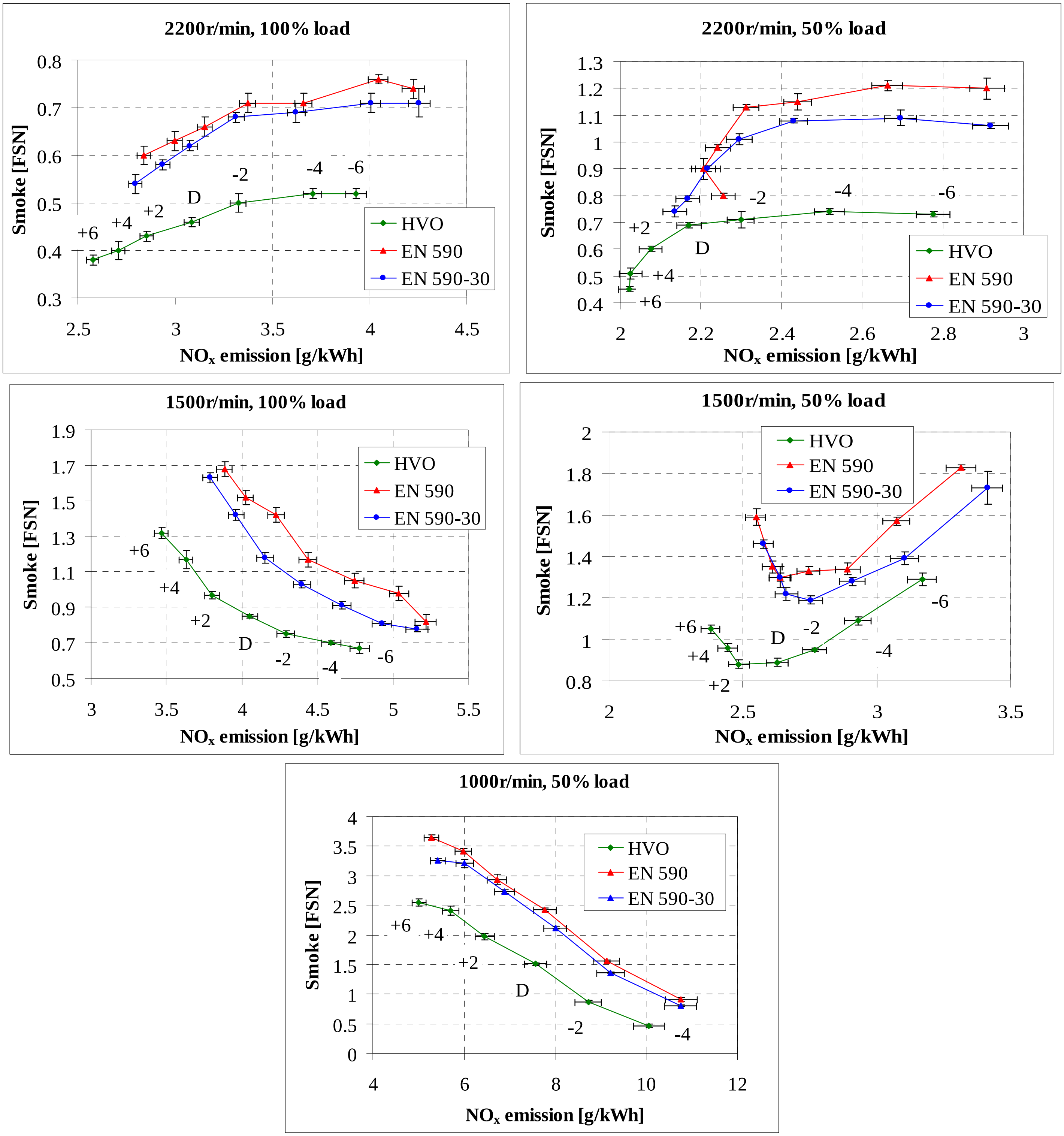

Figure 5. Trade-off between NO_x and smoke. “D” means the default main injection timing. + or - sign and a number means the start of main injection in ℃A after or before the default setting.

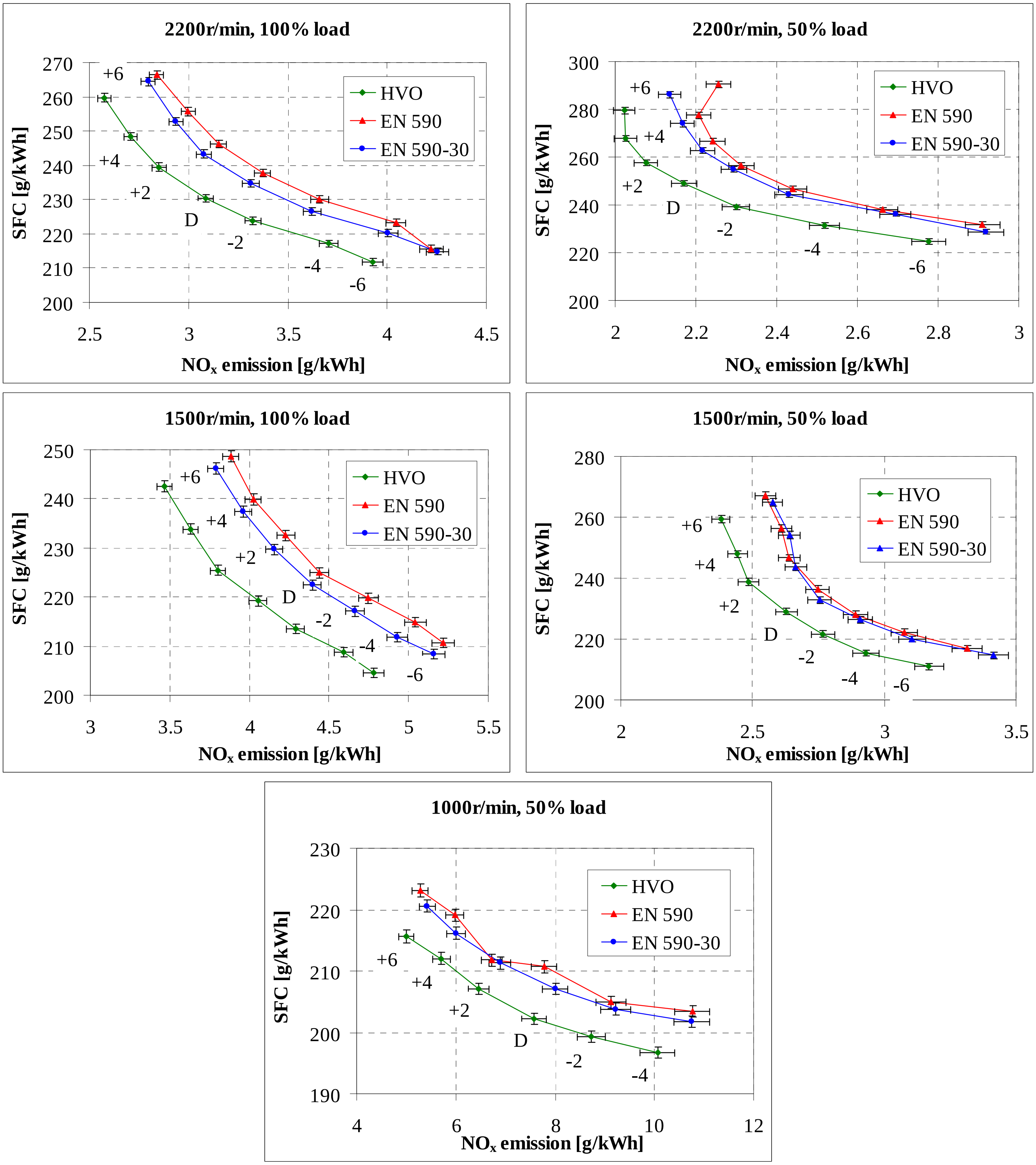

Figure 6. Trade-off between NO_x and specific fuel consumption (SFC). "D" means the default main injection timing. + or - sign and the number means a start of main injection in °CA after or before the default setting.

CONSTANT VALUE STUDY - In this part of the study, NO_x emission or SFC of the engine was kept constant between the test fuels and the values of other parameters were then determined. An example of the method is presented in Figure 7 and proceeds as follows. First, the default injection timing setting is selected for the EN 590 diesel fuel. Second, in the example case, the NO_x emission value for the EN 590 diesel fuel is checked. Then the same NO_x emission value is linearly interpolated for the two other test fuels and the smoke values are then checked and compared with the smoke value of the engine when using EN 590 diesel fuel. In the example, a NO_x value of 4.44g/kWh is measured with EN 590 diesel fuel the engine producing then a smoke value of 1.17FSN (see Figure 7). With the same NO_x value, for EN 590-30 diesel fuel a smoke value of

1.01FSN and for HVO a smoke value of 0.73FSN is measured.

Constant smoke value study was not made because of there was no trade-off between smoke and NO_x emission at 2200r/min with either of the engine loads (see Figure 5). This is due to the increase in boost pressure at late injection timings. The same phenomenon can be noticed at 1500r/min with 50% load when changing the injection timing from the earliest timing (D-6°CA) to D+2°CA. At 1500r/min with 50% load the measured smoke values with HVO are also lower at all injection timings than with EN 590 diesel fuel so the constant smoke study can not be made at this speed and load configuration.

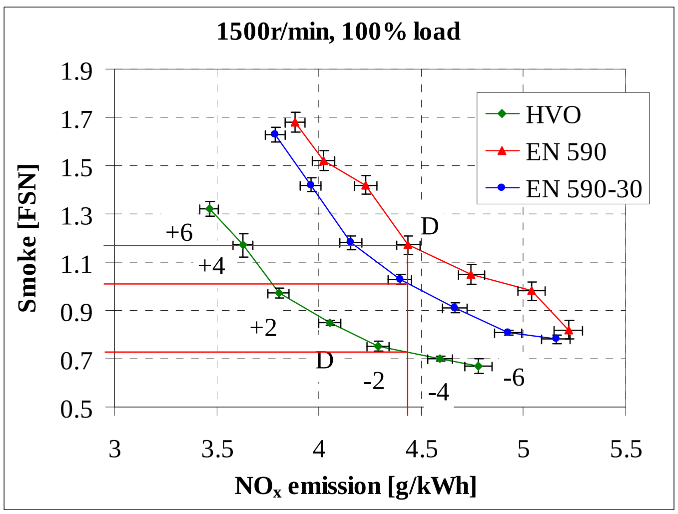

Figure 7. Example how smoke is obtained when NO_x is considered equal between the test fuels.

Constant NO_x emission - The relative change in engine smoke and in SFC compared with the results of EN 590 diesel fuel when NO_x emission is equal between the test fuels is showed in Figure 8. As it can be seen, when using HVO the engine smoke decreased 29 ... 42% compared to EN 590 diesel fuel depending on engine speed and load configuration.

An average reduction, calculated from the absolute FSN-values of each engine speed and load, was 37% with the 1000r/min operating point having the most significant effect to the average value because of the largest smoke value of all measured engine speeds and loads (see Figure 5). At the same time with the smoke reduction, SFC decreased 4 ... 7% depending on the engine speed and load with an average drop of 6%. Because of the lower density of HVO compared to EN 590 diesel fuel there was a 0.8 ... 3.5% increase in volumetric fuel consumption depending on engine speed and load configuration. The average increase of volumetric fuel consumption was approximately 1.7%. End users of engines are usually interested in volumetric fuel consumption since they purchase the fuel in volume units. Since CO_2 emission of the engine depends on mass based fuel consumption, SFC of the engine is also an important factor.

With the EN 590-30 diesel fuel, engine smoke decreased 4 ... 14% depending on engine load and speed configuration. An average reduction with EN 590-30 diesel fuel was 9%. With EN 590-30 diesel fuel, depending on engine speed and load, SFC decreased 1 ... 2.5% compared with EN 590 diesel fuel. An average reduction of 1.5% was measured.

Again, because of the lower density of EN 590-30 diesel fuel compared with EN 590 diesel fuel, volumetric fuel consumption increased 0 ... 1.2% with EN 590-30 diesel fuel depending on engine speed and load. An average increase was 0.8%.

With constant NO_x emission of the engine between all test fuels, when using HVO, fuel injection can be advanced to achieve the same NO_x level as with the EN 590 diesel fuel. Because of the earlier fuel injection, SFC decreases even more than in the case of just changing the fuel.

The conditions for soot oxidation are in the most cases also better when fuel injection is advanced. This leads to even lower FSN than in the situation where only the fuel is changed.

Constant SFC - The relative change in engine smoke and NO_x emission compared with the results of EN 590 diesel fuel when SFC is equal between the test fuels is showed in Figure 9. When SFC is constant, volumetric fuel consumption is increased with HVO and EN 590-30 because of their lower densities. The increase is defined by the density ratios between the fuels and is about 8% for HVO and about 2.3% for EN 590-30.

Figure 9 shows that compared with EN 590 diesel fuel the engine smoke decreased 5 ... 46% when using HVO. Average reduction in engine smoke was 23%. At the same time with a smoke reduction, NO_x emission was reduced by 8 ... 24% with an average reduction of over 16%. With the EN 590-30 diesel fuel, smoke increased almost 9% when running the engine at 1000r/min with 50% load. At the other tested speeds and loads, smoke decreased 6 ... 12%. As an average, smoke decreased nearly 3% even though at 1000r/min with 50% load the smoke is the highest of all measured speeds and loads.

With SFC constant, usage of HVO allows to retard fuel injection compared with EN 590 diesel fuel. This is due to the higher effective heating value of the HVO (see Table 4). Because of the later fuel injection, NO_x emission of the engine is decreased. This decrease adds to the reduction already measured without changing fuel injection timing making it even more considerable. Conditions for low soot oxidation are usually worse when retarding the fuel injection. Still, when using HVO engine smoke is considerably lower than with EN 590 diesel fuel.

CO AND THC EMISSION - With the default fuel injection timing, when using HVO or EN 590-30 diesel fuel, CO and THC emission decreased on all measured speed and load configurations compared with EN 590 diesel fuel (see Figure 4). With the other tested fuel injection timings, CO and THC emission either decreased or were at the same level as with EN 590 diesel fuel. At 1000r/min with 50% load reduction in CO emission was significant but at other speeds and loads reduction was clear in relative value but because of the low absolute values (g/kWh) not very significant in absolute terms. THC emission was also reduced clearly in relative value at most of the measurements, but the reduction was usually quite low at absolute terms because of the already low THC emission of the engine.

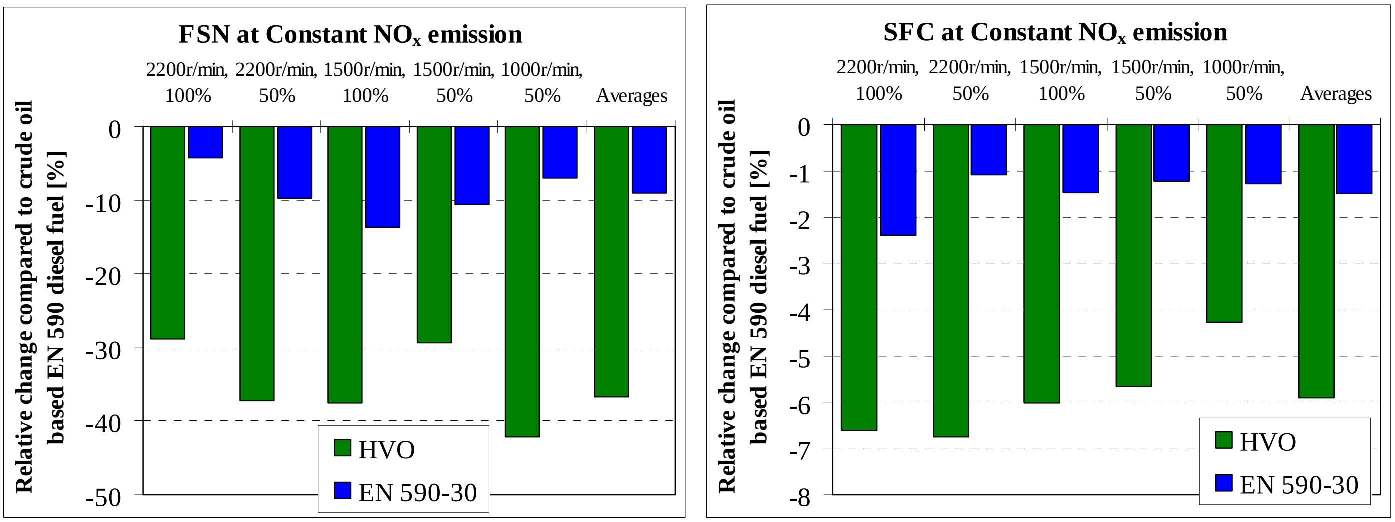

Figure 8. Engine smoke (FSN) and specific fuel consumption (SFC) when NO_x is equal with all fuels.

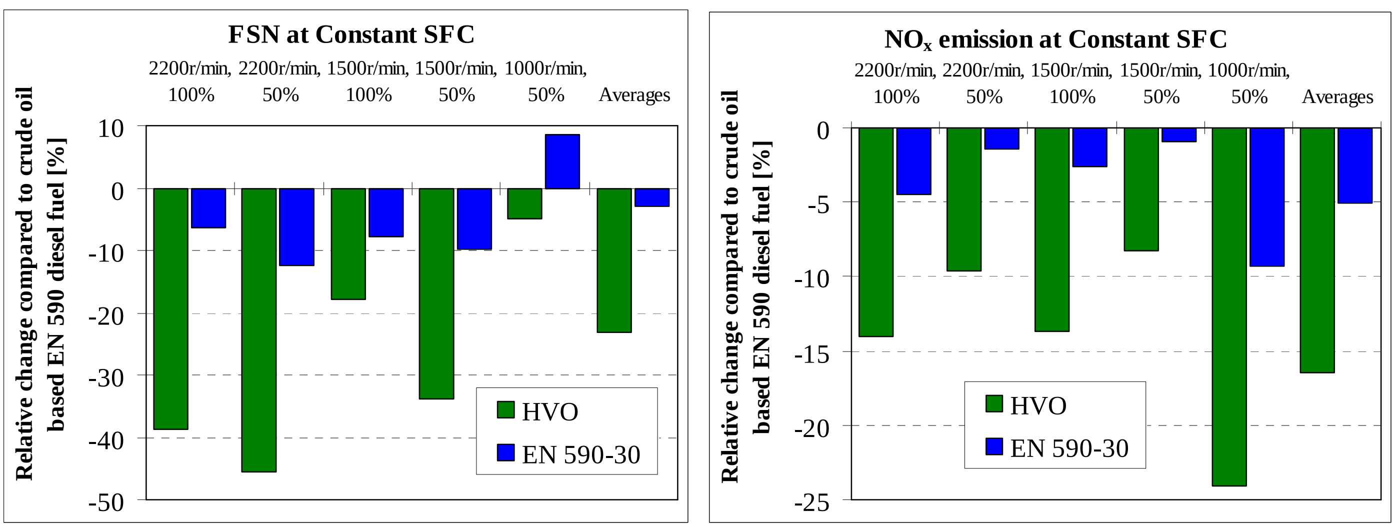

Figure 9. Engine smoke (FSN) and NO_x when specific fuel consumption (SFC) is equal with all fuels.

DISCUSSION

In earlier studies [7, 8, 9, 10], the results show consistently lower soot emission with GTL or FT-BTL fuel than with crude oil based diesel fuel but reductions in NO_x emission are not clear. In this study, the reductions in engine smoke are similar with HVO when comparing with the earlier studies made with GTL or FT-BTL, but NO_x with HVO is found to be reduced clearly. In the studies in which emissions of a passenger car or passenger car size engine [7, 8, 9, 10, 11] are measured with GTL, there are no clear and consistent reductions in NO_x compared to crude oil based diesel fuel. In the studies performed with heavy-duty engines [12, 13, 14], consistent NO_x reductions are measured. The results of this study with HVO are similar to the studies performed with heavy-duty engines with GTL and FT-BTL.

Serial production engines have to pass type approval exhaust emission test with a certain type of reference fuel defined by legislation. These reference fuels correspond to average market fuel quality. This means that the exhaust benefits of an enhanced fuel quality can be obtained only partly by using standard engine control settings. Still, better air quality – as a result of a better fuel quality – is a benefit for the society and the environment.

On the other hand, the full benefits of enhanced fuel quality and engines optimized for that fuel could be obtained in dedicated centrally fuelled vehicle fleets. Examples could be city buses, non-road equipment operating in mines, fork-lift trucks operating in confined spaces, tractors towing containers from and to ships in harbors etc. where reduction of local emissions is especially important.

At present, spark ignition engines are capable of automatic optimization according to the gasoline grade by using closed loop knock sensing, or between gasoline and E85 by using closed loop lambda sensing. It could also be possible in the near future, that diesel engines could obtain additional benefits from enhanced fuel grades, for example by closed loop cylinder pressure sensing which will soon be used in some serial production engines.

CONCLUSION

According to this study performed with a heavy duty DI diesel engine, the following conclusions can be made:

- The use of hydrotreated vegetable oil (HVO) enables reductions in CO, THC, and NO_x emission, and in engine smoke without any changes to the engine or its controls. In most of the measurements, CO and THC reductions are not as significant as reductions in NO_x and smoke because of the already low CO and THC values of diesel engines.
- With the default injection timing settings of the test engine, the use of 100% HVO led to 6% lower NO_x and to 35% lower smoke compared with sulfur-free EN 590 diesel fuel.
- The results of this study suggest that with optimized fuel injection parameters for HVO, even more significant reductions in emissions can be achieved.
- When NO_x emission of the engine was kept equal with all test fuels, 100% HVO and EN 590-30 fuel (30vol-% HVO in EN 590) enabled even more reduced smoke and specific fuel consumption (SFC). The use of 100% HVO led to 37% lower smoke and to 6% lower SFC than the use of EN 590 diesel fuel.
- When the SFC of the engine was kept constant with all fuels, HVO and EN 590-30 provided even more significant reduction in NO_x emission with smoke still clearly lower than with EN 590 diesel fuel. The use of 100% HVO led to 16% lower NO_x and to 23% lower smoke than the use of EN 590 diesel fuel.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

BTL: Biomass-to-liquids diesel fuel

CA: Crank angle

CO: Carbon monoxide emission

D: Default setting of injection timing

DI: Direct injection

EGR: Exhaust gas recirculation

EN 590: Diesel fuel meeting EN 590:2004 standard specification (in this case “sulfur-free” with sulfur content ≤10mg/kg)

EN 590-30: Diesel fuel consisting of 30vol-% HVO and 70vol-% EN 590 diesel fuel

E85: Fuel for otto engines: 70 … 85vol-% ethanol and 15 … 30vol-% gasoline

FAME: Fatty acid methyl ester, “biodiesel”

FSN: Filter smoke number

FT-BTL: Biomass-to-liquids diesel fuel made by Fischer-Tropsch synthesis

GHG: Green house gas emissions (weighted sum of fossil CO_2, N_2O and CH_4)

GTL: Gas-to-liquids diesel fuel made from natural gas by Fischer-Tropsch synthesis

HFRR: High frequency reciprocating rig (fuel lubricity test)

HVO: Hydrotreated vegetable oil

IQT: Ignition quality test for cetane number determination (EN 15195, ASTM D6890)

LPG: Liquefied petroleum gas

NExBTL: Brand of Neste Oil for HVO production process technology and for HVO fuels produced with this process

NO_x: Nitrogen oxide emission

PAH: Polycyclic aromatic hydrocarbon

r/min: rounds per minute

SFC: Specific fuel consumption

THC: Total hydrocarbon emission