



Technical Performance of HVO (Hydrotreated Vegetable Oil) in Diesel Engines

2012-01-1585
Published
09/10/2012

Tuukka Hartikka, Markku Kuronen and Ulla Kiiski
Neste Oil Corp.

Copyright © 2012 SAE International
doi:[10.4271/2012-01-1585](https://doi.org/10.4271/2012-01-1585)

ABSTRACT

The objective of this paper is to compile the findings of more than 40 scientific publications and provide information on the technical performance of HVO (Hydrotreated Vegetable Oil) in diesel engines. Fuel properties, emission performance and engine behavior of HVO is evaluated in comparison to fossil diesel. Based on the studies and large field trials it can be concluded that HVO can be used as a drop-in-fuel and that it has properties beneficial for the engine and the environment. HVO has high cetane number, low density, good lubricity when treated with lubricity additives, bulk modulus comparable to fossil diesel, material compatibility similar to fossil diesel and good cold properties regardless of the feedstock. HVO is capable of reducing regulated and unregulated emissions as well as greenhouse gasses. HVO has beneficial effects to aftertreatment systems. Oil dilution with HVO is not a concern and HVO does not cause incompatibility with lubrication oil. Large field trials have shown that the fuel consumption with HVO is nearly proportional to the volumetric heating value, but in some cases the engine efficiency is slightly improved.

INTRODUCTION

HVO (Hydrotreated Vegetable Oil) is a renewable diesel fuel with properties comparable to GTL (Gas-To-Liquids) diesel fuel [see [appendix A](#)]. HVO can be produced from various feedstocks, such as vegetable oils, animal fats and waste oils, without having remarkable effects on the properties of the final product. When feedstocks like algal oils and microbial oils from waste materials become widely available they can be fed into the HVO process to produce high quality traffic fuels. The cold properties of the fuel can be adjusted by isomerization and /or cracking optimization. Severe winter grades can be produced from any of the currently available feedstocks. HVO is fully paraffinic without any aromatics,

olefins or naphthenes. Consequently the cetane number is very high and the density is lower compared to standard fossil diesel fuel. [[1](#), [2](#), [3](#), [4](#), [5](#)]

The distillation curve of HVO is slightly different than that of regular EN590 diesel and the distillation range and final boiling point are much lower compared to FAME (Fatty Acid Methyl Ester). HVO and FAME have different physical and chemical properties and hence they both have their own specification. HVO properties are specified in CWA15940 (CEN Workshop Agreement) and FAME properties in EN14214 respectively. Both HVO and FAME are produced from biobased feedstocks, but the term biodiesel is typically used only for FAME. The blending restrictions set for FAME (e.g. EN590: maximum 7%-vol), do not apply for HVO.

A simplified HVO process consists of feedstock pretreatment, hydrotreatment and isomerization units. Purification of the feedstock is crucial for the hydrotreatment process. Metals, nitrogen, phosphorus and other impurities have to be removed to a certain level in the pretreatment process phase. The catalysts used in the hydrotreatment and isomerization processes will absorb any of the impurities left after the purification and any excess impurities will cause premature deactivation of the catalysts. Hence the end product is free from these impurities. In the hydrotreatment process the double bonds are hydrogenated and oxygen is removed under high temperature and hydrogen pressure. After the hydrotreatment process the fuel mainly consists of straight chain paraffins, of which carbon number range depends on the feedstock. In the final process stage the paraffins will be isomerized, and the cold properties are adjusted according to needs. Isomerization branches linear paraffins into iso-paraffins, which improves the cloud point of the fuel. The isomerization process does not influence significantly on any other fuel properties than the cold properties. As a consequence the high quality properties, like high cetane

number, remain during the cold property adjustment. [1, 2, 3, 4, 5]

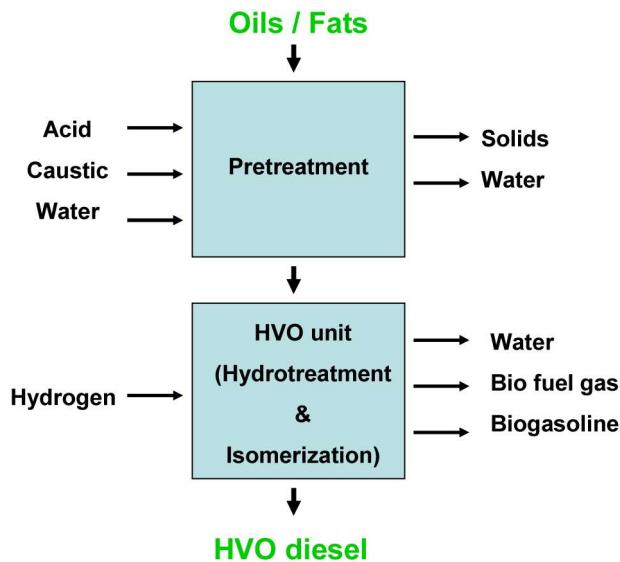


Figure 1. HVO process description

Fuel Properties of HVO

Typical fuel property values of HVO and GTL in comparison with EN590, ASTM D975 and CWA15940 are presented in [appendix A](#). CWA15940 is a CEN Workshop Agreement for paraffinic fuels (eg. GTL, HVO), and it is under update to a technical specification at the time of writing.

Density & Heating Value

The density of HVO is somewhat lower when compared to fossil diesel and to a larger extent compared to FAME. Typically the density of HVO is between 770 to 790 kg/m³ [[Appendix A](#)], regardless of cold properties, whereas density of FAME is around 880 kg/m³. The low density of HVO allows refineries and blenders to use heavier components of fossil diesel and hence achieve larger diesel yields, while complying with the density limit in the European diesel specification.

Lower heating value of the fuel is comparable to the energy released during combustion. Because of heat, friction and gas exchange losses, not all of this energy can be transformed to power output. As a consequence, if the engine efficiency stays the same, lower heating value of a fuel is in straight relation to the fuel consumption. Lower heating value of HVO is some 44 MJ/kg, whereas for fossil diesel it is some 43 MJ/kg and for FAME 37 MJ/kg [6].

Cetane Number

Cetane number is a measure of ignition quality of the fuel. The higher the cetane number the lower the ignition delay. The cetane number of HVO is very high: from 75 to 95 due

to its nature as a mixture of normal- and isoparaffins [7, [Appendix A](#)]. The cetane number increases linearly in the blend according to the blending ratio. A high cetane number is advantageous for cold startability, white smoke formation, noise and emissions [8].

Cold Properties

Cold properties of HVO can be adjusted by the isomerization process. HVO can be produced with a cloud point of -40 °C, or even lower if required. The same process has been used to produce renewable jet fuel, in which the cloud point is as low as -55°C. Typically CFPP (Cold Filter Plugging Point) is two to three degrees lower than CP (cloud point). Because of rather narrow carbon distribution (mainly C₁₅ ... C₁₈) it is not possible to improve CFPP with conventional cold flow additives designed for fossil diesel fuels. HVO does not contain any impurities, like saturated monoglycerides or sterol glucosides which are present in FAME and which could precipitate above cloud point and lead to clogged fuel filters. Because of the heavy hydrotreatment process (high temperature and hydrogen pressure), all the vegetable oils are converted into n-paraffins and there are no glycerides, glycerol or free fatty acids left after this process stage. [1, 2, 3, 4, 5]

Bulk Modulus of Compressibility

The bulk modulus of compressibility has an effect on the start of injection in injection systems that do not operate under constant pressure and have long fuel transfer lines from the pump to the injectors [9]. For example in a pump-line-nozzle system 10 % change in compressibility changes the start of injection by 0.5 crank angle degrees [10]. The reason for this is that less compressible fuel results in faster pressure increase, higher maximum pressure and faster pressure pulsations [9, 11]. There are contradicting results in literature about the bulk modulus of paraffinic fuels [9, 12]. Lapuerta et al found that the bulk modulus of HVO is higher (less compressible) at pressures from 5-15 Mpa and slightly lower at higher pressure compared to fossil diesel. Boehman et al found that the bulk modulus of paraffinic distillate was some 10 % lower compared to fossil diesel and that this led to a retarded start of injection by 0.4 crank angle degrees. Most likely the reason for the contradicting results is the different composition of the paraffinic fuels and the reference fuels. But despite the differences in the results, it can be concluded that the difference in bulk modulus of HVO and fossil diesel at high injection pressures is quite small and thus does not have a large influence on the injection timing, especially with modern common rail injection systems [13].

Lubricity

HFRR (High Frequency Reciprocating Rig) method (ISO 12156-1, ASTMD 6079) is used for evaluating sliding wear and a limit value for HFRR is specified in many diesel fuel standards. The test procedure is as follows: a metal ball fully

immersed in the sample is oscillated against a stationary plate under known conditions. The wear scar in the ball is measured with a microscope. The bigger the wear scar is, the worse are the lubricating properties of the fuel. SL-BOCLE (Scuffing Load BOCLE) method (ASTMD6078) on the other hand measures scuffing type of wear. On SL-BOCLE test the lubricity of a fluid is evaluated by the minimum applied load in grams to a stationary ball on a rotating fuel-wetted ring that leads to fretting. This is detected by a friction coefficient greater than 0.175.

Lubricity of neat HVO corresponds to that of sulfur-free winter grade fossil diesel or GTL diesel fuels. It is essential that all of these contain lubricity additive in order to meet the European HFRR specification <460 µm for protecting the fuel injection equipment against excess wear. Lubricity additives commonly used in fossil diesel fuels are also suitable to be used in HVO. The additive dosage for HVO is typically about the same level as in winter grade fossil diesel fuels.

In addition to the specified HFRR tests the lubricity of HVO was evaluated with two 1000 hours test runs with fuel lubricated distributor type fuel injection pumps. This test is based on a CEC/Bosch procedure where a distributor type VE-type pump with injectors is driven by an electric motor at varying loads with a fuel temperature of +60 °C. Two HVO batches with two different lubricity additives were prepared for the test. Both of the batched were prepared so that the HFRR value was as close as possible to the borderline acceptance (460 µm). HFRR of the first test fuel was 446 µm and the second 443 µm. After the 1000 hours tests all the inside parts of the pumps were evaluated and found to be in good condition, and the overall ratings of the pumps were 3.0 and 2.5 respectively, where below 3.5 means passed test. Distributor pumps are no longer used in new engines, but they are known to be sensitive for fuel lubricity.

HVO with two types of different commercial lubricity additives and FAME (RME) were evaluated with the SL-BOCLE test and the outcome was compared with HFRR results. HVO responded well to both additives in SL-BOCLE test and the results correlated with corresponding HFRR measurements. Lubricity response of FAME (RME) on HVO was similar to fossil diesel fuels. According to Bosch seizure protection strongly depends on the additive type and dosage rate. An HFRR result below 460 µm provides sufficient lubricity of paraffinic fuels against sliding wear but does not always guarantee a SL-BOCLE value above 3500g, which is known to safely exclude seizure [14, 15, 16].

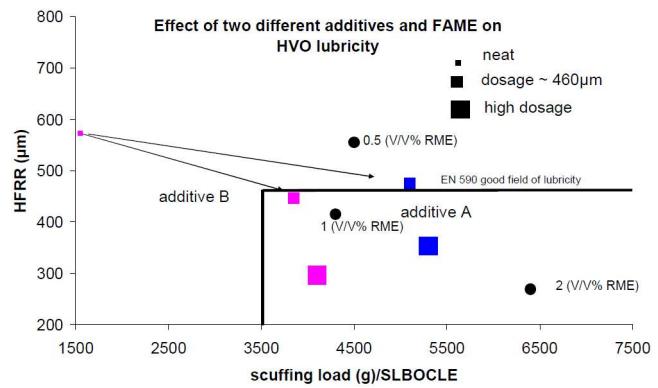


Figure 2. HFRR and SLBOCLE test results with two different types of lubricity additives and FAME in HVO. These tests were done in co-operation with Bosch diesel systems.

HVO and Material Compatibility

HVO is aromatic and sulfur free and contains only n- and i-paraffins. Laboratory tests and field trials have shown that the same seal materials in vehicles and logistics can be used with HVO than with fossil diesel [17, 18, 19, 20]. Material compatibility of HVO is comparable to GTL, because it has the same kind of physical and chemical properties [Appendix A]. The swelling properties of standard rubber materials are basically the same for GTL and low sulfur diesel fuel [21]. The swelling of rubber seals is dependant on the aromatic content of the fuel [21], hence some changes in the seals could occur when switching from high aromatic fuel to zero aromatic fuel like HVO or GTL. Nevertheless no field issues due to this effect have been seen [17, 18, 22]. Based on field experiences the materials used in the logistic systems, for example carbon steel and stainless steel, are fully compatible with HVO [17].

Water Tolerance and Storage Stability

Due to paraffinic composition and non-polar nature HVO rejects water and water separation occurs far better than with fossil diesel fuels and remarkably better than with FAME or diesel fuels containing FAME. A minimized amount of dissolved water in fuel is extremely important especially during cold winter season.

A test with three different fuels was conducted to evaluate the water separation capabilities of these fuels. At first 100 ml of water was mixed with 500 ml of fuel in a temperature of 60 °C. Then the samples were kept at this temperature for 24 hours and the water content was measured from the top of the fuel. Next the samples were cooled down by 10 °C and kept again for 24 hours at this temperature and the water content was determined. This cycle was repeated until the temperature reached -20 °C. The results of this test are presented in Figure 3. Eg. at 0°C HVO keeps water 16 ppm while for fossil fuel the figure is 42 ppm and for FAME (RME) 1600 ppm respectively.

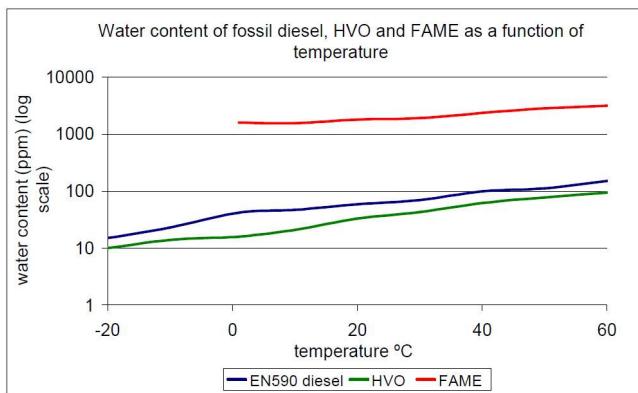


Figure 3. Solubility of water to fossil diesel, HVO and FAME at different temperatures (note logarithmic y-axis scale)

HVO does not contain any double bonds unlike FAME and thus has no such reactivity characteristics. As a consequence good oxidation stability is experienced. Based on field trials and long term storage tests, also in severe winter conditions, it can be concluded that the stability of the fuel is very good [17].

Performance in Engines

HVO Combustion Behavior

Since HVO consists of only iso- and n-paraffins, just like GTL diesel, the cetane number is very high and the density relatively low. Both of these properties have an influence on the combustion process of a diesel engine. Lower heating value of HVO per mass is slightly higher than that of EN590 diesel because of higher hydrogen content. But due to the lower density the heating value per volume is some 5 % lower compared to summer grade fossil diesel. To compensate for this energy content difference, more fuel in volume needs to be injected. This can have an influence on the ECU control parameters and thus change the injection timing or EGR rate. In modern common rail systems the actual injection quantity with HVO can be somewhat higher than with fossil diesel as explained in the following chapter. Consequently in common rail injection systems the change in the load point on the engine map is not necessarily as big as with volume controlled injection systems.

The high cetane number shortens the ignition delay and accelerates the start of combustion especially in low and medium load conditions [Figure 4]. This can lead to shorter premixed combustion which can have an influence on the engine noise, particulate and NOx emissions. When pilot injection is applied the main combustion is less influenced by the cetane number, and the changes in combustion phasing are smaller [23]. It should be noted that optimal timing of the pilot injection is important for the combustion noise and particulate emission formation, and HVO can have a different optimal offset between pilot and main injection than standard

EN590 diesel [24, 25]. On high loads the influence of high cetane number on start of combustion is less dominant, because of high bulk gas temperature, and the combustion tends to be similar with HVO and EN590 diesel. Applying pilot injection in high engine loads further stabilizes the combustion and decreases the difference between HVO and standard diesel [23, 26].

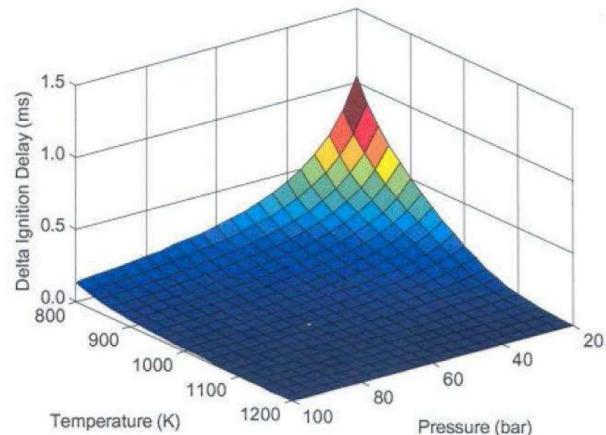


Figure 4. Difference in ignition delay between GTL diesel fuel and conventional diesel fuel as a function of temperature and pressure [26] (Paul Schaberg, Sasol)

Reprinted with permission from SAE paper
2005-01-2187 (c) 2005 SAE International

Influence of HVO on Injection Systems and Spray Pattern

Several studies have found that with modern common rail injection systems fuel penetration, droplet size and spray angle are virtually the same for HVO and fossil diesel [23, 26, 27, 28, 29]. But the spray tip velocities in non-evaporative conditions have been found to be higher with HVO compared to standard EN590 diesel fuel [27]. Sugiyama et al. demonstrated that the injection quantity with the same indicated value of injection duration was approximately 3-5 % higher with HVO compared to fossil diesel with injection pressures from 40 Mpa to 200 Mpa [23]. Similar behavior has also been found with GTL fuel, which has fuel properties comparable to that of HVO [30]. This can explain the results which indicate no power loss with HVO in common rail equipped engines, although the volumetric energy content is some 5 % lower [22, 23, 30, 31]. One explanation for this phenomenon was proposed by Crepeau et al: Bernoulli's equation indicates that the volume flow rate is inversely proportional to the square root of the fluid density. Since the densities of HVO and GTL are lower compared to typical EN590 diesel the flow rate would therefore be approximately 4 % higher [30].

In volume controlled injection systems, such as in-line pump, distributor pumps or pump-line-nozzle, the amount of fuel to be injected is pre-metered in the pump barrel. Since the fuel

is metered volumetrically into the chamber, the injection quantity does not change when the fuel's density changes [32]. Thus in the volumetrically controlled injection systems the injected fuel quantity with the same gas pedal position will be smaller with HVO than with EN590 diesel. This leads to some 5 % lower maximum power and torque with HVO [17]. The bulk modulus of HVO is not very different from fossil diesel and therefore the start of injection is not effectively changed (maximum 0.4 CAD retarding) in volume controlled injection systems when switching from fossil diesel to neat HVO [9, 12].

It is worth noting that a low IBP (Initial Boiling Point) could increase the risk of cavitation damages in fuel injection systems. Some FIE manufactures have indicated that if the IBP is below 160°C there might be increased cavitation inside the fuel injection system. [14]

HVO's Influence on Oil Dilution

Diesel Particulate Filters (DPF) accumulates diesel particulates produced during the combustion. DPFs need periodic active cleaning, called regeneration, to oxidize the collected soot. Active regeneration is done by increasing the exhaust temperature above normal operating temperatures, typically above 500 °C to burn off the soot. The temperature increase can be done with an electric heater or by a more commonly used method; introducing diesel fuel upstream the DPF and oxidizing the fuel in an oxidizing catalyst (DOC). The additional fuel can either be injected with an additional injector in the exhaust pipe or by using the existing injectors and a late post injection. Ideally the fuel vaporizes without oxidation and provides hydrocarbons upstream DOC. [33]

Engine oil dilution is a concern of original equipment manufacturers' (OEM) with engines that use post injection for the DPF regeneration. Fuel entrainment into the oil pan is taking place when the high boiling components in diesel fuel, mainly due to addition of FAME, do not evaporate and the liquid fuel hits the cylinder walls during the late post injection [34]. FAME in lubrication oil causes deterioration of the oil by oxidation and increased total acid number (TAN) [34, 35, 36]. Another problem with FAME is that when it enters the oil pan it does not leave through evaporation, because of the high boiling temperature [34, 37]. Since HVO has a much narrower distillation range, and even lower final boiling point compared to fossil diesel, less fuel enters into the lubrication oil and the evaporation rate is higher [34, 38]. Since HVO consists of only non-reactive paraffinic hydrocarbons it does not cause chemical incompatibility with lubrication oil. Field trials with city busses showed that engine oil dilution, TAN and viscosity of the used oil were on the same level with 100 % HVO and EN590 diesel without FAME [17].

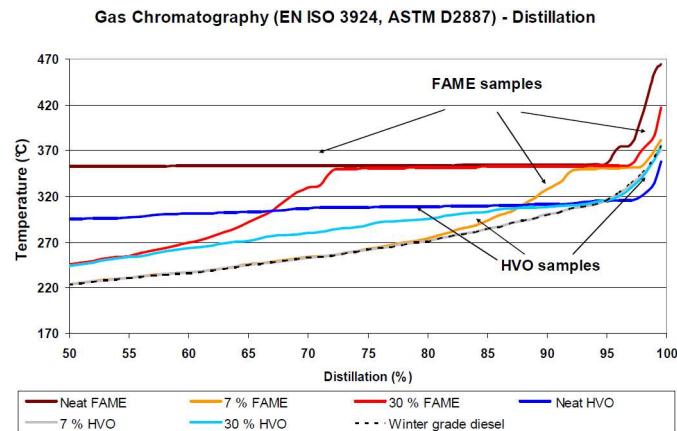


Figure 5. Gas Chromatographic distillation (EN ISO 3924, ASTM D2887) curves highlighting the 50% to FBP distillation of various fuel blends. GC distillation is used here to emphasize the back-end distillation

Fuel Consumption

Table 1. Energy content of various biofuel compositions

		Diesel fuel (typical summer grade without biocomponent)	HVO	FAME
Density	kg/m ³	835	780	880
Heating value	MJ/kg	43.1	44.1	37.2
Heating value	MJ/l	36.0	34.4	32.7
• difference to diesel fuel	%		-5	-9
Heating value, 10 vol-% blend	MJ/l		35.8	35.7
Heating value, 30 vol-% blend	MJ/l		35.5	35.0

Because of lower density of HVO the volumetric heating value is approximately 4 to 5 % lower compared to summer grade fossil diesel and some 5 % higher than that of FAME [6]. Several studies have shown that some engines show a small improvement in engine efficiency with HVO, around 1 % [22, 31, 39, 40]. According to field trials and laboratory tests the volumetric fuel consumption of neat HVO is from 3 to 6 % higher than that of fossil diesel [17, 40, 41, 42]. If an engine would be recalibrated to take advantage of HVO's fuel properties, fuel consumption could be lowered even more than 5 % [17, 23, 39]. Table 1 presents different heating values of various fuel compositions with certain bioenergy percentages. It should be noted that in most countries nowadays there is a biofuel quota and hence fossil diesel

without a biocomponent is not anymore a comparable baseline in fuel consumption comparisons.

EMISSION CHARACTERISTICS

Influence of Fuel Properties on Emissions

Because HVO consists of only paraffinic hydrocarbons the emissions from the combustion are lower when compared to fossil diesel, which consist of aromatics, napthenes and paraffins. Emission behavior with HVO is similar to GTL which also only consist of n- and iso-paraffins [31, 42, 48]. Engine out NO_x and PM emissions are reduced mainly due to absence of aromatics, higher H/C ratio and lower final boiling point [7, 87, 23, 43, 44, 45] and CO and HC emissions due to high cetane number and absence of aromatics [7, 23, 25, 44, 46, 47]. High flame temperatures during combustion increase the formation of NO_x emission [87]. Aromatic hydrocarbons, which have high carbon content compared to hydrogen, are known to have higher adiabatic flame temperatures than paraffins [8, 26, 45]. Hence zero aromatics and high H/C ratio reduces the NO_x formation. Reduction in aromatics and high boiling components is also shown to decrease particulate matter emissions [8, 45]. The magnitude of emission reductions is dependant on the load and speed conditions of the engine, because of changes in the combustion phasing as explained earlier. Even though the emission formation during the combustion is reduced, the actual tailpipe emissions also depend on several factors, like EGR rate, SCR's NO_x reduction capability (urea injection quantity) and operation of the DPF (Diesel Particulate Filter) and/or DOC (Diesel Oxidation Catalyst). So even if all the engine out emission components are reduced, the actual tailpipe emissions depend on several factors.

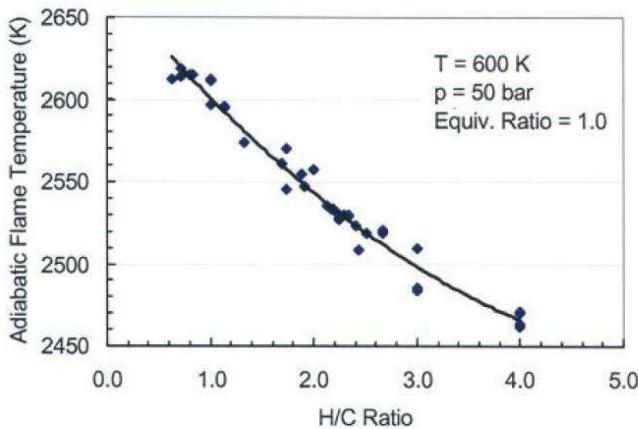


Figure 6. Calculated adiabatic flame temperature as a function of atomic C/H ratio for a variety of hydrocarbon fuels [26] (Paul Schaberg, Sasol) Reprinted with permission from SAE paper 2005-01-2187 (c) 2005 SAE International

Effect of HVO on Regulated Emissions

Engines with a relatively simple control strategy and no complex aftertreatment systems (Euro I, II, III) yield to the largest emission reductions when switching to neat HVO. Modern vehicles (EURO IV, V, VI) equipped with exhaust aftertreatment devices emit much less emission pollutants, which means that the absolute emissions reductions are smaller compared to older vehicles. Modern engines also have very precise control algorithms, therefore changing to a fuel with a low density and high cetane number might influence several control parameters. Because of this the emission reductions with the most modern engines vary from test to test. Some engines yield to very low NO_x emission with negligible PM reduction, whereas some engines might have the opposite effect [17, 41]. There are also differences between heavy-duty and light-duty engines. In most modern passenger cars HVO usually has a negligible effect on NO_x emissions, but other emission components are lowered [12, 23, 46]. Heavy-duty engines on the other hand typically show a decrease in all the emission components [17, 31, 40, 41, 42, 48, 49, 50].

Table 2. Average tailpipe emission reductions with neat HVO compared to EN590 B0 in heavy-duty vehicles [17, 31, 42, 48, 51, 52]

	Euro II	Euro III	Euro IV	Euro V/EEV
Average of 2 tests (2 vehicles)	Average of 8 tests (6 vehicles)	Average of 19 tests (14 vehicles)	Average of 7 tests (7 vehicles)	
NO _x	-8 %	-9 %	-8 %	-9 %
PM	-27%	-27%	-34%	-37%
CO	-31%	-16%	-25%	-37%
HC	-41%	-26%	-26%	-55%
CO ₂ *	-5%	-3%	-4%	-4 %

*Tank-To-Wheels (TTW) CO₂ value measured from the tailpipe, bio-origin not included. CO₂ decrease due to high H/C ratio in HVO.

In Figure 7 average results from passenger car and bus tests with various HVO blends are presented. It can be seen that the reduction of NO_x and PM emissions decrease relatively linearly with increasing HVO content [Figure 7, Figure 8]. It can also be seen from the figures that the emission reductions vary from test to test and therefore single measurement points deviate from the average line. A general trend is that when switching from standard fossil diesel to HVO, all the

regulated emission components can be lowered. Emission reductions are especially high in cold temperatures [17].

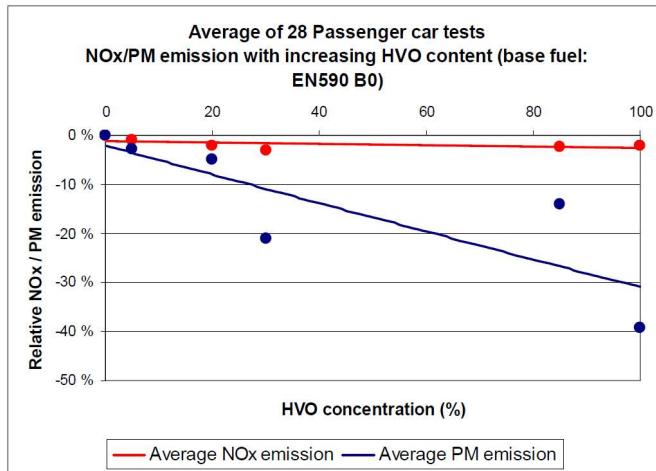


Figure 7. Average NO_x and PM reduction with increasing HVO content in passenger cars. 8 tests with 5 % blend, 8 tests with 20 % blend, 20 tests with 30 % blend, 8 tests with 85 % blend and 23 tests with neat HVO. [12, 23, 26, 42, 52, 53, 54]

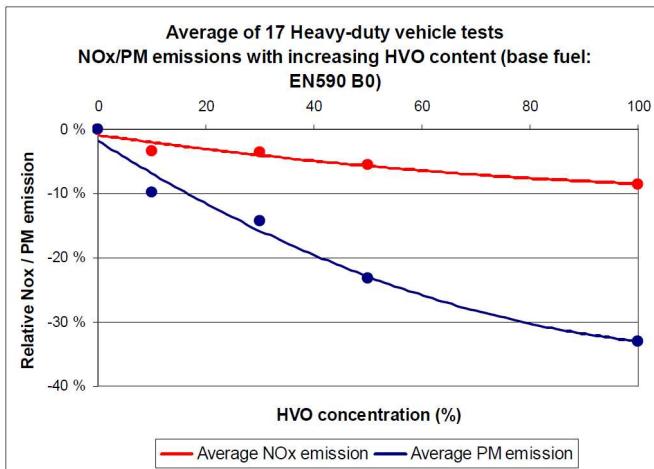


Figure 8. Average NO_x and PM reduction with increasing HVO content in heavy-duty vehicles [17, 31, 49, 50].

HVO and Unregulated Emissions

HVO's effects on unregulated emissions; (i.e.PAH, aldehydes, mutagenicity and particulate number) are described in several studies. Nylund et al found that particulate number in all size classes was reduced by 17-40 % by switching from EN590 diesel to HVO [17]. Murtonen et al measured particulate number by CPC (Condensation Particle Counter) from a Scania Euro 4 truck engine and found that the total number of particulates with HVO and GTL were 20% and 14% lower compared to EN590 diesel, respectively [31]. PAH emissions and mutagenicity of particulates are

radically lower with HVO compared to fossil diesel [17, 31, 41, 42, 51, 59]. The soluble organic fraction (SOF) of the particulate matter is not substantially different with HVO than it is with EN590 B0, hence the largest reduction in particulate mass comes from the soot fraction [31, 42]. Several studies have also shown that HVO either lowers or has no effect on aldehyde emissions [17, 31, 51].

Optimizing Engines for HVO

The best trade-off between emissions and fuel consumption would be achieved by optimizing engines for neat HVO. Several studies have shown that HVO has properties beneficial for optimizing engines [17, 23, 39]. Especially the trade-off between NOx and particulates tends to be better with HVO compared to standard fossil diesel, which allows the injection timing to be adjusted for lower fuel consumption [39]. Most benefits can be achieved by optimizing the entire engine including injection timings, EGR rates, SCR, and valve opening times for neat HVO. For example HVO allows the usage of high EGR rates for NOx reduction without an increase in PM emissions compared to EN590 diesel [55]. Also applying Miller timing together with HVO is an effective way to further reduce emissions [56].

HVO Compatibility with Aftertreatment Devices

It has been a concern of aftertreatment system manufacturers that ash forming components in biodiesel (FAME) cause excessive amounts of ash, which can lead to deactivation of the aftertreatment devices [57]. HVO is virtually free of ash forming components, like P, Na, Ca, Mg and sulfur, because of the efficient pretreatment processes as described in the introduction chapter. The pretreatment process has to be capable of removing impurities, otherwise these impurities originating from the feedstock could cause premature deactivation of the catalysts used in the hydrotreatment and isomerization processes. Field trials with busses and passenger cars have shown that the long term durability of DPFs and SCR systems with HVO is not a concern [17, 31]. Active coated particulate filters like continuously regenerating particulate filters and flow-through-filters are critical for the right PM-NOx ratio and the exhaust temperature [17]. HVO provides conditions more favorable than fossil diesel for this type of aftertreatment systems [17]. Combustion of HVO produces particulates with similar oxidation properties and surface structure to that of fossil diesel, which implies that oxidative aftertreatment devices designed for EN590 diesel, should also work well with HVO [58].

Table 3. Elemental analysis of three HVO samples with Inductively Coupled Plasma Spectroscopy (ICP-OES)

Analysis results of 3 samples	
Element	Concentration (mg/kg) all below detection limit
Al	<0,5
Ca	<0,1
Cr	<0,1
Cu	<0,1
Fe	<0,1
Mg	<0,1
Mn	<0,1
Mo	<0,1
Na	<0,5
Ni	<0,1
Pb	<0,1
V	<0,1
Zn	<0,1
F*	<1
Cl*	<1
P*	<0,1

*from different HVO batch

SUMMARY

HVO (Hydrotreated vegetable oil) can be produced from various feedstocks. The properties of the final product are not influenced by the feedstock. Cold properties can be adjusted by isomerization and/or cracking optimization.

HVO can be used for blending and fulfilling biomandate without technical blending restrictions. Also HVO can be used as such in dedicated fleets without operability issues.

HVO properties are specified in CWA15940 (CEN Working Agreement) and FAME properties in EN14214 respectively.

More than 40 scientific publications have been published on HVO and the performance in diesel engines. According to these publications HVO can be used as a drop-in-fuel for both modern and aged diesel engines. The key findings are

- HVO can be used in present car population and logistic systems without any material or legislative limitations. If used as such, the engine manufacturer should be consulted for the approval of the fuel.
- Because of the high cetane number the start of combustion is advanced in low and medium loads, but is less influenced at high loads. Combustion phasing is less influenced by the cetane number when pilot injection is applied. The high cetane number particularly improves cold startability, reduces white smoke formation, noise and emissions.
- Neat HVO reduces NOx emission by 9 %, PM emission by 32 %, CO emission by 25 % and HC emission by 31% on average in heavy-duty vehicles. Also unregulated emissions can be lowered.

• Neat HVO reduces NOx emission by 2 % and PM emission by 39 % on average in passenger cars. Also CO, HC and unregulated emissions can be lowered. In cold temperatures the emissions are radically lower with HVO compared to conventional diesel.

- HVO does not cause clogging or premature deactivation of aftertreatment devices, like DPFs, DOCs or SCRs.
- Oil dilution with HVO is lower than with fuel containing FAME and it does not cause chemical incompatibility with lubrication oil. Also the evaporation rate out of the oil pan is higher.
- Spray characteristics (fuel penetration, droplet size and spray angle) are virtually the same for HVO and fossil diesel.
- The fuel injection quantity with the same indicated value of injection duration is slightly higher with HVO than it is with fossil diesel in common rail engines. Hence there is no power loss despite the lower volumetric heating value.
- Engine's energy efficiency can be slightly improved with HVO, but due to the lower volumetric heating value the volumetric fuel consumption of neat HVO is some 3-6 % higher than with fossil diesel.

REFERENCES

1. "Process for the manufacture of diesel range hydrocarbons", EP1741767 (A1), 2007-01-10
2. "Process for the manufacture of diesel range hydrocarbons", US2007006523 (A1) - 2007-01-11
3. "Process for the manufacture of diesel range hydrocarbons", EP1741768 (A1) - 2007-01-10
4. "Process for the manufacture of diesel range hydrocarbons", US2007010682 (A1) - 2007-01-11
5. "Process for the manufacture of diesel range hydrocarbons", US8022258 (B2) - 2011-09-20
6. Renewable energy directive 2009/28/EC, 2009
7. Tilli, A., Imperato, M., Aakko-Saksa, P., Larmi, M., Sarjovaara, T., Honkanen, M., "High Cetane Number Paraffinic Diesel Fuels and Emission Reduction in Engine Combustion". Cimac technical paper No. 26, 2010
8. "Worldwide fuel charter, fourth edition", Fuel specification, 2006
9. Boehman, A., Morris, D., Szybist, J., "The Impact of the Bulk Modulus of Diesel Fuels on Fuel Injection Timing". Article Energy & Fuels 2004, 18, 1877-1882, 2004
10. Rakopoulos, C., Hountalas, D., "A Simulation Analysis of a DI Diesel Engine Fuel Injection System Fitted with a Constant Pressure Valve". Energy Convers. Manage. 1996
11. Arcoumanis, C., Gavaises, M., Yamanishi, M., and Oiwa, J., "Application of a FIE Computer Model to an In-

- Line Pump-Based Injection System for Diesel Engines," SAE Technical Paper [970348](#), 1997, doi:[10.4271/970348](#).
- 12.** Lapuerta, M., Agudelo, J., Prorok, M., Boehman, A., "Bulk modulus of compressability of Diesel/biodiesel/HVO blends". Energy & Fuels article, 2011
 - 13.** Tilli, A., Kaario, O., Imperato, M., and Larmi, M., "Fuel Injection System Simulation with Renewable Diesel Fuels," SAE Technical Paper [2009-24-0105](#), 2009, doi: [10.4271/2009-24-0105](#).
 - 14.** Stutzenberger, H., Ullmann, J., Eppinger, D., von Stockhausen, A., Robert Bosch GmbH, personal communication, Jan 2012.
 - 15.** FprCEN/TR 16389, Automotive fuels - Paraffinic diesel fuel and blends - Background to the parameters required and their respective limits and determination
 - 16.** FprCEN/TS 15940:2012, Automotive fuels - Paraffinic diesel fuel from synthesis or hydrotreatment - Requirements and test methods
 - 17.** Nylund, N., Erkkilä, K., Ahtiainen, M., Murtonen, T., Saikonen, P., Amberla, A., Aatola, H., "Optimized usage of NExBTL renewable diesel fuel - OPTIBIO". VTT research notes 2604 (<http://www.vtt.fi/inf/pdf/tiedotteet/2011/T2604.pdf>), 2011
 - 18.** Masuko, M., Sakamoto, Y., Okabe, N., Uchida, N. et al., "Effect of Fischer-Tropsch Diesel on Fuel Supply System," *SAE Int. J. Fuels Lubr.* 5(1):198-204, 2012, doi: [10.4271/2011-01-1950](#).
 - 19.** Paasi, J., Lahtinen, R., Kalliohaka, T., Kytö, M., "Biopolttoneesteiden turvallinen jakelu". VTT technical report VTT-R-07049-08, 2008
 - 20.** Virkkunen, S., "Study of biofuel resistant elastomeric materials". Tampere polytechnic of applied sciences, Engineering thesis, 2007
 - 21.** Oguma, M., Goto, S., and Chen, Z., "Fuel Characteristics Evaluation of GTL for DI Diesel Engine," SAE Technical Paper [2004-01-0088](#), 2004, doi:[10.4271/2004-01-0088](#).
 - 22.** Amberla, A., Saikonen, P., Nylund, N., Erkkilä, K. et al., "Bus Fleet Operation on Renewable Paraffinic Diesel Fuel," SAE Technical Paper [2011-01-1965](#), 2011, doi: [10.4271/2011-01-1965](#).
 - 23.** Sugiyama, K., Goto, I., Kitano, K., Mogi, K. et al., "Effects of Hydrotreated Vegetable Oil (HVO) as Renewable Diesel Fuel on Combustion and Exhaust Emissions in Diesel Engine," *SAE Int. J. Fuels Lubr.* 5(1):205-217, 2012, doi: [10.4271/2011-01-1954](#).
 - 24.** Pflaum, H., Hofmann, P., Geringer, B., and Weissel, W., "Potential of Hydrogenated Vegetable Oil (HVO) in a Modern Diesel Engine," SAE Technical Paper [2010-32-0081](#), 2010, doi:[10.4271/2010-32-0081](#).
 - 25.** Pflaum, H., "Potenzial von synthetischen Dieselkraftstoffen im motorischen Betrieb unter besonderer Berücksichtigung der auswirkung alternativer Brennverfahren und Einspritzstrategien auf die Ruß- und Stickoxidbildung", Technische universität Wien Dissertation, 2010
 - 26.** Schaberg, P., Botha, J., Schnell, M., Hermann, H. et al., "Emissions Performance of GTL Diesel Fuel and Blends with Optimized Engine Calibrations," SAE Technical Paper [2005-01-2187](#), 2005, doi:[10.4271/2005-01-2187](#).
 - 27.** Hulkkonen, T., Hillamo, H., Sarjovaara, T., Larmi, M., "Spray Studies and Diesel Fuel Comparison". IFRF technical paper, 2011
 - 28.** Gong, Y., Kaario, O., Tilli, A., Larmi, M. et al., "A Computational Investigation of Hydrotreated Vegetable Oil Sprays Using RANS and a Modified Version of the RNG k-ε Model in OpenFOAM," SAE Technical Paper [2010-01-0739](#), 2010, doi:[10.4271/2010-01-0739](#).
 - 29.** Hulkkonen, T., Hillamo, H., Sarjovaara, T., and Larmi, M., "Experimental Study of Spray Characteristics between Hydrotreated Vegetable Oil (HVO) and Crude Oil Based EN 590 Diesel Fuel," SAE Technical Paper [2011-24-0042](#), 2011, doi:[10.4271/2011-24-0042](#).
 - 30.** Crepeau, G., Gaillard, P., van der Merwe, D., and Schaberg, P., "Engine Impacts and Opportunities of Various Fuels, Including GTL and FAME: Toward Specific Engine Calibration?", SAE Technical Paper [2009-01-1787](#), 2009, doi:[10.4271/2009-01-1787](#).
 - 31.** Murtonen, T., Aakko-Saksa, P., "Alternative fuels with heavy-duty engines and vehicles". VTT working papers No. 128, 2009
 - 32.** Dieselnet, "Diesel fuel injection", http://www.dieselnet.com/tech/diesel_fi.php, March 2010.
 - 33.** Dieselnet, "Diesel particulate filters", <http://www.dieselnet.com/tech/dpf.php>, March 2011.
 - 34.** Baumgarten, J., Garbe, T., Haupt, J., Ludzay, J., Schmidt, M., Sorsche, P., "Influences and parameters of diesel fuels with 10 % (v/v) FAME", DGMK research report 686, 2008
 - 35.** Devlin, C., Passut, C., Campbell, R., and Jao, T., "Biodiesel Fuel Effect on Diesel Engine Lubrication," SAE Technical Paper [2008-01-2375](#), 2008, doi: [10.4271/2008-01-2375](#).
 - 36.** Watson, S., Wong, V., "The Effects of Fuel Dilution with Biodiesel on Lubricant Acidity, Oxidation and Corrosion - a Study with CJ-4 and CI-4 PLUS Lubricants", Diesel-efficiency and emissions research (DEER) conference presentation, 2008
 - 37.** Andreae, M., Fang, H., and Bhandary, K., "Biodiesel and Fuel Dilution of Engine Oil," SAE Technical Paper [2007-01-4036](#), 2007, doi:[10.4271/2007-01-4036](#).
 - 38.** Kaebernick, T., "Ölverdünnungsuntersuchungen mit verschiedenen biodieselhaltigen kraftstoffen". APL testreport projectnummer 104 007 021 0004, 2007

- 39.** Aatola, H., Larmi, M., Sarjovaara, T., and Mikkonen, S., "Hydrotreated Vegetable Oil (HVO) as a Renewable Diesel Fuel: Tradeoff between NOx, Particulate Emission, and Fuel Consumption of a Heavy Duty Engine," *SAE Int. J. Engines* 1(1):1251-1262, 2009, doi:[10.4271/2008-01-2500](https://doi.org/10.4271/2008-01-2500).
- 40.** Erkkilä, K., "NExBTL-polttoaineen vaikutus polttoaineenkulutukseen ja säänneltyihin pakokaasupäästöihin - Kaupunkibussien mittaukset alustadynamometrilla 2007". VTT technical report VTT-R-02071-08, 2008
- 41.** Mikkonen, S., Saikkinen, P., Mäkinen, R., Hulkkonen, T. et al., "Emission performance of paraffinic HVO diesel fuel in heavy duty vehicles," SAE Technical Paper [2011-01-1966](#), 2011, doi:[10.4271/2011-01-1966](https://doi.org/10.4271/2011-01-1966).
- 42.** Kuronen, M., Mikkonen, S., Aakko, P., and Murtonen, T., "Hydrotreated Vegetable Oil as Fuel for Heavy Duty Diesel Engines," SAE Technical Paper [2007-01-4031](#), 2007, doi:[10.4271/2007-01-4031](https://doi.org/10.4271/2007-01-4031).
- 43.** Mizushima, N., Sato, S., Kawano, D., Saito, A. et al., "A Study on NOx Emission Characteristics When Using Biomass-derived Diesel Alternative Fuels," *SAE Int. J. Fuels Lubr.* 5(2):892-899, 2012, doi:[10.4271/2012-01-1316](https://doi.org/10.4271/2012-01-1316).
- 44.** Hochhauser, A., "Review of Prior Studies of Fuel Effects on Vehicle Emissions," *SAE Int. J. Fuels Lubr.* 2(1):541-567, 2009, doi:[10.4271/2009-01-1181](https://doi.org/10.4271/2009-01-1181).
- 45.** Azetsu, A., Sato, Y., and Wakisaka, Y., "Effects of Aromatic Components in Fuel on Flame Temperature and Soot Formation in Intermittent Spray Combustion," SAE Technical Paper [2003-01-1913](#), 2003, doi:[10.4271/2003-01-1913](https://doi.org/10.4271/2003-01-1913).
- 46.** Pflaum, H., Hofman, P., Geringer, B., "Emission performance of hydrogenated vegetable oil (HVO) in a modern compression ignition engine". 8th international colloquium Esselingen (TAE), 2011
- 47.** Lance, D., Goodfellow, C., Williams, J., Bunting, W. et al., "The Impact of Diesel and Biodiesel Fuel Composition on a Euro V HSDI Engine with Advanced DPNR Emissions Control," *SAE Int. J. Fuels Lubr.* 2(1):885-894, 2009, doi:[10.4271/2009-01-1903](https://doi.org/10.4271/2009-01-1903).
- 48.** Murtonen, T., Aakko-Saksa, P., Kuronen, M., Mikkonen, S. et al., "Emissions with Heavy-duty Diesel Engines and Vehicles using FAME, HVO and GTL Fuels with and without DOC+POC Aftertreatment," *SAE Int. J. Fuels Lubr.* 2(2):147-166, 2010, doi:[10.4271/2009-01-2693](https://doi.org/10.4271/2009-01-2693).
- 49.** Aakko, P., Murtonen, T., "Emission measurements with city busses using NExBTL renewable diesel". VTT technical paper VTTR-02602-07, 2007
- 50.** Kleinschek, G., "Emission tests with synthetic diesel fuels (GTL & BTL) with modern Euro 4 (EGR) engine". Kollaquium "fuel" der technischen akademie Esselingen (TAE), 2005
- 51.** Rantanen, L., Linnaila, R., Aakko, P., and Harju, T., "NExBTL - Biodiesel Fuel of the Second Generation," SAE Technical Paper [2005-01-3771](#), 2005, doi:[10.4271/2005-01-3771](https://doi.org/10.4271/2005-01-3771).
- 52.** Harju, T., Aakko, P., "Uuden biokomponentin päästöt henkilö- ja linja-autolla". VTT research report PRO3/P5159/04, 2004
- 53.** Murtonen, T., Aakko, P., Eurasto, R., "Passenger car emission measurements with NExBTL and EN590 fuels". VTT technical paper VTT-R-00436-07, 2007
- 54.** Harju, T., Aakko, P., "NExBTL biodiesel - study of exhaust emissions". VTT project report PRO3/P3023/05, 2005
- 55.** Imperato, M., Tilli, A., Sarjovaara, T., and Larmi, M., "Large-Bore Compression-Ignition Engines: High NOx Reduction Achieved at Low Load with Hydro-Treated Vegetable Oil," *SAE Int. J. Fuels Lubr.* 5(1):225-232, 2012, doi:[10.4271/2011-01-1956](https://doi.org/10.4271/2011-01-1956).
- 56.** Lehto, K., Elonheimo, A., Häkkinen, K., Sarjovaara, T. et al., "Emission Reduction Using Hydrotreated Vegetable Oil (HVO) With Miller Timing and EGR in Diesel Combustion," *SAE Int. J. Fuels Lubr.* 5(1):218-224, 2012, doi:[10.4271/2011-01-1955](https://doi.org/10.4271/2011-01-1955).
- 57.** Williams, A., McCormick, R., Luecke, J., Brezny, R. et al., "Impact of Biodiesel Impurities on the Performance and Durability of DOC, DPF and SCR Technologies," *SAE Int. J. Fuels Lubr.* 4(1):110-124, 2011, doi:[10.4271/2011-01-1136](https://doi.org/10.4271/2011-01-1136).
- 58.** Happonen, M., Lähde, T., Messing, M., Sarjovaara, T., Larmi, M., "The comparison of particle oxidation and surface structure of diesel sootparticles between fossil fuel and novel renewable diesel fuel". Fuel, Volume 89, Issue 12, December 2010
- 59.** Jalava, P., Tapanainen, M., Kuusipalo, K., "Toxicological effects of emission particles from fossil-and biodiesel-fueled diesel engine with and without DOC/POC catalytic converter", Technical report, Inhalation Toxicology, 2010; 22(S2): 48-58, 2010

CONTACT INFORMATION

Tuukka Hartikka
Neste Oil Corporation, Technology Centre
Kilpilahti POB 310, FI-06101 Porvoo, Finland
Tuukka.hartikka@nesteoil.com

ACKNOWLEDGMENTS

The authors would like to acknowledge Robert Bosch GmbH for the good co-operation and assistance on performing the lubricity tests. Also the authors would like to acknowledge the personnel from Neste Oil who assisted on providing data for this paper.

DEFINITIONS/ABBREVIATIONS

ASTM - American Society for Testing and Materials

BTL - Biomass-To-Liquids

B_{xx} - xx concentration (% v/v) of FAME in diesel

CAD - Crank Angle Degree

CFPP - Cold Filter Plugging Point

CP - Cloud Point

CPC - Condensation Particulate Counter

CO - Carbon Monoxide

CO₂ - Carbon dioxide

DOC - Diesel Oxidation Catalyst

DPF - Diesel Particulate Filter

ECU - Engine Control Unit

EEV - Enhanced Environmentally Friendly Vehicle

EGR - Exhaust Gas Recycling

EN590 - European diesel fuel standard

EURO I-VI - Emission certification classes for Europe

FAME - Fatty Acid Methyl Ester, “biodiesel”

FBP - Final Boiling Point

FIE - Fuel Injection Equipment

GC - Gas Chromatography

GTL - Gas-To-Liquids

HC - Hydrocarbon

HFRR - High Frequency Reciprocating Rig

HVO - Hydrotreated Vegetable Oil

IBP - Initial Boiling Point

LHV - Lower Heating Value

NHV - Net Heating Value

NO_x - Nitrogen oxides

OEM - Original Equipment Manufacturer

PAH - Polycyclic Aromatic Hydrocarbons

PM - Particulate Matter

RME - Rapeseed Methyl Ester

SCR - Selective Catalytic Reduction

SLBOCLE - Scuffing Load Ball-on-Cylinder Lubricity Evaluator

SOF - Soluble Organic Fraction

TAN - Total Acid Number

APPENDIX

Appendix A: Diesel fuel standards in USA and Europe and typical values for HVO and GTL.

			USA ASTM D975 2-D S15	Europe EN590	HVO typical values	GTL avg. values from several batches	CWA15940
Flash point	°C	min	52	>55	61	60	55
Water	mg/kg	max	500	200	50		200
Oxidation stability	g/m3	max		25	10		25
Total contamination	mg/kg	max		24	1		24
Distillation	5 %	°C			234		
	10 %	°C			252	195	
	50 %	°C			276	260	
	90 %	°C	min/max	282 ... 338	288		
	95 %	°C	max		360	292	330
	end point	°C			298	340	360
Density	kg/m3	min/max		800*...820 ... 845	778	770	770 ... 800
Viscosity +40 C	mm2/s	min/max	1.9 ... 4.1	2.0 ... 4.5	2.8	2.5	2.0 ... 4.5
Ash	wt-%	max	0.01	0.01	<0.001	<0.001	0.01
Sulfur	mg/kg	max	15	10	<5	<5	5
Copper corrosion			No. 3	Class 1	Class 1		Class 1
Cetane number		min	40	51	75	>70	70
Cetane index		min	40	46	>56.5	>56.5	
Total aromatics	vol-%	max	35		<0.1	<0.1	1
Polyaromatics (di+tri+)	wt-%	max		8	<0.1	<0.1	0.1
Cloud point	°C	max	Local	Local	0 ... -40		
CFPP	°C	max	Local	Local	0 ... -40		
Carbon residue of 10 %	wt-%	max	0.35	0.3	<0.01	<0.01	0.3
Lubricity HFRR	µm	max	520	460	<460**	<460**	460
Conductivity	pS/m	min	25		>100***		
FAME content	% v/v	max		7	0	0	
Heating value	MJ/l				34.2	34	
C/H molar ratio					1 : 2.11	1 : 2.1	

* Severe winter grades ** with lubricity additive *** with conductivity additive

The Engineering Meetings Board has approved this paper for publication. It has successfully completed SAE's peer review process under the supervision of the session organizer. This process requires a minimum of three (3) reviews by industry experts.

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise, without the prior written permission of SAE.

ISSN 0148-7191

Positions and opinions advanced in this paper are those of the author(s) and not necessarily those of SAE. The author is solely responsible for the content of the paper.

SAE Customer Service:

Tel: 877-606-7323 (inside USA and Canada)

Tel: 724-776-4970 (outside USA)

Fax: 724-776-0790

Email: CustomerService@sae.org

SAE Web Address: <http://www.sae.org>

Printed in USA