

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 “bio-diesel” 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 _n H _{2n+2} HVO	+	+++	-
≈ 2015 ...	Gasification + Fischer-Tropsch	Renewable diesel C _n H _{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 O's Porvoo oil refinery in Fin-

land. 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.

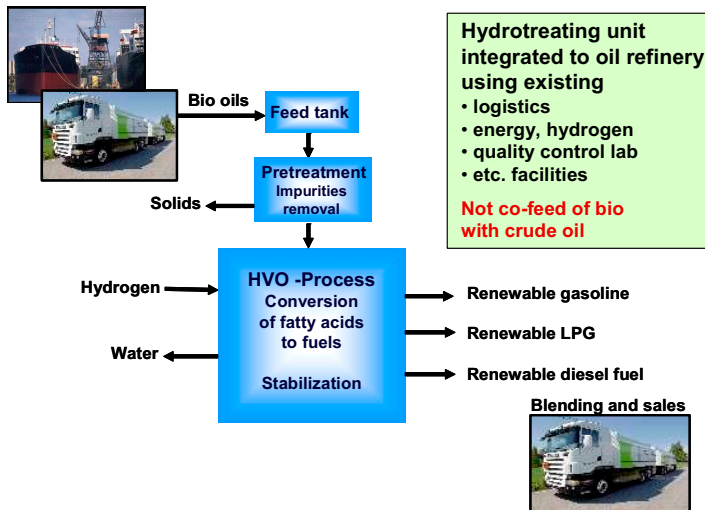


Figure 1. HVO-unit. In addition to the renewable diesel fuel also some biobased hydrocarbon-type gasoline and gases are produced.

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).

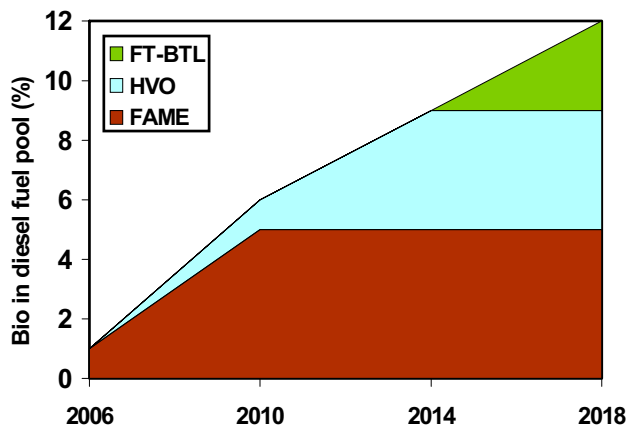


Figure 2. An illustrative market penetration estimate for biobased diesel fuels. [1]

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.

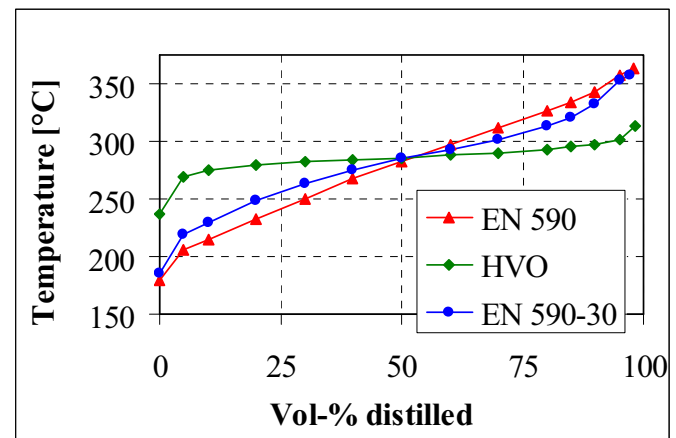


Figure 3. Distillation curves of the test fuels.