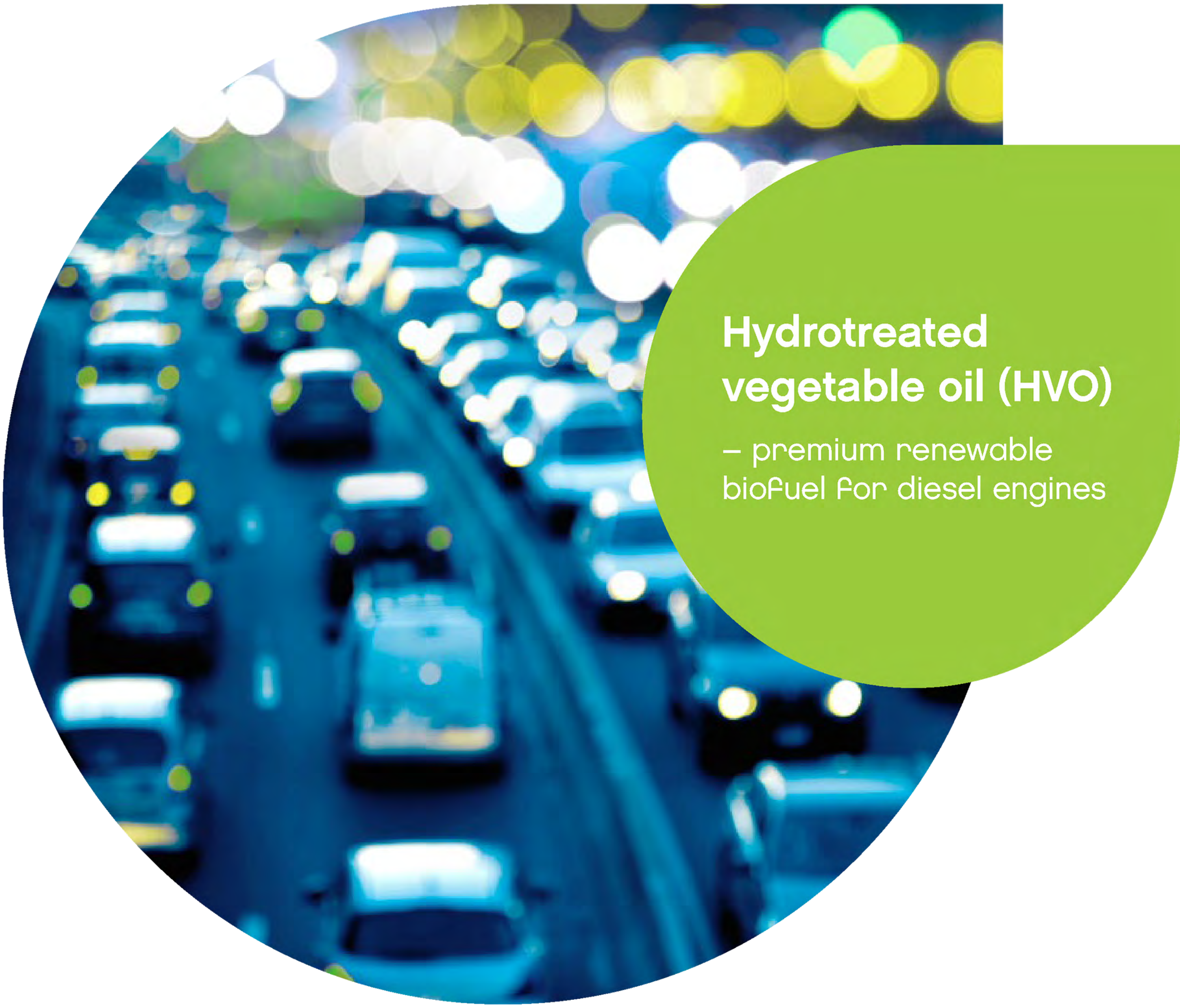
NESTE OIL



Hydrotreated vegetable oil (HVO)

– premium renewable biofuel for diesel engines

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Foreword

Purpose of this booklet is to offer technical information about Hydrotreated Vegetable Oil (HVO) and its use in diesel engines. Potential readership consists e.g. of fuel and exhaust emission profess-sionals in oil companies, automotive industry, fuel blenders, research facilities and people preparing fuel standards and regulation.

Mainly Ari Engman, Tuukka Hartikka, Markku Honkanen, Ulla Kiiski, Markku Kuronen, Seppo Mikkonen and Pirjo Saikkonen from Neste Oil have contributed this text.

This booklet will be updated when enough new or additional information is available.

Possible questions are welcome to Markku Kuronen, markku.kuronen@nesteoil.com as well as proposals for issues to be taken into account in the next update.

Espoo, March 2014

Neste Oil Oyj

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General

The hydrotreating of vegetable oils (HVO) and animal fats is a new process. It is based on oil refining know-how and is used for the production of biofuels for diesel engines. In the process, hydrogen is used to remove oxygen from the triglyceride vegetable oil molecules and to split the triglyceride into three separate chains thus creating hydrocarbons which are similar to existing diesel fuel components. This allows the blending in any desired ratio without any concerns regarding quality.

Traditionally, diesel components produced from vegetable oils are made by an esterification process. The products are called fatty acid methyl esters, FAME or biodiesel. Other acronyms are also used such as rape seed methyl ester RME, soybean methyl ester SME or palm oil methyl ester PME.

A very simplified scheme about inputs and outputs of esterification and hydrotreating processes is shown in the figure. More detailed descriptions about all feedstock and energy streams as well as products, side products and emissions from the production plan can be found from case-by-case Life Cycle Assessments. Both the FAME and HVO processes are similar in that they use intermediates produced from natural gas. In the future both hydrogen and methanol could be produced from biomass or biogas. The need for natural gas is about the same in both FAME and HVO processes and is confirmed by figures published by the Renewable Energy Directive 2009/28/EC ("RED") which show that life cycle greenhouse gas emissions of HVO are slightly lower than those of FAME if the both are made from the same feedstock.

The same type of feedstocks are used today both for FAME and HVO which means that sustain-nability, indirect land use change (ILUC) and agricultural issues are the same for the both. Intensive research is going on in order to find new feedstocks like algae and microbial oils to be used for HVO production. The use of waste and residue fractions for HVO production is remarkable already today.

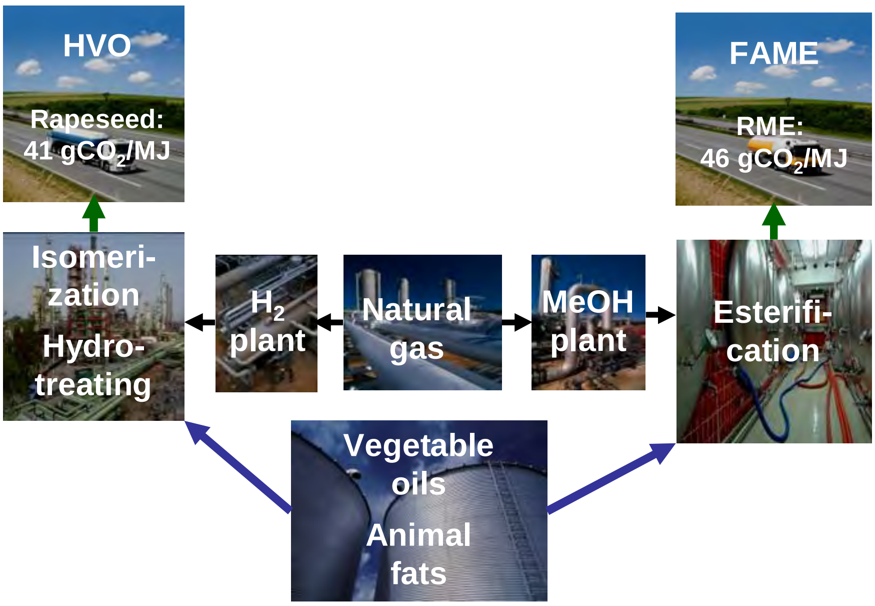

Figure. Simplified scheme about inputs and outputs of esterification and hydrotreating processes for biofuel production. Well-to-tank GHG values are according to RED Annex V D with rape seed feedstock.

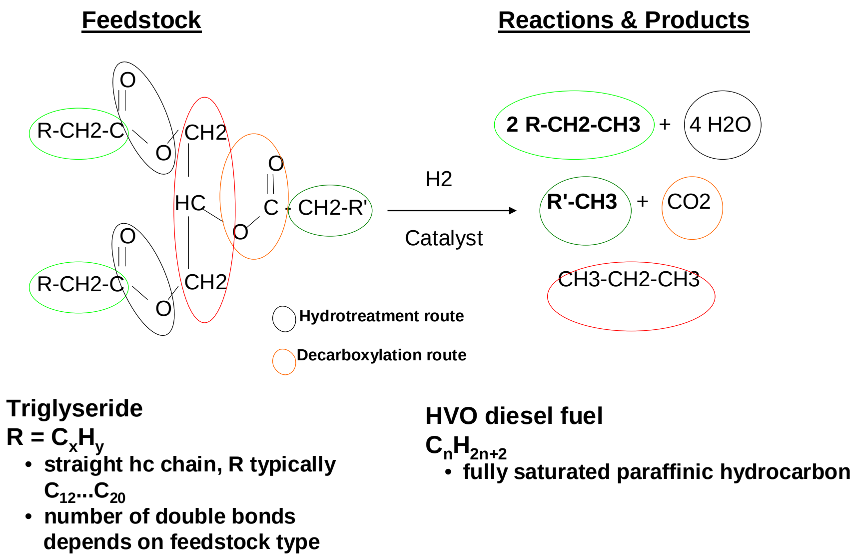

Figure. HVO chemistry.

HVO is a mixture of straight chain and branched paraffins – the simplest type of hydrocarbon molecules from the point of view of clean and complete combustion. Typical carbon numbers are C_{15} ... C_{18}. Paraffins exist also in fossil diesel fuels which also contain significant amounts of aromatics and naphthenics. Aromatics are not favorable for clean combustion. HVO is practically free of aromatics and its composition is quite similar to GTL and BTL diesel fuels made by Fischer Tropsch synthesis from natural gas and gasified biomass.

HVO is also called as Renewable diesel or HDRD (Hydrogenation Derived Renewable Diesel) especially in USA and HBD (Hydro-generated Biodiesel) in Far East.

At least the following companies have developed stand-alone HVO production processes and products:

- Axens IFP: Vegan
- Honeywell UOP: Green Diesel
- Neste Oil: NEXBTL™
- Syntroleum
- UPM: BioVerno

The following description provides an overview of the NEXBTL™ HVO production process and HVO products. The current sites are optimized for diesel fuel yields. In addition to diesel fuel, small amounts of light biohydrocarbons and biopropane are formed as side products. Light fractions can be blended into gasoline where they provide high bioenergy value but suffer from low octane numbers compared to for example ethanol. Biopropane can be used in cars running on LPG or as renewable process energy at the production site reducing carbon footprint of HVO products. NEXBTL™ process includes an isomerization unit for improving cold properties even down to arctic diesel fuel grades. There is potential also for aviation kerosene production.

When considering future biofuel options, HVO offers a seamless progress to synthetic BTL fuels regarding vehicle technologies and fuel logistics because of the similar product quality (Figure). However, due to the current high BTL capital costs it is unlikely that BTL would be produced on a large scale in the near future.

Commer-cial scale	Process	Product	Feedstock availability	Product quality *Chemistry*	Process plant capital cost
≈ 1995 ...	Esterifi-cation	FAME	- Some veg oils Animal fats	- *Ester*	++
2007 ...	Hydro-treating	HVO	+ Various veg oils Animal fats	+ + + *Paraffin*	-
≈ 2017 ?	Gasification + Fischer-Tropsch	BTL	+ + + All biomass	+ + + *Paraffin*	- - -

+ Benefit - Challenge

Figure. Biofuel technologies for diesel engines.

Fuel specifications

HVO

- can be used in EN 590 diesel fuel without any limit ("blending wall") or labeling at retail pumps
- can be used in ASTM D975 diesel fuel without any blending wall or labeling at retail pumps
- meets CEN TS 15940 specification of paraffinic diesel fuels for dedicated vehicles
- meets ASTM D975 and Canadian CGSB-3.517 requirements
- meets EN 590 requirements except density which is lower
- amount of HVO in diesel fuel blend can be estimated by radioisotope carbon ^{14}C methods
- chemistry and properties remarkably different from FAME: EN 14214 is not valid for HVO
- comparable to GTL as a blending component, in addition to that HVO has also biovalue
- Worldwide Fuel Charter (WWFC) recommends to use HVO as a biocomponent

CEN Technical Specification TS 15940

HVO meets CEN Technical Specification TS 15940:2012 for paraffinic diesel fuels (specification or pre-standard without a status of a formal standard). This specification covers also synthetic Fischer-Tropsch products GTL, BTL and CTL. Before TS 15940:2012 paraffinic diesel fuel was specified by CEN Workshop Agreement CWA 15940:2009. Since there are no practical methods for measuring paraffinic content the paraffinic nature is proven by limiting aromatic content to practically zero. Usually HVO is delivered without any FAME although 7 vol-% FAME is allowed as a blending component by TS 15940 (CWA 15940 did not allow FAME). As the next step TS will be updated to a formal EN 15940 standard.

In many cases an abbreviation "XTL/HVO" is used for paraffinic fuels. XTL is a term used to describe synthetic GTL, BTL and CTL Fischer-Tropsch production paths.

The common ester type biodiesel (FAME) specification EN 14214 is not valid for HVO since HVO consists of only hydrocarbons. HVO as such meets the European diesel fuel standard EN 590 except density which is below the lower limit. The American diesel fuel standard ASTM D975 and Canadian CGSB-3.517 are met as such.

Table. Typical properties of pure HVO and how it relates to TS 15940 and EN 590 standard.

Property		HVO (typical NExBTL)	TS 15940:2012 Class A	EN 590:2013
Appearance at +25 °C		Clear & Bright		
Cetane number		> 70.0	≥ 70.0	≥ 51.0
Density at +15 °C	kg/m^3	770.0 … 790.0	765.0 … 800.0	820.0 … 845.0 ≥ 800.0 *
Total aromatics	% (m/m)	< 1.0	≤ 1.0	
Polyaromatics	% (m/m)	< 0.1		≤ 8
Sulfur	mg/kg	< 5.0	≤ 5.0	≤ 10.0
FAME-content	% (V/V)	0	≤ 7.0	≤ 7.0
Flash point	°C	> 61	> 55	> 55
Carbon residue on 10 % distillation	% (m/m)	< 0.10	≤ 0.30	≤ 0.30
Ash	% (m/m)	< 0.001	≤ 0.01	≤ 0.01
Water	mg/kg	< 200	≤ 200	≤ 200
Total contamination	mg/kg	< 10	≤ 24	≤ 24
Copper corrosion		Class 1	Class 1	Class 1
Oxidation stability	g/m^3	< 25	≤ 25	≤ 25
Lubricity HFRR at +60 °C	µm	≤ 460 ** ≈ 650 ***	≤ 460	≤ 460
Viscosity at +40 °C	mm^2/s	2.00 … 4.00	2.00 … 4.50	2.00 … 4.50 ≥ 1.20 *
Distillation 95 % (v/v)	°C	< 320	≤ 360	≤ 360
Final boiling point	°C	< 330		
Cloud point and CFPP ****	°C	As needed -5 … -34	As in EN 590	Down to -34
Antistatic additive		Added		

*) Winter grades
**) Including lubricity additive when delivered to be used as such in vehicles which are validated for TS 15940 fuel
***) If delivered without lubricity additive to be used as a blending component, preference is to add lubricity additive into the final blend
****) If delivered as such, CFPP is near the cloud point

EN 590:2013 diesel fuel standard

EN 590

- defines properties of "B7" diesel fuel sold at retail
- does not take any position on how and from what feedstock fuel is processed
- limits the use of FAME to max. 7 vol-%
- allows HVO without any limit
  - o HVO can be blended as such or in addition to max 7 vol-% FAME in the B7-grade
- allows HVO without pump labeling

Fuel standard EN 590 is a voluntary fuel quality agreement to be used for fuel manufacturing and commerce. It defines properties that are important for operability, durability and tailpipe emissions of diesel vehicles. In principle such properties must be satisfied at retail points where vehicles are refueled but in practice they are controlled at the level of fuel blending and bulk sales. EN 590 does not take into consideration whether the fuel's origin is fossil or renewable. It also does not comment on the production processes used.

This standard is developed, updated and approved by CEN bodies which consist of fuel and automotive experts nominated by national member bodies of CEN. This drafting exercise takes place outside any political setting and is carried out by experts with no direct legislative mandate. In addition, the CEN includes members from non-EU countries.

The fuel properties laid down in Annex II of the Fuel Quality Directive 2009/30/EC ("FQD") are copied into EN 590 as such. Fuel which does not meet the specifications contained in EN 590, but satisfies the requirements laid down in the FQD, can be put on the market but they may not be labeled to EN 590. For example B10 (maximum 10.0 vol-% FAME) can be sold on the condition that the appropriate fuel quality information is provided to consumers, it is compliant with the vehicle manufacturer's requirements, and a national waiver according to FQD has been given for >B7. If a vehicle's owner decides to use a fuel not compliant with the car manufacturers' recommendations, it is then at his/her own responsibility. This is confirmed even by Article 4(1) of the FQD.

EN 590 does not require any labeling of bio content at retail points provided that the fuel meets the EN 590 specifications (maximum 7.0 vol-% FAME). This means there is no need to label HVO at retail points at any blending ratio. The common abbreviations B7 or B10 define only the maximum allowed FAME-content in vol-%. HVO can be used as such or in addition to FAME regardless of B7 or B10 definition.

HVO's position in EN 590:2013

EN 590 does not take any position on the type of feedstock used to produce fuel components or on the way such components are processed and blended. The only requirement is that the final fuel meets defined technical requirements. All suitable hydrocarbon-type blending components like straight run gas oils or kerosenes, various types of cracked gas oils or kerosenes, gas-to-liquid diesel fuels (GTL), hydrotreated vegetable oils and animal fats (HVO), and bio-to-liquids fuels (BTL) can be used. It does not matter whether the components to be blended are handled only inside a specific refinery site or whether they are traded as bulk batches between fuel suppliers before the final blending. The allowance of HVO is especially mentioned in EN 590 paragraph 5.4 "Other (bio)components".

HVO belongs to the group of hydrocarbons which are miscible with a hydrocarbon matrix of a fuel blend. Therefore, the use of HVO as a blending component does not need to be regulated further through technical standards.

The maximum amount and quality of FAME (EN 14214) are defined by EN 590 since FAME has different chemistry, properties and levels of impurities compared to hydrocarbons. These requirements in EN 590 are not applicable to any other biocomponents than FAME. In the same vein, Annex II of the FQD requires FAME to comply with EN 14214. For example, the presence of phosphorous which may be harmful to vehicles' exhaust after treatment systems can only be originated from FAME. It is more convenient to control phosphorous content at a robust level from neat FAME before blending than to measure phosphorous from all diesel fuels using accurate analytical methods after FAME has been diluted by 93 % of phosphorous-free hydrocarbon fuel. The same applies for decomposition during storage which is different for hydrocarbons and esters. As a consequence, different requirements apply to neat FAME (EN 14214), fuels containing 2 to 7 vol-% FAME and pure hydrocarbons.

In addition, the analytical method EN 14078 for measuring the biofuel content of diesel fuel is valid only for FAME. This means that the amount of HVO in diesel fuel has to be shown by audit trail and mass balance from the fuel blending. If an audit trail is contested, a radioisotope carbon ^{14}C method can be used for estimating the biofuel content. This method has already been referred to in EN 228:2012 for proving the bio-origin of ethanol in gasoline but this test is too laborious for routine fuel quality control.

HVO and EN 14214 FAME standard

HVO

- due to different chemical composition and properties can not meet any FAME standards
- paraffinic fuels have on own specification: TS 15940

Since HVO consists of parafinic hydrocarbons, it cannot meet the requirements set by EN 14214 which is a standard developed and valid only for methyl ester chemistry type biodiesel, namely

FAME. As a matter of fact HVO meets EN 590 except requirement for minimum density. Because of this, attempts to require that all biocomponents meet EN 14214 are technically impossible and disctiminatory.

HVO as well as BTL and GTL meet the specifications contained in CEN TS 15940 for paraffinic diesel fuels. The purpose of the TS is to define properties of paraffinic diesel fuel when it is used as such in dedicated vehicles like city bus fleets.

For example TS 15940 specifies a certain density range which is remarkably below FAME's density range defined by EN 14214.This shows that properties of HVO and FAME are so far from each other that they cannot be covered by the same standard.

When HVO is used as a blending component in EN 590 diesel fuel, HVO does not need to meet TS 15940 requirements because HVO is fully miscible with diesel fuel. EN 590 requires only that the final fuel blend meets limits set by the EN 590.

Worldwide Fuel Charter (WWFC)

Worldwide Fuel Charter (WWFC) is a recommendation published by automotive companies for fuel qualities to be used with different vehicle emission requirements. WWFC includes also justifications for each parameter required. The 5th edition (2013) of WWFC pays attention on challenges related to the use of FAME and recommends to use HVO as a biocomponent.

WWFC can be downloaded from
http://www.acea.be/uploads/publications/Worldwide_Fuel_Charter_5ed_2013.pdf and justifications for biofuels can be found from

- page 53 … 54 for FAME
- page 55 … 56 for HVO

Legislative fuel composition requirements

HVO

- by definition is not biodiesel (only FAME is biodiesel)
- meets compositional requirements set by FQD Annex II for diesel fuels
- may be blended into diesel fuel without any limit or labeling at retail pumps because of it's hydrocarbon nature according to FQD recital 33
- however, RED can be interpreted to require labeling of any biocomponent used more than 10 %
- energy content is defined in RED Annex III
- typical and default greenhouse gas values are defined in RED Annex V and FQD Annex IV
- the original FQD (98/70/EC) requires free circulation of fuels complying directive: a member state may not discourage HVO
- RED and FQD define feedstock issues and properties of final fuels but not production processes: a manufacturer or fuel supplier is free to choose between HVO and FAME

The following paragraphs present a detailed account how HVO has been treated in the European directives. It is important to note that directives do not set any limits on how fuels or fuel components are processed which means that fuel company shall be free to choose between HVO, FAME, co-processing, GTL or what ever technically suitable production processes. The regulation only sets limits regarding sustainability issues of feedstock, amount of bioenergy, greenhouse gas emissions and quality of the final fuel when it is related to tailpipe emissions or technical compatibility with vehicles.

Directives of the European Union

FQD and RED

- fully define HVO and it's energy and greenhouse gas values as well as FAME
- define only sustainability etc. issues for feedstock and properties of the product
- manufacturing processes (esterification, hydrotreating etc) are not limited
- only the use of FAME is limited due to technical properties

The fuel quality Directive 98/70/EC ("FQD") as last amended by Directive 2009/30/EC lays down fuel requirements which are related to health, environment and engine technology (Article 1 (a)), and determines targets for the reduction of greenhouse gas emissions (Article 1(b)).

The regulatory technical requirements for diesel fuel are related to the minimum cetane number and the maximum density, 95 % distillation point, polyaromatics, sulphur and FAME. When FAME is used, it must comply with the EN 14214 standard (FQD Annex II).

The use of biocomponents in diesel fuel was not limited by legislation until the latest amendment brought by Directive 2009/30/EC which limited the use of FAME to maximum 7 vol-%. This limitation is justified by the technical properties of FAME (Recital 33), mainly with respect to engine and vehicle operability and durability (Recital 31).

According to Article 1(9) of the FQD, that Directive applies to biofuels within the meaning of Directive 2009/28/EC ("RED"). Article 2(e) and (i) of the RED define biofuels on the basis of their feedstock path without any requirements as to how the final fuel has been produced or as to their chemical composition. Furthermore, according to Article 3(4)(b) of the RED, all types of energy from renewable sources must be taken into account in the calculation of the share of energy from renewable sources used in each Member State. It follows from these provisions that biofuel process paths and compositions are allowed without any limitations, in accordance with the principles of technical and commercial neutrality.

In this respect, the FQD specifically provides that the use of other biofuels than FAME in diesel fuel is not limited. Hydrotreated vegetable oil is explicitly mentioned as one of the unlimited diesel-like hydrocarbon biofuels (Recital 33). As a matter of fact, even in its pure state, hydrotreated vegetable oil (HVO) meets all the diesel fuel specifications set forth in Annex II of the FQD.

It follows from footnote 3 of Annex II of the FQD that the requirements set out in EN 14214 only apply to FAME. Also, the analytical method contained in EN 14078 (annex II) for measuring the biofuel content of diesel fuel is valid only for FAME. This means that the amount of HVO used in diesel fuel has to be shown by audit trail and mass balance from fuel blending which is defined both in the RED (Article 18 (1)) and in the FQD (Article 7c (1)). If an audit trail is contested, the biofuel content can be estimated by a radioisotope carbon ^{14}C method.

On a separate note, Article 21(1) the RED requires that information is provided to the public when a fuel contains more than 10 vol-% of biofuel. This is different from the information requirements set by the FQD, the goal of which is to avoid the misfueling of vehicles that are not suitable for more than 7 % FAME (Article 4 (1)) or for more than 5 % ethanol (Article 3 (a) 3). FQD allows HVO without limits since it is pure diesel-like hydrocarbon made from biomass (Recital 33).

Greenhouse gas emission values are defined by the FQD (Annex IV) and the RED (Annex V). Hydrotreated vegetable oil (HVO) from several production pathways is mentioned besides biodiesel (FAME) in the both directives. The same applies to energy content which is determined in Annex III of the RED as regards hydrotreated vegetable oil. HVO is also considered to be fully originated from renewable sources.

As a result, HVO is explicitly mentioned by both the RED and the FQD, which allow for the marketing of HVO exactly like for the marketing of FAME provided that such biofuels meet the sustainability and greenhouse gas emission requirements. It is only FAME that has a technical based blending limit of 7 vol-% and that is subject to the quality requirements contained in EN 14214.

Legislative requirements for free markets

HVO

- directive 98/70/EC (original FQD) requires free circulation of fuels:
    - HVO or any fuel shall not be discouraged if it complies with specification

Article 34 TFEU ("Treaty on the Functioning of the European Union") and the free movement clause contained in Article 5 of Directive 98/70/EC preclude Member States from prohibiting, restricting or preventing the placing on the market of fuels which comply with the requirements of that Directive (as amended). This means that a Member State may not limit the use of HVO as a biocomponent in diesel fuel provided that such HVO satisfies the greenhouse gas and sustainability requirements set forth in the RED and the FQD, and provided that the final diesel fuel complies with the limits imposed by Annex II of the FQD as regards cetane, density, distillation, polyaromatics, sulphur and FAME.

In this respect, the European Court of Justice has consistently held that Member States are not allowed to impose additional requirements on products the specifications of which have been fully harmonized at EU level.

The RED and the FQD do not require diesel fuel to meet the EN 590 specifications. The FQD only refers to EN 590 in relation to the test methods in order to ensure that fuel producers and regulators use the same laboratory methods for demonstrating and monitoring compliance with its requirements (Article 8(1) and Annex II of the Directive). As a result, Member States cannot make the marketing of HVO or of any other diesel fuel conditional upon it satisfying the EN 590 specifications.

In any event, it should be noted that technical standards such as EN 590 are not compulsory, as explicitly stated in Article 1(4) of Directive 98/34/EC laying down a procedure for the provision of information in the field of technical standards and regulations.

This is further confirmed in the Commission's Guide to the implementation of directives based on the New Approach and the Global Approach, according to which "the application of harmonized standards, which give a presumption of conformity, remains voluntary […]. Thus, the product may be manufactured directly on the basis of the essential requirements [contained in the relevant Directive]".

Case: Fuel taxation in Finland

Fuel taxation in Finland

- based on energy content (MJ/l), well-to-wheels CO_2 and locally harmful tailpipe emissions
- promotes
    - paraffinic diesel fuels (HVO, GTL, BTL) because of their lower tailpipe emissions
    - biofuels
    - biofuels made from waste or cellulosic feedstock (double counting)

Fuel taxation in Finland (act 1131/2013) promotes the use of renewable and clean combusting fuels. Taxes are based on energy content, greenhouse gas emissions and tailpipe emissions. In addition to those a security of supply levy is charged.

Energy tax of diesel fuels is 0.85 euro cents per megajoule (MJ). For practical reasons energy tax is converted to cents per liter of fuel to be paid.

CO_2 tax is 58 euros per ton of CO_2. Here CO_2 is the CO_2 formed in the final combustion using well-to-wheels approach which is common for biofuels. Again, this tax is calculated to cents per liter of fuel to be charged. Renewable fuels which meet sustainability and GHG-criteria of directive 2009/28/EC ("RED") are entitled for 50 % reduction in CO_2 tax. Fuels which meet so called double counting criteria of waste or cellulosic based feedstock are free of CO_2 tax. Renewable fuels which do not meet criteria set by RED are taxed like fossil fuels.

Locally harmful tailpipe emissions are taken into account by monetizing NO_x, HC and particulate emissions by using principles presented in directive 2009/33/EC which promotes clean and energy-efficient road vehicles. The directive gives the following external cost effects for emissions: NO_x 0.44 cents/g, HC 0.1 cents/g and particulate matter 8.7 cents/g, which can be doubled according to a local consideration.

The use of paraffinic diesel fuels instead of standard fuels reduces emissions which have been monetized by using doubled values since it is a question of urban air quality. The result is calculated to cents per liter of fuel and taken off from the energy tax (Table). Corresponding benefit is given for vehicle tax of methane vehicles because fuel tax of methane is so low that there is no room for reduction. Biodiesel does not qualify to any air quality benefit due to its higher NO_x but tax per liter is slightly lower because energy tax per megajoule is the same but heating value per liter is lower than that of fossil diesel fuel. The same applies for ethanol diesel fuel (ED95) which has quite a low energy content.

Paraffinic diesel fuel is defined in the Finnish act 1399/2010 by parameters set by directive 2009/30/EC (“FQD”) by choosing limit values which make a clear difference between paraffinic and common diesel fuel: cetane number min 70, density 770 ... 800 g/l, polyaromatics max 0.1 wt-%, sulfur max 5 mg/kg and 95 % distillation max 360ºC.

Table. Diesel fuel taxes in Finland from January 2014, euro cents per liter without value added tax (act 1131/2013). Taxes of ethanol diesel fuel (ED95) for dedicated engines are also presented for reference.

	Energy tax (c/l)	CO_2 tax (c/l)	Security of supply levy (c/l)	Total (c/l)	Difference to diesel fuel (c/l)
Diesel fuel	30.70	18.61	0.35	49.66	
Paraffinic diesel (e.g. GTL, CTL)	24.00	17.58	0.35	41.93	- 7.73
Renewable paraffinic diesel (e.g. HVO)	24.00	8.79	0.35	33.14	- 16.52
Double counted paraffinic diesel (e.g. HVO from waste, BTL)	24.00	0.00	0.35	24.35	- 25.31
Biodiesel (e.g. FAME)	28.14	8.53	0.35	37.02	- 12.64
Double counted biodiesel (e.g. FAME from waste)	28.14	0.00	0.35	28.49	- 21.17
Renewable ethanol diesel (e.g. ED95)	13.97	5.99	0.35	20.31	
Double counted ethanol diesel (e.g. ED95)	13.97	1.07	0.35	15.39	

Tax benefit can be utilized when paraffinic diesel fuel is used as such for example in city bus fleets. When paraffinic fuel is blended into diesel fuel, tax is based on a blending ratio only if the base fuel meets requirements set by FQD before adding the paraffinic component. On other words, base fuel has to meet FQD and the blended one has to be a premium grade producing fewer emissions as a function of the paraffin blending. If blending of paraffinic fuel is used for upgrading gas oils not yet meeting FQD to meet FQD, energy tax benefit is lost but the reduced CO_2 tax is valid according to the renewability.

Fuel properties

HVO

- highest heating value amongst current biofuels: less blending needed for meeting a defined biomandate
- severe winter and arctic grades available thanks to the isomerization process
- benefits for blending diesel fuels at refineries or terminals:
  - very high cetane number (>70)
  - low density (~780 kg/m^3)
  - sulfur-free (< 5 mg/kg)
  - zero aromatics
  - reasonable distillation range: easy to meet final boiling area requirements
- effect of cetane number, density, sulfur and aromatics practically linear in blending
- like fossil diesel fuel in logistics, no new issues with:
  - stability: no need for "use before" date
  - water separation
  - microbiological growth
  - precipitation above cloud point
- practically free of metals and ash-forming elements
- if used as such, lubricity additive needed as in all modern sulfur-free diesel fuels

Properties of HVO have much more similarities with high quality sulfur free fossil diesel fuel than with FAME. As a matter of fact properties of HVO are very similar to the synthetic GTL diesel fuel which was earlier considered to be the best diesel fuel for engines and regarding tailpipe emissions. Now HVO offers the same compositional benefits as GTL and in addition to that is also from renewable origin. Also the same analytical methods as used with fossil fuels are valid for HVO.

It is worth for knowing about properties of HVO and analytical methods to be used since they are different from FAME which begins to be familiar for oil companies as a biocomponent. The same applies regardless of that is HVO used as a blending component in diesel fuel or as such in vehicles which have been validated for XTL/HVO.

Density and energy content

HVO

- lower density (780 kg/m^3) compared to common European diesel fuels (800 ... 845 kg/m^3)
- higher energy content than that of FAME
  - less HVO in mass and volume needed to fulfill a given biomandate

Due to the paraffinic nature and the low final boiling point, the density of HVO is lower than that of fossil diesel fuels. Fuel density has traditionally been an important factor as it has a positive effect on engine maximum power output and volumetric fuel consumption. This is because the heating value of diesel fuels is quite constant per mass for various fossil diesel fuel grades when they are inside a certain range of aromatic content. If density is reduced, heating value per volume is decreased as a function of density. With a lower volumetric heating value engine gets less energy in with full throttle and needs more fuel volume in order to provide the same energy output at part loads.

With HVO the case is different since energy content is higher per mass compensating part of the effect of lower density (Table). The higher heating value of HVO per mass is based on the fact that hydrogen content of HVO is about 15.2 wt-% compared to about 13.5 wt-% of standard diesel fuel.

Slightly smaller HVO blending ratio is needed compared to FAME for meeting the same bioenergy mandate because HVO's energy content is higher than that of FAME, both per liter and per kg. Compared to ethanol HVO's volumetric benefit is large since heating value of ethanol is only 21 MJ/l.

The low density offers often benefits when HVO is used as a blending component in diesel fuel production because it may allow the use of heavier fractions that would in other case have to be used for lower profit products like heating gas oil. In blending recipes density behaves linearly.

Table. Typical densities and lower calorimetric heating values.

		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

Distillation

HVO

- no detrimental effect on final boiling area like with FAME

Distillation curves give the amount of a fuel sample that is evaporated in atmospheric pressure at each temperature when the temperature is increased gradually. Distillation characteristics illustrate how fuel is evaporated when it is sprayed into the combustion chamber of a diesel engine. Some fractions boiling at low temperatures are needed for engine start-up while fractions boiling at too high temperatures may not combust completely forming engine deposits and increasing tailpipe emissions. A typical boiling range of a summer grade diesel fuel is from about 180 °C to about 360 °C. HVO's distillation range is within that of fossil diesel, but FAME contains significantly heavier compounds (Figure).

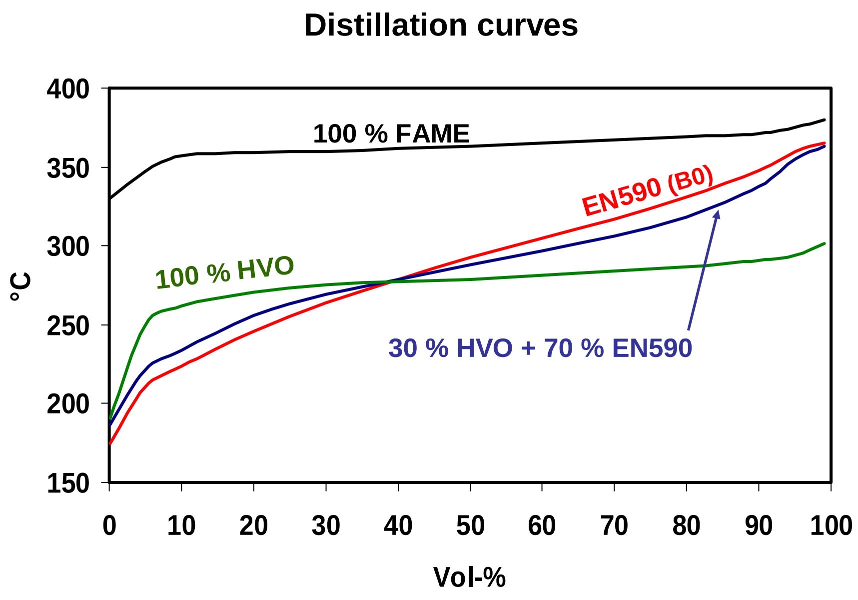

Figure. Distillation curves of a typical diesel fuel without any biocomponents (fuel meets EN 590), FAME, HVO and diesel fuel containing 30 vol-% HVO.

Cold properties

HVO

- excellent cold properties: cloud points down to -40ºC achievable
  - high biomandate blending ratios possible all year round
- CFPP practically the same as cloud point: cold operability characteristics made mainly by adjusting cloud point
- no risky impurities which might precipitate above cloud point
- no density change as a function of cloud point thanks to isomerization process

Fit-for-purpose at all times of the year is an essential requirement for diesel fuels. In the case of HVO, cold properties can be improved to satisfy severe and arctic climate grades by the extent or severity of operating conditions in the isomerization unit. With a HVO process, it is possible to produce high quality winter grades from all feedstocks including palm oil or animal fats which are limited to small amounts in the FAME process. This means that high biomandate content can be met by using HVO all year round without risking cold operability of vehicles and getting troubles in fuel logistics. Even production of aviation kerosene is possible with HVO process.

The cold properties of neat HVO such as the cloud point can be produced by the severity of the isomerization down to -40 °C. HVO's narrow distillation range and narrow carbon chain distribution (C_{15} ... C_{18}) of paraffinic hydrocarbons is challenging for cold flow additive recipes. This means that with HVO, the cold filter plugging point (CFPP) may be only a few degrees better than cloud point. It is safe to say that CFPP value is the same as cloud point. Pour point can be a couple of degrees better than cloud point, but due to the inaccuracy of pour point measurements, it is safe to guarantee only that pour point is better than cloud point.

Some attention is needed when HVO is blended in high blending ratios into diesel fuel; it is recommended to confirm cold flow properties of the final blend.

In conventional oil refining, the required cold properties are obtained by distilling fuels to lighter and narrower fractions in order to achieve the desired cloud point. Additional help is obtained from cold flow additives which reduce CFPP and pour point. Density and viscosity will be lower, which cause reduced engine performance and higher volumetric fuel consumption. Isomerization of HVO has a negligible effect on density since the process changes shape of the molecules keeping distillation curve practically the same. As a side effect reduction of cetane number by some units takes place when cold properties are enhanced, but cetane number of winter grade HVO is also very high, usually above 75. However, due to economic and yield challenges better cold properties than really needed should be avoided.

Viscosity may also have an effect on cold operability in some applications. Viscosity of HVO at e.g. -15 °C is about 15 mm^2/s. That is around the same as of fossil diesel fuels and only half of FAME's viscosity.

During long time storage, pure HVO as well as blends containing HVO behave like traditional diesel fuels. HVO does not contain any risky impurities, eg. saturated monoglycerides, like FAME. So there is no risk for precipitation at temperatures above cloud point. As with traditional diesel fuels, some precipitation of long chain paraffins originating either from the fossil part or HVO may take place if temperature is below cloud point for a long period.

In addition to the standardized cloud point and CFPP requirements HVO and blends containing 10, 30 and 50 % of HVO have been tested by running diesel cars in a climate chamber and by using a cold test rig consisting of a complete fuel system of a passenger car built in a deep-freezer. The tested fuels, HVO and blends, did operate as expected in severe winter conditions [Nylund et al. 2011]. Based on these tests cold operability problems that are well known for FAME blends can be avoided by using only HVO.

Figure. Testing of cold properties with diesel cars in a climate chamber..

Cetane number

HVO

- very high cetane number: 75 ... 95
- in blends increases cetane number linearly according to blending ratio

Cetane number of most paraffinic diesel fuels is very high, from 75 to 95, because of their nature as a mixture of n- and isoparaffins.

When HVO is used as a blending component, the cetane number increases linearly (Figure, non-linearity is caused by inaccuracy of the method). A well known possibility is to use 2-ethyl hexyl nitrate additive for improving cetane number, but the effect of it especially in winter grade fuels is limited to about maximum 4 cetane units since response curve as a function of dosage flattens gradually. Automotive companies claim that cetane number enhanced by additives is not so valuable for real engine performance than increased natural cetane number which can be made by blending HVO. So, the use of HVO as a blending component is a good way to increase cetane number either for getting the blend to meet regulated cetane number or for producing premium diesel fuel grades.

Derived cetane number (DCN) is more suitable than cetane engine for measuring cetane number of HVO. If cetane engine is used, HVO has to be blended with a known low cetane fuel so that cetane number of the blend is below 70 to be inside measurement range of the engine. Then cetane number of the pure HVO sample can be estimated by linear extrapolation. Formula of cetane index is designed only for average traditional diesel fuels which mean that cetane index is not suitable for neat HVO.

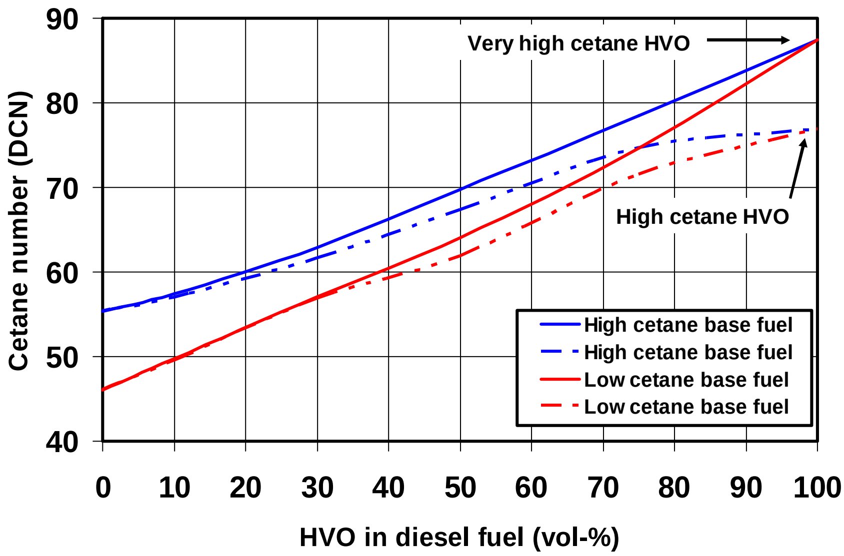

Figure. Cetane number of blending two different HVOs (high and very high cetane) to two different diesel fuels (low and high cetane).

Stability

HVO
- stability is good
    - comparable to fossil diesel
    - challenges related to FAME are not a concern with HVO
    - does not need "best before" date

Since HVO consists of only hydrocarbons, the traditional stability methods used for fossil diesel fuel are applicable. Because of this, the methods developed for FAME do not apply for HVO. In particular it should be noted that the "Rancimat" method EN 15751 designed for neat FAME and diesel fuel containing from 2 to 7 vol-% FAME is not valid for HVO or diesel fuel containing only HVO as a biocomponent.

HVO's stability is at the same level of normal diesel and this means that it is not applicable to apply for a "use before" date [Hartikka et al, 2013]. There is no risk of problems if vehicles or stationary engines are not used during extended periods. This may take place with e.g. mobile homes used seasonally, vehicles parked on dealers' yards, seasonal agricultural machinery, boats and emergency generator sets.

A fuel efficient diesel family car may be refueled once per month or even only once per two months especially if it is the second car of a family. New sophisticated fuel injection systems may also be even more sensitive for deposits than older ones. So, fuel stability is today even more important factor than before.

Sulfur content

The sulfur content of HVO coming out from the production process is < 1 mg/kg. But since HVO is used in the normal diesel fuel logisitics system, a ≤ 5.0 mg sulfur is the normal fuel HVO specification due to possible contaminants. This meets requirements set by the most modern exhaust aftertreatment systems, especially because most of the sulfur entering into the exhaust originates today from engine oil.

If sulfur content of the base diesel fuel or blending component is slightly above a legal specification, blending of HVO can bring the blend to meet specification.

Ash and metals content

Ash content of HVO is very low, < 0.001 %.

The amount of vegetable oil feedstock originated compounds like P, Ca and Mg are well below practical detection limits of analytical methods (< 1 mg/kg) since contaminants have to be removed in feedstock pretreatment unit in order to guarantee a long life time for the HVO production plant catalysts.

Because of the ash-free combustion HVO offers at least as long life time as high quality fossil diesels fuel for exhaust aftertreatment systems which are used in the current and future vehicles.

Water content

Water is polar and HVO is non-polar like fossil hydrocarbons. Due to that solubility of water into HVO is similar to traditional diesel fuels or even lower. This means that water issues do not require any additional measures in fuel logistics compared to traditional diesel fuels.

Microbial growth

Microbial growth is an issue which has created a lot of debate recently. It has been mainly related to special applications like marine fuels and extended parking periods but cases have happened also with automotive vehicles. It is well known that ester type biodiesel (FAME) used in diesel fuel may promote microbial growth since FAME is biodegradable and it tends to increase water content of diesel fuel.

Results show that HVO as such or used as a blending component in diesel fuels does not require any additional precautions compared to fully fossil diesel fuels. However, good housekeeping is needed in any case since microbes may grow even pure fossil fuels during a long time strorage if free water is present. High temperatures (~+ 30°C) may strongly enhance the microbiologial growth in fossil diesel and HVO especially when mineral salts are present in water phase. In low temperatures (<+10 °C) no microbiological growth was observed. Tests were performed at the Tampere University of Technology.

Appearance and odor

In temperatures above cloud point HVO is clear and bright, color is almost water-like (Figure). It does not have unpleasant diesel fuel type odor. There are no impurities that precipitate in temperatures above cloud point in neat HVO and FAME-free diesel fuel blends. Below cloud point paraffins make HVO hazy and paraffins may precipitate during an extended storage which is a known phenomena also for fossil fuels.

Figure. Apprearance of HVO.

Lubricity

HVO
- as neat HVO requires lubricity additive as sulfur free diesel fuels and GTL
- same lubricity additives can be used with traditional diesel fuel and HVO

Lubricity of neat HVO corresponds to that of sulfur-free winter grade and GTL diesel fuels. It is essential that all of these types of fuels contain lubricity additives in order to meet HFRR specification <460 μm for protecting fuel injection equipment against excess wear. Lubricity additives generally used in diesel fuels operate also in HVO. If HVO is used as such, additive dosage is typically about the same as in winter grade diesel fuels.

HVO can be delivered with lubricity additive to be used as such or as a blending component. It is also common to deliver HVO without lubricity additive when HVO is used for blending. Lubricity of blends has to be checked if the base fuel already contains lubricity additive and tens of percents of HVO without additive is added. In that case the additive dosage may need to be increased to cover also the part of HVO in the blend.

In addition to the specified HFRR tests lubricity has been evaluated with two 1000 hours test runs with fuel lubricated distributor type fuel injection pumps. This test is based on a CEC/Bosch procedure which runs a distributor type VE-type pump with injectors by an electric motor at varying loads at +60 °C fuel temperature. For the tests two HVO batches were treated with a minimum dosage of lubricity additives to be at a borderline acceptance so near the <460 μm HFRR limit as possible. So, HFRR of one test fuel became 446 μm and of another 443 μm. After the 1000 hours tests all inside parts of the pumps were in good condition, and the overall rating of the both pumps was 3.0 where <3.5 means pass. Distributor pumps are not any more used in new engines but since they were known to be sensitive for fuel lubricity, pass in the pump test gives additional confidence over HFRR on lubricity of HVO treated with lubricity additive. Standardized pump tests with more modern designs like Common Rail systems are not yet available. However, some in-house Common Rail tests are already going on in order to guarantee operability of both EN 590 diesel fuels as well as HVO.

In commercial fuels HFRR is typically clearly better than <460 µm. This is based on the fact that HFRR test is quite inaccurate and fuel blenders add additive somewhat more than needed at the fist adding in order to avoid need for re-adding and re-blending.

Production and logistic issues

HVO

- to be used for
  - meeting biomandate without 7 % blending wall set today for FAME by EN 590
  - upgrading gasoils to meet retail diesel fuel requirements with blending ratios up to ~30 %
  - producing premium diesel fuels with blending ratios up to ~30 %
  - dedicated vehicles like city bus fleets for reducing locally harmful tailpipe emissions and greenhouse gases
- fully fungible with current logistical systems: stability, water and microbiological issues similar to fossil diesel fuel
- reporting of bioenergy content shall be based on bookkeeping of mass balance
- after blending biocontent can be determined only by ^{14}C isotope method if audit trail is contested
- if blended with FAME, special attention is needed in order to avoid precipitation of FAME-originated impurities, especially in cold conditions

Ways to use HVO

Renewable diesel fuel component can be used in four ways:

1. By adding some percents into diesel fuel in order to meet bioenergy mandates. This is the common approach with FAME with which the amount is currently limited to maximum 7 vol-% by FQD and EN 590:2013 standard. Even 7 % is challenging is some cases. Higher amounts, like 10 % or 30 % FAME, are considered but they need more extra precautions because of fuel stability, high final boiling point causing engine oil dilution, deposit formation in fuel injection systems, storage stability, cold operability, exhaust emission and engine calibration.

   HVO is superior in this application since it offers premium blending properties including cold properties which can be tailor made to meet even severe winter and arctic requirements. Low density of HVO offers some benefits for refineries in their blending procedures. For this purpose HVO can be used as in addition to the max 7 % FAME or as such without a blending wall.

2. By adding tens of percents into diesel fuel in order to upgrade the final fuel to meet EN 590. When HVO is blended, the original fossil fuel or fuel component does not need to meet standard requirements since HVO has remarkable beneficial blending value for diluting aromatics, reducing density and increasing cetane number. HVO can also be added without any detrimental effects on the final boiling area. Since target needs to be that only the final blend meets e.g. FQD and EN 590 specification, the fossil part can be out of FQD and EN 590 requirements and HVO fixes it. So HVO as a blending component offers new economic benefits for refineries and fuel blenders.

3. By adding tens of percents into diesel fuel in order to prepare a premium diesel fuel. By adding HVO into an EN 590 or an other base fuel it is possible to blend premium fuels. This is caused by the fact that HVO increases cetane number and decreases aromatic content resulting in reduced exhaust emissions and better overall performance. This takes place also in cold conditions because cloud point of HVO can be as low as needed. These blends meet diesel fuel standards like EN 590 and ASTM D 975 without any technical blending wall for the biofuel part. For retail marketing fuel can be produced to meet e.g. the highest Worldwide Fuel Charter (WWFC) requirements which are the tough ones set by automotive industry for premium fuels [Hartikka et al, 2013].

A fleet operator may decide to use e.g. 30 % biocontent. For these applications fuel containing 30 % HVO can be produced meeting FQD and EN 590 limits so that it can be used as a drop-in fuel in vehicles without any additional validations. If the same biocontent is made by FAME, engines have to be validated and accepted separately for B30 fuel since B30 is far outside from FQD and EN 590 requirements.

4. By using HVO as such in fleet operations like city buses, taxis or mine vehicles in order to improve local air quality. This will reduce emissions of all vehicles concerned, including old high-emitters. Also task for of exhaust aftertreatment device will be easier when engine-out particulate and NO_x emissions are lower and ash content of the fuel negligible. To attain full benefits of the fuel and engine, fuel injection system may need recalibration due to the lower density and higher cetane number of HVO.

   This approach offers double benefits: Reduced exhaust emissions where local air quality is important, and allocation of the high biofuel content to fulfill country's bioenergy and GHG reduction mandates.

GHG emissions are a global issue and depend on a combination of the total amount of biofuels used and life cycle emissions of the fuel. Therefore GHG-reduction or mandated bioenergy requirement in a country or a quota area is the same in all these three cases if equal total amount of HVO is utilized.

Blending properties with diesel fuel

HVO in blend
- preserves high quality properties of diesel fuel, and even improves some properties
- effects depend practically linearly on blending ratio
- minimum limit of diesel density defines maximum amount to be used in EN 590 fuel

HVO can be blended into diesel fuels as "drop in fuel" without "blending wall" set by vehicle technology or limitations by fuel logistics. Fuel Quality Directive 2009/30/EC "FQD" (recital 33) states that limit is not required for diesel-like hydrocarbon biofuels and hydrotreated vegetable oil. In practice maximum amount of HVO to be blended is limited by the lower density limit in EN 590 which means often adding about 30 % HVO. Even more could be added if density of the base diesel fuel is over the 845 kg/m^3 limit defined by FQD since only the value of the final blend needs to be taken into account in order to meet EN 590 and legislative requirements. In the American ASTM D975 there is no limit for density – so adding of HVO is free from that point of view.

Thanks to zero aromatics, reasonable distillation range, low density and high cetane number HVO is a superior blending component. It is fully fungible with the current logistic systems and practices since it's tendency to pick up and solve water is even lower than that of traditional diesel fuels. Storage stability of HVO is good without any need for a "use before" date. HVO is a valuable component for oil refineries since it enhances practically all properties of base diesel fuel (Table). The only property where FAME is better is that it can replace lubricity additive which has to be used in all high quality hydrocarbon fuels.

Table. Example of blending properties. The referred base fuel is free of biocomponents and represents very good fossil quality due to the very low polyaromatics.

		Required by regulation (FQD) and markets	Base fuel sample	HVO sample	30 % HVO + 70 % base fuel	Effect of HVO in blending
Density	kg/m³	820 * … 845	837	780	820	Benefit
Cetane number		≥ 51.0	55	88	65	Benefit
Polyarom.	%	≤ 8.0	1.1	< 0.1	≈ 1	Benefit
Sulfur	mg/kg	≤ 10.0	3.6	≈ 1	≈ 3	Benefit
Ox. stability	g/m³	≤ 25	≤ 25	≤ 25	≤ 25	No effect
Viscosity	mm²/s	2.0 … 4.5	3.6	3.0	3.4	No effect
Water	mg/kg	≤ 200	20	20	20	No effect
Ash	%	≤ 0.01	0.001	0.001	0.001	No effect
Metals	mg/kg	-	~ 0	~ 0	~ 0	No effect
Dist. 95 %	°C	≤ 360	360	298	355	Benefit
Cloud point	°C	As needed	-1	-11	-3	Benefit, even -40 possible with HVO

*) For winter ≥ 800 kg/m³

If the base fuel does not meet regulative requirements, for example density being above 845 kg/m³, cetane number below 51 or polyaromatics above 8 % as set by the FQD, the effect of adding HVO is practically linear on the values to be corrected by blending.

Storage and blending of HVO with FAME

HVO
- due to the paraffinic nature not a good solvent for impurities that may exist in FAME
- some care needed if FAME and HVO blended together as such

Since HVO is fully paraffinic, it does not have such good solvency characteristics as fossil diesel fuels which in almost all cases contain 15 ... 30 % total aromatics. In Swedish Class 1 the total aromatics are limited to <5 %. The less severe solvency may have benefits regarding material compatibility but on the other hand possible impurities existing in fuels may precipitate easier.

It is not recommended to store a blend of HVO and FAME. This is caused by the fact that there may be some impurities in FAME, and there is a risk for precipitation if FAME is mixed with low aromatic or aromatic free fuel. Precipitation may take place even at temperatures higher than cloud point of the blend. Due to limited tank capacity the same tank might be used for FAME and HVO. If the same tank is used either for FAME or HVO, normal procedure with quality change should be performed, like as low as possible level of FAME in storage tank before changing to HVO. Blending temperatures should be well above both fuels' cloud points. And when changing back to FAME, HVO level in storage tank, should be as low level as possible.There is also a remarkable difference in densities between FAME and HVO which may have a negative effect on blending behaviour.

When HVO and FAME are blended into fossil diesel fuel, it is recommended to start by mixing diesel fuel and HVO since HVO and diesel fuel are chemically close to each other. After that FAME may be added to this blend.

A maximum 7 % of high quality FAME (total monoglyserides max 0.3 wt%) can be mixed with HVO as defined by TS 15940. Precipitation risk of FAME's impurities increases if more or low quality FAME is used. CONCAWE has given a recommendations for EN590 diesel SMG (saturated monoglyceride) content [Engelen et.al, 2009] as well as Annex C in the FAME standard EN 14214. These recommenddations can be used also when blending FAME with HVO. Swdish class 1 and HVO behave similarly when blending with FAME so the same SMG levels in final blend can be required also for HVO. The max level of SMG coming from FAME can be 20 mg/kg in final blend.

Aromatic content of diesel fuel has an effect on precipitation risk of FAME's impurities. The better the diesel fuel is (lower aromatics), the higher is the risk for precipitation and FAME's quality becomes even more important for avoiding problems in fuel filters.

Blending of GTL and HVO

In some urban areas the use of neat GTL diesel fuel has been considered in order to reduce locally harmful tailpipe emissions and dependence on crude oil. If adding of biocomponent is also required, HVO fits perfectly to be blended into GTL. If FAME is added into the aromatic free GTL, it may encounter solubility challenges even more than in standard diesel fuels which contain aromatics.

Logistics

HVO and HVO blends
- behave like traditional fossil diesel fuel
- no additional issues related to storage stability, water separation and microbiological growth
- no additional material compatibility issues
- small cross-contamination does not risk aviation jet fuel quality

HVO can be handled in a similar way to fossil diesel fuel. It can be mixed with diesel in any ratio, and there is no risk of precipitations or phase separation. Well known practices used for fossil diesel fuels apply also for blends containing HVO and for HVO as such.

Water solubility and storage stability properties of HVO are so similar to fossil diesel fuels that no extra precautions are needed in pipelines, tank farms, tanker trucks or service stations. No needs for extra precautions regarding microbiological growth or storage stability have been noticed.

Water separation is fast from HVO and usually it contains less than 100 mg/kg water, typical values are below 50 mg/kg. General good storage tank maintenance and housekeeping is recommended. Storage tanks should be kept free of water, and tanks should have provisions for water draining on a scheduled basis. Water promotes corrosion, and microbiological growth can occur at a fuel-water interface.

Neat HVO was left for 8 months into a refueling storage tank of a bus operator after a large field test of several years was completed. The fuel was clear and free from microbiological growth after the additional storage time [Nylund et al. 2011].

Flash point of HVO is regulated to minimum +55 °C meaning that it can be stored and transported like standard diesel fuel. Electrical conductivity is low and comparable to sulfur free diesel fuels. Because of that the use of an antistatic additive is recommended in order to allow high pumping velocities in pipelines and loading racks.

HVO processed to extremely good cold properties has already been accepted to be used as a blending component of aviation kerosene. So, HVO pumped through common logistics does not cause any contamination risk for aviation fuels.

As a pure component HVO is shipped with the proper shipping name Alkanes (C_{10} — C_{26}), linear and branched under MARPOL Annex II, Category Y and ShipType 3. This means that cargo shall be carried on chemical tankers with prewash requirements.

HVO (NEXBTL Renewable Diesel) is included into the IMO Biofuel category. Thus as a blend containing HVO and minimum 75 % of diesel fuel or gasoil is shipped as a MARPOL Annex I cargo. If a blend contains less than 75 % of diesel or gasoil then a cargo is carried under MARPOL Annex II requirements, Category X and ShipType 2. This means that tank wash waters need to be unloaded to a shore facility.

Custom nomenclature (CN codes)

In general, Directive 98/70/EC article 2 with its amendments ("FQD") defines that diesel fuel and gas oil (non-road diesel fuel) fall within CN codes 2710…. Further CN nomenclature defines that 2710… “contains 70 wt-% or more petroleum oils” which can be interpreted so that the maximum amount of biocomponents is limited to max. 30 wt-%. However, CN nomenclature chapter 27 note 2 defines “2710 petroleum oils include not only petroleum oils… but also similar… as well as consisting of unsaturated hydrocarbons… provided that non-aromatic constituents exceeds aromatic constituents”. Based on this HVO belongs to the 2710… CN group of diesel fuels although HVO’s origin is renewable.

There are binding custom nomenclature decisions for HVO shown in the table. In practice codes for the sulphur ≤ 0.001 wt-% (≤ 10 mg/kg) grades are used for the current diesel fuels.

Table. CN codes.

Gas oils, containing non-fossil origin	CN-code	Taric -code (import)
HVO with sulphur ≤ 0.001 wt-% - pure (more than 20 %)* - blends (20 % or less)**	 2710 19 43 2710 19 43	 2710 19 43 29 2710 19 43 30
HVO with sulphur > 0.001 wt-% and ≤ 0.002 wt-% - pure (more than 20 %)* - blends (20 % or less)**	 2710 19 46 2710 19 46	 2710 19 46 29 2710 19 46 30
HVO with sulphur > 0.002 wt-% and ≤ 0.1 wt-% - pure (more than 20 %)* - blends (20 % or less)**	 2710 19 47 2710 19 47	 2710 19 47 29 2710 19 47 30

*) Paraffinic gasoil obtained from synthesis and/or hydro-treatment, of non-fossil origin, in pure form; blends containing more than 20 wt-% of paraffinic gasoil obtained from synthesis and/or hydro-treatment, of non-fossil origin.
**) Blends containing 20 wt-% or less of paraffinic gasoil obtained from synthesis and/or hydro-treatment, of non-fossil origin.

Compatibility with materials

HVO may be considered having the same compatibility regarding parts and materials as petroleum diesel, for example with seals, hoses, diaphragms, dry couplers and base swivel joints. Materials of construction may include carbon and stainless steel which are suitable for petroleum diesel fuel. The use of both welded and riveted tanks is acceptable. Tanks may have internal floating roofs made of aluminum. Nitrogen blanketing can be used.

HVO is compatible with nitriles, fluoroelastomer, PTFE, vinyl ester resins and epoxy resins. In principle the lack of aromatic compounds may shrink elastomers that have already been swollen when used with aromatic or FAME containing fuels but no fuel leakages have been observed during several large field tests with HVO. Generally speaking large changes of the liquid composition are able to cause changes in elastomer's volume meaning swelling or shrinking especially regarding very old seals.

Mechanical seals of pumps can be considered to be compatible with HVO if they are compatible with diesel fuel.

Measurement of HVO content in diesel fuel

HVO

- can not be detected by mature routine analytical methods used for FAME
- can be detected by ^{14}C isotope methods but they are quite laborious

HVO consists of paraffinic hydrocarbons that exist naturally also in fossil diesel fuels. So the amount of HVO in a blend can not be analyzed afterwards by so mature analytical methods as FAME content of diesel fuel or ethanol in gasoline. Due to this analytical challenge HVO content of a blend shall be based on the seller's declaration and bookkeeping of the blending procedures. If analyses of the both pure blending components are known, for example density of the blend indicates how much HVO has been added.

If required, HVO content in a diesel blend can be determined by ^{14}C isotope methods. CO_2 in the atmosphere contains unstable ^{14}C and stable ^{12}C carbon isotopes in a fixed ratio. The same ratio can be found from living plants and animals. When these organisms stop their growth ^{14}C begins to decline gradually. The half-life of ^{14}C is 5730 years, and finally fossil carbon does not contain ^{14}C isotope. So, time when the plant stopped growth naturally or was harvested can be estimated afterwards which makes a clear difference between fossil and renewable carbon. Principles can be found from the standard ASTM D 6866. ^{14}C dating methods have been used for example for archeological studies.

Bio content of a fuel can be determined by two methods based on ^{14}C dating: Liquid Scintillation Counting (LSC) and Accelerated Mass Spectrometry (AMS). These methods are available in some commercial laboratories in a case of dispute, but due to the time needed for analysis and limited availability of services this is not practical for everyday use. Some custom's laboratories use ^{14}C dating methods. Preliminary results show that more than 2 % HVO in a fuel blend can be determined by AMS, and more than 5 % by LSC. If for example 10 % of HVO has been blended, analyzes are able to confirm that there is about 8 … 12 % HVO. AMS seems to be more accurate but it is more laborious because fuel sample has to be combusted before analyzing. Liquid fuel sample fits for LSC. Both LSC and AMS are also able to confirm that paraffins are biobased (HVO or BTL) and not fossil (GTL or CTL).

These methods measure all renewable carbon. If a sample contains both FAME and HVO, the amount of FAME needs to be measured with traditional methods and subtracted from the total biocontent in order to find out HVO content. Some further calculations may be needed in order to change the ^{14}C results to vol-%, wt-% or bioenergy-% whatever is needed in each case.

Since ^{14}C methods do not belong to everyday laboratory practices at oil companies or authorities, they should be used only in cases where the audit trail approach is contested. This approach is already mentioned in prEN 228:2010 standard draft in order to make a difference between fossil and renewable ethanol in gasoline. European Custom Administration has noticed this challenge and Round Robin tests with the methods are already going on.

Environmental properties

HVO

- highest energy content of biofuels: less blending for meeting a defined biomandate
- higher greenhouse gas savings than with FAME from the same feedstock
- very low well-to-wheels greenhouse gas emissions
- generally reduces both NO_x and particulate emission
    - some engines prefer particulate reduction over NO_x and vice versa
    - may require updated engine software for optimal control of injection, EGR and aftertreatment
- reduces CO, HC, PAH, aldehyde, mutagenic and nanoparticle emissions
- reduces emissions at low ambient temperatures substantially
- many tailpipe emission benefits also when used as blending component
- ash-free combustion: long life-time for exhaust aftertreatment systems
- fuel itself is classified to be less hazardous as fossil diesel fuel
    - the only issue is aspiration hazard

Renewable energy and greenhouse gas savings

The European directive promoting the use of renewable energy ("RED", directive 2009/28/EC) requires that at least 10 % by energy used in the transport sector has to be from renewable sources by 2020. In addition, the directive regulating fuel quality and overall greenhouse gas emissions ("FQD", directive 2009/30/EC) demands a 6 % reduction of fuels' greenhouse gases by 2020. Individual member states may have even more challenging requirements. Energy contents to be used in reporting for authorities are defined by RED Annex III (Table).

Table. Energy contents (heating values, lower calorific values) of diesel fuel and some neat biofuels defined by RED.

	By weight (MJ/kg)	Compared to diesel fuel by MJ/kg	Compared to FAME by MJ/kg	By volume (MJ/l)	Compared to diesel fuel by MJ/l	Compared to FAME by MJ/l
Diesel fuel	43			36		
HVO	44	+2.2 %	+19 %	34	-5.6 %	+3 %
BTL	44	+2.2 %	+19 %	34	-5.6 %	+3 %
FAME	37	-14 %		33	-8.3 %	
Ethanol	27	-37 %	-27 %	21	-42 %	-36 %

These figures, where also ethanol is presented for comparison, show that HVO is the best existing biofuel regarding energy content. This means that less HVO is needed for meeting a given legislated biomandate compared to FAME, and remarkable less compared to ethanol.

Both RED Annex V and FQD Annex IV define greenhouse gas emission savings if case by case calculated values are not available. Figures show that HVO's performance is slightly better than that of FAME if they are made from the same feedstock (Table). These figures should be well comparable to each other since they have been taken from the same study.

Table. Greenhouse gas savings defined by RED and FQD.

	Typical savings	Default savings
FAME from rape seed oil	45 %	38 %
HVO from rape seed oil	51 %	47 %
FAME from sunflower	58 %	51 %
HVO from sunflower	65 %	62 %
FAME from palm oil, process not specified	36 %	19 %
HVO from palm oil, process not specified	40 %	26 %
FAME from palm oil, methane capture at oil mill	62 %	56 %
HVO from palm oil, methane capture at oil mill	68 %	65 %

RED and FQD calculate greenhouse gas emissions ending up to the lower calorific value of fuels which represents only theoretical combustion. From the point of view of the environment greenhouse gas emissions shall be counted by well-to-wheels principle taking also efficiency of the engine and vehicle into account. So, the comparisons should be made in grams CO_2/passenger-km or in grams CO_2/ton-km for trucks rather than grams CO_2/MJ fuel used today in directives.

Efficiency of diesel engine is clearly better than that of spark ignited engines which means clearly lower fuel consumption for diesel. Although well-to-tank greenhouse gas values of for example sugar cane ethanol are low per MJ of ethanol's calorific value, even a current HVO can be better in well-to-wheels basis because of the diesel engine's better efficiency (Figure).

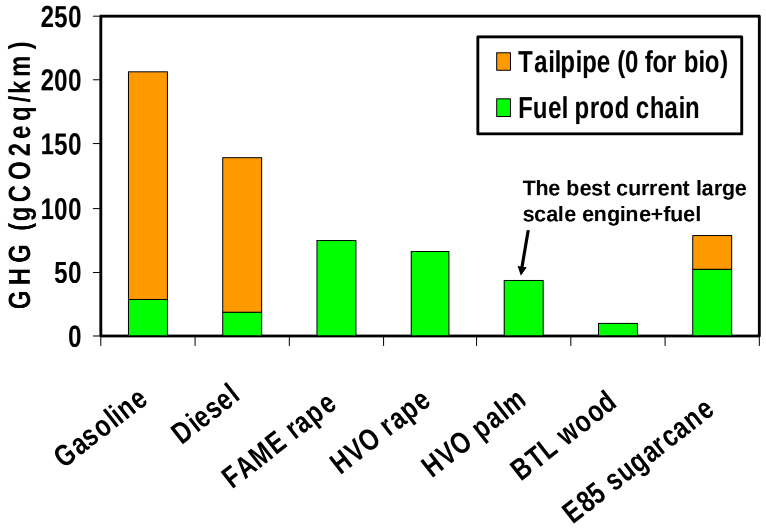

Figure. Well-to-wheels greenhouse gas emissions of a typical middle size class car. Well-to-tank part (fuel production chain) is based on RED and FQD values.

Case: Greenhouse gas balance of NExBTL

Fuel suppliers are allowed to use default savings values given by the directives (Table before) or case by case calculated actual values for greenhouse gas emissions when they report about their fuels for authorities. Greenhouse gas savings of the commercially produced HVO, Neste Oil's NExBTL™, have been estimated for several feedstocks: Palm oil 47 %, rapeseed oil 49 % and animal fat 91 %. Details and updates can be found from a separate document:

http://www.nesteoil.com/default.asp?path=1,41,11991,12243,12335,14116,12340

Tailpipe emissions

HVO

- reduces NO_x and particulate emissions of the combustion remarkably
    - tailpipe emissions depend also a lot on EGR and exhaust aftertreatment strategy
- reduces CO, HC, PAH, aldehyde and mutagenic emissions
- reduces all size classes of particulate emissions including nanoparticulates
- reduces cold start smoke and emissions in winter conditions
- effects seen already at 10 ... 30 % blending ratios
- ash-free combustion offers a long life-time for particulate filters

Exhaust emission tests have been performed totally with over 32 trucks and buses or their engines, and several passenger cars in vehicle and engine test beds. These tests consist of transient tests simulating real driving conditions and artificial driving cycles. Both of them are including also acceleration phases. A summary of the results is shown in Figure where remarkable reduction of particulate mass, carbon monoxide (CO) and hydrocarbon (HC) emissions can be noticed. It is also important that nitrogen oxides (NO_x) rather decrease or do not change since the use of FAME typically increases NO_x emissions.

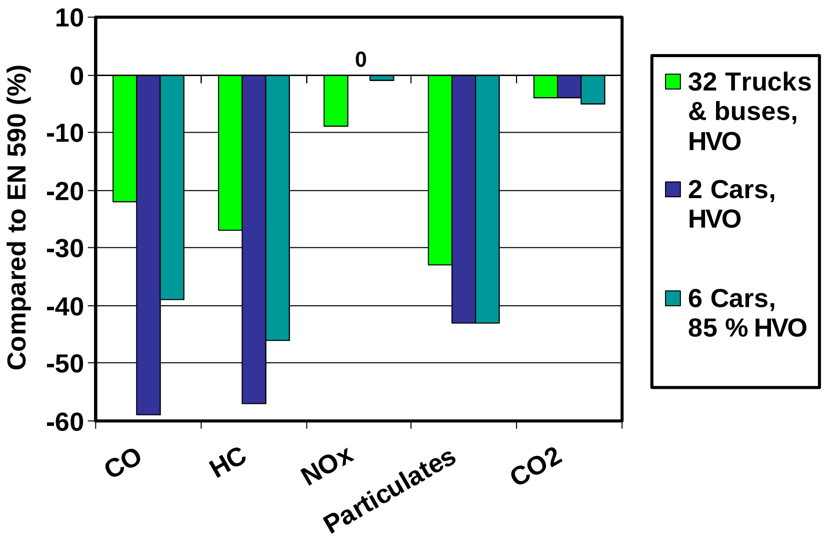

Figure. Average effect of neat and almost neat (85%) HVO on tailpipe emissions in EURO II to EURO V vehicles compared to a sulfur free EN590 diesel fuel.

CO_2 of all these vehicle and engine measurements is based on the measured tailpipe values without making any difference between carbon's origin is it renewable or fossil. So, this CO_2 corresponds only to the tank-to-wheels part of a life cycle assessment without assuming renewable CO_2 to be absorbed back by growing plants. The reduced CO_2 from tailpipe is caused by the higher hydrogen content of HVO compared to common fossil diesel fuel. Many studies have also shown slightly better (~ +1 %) engine efficiency with HVO, but due to the measurement accuracy these results are only indicative.

Several unregulated exhaust emissions have been measured showing that the use of HVO reduces:

- polyaromatic hydrocarbons (PAH)
- aldehydes
- mutagenicity

- particulate number ($PM_{2.5}$, PM_{10})

Many stakeholders have been worried about nanoparticles. Test results have shown that HVO reduces number of particulates in all size classes (Figure).

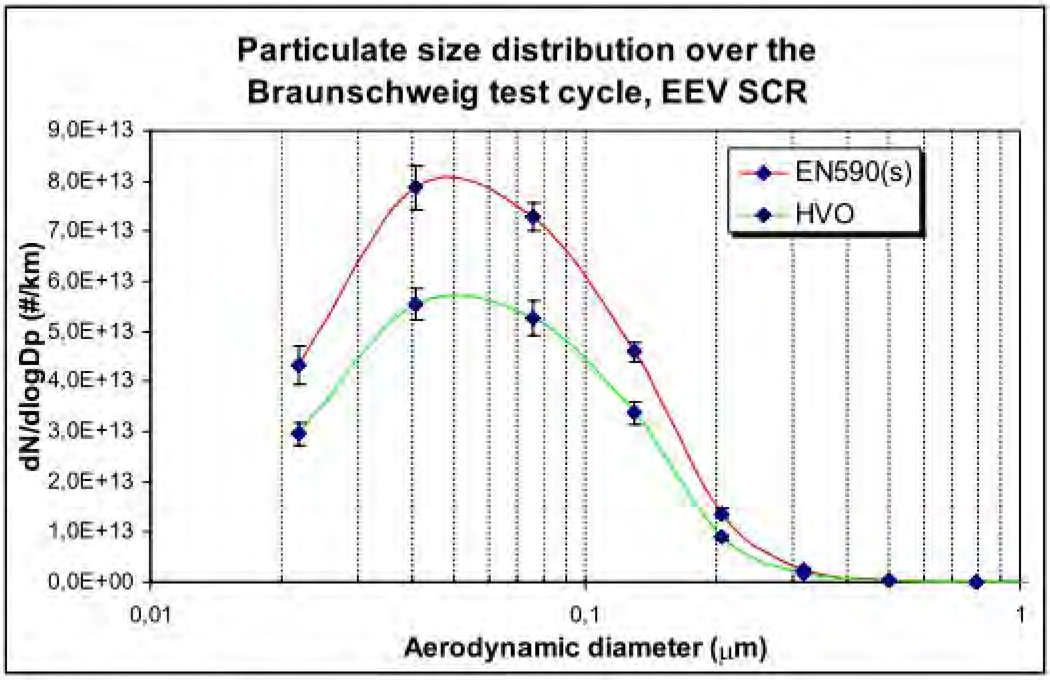

Figure. Example of particulate size distribution with summer grade EN 590 fossil diesel fuel and neat HVO in a Euro V/EEV city bus [Nylund et al. 2011].

However, spread between individual engines has been large so that some truck or bus types have preferred reduction of particulate mass up to -47 % together with a negligible or even slightly increasing effect on NO_x. Vice versa, in some engines NO_x is reduced more, up to -14 %, and particulate emissions less. In any case, HVO moves the well known NO_x – particulate emission trade-off-curve of the base engine towards the origin which is a desired effect for every engine designer. The total effect of HVO depends then on the engine's fuel injection and EGR control strategy (Figure).

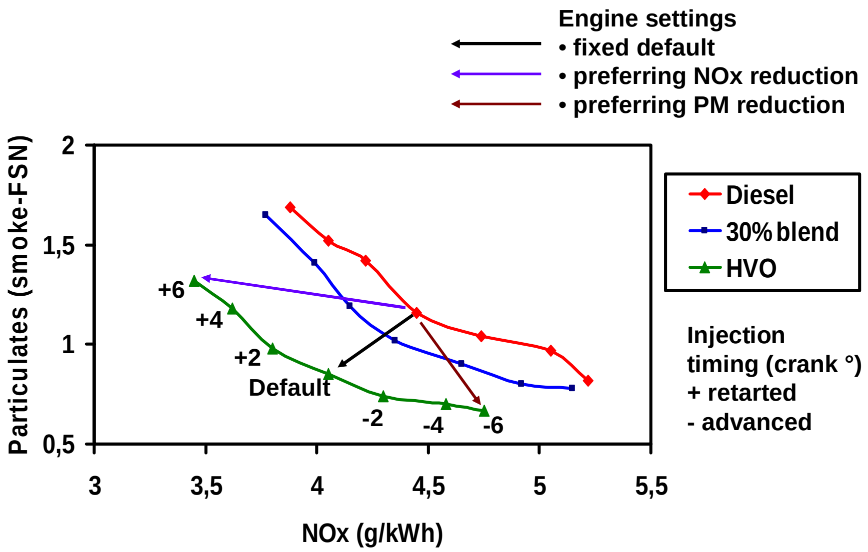

Figure. NO_x – particulate emission trade-off curves of diesel fuel, diesel fuel with 30 % HVO and neat HVO. A modern direct injection heavy-duty engine, common rail fuel injection with different fuel injection advance settings [Aatola et al, 2008].

When HVO is used as a blending component, particulate and NO_x emissions reduce quite linearly according to the blending ratio. Typically already quite a small blending of HVO reduces regulated emissions, especially HC and CO (Figure). However, HC and CO emissions of diesel vehicles are low in grams per kilometer in any case. The main attention shall usually be paid on HVO's capability to reduce NO_x and particulate emissions which are the Achilles heels of diesel vehicles, and also to the unregulated emissions mentioned above.

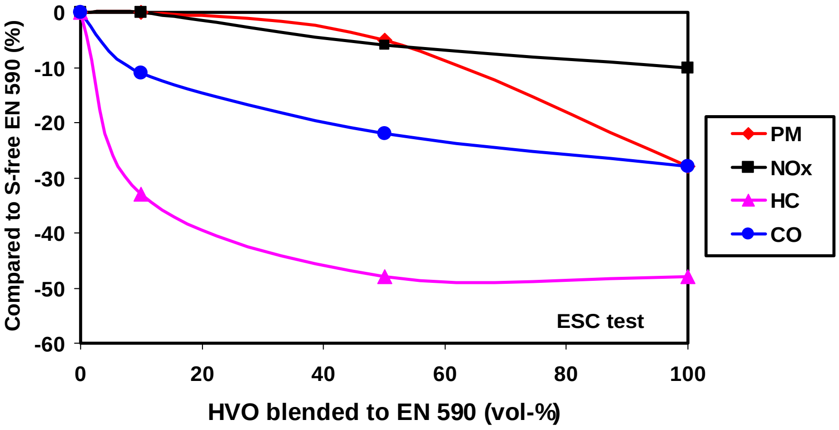

Figure. Effect of HVO blending ratio on emissions of a Euro 4 truck engine with EGR but without any aftertreatment [Kuronen et al. 2007]. .

When tens of percents of HVO was added into a standard diesel fuel in order to produce a premium EN590 diesel fuel, the effect of HVO on exhaust emissions of passenger cars was as follows:

- particulate mass 0 … -10 %
- nitrogen oxides (NO_x) 0 … -10 %
- hydrocarbons (HC) -10 … -30 %
- carbon monoxide (CO) -20 … -40 %
- less polyaromatic hydrocarbons (PAH)
- less aldehydes, benzene and 1,3-butadiene
- less mutagenic activity
- faster and easier cold start, less cold start smoke
- less engine noise after a cold start

Example of a passenger car with common rail fuel injection, EGR and oxidation catalyst but without a particulate filter is presented in Figure. It shows a case with high NO_x reduction and no influence on particulate emissions.

In cold conditions (-7ºC, -20º) the effect of neat HVO and 30 % blends on reducing CO, HC and particulate emissions of cars was remarkable, up to -70 ... -90 %. As a matter of fact emissions of HVO at -20ºC were about the same as of standard diesel fuel at +23ºC [Nylund et al. 2011]. Reductions of this magnitude can have an immediate effect on ambient air quality in downtown areas during cold seasons.

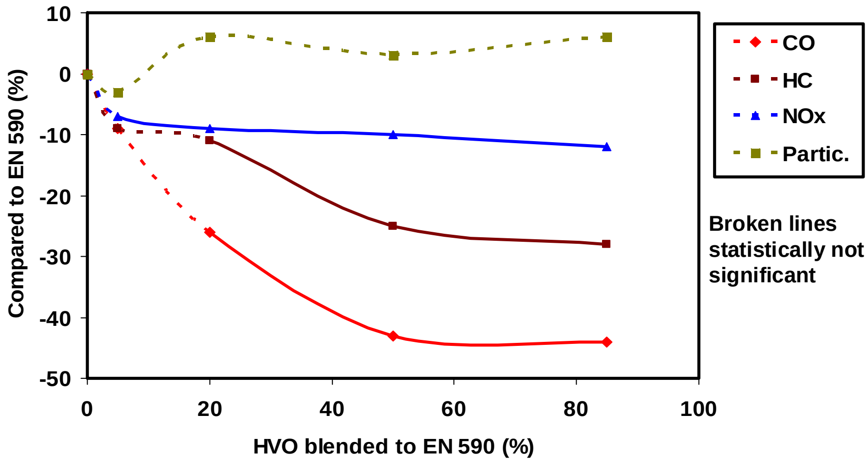

Figure. Effect of HVO blending ratio on emissions of a car in which reduction of NO_x was clear but particulate emissions were practically unchanged.

Spread in emissions of passenger cars seems to depend highly on the type of fuel injection system, engine calibration and exhaust aftertreatment system. Strategy for controlling exhaust gas recirculation (EGR) is assumed to have a remarkable effect on NO_x emissions. In the tests these factors were not taken into account since tests were made using factory engine mappings. Results allow also concluding that the biggest benefits of paraffinic fuels used as such or in high concentrations can be achieved if cars can be designed in the future to detect fuel quality or combustion and then optimize engine parameters on-line. This could be a "Diesel-Flex-Fuel-Vehicle" (Diesel-FFV) -approach mirroring the development has already taken place for otto-ignition FFV-cars which adjust engines automatically to ethanol contents from 0 to 85 %.

Reduced exhaust emissions lead to a better local air quality. This is important in many downtown areas where air quality is still a remarkable challenge even though standard fuels and vehicle technologies have evolved a lot during the last decades. Some special working conditions like mines or construction of tunnels may also need attention to be paid on tailpipe emissions, and there HVO offers remarkable benefits over standard diesel fuels or non-road fuels.

Practically all new diesel cars today and heavy duty vehicles in the future are equipped with a particulate filter (DPF, diesel particulate filter) which reduces emissions effectively. The lower engine-out particulate emissions of HVO are beneficial also in these vehicles since exhaust back-pressure is lower and there is no need to clean the filter so often using a so called regeneration phase [Kopperoinen et al, 2008]. This can lead to slightly lower fuel consumption with HVO compared to other fuels if control system of the particulate filter could be able to detect actual soot build up according to the fuel quality used. Life-time of filters is long since HVO is practically free of ash forming components.

HVO's excellence is based on facts that it is practically free of aromatics, polyaromatics, olefins, sulfur and high boiling fractions. Also cetane number is very high. In these sets of tests the EN590 fuel which was used as a reference represented already high environmental quality. In many areas of the world standard diesel fuel may contain more sulfur and aromatics, and so compared to those fuels benefit of HVO is even more remarkable.

Most of the reports listed in "Public reports and articles" deal with detailed exhaust emission test results.

Other health and environmental properties

HVO
- accepted by REACH regulation
- well known practices for handling and safety precautions of diesel fuels apply

HVO health and environmental properties have been subject to a thorough testing program in order to comply with the EU REACH regulation. HVO as such is biodegradable according to OECD test guideline 301 B. Under the EU and globally harmonized hazard classification system, HVO as such is not classified as hazardous for any other endpoint than aspiration hazard. Aspiration hazard is characteristic for all low viscosity hydrocarbons, both fossil and renewable. HVO as such is practically insoluble in water.

Odor of HVO is very weak and of paraffinic nature without any typical odour of diesel fuel. When handling 100% HVO the precautions for personal safety described in the Safety Data Sheet of the product must be followed. Safety Data Sheet is available upon request.

When HVO is blended into diesel fuel, well known practices used for diesel fuel apply as such for the blend.

Performance in engines

HVO

- reasonable distillation range without high boiling fractions
- hydrocarbon, very high cetane number, free of aromatics
- no ash forming components reducing life-time of exhaust aftertreatment systems
- highest heating value of existing biofuels
- no engine oil dilution issues
- no chemical incompatibilities with engine oil
- good oxidation stability
- low tendency to form deposits in fuel injection system and fuel injectors
- the same torque and maximum power than with fossil diesel fuel in modern engines
- if used as such, due to low density higher volumetric fuel consumption than with fossil diesel fuel, but lower than with FAME
- no cold operability issues with severe winter grades
- possibility to design more fuel efficient low emission diesel engines (“diesel-FFV-vehicles”)
- supported by automotive industry association ACEA
- supported by Worldwide Fuel Charter published by automotive and engine manufacturers

Some decades ago diesel engines were used mainly in robust commercial applications like trucks and buses. Today diesel engines are common also in passenger cars where customers’ requirements for convenience are high. More stringent emission legislation has led to sophisticated engine, fuel injection system and exhaust aftertreatment designs in both on-road and non-road applications.

Fuel properties and quality are integral parts of a proper operation and durability of engines and exhaust systems. From this point of view adding of biocomponents shall lead rather to an enhanced fuel quality than deteriorated properties.

Hydrocarbon type fuels

Fuel quality

- most fossil fuels have been of high quality
- adding of biocomponents shall not cause quality drawbacks
- new emission control systems require even higher quality fuels
- HVO is a high quality hydrocarbon enhancing quality of a fuel blend

Vehicle owners are used to high-quality ultra-low sulfur or sulfur-free hydrocarbon type diesel fuels which are practically free of ash, heavy hydrocarbon fractions and unstable components. For engines and emission control systems this has enabled longer life times, less maintenance and extended oil-change intervals compared to the situation a decade or more ago.

In addition to the requirements set by legislation and fuel standards for operability at +20ºC in a test chamber, “fit for purpose” has risen as an essential requirement for fuels. Thus the addition of biofuels should not cause fuel quality problems from the point of view of cold operability, engine cleanliness and durability of emission control systems. Fuel requirements are in fact becoming more stringent due to the extending mileage durability requirements for emission control systems and more stringent requirements for exhaust emissions, fuel economy and on-board diagnostics (Table).

Table. Fuel effects on reliability and need for maintenance of vehicles.

	Sulfur free fossil diesel fuel	HVO in a blend or as neat	Importance for vehicle technology and vehicle owner
Distillation range	Reasonable	Reasonable	Low engine oil dilution Low risk for degraded lubrication Long engine oil drain periods
Cetane number	Reasonable	Excellent	Rapid cold start Lower exhaust emissions Less noise
Chemical composition	Hydrocarbon	Hydrocarbon	Low engine oil aging Low engine oil thickening Low material compatibility issues
Carbon/hydrogen -ratio	Traditional	Better than in fossil fuels	Enhanced combustion Lower engine out CO_2 Lower well-to-wheels CO_2
Oxidation stability	Good	Good	Low deposit formation in fuel system Low fuel injector fouling No acid formation in fuel
Ash, S, P, metals	Practically zero	Practically zero	High exhaust catalyst performance Long lifetime for particulate filter
Cold properties	As needed 0 … -40 °C	As needed 0 … -40 °C	Fit for purpose even in arctic winters
Solubilityu of water	Low	Very low	Low risk for water pick up from logistics
Corrosion protection	Good with performance additive package	Good with performance additive package	Low risk for troubles if some water condensates and precipitates in fuel tanks

Fuel consumption

Volumetric fuel consumption

- vehicle results practically in line with measured calorific heating values (MJ/l)
- HVO's heating value higher than that of FAME
  - smaller amount of HVO than FAME needed for meeting a fixed bioenergy mandate
  - fuel consumption slightly lower with HVO-blends compared to FAME-blends at the same bioenergy level
- with neat HVO fuel consumption about 4 % higher than with B7 summer grade fuel
- with neat HVO fuel consumption about 5 % lower than with neat FAME

The fuel property which has the largest effect on volumetric fuel consumption is the heating value which is normally expressed in MJ/liter. The fuel's heating value can measured more accurately than fuel consumption measurements made in test bed engines, vehicles in dynamometer or vehicles in real traffic can ever be.

Traditionally, fuel density has been the factor having the greatest effect on volumetric fuel consumption since the heating value per mass (MJ/kg) is practically the same for diesel fuels within a reasonable range of aromatic contents. So, for a fuel with a lower density, the heating value per volume is lower. This means that more fuel volume is needed in order to provide the same energy output. HVO's density is clearly lower than of standard diesel fuels due to the paraffinic nature and reasonable distillation range.

HVO does not behave exactly by the same way as traditional fuels. HVO's heating value per mass (MJ/kg) is higher because of the paraffinic nature, which can be explained also by hydrogen content which is 15.2 wt-% for HVO compared to about 13.5 wt-% of standard diesel fuel. So, the higher heating value per mass of HVO partly compensates for the effect of lower density on heating value per volume. (Table).

HVO's heating value is clearly higher than that of FAME per mass since HVO does not contain oxygen like FAME. The high density of FAME partly compensates the difference but even after compensation HVO's heating value per volume is better.

Table. Typical densities and lower calorimetric heating values.

		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			-4.6 %	-9.2 %
Heating value, 7 vol-% blend	MJ/l		35.9	35.8
Heating value, 10 vol-% blend	MJ/l		35.8	35.7
Heating value, 30 vol.% blend	MJ/l		35.5	35.0

Slightly less HVO compared to FAME is needed in a diesel fuel for meeting the same bioenergy mandate because HVO's energy content is higher than that of FAME (Table). Compared to ethanol the benefit is large since heating value of ethanol is only 21 MJ/l.

Because of the differences in heating values, fuel consumption of a diesel fuel containing HVO instead of FAME at 6 % bioenergy level should be about 0.4 % lower. However, no vehicle driver is able to identify this size of difference but in any case heating value shows the trend that HVO is better. In this comparison analytically measured heating values have been used instead of the rounded ones used by FQD for reporting bioenergy for authorities since engines run according to precise actual heating values.

Table. Energy contents of neat fuels and blends containing 6.0 % bioenergy as an example (6 % energy is the biomandate in Finland from 2011 to 2014).

	Bioenergy (%)	Heating value (MJ/l
Fossil diesel fuel, summer grade	0	36.0
100 % HVO	100	34.4
100 % FAME	100	32.7
Diesel incl. 6.3 vol-% HVO	6.0	35.9
Diesel incl. 6.6 vol-% FAME	6.0	35.8

Heavy duty vehicle tests showed about 5 % increase in volumetric fuel consumption with neat HVO compared to fossil summer grade diesel fuel. The difference was about 3.5 % compared to a winter grade fuel having a lower density than summer grade. This is well in line with differences in heating values. A slight tendency (0.5 %) towards a lower energy consumption in MJ/km and better engine efficiency was also found with neat HVO. [Nylund et.al, 2011].

Passenger car tests with neat HVO also show about 5 % increase in volumetric fuel consumption compared to fossil summer grade diesel fuel.

However, reference fuel used both in car and heavy duty tests was without any biocomponents (EN 590 "B0") meaning that these results show the maximum possible difference in fuel consumption. Today a relevant reference in most of the cases might be B7 reducing the effect of HVO to about 4 % in summer grade fuels. If fuel consumption of neat FAME and neat HVO are compared, volumetric consumption of FAME would be about 5 % higher based on the differences in heating values.

Engine power and torque

HVO

- no change in maximum power and acceleration time with modern vehicles (common rail fuel injection)
- slightly lower performance with older engines due to lower volumetric heating value of neat HVO
- no noticeable differences when HVO used as a blending component

In modern engines the amount of fuel injected into the combustion chamber is controlled by the energizing time of the fuel injector and fuel pressure. Engine control unit calculates the right signal length and timing for the requested engine load and speed conditions. Thus the maximum power output of the engine is related to the efficiency of the engine, injector energizing time, fuel pressure and energy content of the fuel. In some modern common rail injection systems it has been seen that with the same indicated injection duration, more paraffinic fuel is actually injected. With this type of injection systems, HVO produces the same engine power and torque than EN 590 diesel. The maximum power of the engine can even be higher, if compared to winter grade diesel [Sugiyama et al. 2011].

In older injection systems (in-line pump, distributor pump, pump-line-nozzle, pump injector) the volume of fuel injected is almost equal with HVO and EN 590 diesel. Thus the maximum power is reduced some 3 ... 5 % with neat HVO because of the lower volumetric energy content compared to EN 590 diesel. The slightly better engine efficiency with HVO cannot compensate the lower volumetric energy content.

Passenger car tests have shown no measurable differences in power output with neat HVO compared to summer grade diesel fuel.

Since differences in vehicle performance are negligible between neat HVO and diesel fuel in modern vehicles, HVO does not have any noticeable effects when it is used as a blending component.

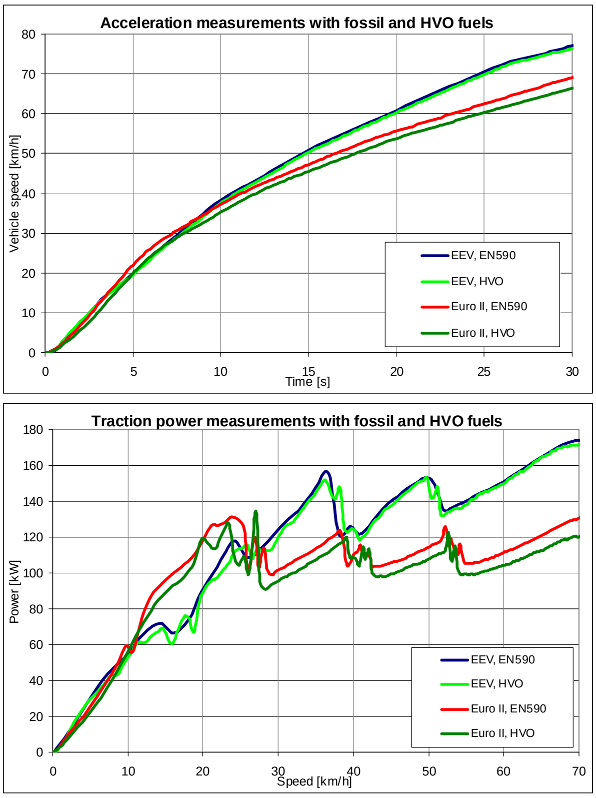

Figure. Acceleration performance and traction power of Euro II and EEV city buses in a dynamometer. Euro II bus was equipped with an in-line injection pump representing old technology, and EEV bus with a modern common rail fuel injection system [Nylund et al. 2011].

Engine oil dilution and deterioration

HVO

- no risk for engine oil due to reasonable distillation range and hydrocarbon type chemistry

Distillation curve shows how much of a fuel sample is evaporated at each temperature when temperature is increased gradually. In this case gas chromatographic distillation (GC) was used in order to see heavy boiling fractions clearly which may not be the case with the common atmospheric distillation (Figure). Distillation characteristics have an effect on how fuel is evaporated when it is sprayed into the combustion chamber. Fractions boiling at too high temperatures may not burn completely or they may wet cylinder walls. HVO is well inside that range of diesel fuels but FAME boils at remarkably higher temperatures.

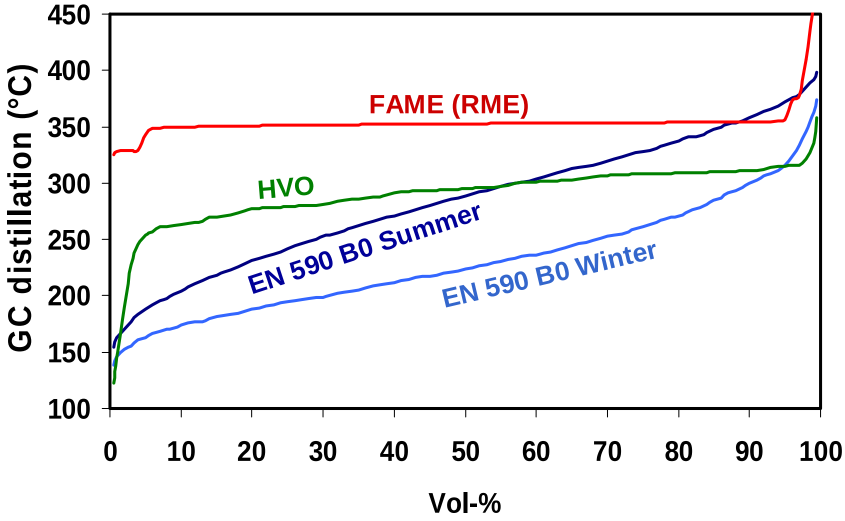

Figure. GC distillations of typical diesel fuels without biocomponents (meeting EN 590), neat FAME and neat HVO. Remark that temperature scale of CG distillation is different from atmospheric distillation which is commonly used for diesel fuels.

A new challenge has arisen with modern vehicles with particulate filters (DPF). They need to be periodically cleaned, “regenerated”, by increasing exhaust temperature to above +500ºC so that the soot collected is combusted. This kind of temperatures cannot usually be achieved during normal driving. In most cars today, this temperature increase is assisted by injecting an additional amount of fuel into the cylinders after actual combustion strokes. However, the highest boiling fuel fractions may not evaporate completely enough, wet cylinder walls and then enter into the engine oil though piston rings. This will cause engine oil dilution reducing viscosity of the oil and is a known challenge when FAME is used as a blending component since it increases final boiling area. That can be seen from distillation characteristics of both summer and winter grade fuels (Figures). HVO does not cause additional engine oil dilution thanks to its reasonable distillation range.

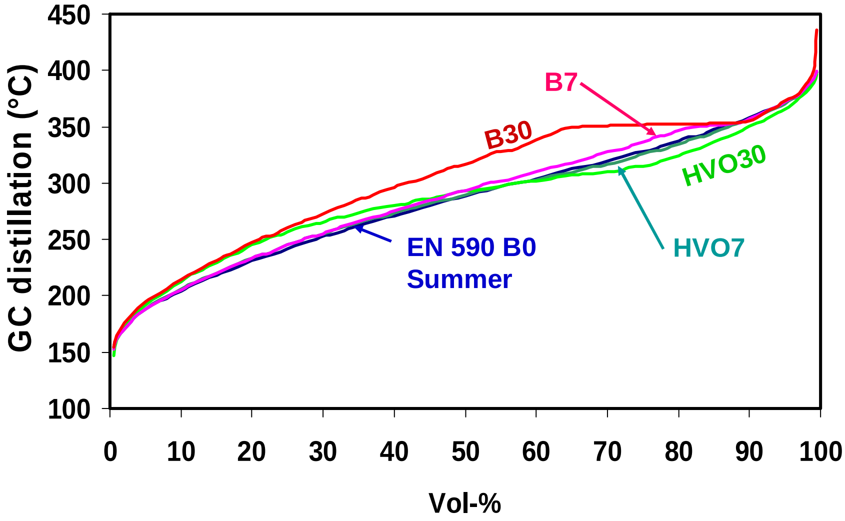

Figure. GC distillations of summer grade fuel and its blends with biocomponents (numbers show vol-% of bio added). Remark that temperature scale of CG distillation is different from atmospheric distillation which is commonly used for diesel fuels.

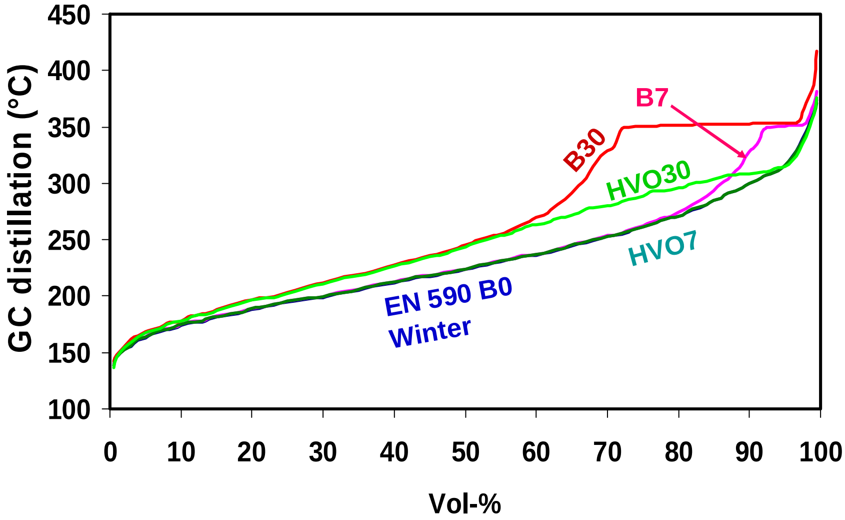

Figure. GC distillations of winter grade fuel and its blends with biocomponents (numbers show vol-% of bio added). Remark that temperature scale of CG distillation is different from atmospheric distillation which is commonly used for diesel fuels. (B30 may not be suitable fuel also because of cold operability).

When some FAME enters into crankcase oil, the ester type composition may also cause harmful chemical reactions in the oil during the long engine oil drain periods used today. Since HVO consists of hydrocarbons it does not cause chemical incompatibility with the engine oil if some HVO enters into the crankcase. So, HVO does not risk engine oil condition or engine durability, and there is no need for any additional measures like changing engine oil more often than with traditional high quality fossil diesel fuels.

Engine oil dilution has been tested in an engine test which simulates DPF regenerations. However, diesel fuel without any biocomponent was not tested since bio-free grade was not relevant as a reference fuel in Germany where the tests were performed (Figure). Engine oil dilution with 30 % HVO was clearly lower than with 5 % FAME in the fuel.

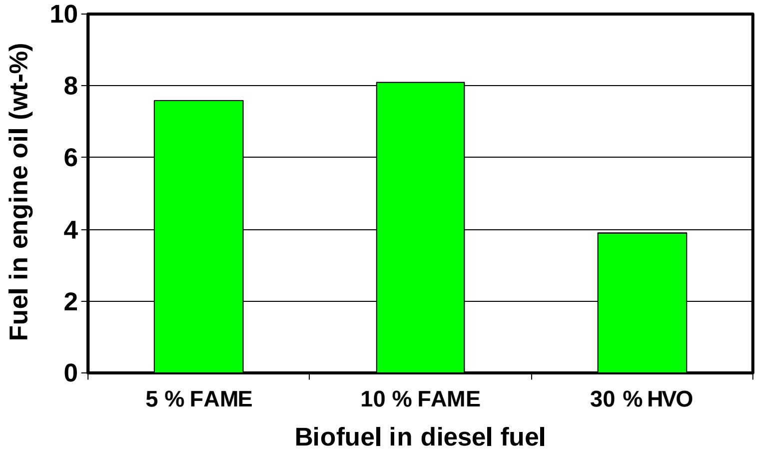

Figure. Engine oil dilution during a 55.5 h test with a car engine simulating DPF regeneration [Baumgarten et al. 2008].

Injector fouling

HVO

- low tendency for injector fouling as neat and in diesel fuel blends
- the same detergent additives suitable as for standard diesel fuels

Deposit formation in fuel injectors of engines is a phenomenon that shall be limited in order to keep engine power output and exhaust emissions constant over the entire life of a vehicle. Injector fouling of has been tested with a Peugeot DW10 Common rail direct injection engine and Peugeot XUD9 indirect injection engine.

The DW10 test is based on CEC F-098-08 test method, which reprecent Euro 5 standart fuel injection equipment with a maximum injection pressure of 1600 bar. The method mesures injector fouling directly from engine power a lower power loss means cleaner injectors. Without Zn dosing HVO showed clean injectors and also with Zn dosing and effective detergent showed clean injectors. HVO blend (20%) behaved like EN590 B0 (DF-79-07 reference fuel).

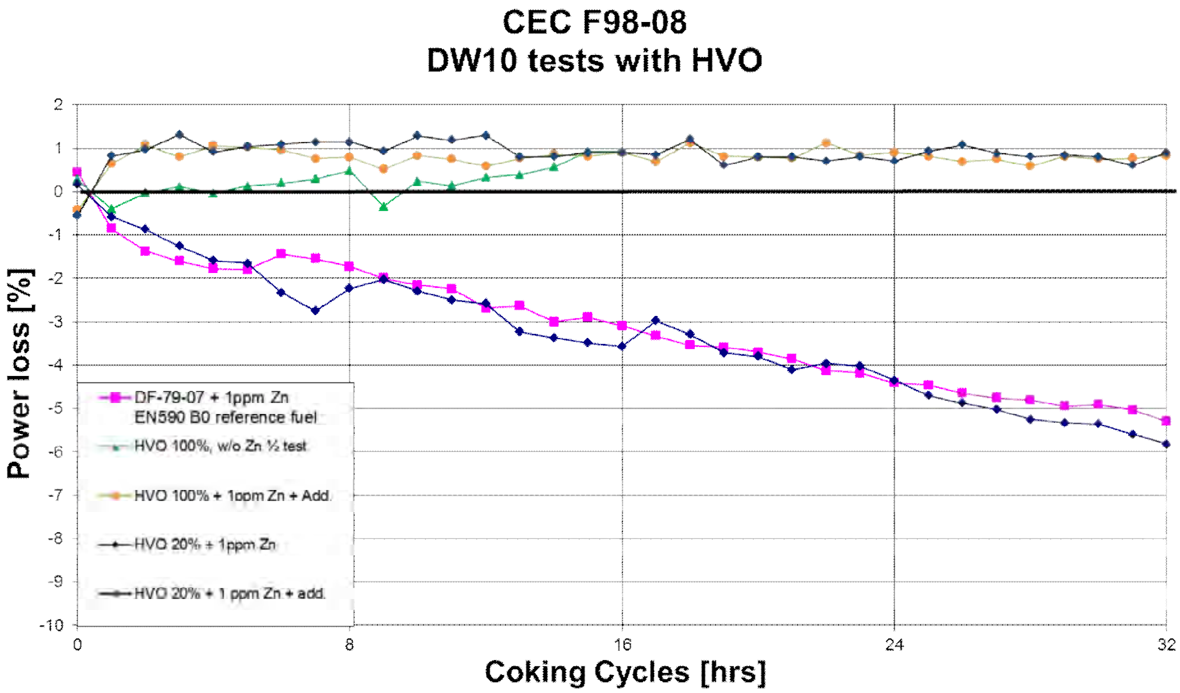

Figure. Injector fouling tests with DW10 engine. [Neste Oil Engine Laboratory tests].

The XUD9 test is based on a widely used old CEC test method which has been modified according to some engine updates. Because of that numerical scale of the results is not binding but in any case a lower value means cleaner injectors. HVO showed cleaner injectors than a high quality standard diesel fuel both as such and as a 30 % blend (figure).

Performance additive packages containing for example detergent, corrosion inhibitor and antifoam agents are used commonly in high quality diesel fuels. Although HVO has a good performance in injector fouling tests (XUD9), an additive package shall be considered at least for corrosion protection for cases where some water condensates in fuel logistics or vehicle fuel systems.

Sodium (Na) contamination in diesel fuel has been suspected to cause harmful internal deposits in fuel injectors. HVO should not have any negative effects since sodium content has been in all measurements below detection limit of analytical methods.

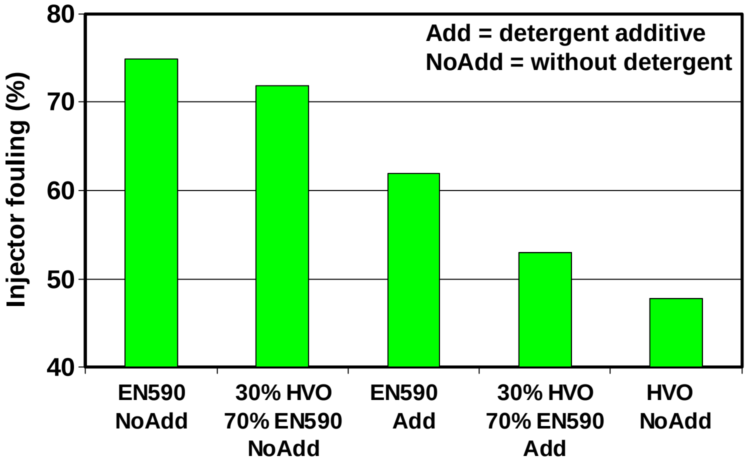

Figure. Injector fouling test results with XUD engine. Lower values are better. [Neste Oil Engine Laboratory tests].

Auxiliary heaters

HVO operates in fuel burning auxiliary heaters as well as or even better than fossil diesel. As opposed to FAME, HVO does not have any problems with cold properties and so it operates without troubles also in cold conditions.

A test with Webasto auxiliary heaters was conducted in 2013 in Finland. Deposit build up of the combustion chamber was assessed. A test cycle consisting of a 10 minute heating period and 50 minute cooling period was used. The cycle was run consequetively for 21 hours after which the heater was pulled apart and the combustion chamber was examined. Difference between commercial fossil EN 590 diesel and 100 % HVO was clear (Figure). Even after this relatively short test the combustion chamber of the fossil diesel heater had some deposits clearly visible as the HVO heater was practically clean.

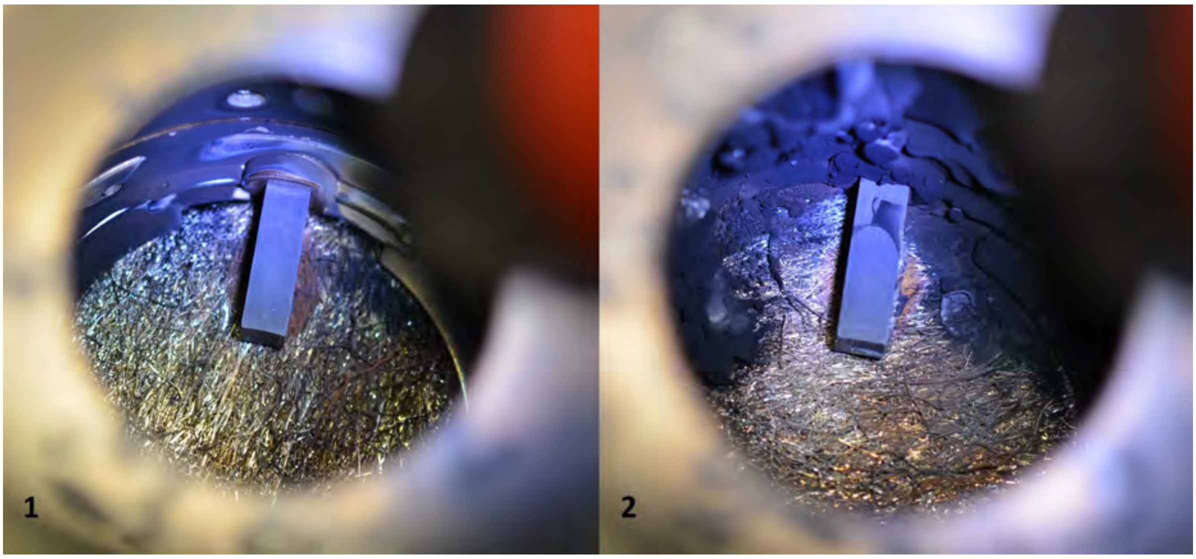

Figure. Combustion chambers of Webasto auxiliary heaters after the 21 hour test. A heater using 100 % HVO on the left (1) and a heater using fossil EN 590 diesel on the right (2).

Statements made by automotive industry

Automotive and fuel injection system companies
- prefer advanced paraffinic type biocomponents
- HVO supported by Worldwide Fuel Charter (WWFC) in order to avoid concenrs associated with FAME

Worldwide Fuel Charter (WWFC) published by engine and automotive manufacturer associations was updated in 2013. The new 5th edition (September 2013) does not allow the use of FAME at all in the best fuel category 5 as well as FAME was not allowed in category 4 of the previous 4th edition (September 2006). HVO is fully allowed without any blending limit in all fuel categories if the final fuel blend meet limits of each category.

The 5th edition of WWFC can be downloaded from
http://www.acea.be/uploads/publications/Worldwide_Fuel_Charter_5ed_2013.pdf
where part "Technical Background" defines comprehensively challenges and limitations related to the use of FAME and supports the use of HVO as a way to increase renewable content of diesel fuel:
- page 53 … 54 for FAME
- page 55 … 56 for HVO

The European Automobile Manufacturers Association ACEA reported in April 2010:

> *"Political support and appropriate policy tools are needed now to encourage the development and wider market access to new and more sustainable 'drop-in' advanced biofuels that could increase the biocontent in road transport fuels, e.g. HVO, BTL, cellulosic (or advanced) ethanol.*"

Bosch, Continental, Delphi, Denso and Stanadyne, all of them manufacturing diesel fuel injection systems, told in September 2009:

"The FIE manufacturers support the use of bioparaffins obtained by hydro-treatment or coprocessing of plant oil. Due to their paraffinic nature and high fuel and transport system compatibility, bioparaffins are also well-suited for blends with biogenic portions above 7 %."

Optimizing engines for HVO

HVO

- moves NO_x – particulate emission trade-off-curve towards origin
- moves NO_x – fuel consumption trade-off-curve towards origin
- for engine designers more freedom to choose between low NO_x, low particulates and/or good fuel economy
- up to -6 ... -8 % savings in mass fuel consumption: remarkable benefit also for CO_2
- already 30 % blend shows benefits
- optimum solution: combine development of fuel, engine and exhaust aftertreatment

Diesel engines today have been designed for fuel fulfilling EN 590 diesel standard in Europe or relevant standards on other continents. There has not been a major need for diesel engines that can adapt to fuel composition like gasoline-FFV vehicles. Now that high quality diesel fuels, like HVO and GTL, are available users would benefit from optimized engine calibrations based on fuel quality.

Diesel engines run without operability problems with neat HVO, but more benefits are obtained if engines are optimized for HVO or high amounts of HVO in the fuel. This is caused by the fact that HVO gives more freedom under NO_x – particulate emission and NO_x – fuel consumption trade-off phenomena which are well known challenges for engine designers. Also the control of EGR is essential for reducing NO_x as well as optimizing urea feed for SRC catalysts according to the real need. There are also studies made with other paraffinic fuels (GTL) which show development potential for optimizing the engine, fuel and exhaust aftertreatment together. By this approach "Diesel-FFV" vehicles could be designed as well as FFV-cars today adapting themselves automatically for gasoline, 85 % ethanol or any mixture of them. An other possibility could be to change engine mapping if vehicles are used by dedicated fleets which use only neat HVO as an alternative fuel.

Studies were made by changing engine software settings in a heavy duty engine (Table, Figure). With default engine settings results were in line with other tests made by heavy duty engines. With advanced fuel injection timing fuel consumption can be reduced remarkably, up to -6 ... -8 % by mass, if NOx reduction is done in an aftertreatment device. The reduced fuel consumption means smaller well-to-wheels CO_2 emissions which are important also for renewable fuels.

With retarded timing NO_x can be reduced remarkably but in this case the fuel consumption will be increased. Preliminary studies show that even more benefits can be obtained if the amount of EGR is optimized for HVO.

Table. Effect of HVO on emissions and fuel consumption by using different injection timing settings in a heavy duty engine without EGR and aftertreatment. Reference is EN 590 diesel fuel. [Aatola et al, 2008].

Injection timing ->	Default	Advanced	Remarkably advanced	Retarted
NO_x	-6 %	0 %	+4 %	-16 %
Smoke	-35 %	-37 %	-32 %	-32 %
Fuel cons (mass)	-3 %	-6 %	-8 %	0 %
Fuel cons (volume)	+5 %	+2 %	0 %	+8 %

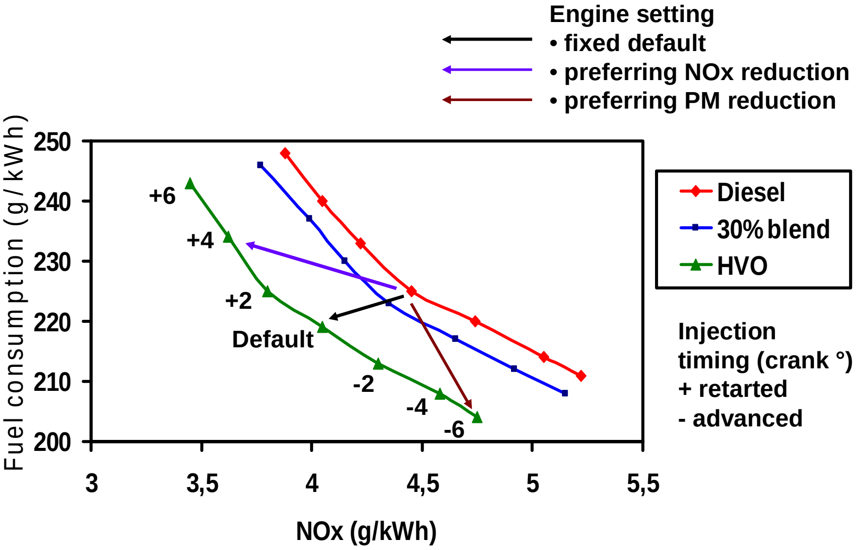

Figure. NO_x – fuel consumption trade-off curves of diesel fuel, diesel fuel with 30 % HVO and neat HVO. A modern direct injection heavy-duty engine, common rail fuel injection with different fuel injection advance settings [Aatola et al, 2008].

Field trials

HVO

- extensive trials in many countries
- fleets up to 300 vehicles
- mileages up to over 200 000 km/vehicle
- all year round including severe winters

Extensive field trials have been carried out with HVO in Finland, Germany and Canada. The fuel has performed excellently in these trials, both at 100 % content and a variety of blending ratios. There haven't been operability issues or need for extra maintenance regarding fuel filters, fuel systems, fuel hoses, seals in fuel systems, engines or exhaust aftertreatment device. The same has applied for fuel logistics: no difference compared to fossil diesel fuel regarding water, microbiological growth, storage stability and material issues.

About 300 buses were driving in Helsinki area from 2007 to 2010 with HVO all year round down to ambient temperatures below -25ºC. Most of the buses used a fuel blend containing up to 30 % of HVO in EN 590 fuel, and 11 buses run with HVO as such. Goal of this project was to improve quality of the urban air and to promote advanced biofuels in public transport. Both old and modern buses from several brands representing Euro II to EEV emission levels were included into the test fleet as well as some retrofit exhaust aftertreatment systems. Totally 50 million kilometers were run with the fuel blend and 1.5 million kilometers with the neat HVO. This means on average 170 000 km/bus and some of them were driving clearly more in this test. Totally 22 000 000 liters of blend fuel and 1 000 000 liters of neat HVO was consumed. There was no need for extra maintenance compared to standard diesel fuel. Analyses of used engine oils did not show any differences compared to running with standard diesel fuel. Neat HVO was left into a refueling storage tank for 8 months after the test was completed. The fuel was clear and free from microbiological growth after the storage time. [Nylund et al. 2011]

An all year round field trial in Germany started in 2008 with 10 Mercedes-Benz trucks and 4 Mercedes-Benz buses. They have run on 100 % HVO already over 3 million kilometers in total and over 200 000 km/vehicle on average. This trial was scheduled to last for three years in total and ended in 2011. Both field trial tests have included also numerous exhaust emission measurements.

A trial with 75 vehicles using 2 % HVO during the winter and 5 % during the summer was conducted in arctic environment in temperatures down to -44 °C in Alberta, Canada between 2006 and 2009. Federal and provincial governments together with Shell Canada sponsored the tests. HVO-blend operated without troubles.

In Finland a field trial with neat HVO started during the spring 2010 with more than 60 passenger cars. The fleet consists of various vehicle brands and different engine and injection system technologies. The objective is to prove the suitability of neat HVO for severe winter conditions and various driving conditions. Some of the vehicles undergo additional check-ups regularly for more detailed investigations. Until March 2012 more than 100 000 liters of neat NExBTL diesel had been consumed and the cars had travelled more than a million kilometers. No fuel related issues have arised during the field trial. This field trial is still on-going.

In Germany under project “Diesel regenerativ” two fleets of passenger cars run over 200 000 km with HVO blended with 2 % and 7 % RME in the course of a year without any fuel-related driver complaints. All vehicles were tested for regulated emissions at the beginning and end of the project period. The more extensive determination of the non-regulated emissions was only carried out on three vehicles of emission standards Euro 3, Euro 5 and Euro 6. Engine oil samples were taken from all vehicles and analyzed over the test period. In sum, emissions reductions for hydrocarbons, carbon monoxide and particulate matter were identified for “Diesel regenerative” in comparison to fossil diesel fuel (DF [B5]). However, the nitrogen oxide values were slightly elevated for “Diesel regenerative”.

In 2011 a field trial with two new 60 ton Scania 500R tanker trucks was started in Finland. The trucks have a 15.8 litre V8 Euro 5 engines using Scania PDE high pressure unit injectors. One truck was running on 100 % HVO and the other on normal commercial EN 590 (B0) diesel fuel. Approximately 300 000 km were driven with both trucks until the spring of 2013. The injectors were then bench tested and dismantled. There were no differencies in performance or wear between the two vehicles. During the trial no repairs or replacement parts were needed for the fuel system.

Market experience

Finland

HVO in Finland

- up to 30 % HVO blends sold publicly since 2007
- all year round including severe winters
- all over the country in thousands of service stations
- no modifications to fuel logistics or service stations
- no modifications to vehicles
- limited sales of HVO as such
- trouble free logistics and operation both with blends and as such
- used as a blending component in a premium diesel fuel meeting Worldwide Fuel Charter "WWFC" category 5

Premium EN 590 diesel fuel containing at least 10 % of HVO, claiming for example benefits of the higher cetane number, was sold in Finland publicly from 100 service stations from 2008 all year round even in severe winter conditions with good experience. The highest blending ratios were about 30 % and it did not contain any FAME.

During the fall of 2012 this premium grade was upgraded to meet Worldwide Fuel Charter ("WWFC", 4th edition 2006) Category 4 diesel fuel specification, which is a target for fuels used in the most modern vehicles. The fuel is fully suitable and beneficial also for old diesel vehicles This fuel was launched under the brand name of "Neste Pro Diesel". Neste Pro Diesel contains a minimum of 15% HVO (NExBTL) renewable diesel. According to studies, Neste Pro Diesel lowers fuel consumption, produces less emissions, increases engine power and fulfills the toughest cleanliness requirements [Hartikka et. al. 2013].

In the fall of 2013 5th edition of Worldwide Fuel Charter was published. The fifth edition introduces category 5 for highly advanced requirements for emission control and fuel efficiency. For diesel fuel, the fifth category establishes a high quality hydrocarbon only specification that takes advantage of the characteristics of certain advanced biofuels, including Hydrotreated Vegetable Oils (HVO) and Biomass-To-Liquid (BTL). Neste Pro Diesel fulfills the requirements of the toughest 5th category.

Biomandate in Finland is counted from the total sales of bioenergy in traffic fuels per calendar year. This means that an oil company is able to choose between different biocontents and biocomponents in gasoline and diesel fuel. As extreme examples, in principle it is allowed to cover the mandate by selling only fossil gasoline and a lot of HVO in diesel fuel, or only a lot of E85 and fossil diesel.

Service stations have sold EN 590 diesel fuel containing varying blending ratios of HVO in order to meet the national biomandate since 2007. The highest blending ratios have been 30 %. Fuel has been used in cars, vans, trucks and buses, and in minor amounts in non-road mobile machinery. Today the total amount of service stations selling this blend is about 2700 meaning that practically all outlets in the country sell HVO-blends.

Four service stations have sold neat HVO for dedicated customers from 2010. This has been used mainly in cars. HVO as such has also been delivered from 2008 into storage tanks of some bus fleets to be used in city buses.

All of the HVO blend and neat HVO deliveries have taken place all year round including also severe winters. Vehicles including the ones driving with neat HVO have been standard vehicles without any modifications. No technical modifications have been made for pipelines, storage tanks, tanker trucks and service stations. Experience shows that HVO blends have behaved similarly to fossil fuels regarding corrosion, storage stability, microbiological growth, water separation, elastomeric materials, delivery pump filters etc. issues that could appear in the logistic chain.

Other countries

HVO has been delivered from Neste Oil's Porvoo, Rotterdam and Singapore plants for many bulk customers in Europe and North America to be used for meeting biomandates and for blending premium diesel fuels with a good experience. Niche volumes have also been used as such by customers which are especially aware and keen on bioenergy or reduced tailpipe emissions. However, due to commercial contract reasons single customers and their fuel blending or marketing strategies cannot be identified here.

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Acronyms

AMS	Accelerated Mass Spectrometry
ASTM	International organization for standardization (previously American Society for Testing and Materials)
BTL	Bio-to-Liquids fuel made from biomass by Fischer-Tropsch synthesis
Bx	x = maximum allowed FAME content in diesel fuel
CEC	Co-ordinating European Council (for engine etc. test methods)
CEN	European Committee for Standardization
CFPP	Cold Filter Plugging Point
CN code	Combined Nomenclature for customs and trade statistics
CO	Carbon monoxide (tailpipe emission)
CO_2	Carbon Dioxide (direct tailpipe emission or well-to-wheels emission)
CTL	Gas-to-Liquids fuel made from coal by Fischer-Tropsch synthesis
CWA	CEN Workshop Agreement (possible 1st step for preparing a standard)
DCN	Derived Cetane Number
DPF	Diesel Particulate Filter
ECU	Engine Control Unit
EGR	Exhaust Gas Recirculation
EN	European Standard prepared by CEN
E95	Fuel for modified diesel engines containing 95 % ethanol and additives
FAME	Fatty Acid Methyl Ester (biodiesel)
FFV	Flexible Fuel Vehicle
FIE	Fuel Injection Equipment
FQD	“Fuel Quality Directive”, directive 2009/30/EC
GC	Gas Chromatographic distillation
GTL	Gas-to-Liquids fuel made from natural gas by Fischer-Tropsch synthesis
HBD	Hydro-generated Biodiesel
HC	Hydrocarbons (tailpipe emission)
HDRD	Hydrogenation Derived Renewable Diesel
HFRR	High Frequency Reciprocating Rig (device for measuring fuel lubricity)
HVO	Hydrotreated Vegetable oil
ILUC	Indirect Land Use Change
IMO	International Maritime Organization
LCS	Liquid Scintillation Counting
LPG	Liquified Petroleum Gas
MARPOL	International Convention for Prevention of Pollution from Ships
NEXBTL^{TM}	Neste Oil’s brand and trademark for HVO process and HVO products
NO_x	Nitrogen oxides (tailpipe emission)
PAH	Polycyclic Aromatic Hydrocarbons (tailpipe emission)
PM	Particulate Matter (tailpipe emission)
PME	Palm oil Methyl Ester (biodiesel)
REACH	European Community Regulation on chemicals and their safe use
RED	“Renewable Energy Directive”, directive 2009/28/EC
RME	Rapeseed Methyl Ester (biodiesel)
SME	Soybean Methyl Ester (biodiesel)
SMG	Saturated Monoglycerides (impurities from FAME)
^{TM}	Trademark
TS	CEN Technical Specification (possible 2nd step for preparing a standard)
XTL	BTL, CTL and GTL fuels made by Fischer-Tropsch synthesis