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Nils-Olof Nylund, Kimmo Erkkilä, Matti Ahtiainen, Timo Murtonen, Pirjo Saikkonen, Arno Amberla & Hannu Aatola

Optimized usage of NExBTL renewable diesel fuel

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Abstract

Helsinki Region Transport, Neste Oil, Proventia Emission Control, VTT Technical Research Centre of Finland and Aalto University carried out a 3.5 year PPP venture "OPTIBIO" to demonstrate the use of paraffinic renewable diesel (hydrotreated vegetable oil HVO) in city buses. The project cooperated with the bus manufacturer Scania. The fleet test in Metropolitan Helsinki, involving some 300 buses at four bus operators, was the largest one in the world to demonstrate this new fuel. The fuels were a 30 % HVO blend and 100 % HVO. The field test was supplemented by a comprehensive in-laboratory research programme on fuel effects on exhaust emissions and low-temperature operability.

All in all, the vehicles accumulated some 50 million kilometres between September 2007 and December 2010, of which some 1.5 million kilometres on 100 % HVO. Average distance per vehicle was some 170,000 km. The amounts of fuel used were about 22 million litres of blended fuel and 1 million litres of neat HVO.

The project confirmed that HVO actually works as a drop-in fuel, meaning that HVO can replace diesel fuel 100 % without any modifications to the refuelling system or to the vehicles, without causing any operational problems. The emission testing, both the screening and the follow-up measurements, demonstrated significant and permanent emission benefits. Based on the findings of the OPTIBIO project, Scania has approved the use of 100 % HVO (NExBTL) in its city and intercity buses with DC9 engines. After the demonstration phase, the markets will determine the future of high concentration HVO fuels in Finland. Low-level blending is already used commercially to fulfil the general biofuels obligation.

Preface

Between the fall of 2007 and December 2010 Helsinki Region Transport, Neste Oil and Proventia Emission Control carried out the world's largest field test on paraffinic renewable diesel fuel. Some 300 buses at four operators in Metropolitan Helsinki and also the bus manufacturer Scania took part in this exercise. VTT Technical Research Centre of Finland, Aalto University and TEC TransEnergy Consulting Ltd provided technical support to the project.

The objective was to demonstrate the feasibility of high-concentration paraffinic renewable diesel fuels for buses, for reduced local emissions as well as for increased use of biofuels. The buses in the test fleet were used in everyday service. The field test was supplemented by a comprehensive in-laboratory research programme on fuel effects on exhaust emissions and low-temperature operability.

The OPTIBIO project had a steering group with representatives from the principal partners and Tekes – the Finnish Funding Agency for Technology and Innovation. Mr. Reijo Mäkinen from Helsinki Region Traffic acted Chairman of the group. Ms. Marjatta Aarniala represented Tekes. Dr. Nils-Olof Nylund served as coordinator of the project.

The OPTBIO project received public research funding from the BioRefine programme by Tekes, and in addition, a tax exemption for the biocomponents used in the project. The project group wants to express its gratitude to the supporters of the project. In addition, the group wants to acknowledge the four bus operators, who made the practical execution of the project possible.

Espoo 30.9.2011

Dr. Nils-Olof Nylund

Coordinator of OPTIBIO

TEC TransEnergy Consulting Ltd/VTT Technical Research Centre of Finland

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List of abbreviations

AA	Acetaldehyde
ASTM	American Society for Testing and Materials
BTL	Biomass-to-liquids
Bxx	xx concentration (v/v) of FAME in diesel
CA	Crank angle
CAN	Controller-area network
CEN	European Committee for Standardization
CFPP	Cold filter plugging point
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalent
CP	Cloud point
CTL	Coal-to-liquids
CVS	Constant volume sampler
CWA	CEN Workshop Agreement
DF	Diesel fuel
DNPH	2,4-Dinitrophenylhydrazine (Brady's reagent) for aldehyde sampling
DPF	Diesel particulare filter
EEV	Enhanced environmentally friendly vehicle
EGR	Exhaust gas recirculation
ELPI	Electrical low pressure impactor
ENxxx	European fuel standard
ESC	European steady cycle
ETC	European Transient Cycle

EU	European Union
Euro II…EEV	Heavy-duty emission certification classes for Europe, EEV meaning “Enhanced Environmentally Friendly Vehicle”
Exx	xx concentration (v/v) of ethanol in petrol
FA	Formaldehyde
FAME	Fatty-acid methyl ester
FBT	Filter blocking tendency
FC	Fuel consumption
FSN	Filter smoke number
FT	Fischer-Tropsch
FTF	Flow-through filter
FTIR	Fourier transform infrared spectroscopy
CG	Gas chromatography
GC/MS-SIM	Gas chromatography – Mass spectrometry with selected ion monitoring
GHG	Greenhouse gases
GTL	Gas-to-liquids
HC	Hydrocarbons
HFRR	High-frequency reciprocating rig
HPLC	High-performance liquid chromatography
HVO	Hydrotreated vegetable oil
ISCC	International Sustainability & Carbon Certification
LPG	Liquefied petroleum gas
MSAT	Mobile source air toxic
MY	Model year
NO_x	Nitrogen oxides
NO_2	Nitrogen dioxide

PAH	Polyaromatic hydrocarbons
p-DPF	Partial diesel particulate filter
PM	Particulate matter
PPP	Public-private partnership
PTFE	Polytetrafluoroethylene
RME	Rapeseed methyl ester
rpm	Revolutions per minute
“s”	Summer grade
SCR	Selective catalytic reduction (for NO_x)
SFC	Specific fuel consumption
TAN	Total acid number
TBN	Total base (buffer) number
THC	Total hydrocarbons
“w”	Winter grade

Background and set-up of the project

Photo: Neste Oil.

1. Introduction

Buses are the backbone of many public transport systems. Although in principle buses are to be favoured over passenger cars, especially older buses can make a significant contribution to local pollution of particulates and oxides of nitrogen. Many cities around Europe suffer from bad air quality, and improved fuels can be helpful in reducing local emissions. When implemented, paraffinic diesel fuels can reduce emissions from new as well as existing vehicles immediately, whereas use of e.g. natural gas (methane) requires new dedicated vehicles and refuelling infrastructure that both require investments and take time.

There are also requirements to introduce renewable fuels in transport, and the public sector is expected to act as a trend-setter. In Europe, the 2003 Biofuels Directive 2003/30/EC set an indicative target of 5.75 % biofuels for 2010. The Directive on the promotion of the use of energy from renewable sources 2009/28/EC sets a mandatory target of minimum 10 % renewable energy (biofuels and renewable electricity) in transport in 2020. As electric vehicles are just only starting to enter the market, it is easy to foresee that the greater part of the renewables target for transport must be met using biofuels. In Finland, a new ambitious obligation law for biofuels (1420/2010) requires 20 % biofuels in 2020.

Today biofuels, especially in the case of biodiesel, is an imprecise word meaning various products with different origin and different end-use properties. Biofuels can, in principle, be used as such or as blending components in conventional fuels.

Biofuels can be divided into two main categories (Nylund et al. 2008):

a. conventional biofuels
b. next generation or second generation advanced biofuels.

However, the terminology is still not fully established, and in reality the situation is not just “black and white,” there are also shades of grey. Setting the criteria could be looked upon from two different angles, from a feedstock and process point of view and from an end-use point of view.

The criteria for advanced biofuels from an end-use point of view could be:

- at least equivalent end-use quality compared with the current high-quality sulphur-free mineral oil based fuels
- compatibility with existing refuelling infrastructure
- compatibility with existing as well as new sophisticated vehicles
- fuel components that do not only provide heating value, but also a possibility for reduced harmful exhaust emissions.

There are technical challenges in using conventional first generation biocomponents. The term “blending wall” has been introduced to describe limitations and critical concentrations. Conventional FAME (fatty-acid methyl ester) biodiesel is troublesome especially in diesel vehicles equipped with exhaust after-treatment devices. High concentration of FAME has been found to cause e.g. poisoning of catalysts and filters due to fuel impurities, and in addition, fuel dilution of the engine oil in engines with active diesel particulate filter (DPF) regeneration (Fukuda et al. 2008, Parsons 2009, Jääskeläinen 2010).

For these reasons the current fuels quality Directive for Europe, 2009/30/EC, limits ethanol concentration in petrol to 10 % v/v (E10) and concentration of esterified biodiesel FAME in diesel to 7 % v/v (B7). The limits are set to ensure proper functioning of vehicles, low emissions and integrity of vehicles including their exhaust after-treatment devices.

Subsequently, the contribution of conventional biocomponents to renewable energy is limited: the addition of 10 % v/v of ethanol to petrol as well as of 7 % v/v of FAME to diesel only delivers approximately 6.5 % of renewable energy. This means that reaching the minimum target of 10 % renewables in transport in 2020 set by Directive 2009/28/EC cannot be met only by using low-level blending of conventional biocomponents.

There are, however, better fuel alternatives, especially in the case of diesel fuels. Paraffinic diesel fuel works as a “drop-in” substitute fuel, meaning that the fuel can be distributed using the existing refuelling infrastructure, and can be used in the existing vehicle fleet without any modifications whatsoever.

Paraffinic diesel, whether from fossil or biogenic sources, is a clean-burning fuel lowering exhaust emissions and local pollution. Synthetic diesel from natural gas (gas-to-liquids, GTL) is probably the best known paraffinic fuel. Another fossil alternative is synthetic diesel from coal (coal-to-liquid, CTL), produced, e.g., in South Africa.

Paraffinic fuels can also be produced from renewable feedstocks, through gasification and synthesis from solid biomass (biomass-to-liquids, BTL) and through hydrotreatment of vegetable oils and animal fats (hydrotreated vegetable oil, HVO). Of these BTL is still in the development phase, whereas HVO is already commercial. Paraffinic diesel from renewable sources is of special interest to municipalities responsible for public transport, as this kind of fuel enables high shares of biocomponents as well as reduced local pollution. Renewable paraffinic diesel could therefore be a viable option in greening the public transport systems based on buses.

2. Goal

The goal of the OPTIBIO project was to verify the feasibility of high quality, high concentration biofuels as fuels for captive urban fleets. In this case, the fuel was paraffinic renewable diesel fuel made by hydrotreatment of vegetable oils and animal waste fats (HVO, Neste Oil's brand name NExBTL). Focused use of high quality renewable diesel fuel will not only reduce greenhouse gas emissions, but most important, also reduce harmful local emissions, especially particulates and oxides of nitrogen.

The effect on greenhouse gas emissions depends on the type of fuel (carbon balance) and the total amount of biofuel, not on how the biofuel is used (low-level blending vs. high concentration). However, to achieve reductions in local emissions low-level blending is not enough, but one has to strive for high-concentration paraffinic fuels, preferably neat paraffinic fuels. Thus the aim was to study how to best make use of the high quality renewable fuel, regarding vehicle performance and integrity, exhaust emissions as well as the performance of various types of exhaust after-treatment systems.

The core activity of the OPTIBIO project was a large fleet test involving some 300 city buses in Helsinki Metropolitan Area. The fleet test was complemented by comprehensive engine and vehicle measurements in laboratory conditions, as well as laboratory analysis.

The widespread use of high concentration biofuels is only possible if these fuels are complying with fuel standards and are approved by the vehicle manufacturers as well as by the fleet operators. Therefore, the field test was conducted in close cooperation with one vehicle manufacturer, Scania, and several bus fleet operators. Regarding standardisation, progress has been made as the European Committee for Standardization CEN launched a so-called Workshop Agreement (pre-standard) for paraffinic diesel fuel in February 2009, CEN CWA 15940 (CEN 2009).

The OPTIBIO project itself focused on end-use issues only and did not cover feedstocks or fuel conversion. Despite, feedstocks and processing are briefly touched upon in this report.

The OPTIBIO project also included testing of retrofit exhaust after-treatment devices in conjunction with HVO fuels, both in laboratory conditions and in the field. High quality fuel in combination with relative simple exhaust after-treatment devices suitable for retrofitting can significantly reduce the emissions of older vehicles, thus extending their service life to be used as e.g., peak hour vehicles.

3. Project partners

The OPTIBIO project is a good example of a successful public-private partnership. The initiative for the OPTIBIO project originally came from Helsinki Metropolitan Area Council. At the time of the start of the project there were two bodies responsible for bus service procurement, Helsinki Metropolitan Area Council and Helsinki City Transport. Helsinki City Transport was responsible for the bus services within the borders of Helsinki, the Helsinki Metropolitan Area Council for the rest of the bus services in greater Helsinki (e.g. internal Espoo and Vantaa, traffic crossing municipality borders). As of 2010, the two bodies merged into one entity, Helsinki Region Transport.

The primary OPTIBIO partners were:

- Helsinki Region Transport (formerly Helsinki Metropolitan Area Council and Helsinki City Transport): municipal body responsible for public bus service procurement
- Neste Oil: refining company, developer and producer of renewable HVO diesel fuel (brand name NExBTL)
- Proventia Emission Control (formerly Finnkatalyt): developer and producer of retrofit exhaust gas after-treatment systems.

Each of the partners had their own special interest. Helsinki Region Transport wanted to demonstrate the environmental benefits of using renewable paraffinic diesel fuel in buses. For Neste Oil, the OPTIBIO project with its comprehensive emission measurements and long-running field test constitutes an important reference in the development and market introduction of advanced renewable diesel fuel. For Proventia Emission Control, the project provided an opportunity to test various kinds of exhaust after-treatment systems with the new fuel and to collect data from actual bus service.

The primary partners invited three subcontractors and one bus manufacturer to join the project:

- VTT Technical Research Centre of Finland: responsibility for chassis dynamometer emission measurements and follow-up of the field test
- Aalto University (formerly Helsinki University of Technology): engine testing to establish the effects of HVO fuel and various engine parameters on the emissions of a diesel engine equipped with a common-rail fuel injection system
- TEC TransEnergy Consulting Ltd: coordination and reporting.
- Scania: bus manufacturer.

In addition, the four bus operators (Helsingin Bussiliikenne, Pohjolan Liikenne, Porvoon Liikenne, Veolia Transport Finland), who were actually operating the 300 buses participating in the project, were instrumental to the success of the project.

4. Tasks of the OPTIBIO project

There were six main experimental tasks within the OPTIBIO project:

1. Field testing of blends of diesel and HVO and neat HVO
2. Analysis of fuels, lubricants and fuel injection equipment
3. VTT's emission and fuel consumption measurements on heavy-duty vehicles using VTT's heavy-duty chassis dynamometer
4. A Thesis for the Master's Degree on the effects of HVO fuel and various engine parameters on the emissions of a diesel engine equipped with a common-rail fuel injection system
5. Testing of retrofitted exhaust gas after-treatment devices using in-laboratory measurements as well as field testing
6. Testing of low temperature operability and low temperature exhaust emissions with HVO using diesel passenger cars.

The most important elements of the OPTIOBIO project were the large field test and the associated emission measurements. The field testing had the following objectives:

- to establish the general functionality and performance of the new fuel
- to bring out possible operational problems (e.g. driveability, low-temperature operability, fuel leaks, filter blocking etc.)
- to establish actual fuel consumption figures
- to establish the effects of HVO fuel on engine wear (e.g. through engine oil analyses and injection equipment inspections)
- to establish possible ageing of the fuels during storage and vehicle operation (analysing fuel samples from storage as well as vehicle tanks)

- to establish emission stability of buses using HVO fuels
- to demonstrate the performance of retrofitted exhaust gas after-treatment devices in conjunction with the new fuel.

Neste Oil was responsible for the fuel and lubricating oil analyses. In addition, Neste Oil coordinated injection equipment check-ups and performed rig testing with injection systems. The objective of these activities was to make sure that no unwanted or sudden degradation took place in the engines of the fleet test vehicles or in the fuel itself.

VTT carried out exhaust emission and fuel consumption measurements on heavy-duty vehicles using a transient type heavy-duty chassis dynamometer for the following purposes:

- screening measurements using different HVO concentrations (0–100 %) in several vehicles representing varying levels of sophistication (emission certification classes Euro II – EEV) to establish the effects of HVO fuels on exhaust emissions (regulated components) and fuel consumption
- special exhaust emission measurements for unregulated emission components with reduced vehicle and fuel matrix (polyaromatic hydrocarbons PAH, particulate size distribution etc.)
- repetitive follow-up measurements of certain field test vehicles to establish emission stability (both regarding HVO fuel and retrofitted exhaust gas after-treatment devices).

All exhaust emission measurements by VTT were carried out with complete vehicles using standard settings of the engines. In general, running 100 % HVO in an engine with standard settings will simultaneously reduce emissions of nitrogen oxides (NO_x) and particulates (PM) compared to regular diesel fuel, with negligible effects on fuel efficiency. However, changing engine parameters, such as injection timing, makes it possible to balance NO_x, PM and fuel consumption. One alternative way of making use of neat HVO would be to tune the engine for a NO_x level corresponding to the baseline case. This kind of setting would enhance fuel efficiency and give further support in particulate suppression. Aalto University carried out measurements with an engine installed in an engine dynamometer to study the effects of varying engine settings.

Proventia Emission Control wanted to study various kinds of retrofit exhaust after-treatment devices in combination with HVO fuel. It is a well known fact that FAME can cause troubles in conjunction with exhaust after-treatment devices. These problems can be avoided with HVO, as HVO does not contain ash forming impurities. In addition, end-of-distillation temperature for HVO is lower than for regular diesel, not higher as in the case of FAME. High boiling end can cause, e.g., incomplete combustion and fuel dilution of the engine oil.

In laboratory conditions, several after-treatment system configurations were evaluated, including flow-through (partial) filters (FTF, p-DPF), actual wall-flow filters (DPF) and combinations of DPF plus SCR (selective catalytic reduction). Some of the older field test vehicles were equipped with FTF-type devices, and the performance of these devices was monitored through emission measurements.

5. Fuel technology

5.1 General

The composition of diesel fuel affects exhaust emissions. Lowering aromatic content, sulphur content and end-point of distillation reduces exhaust emissions and/or harmfulness of the exhaust. Especially heavy polyaromatic hydrocarbons should be avoided. Over the years, exhaust emission regulations and fuel specifications have been developed side-by-side to enable significant emission reductions, both through direct effects on emissions and by enabling the use of sophisticated exhaust after-treatment devices.

In Sweden low-emission diesel fuel, Environmental Class 1 diesel (MK1), has been used already for a long time. The MK1 fuel is characterised by very low sulphur content, low distillation end-point (320 ^{o}C), low content of aromatic compounds (total aromatics max. 5 %, tri- and heavier aromatics max. 0.02 %) and low density (800–820 kg/m^3). Tax incentives have been used to stimulate the use of MK1 fuel. (de Serves 2009)

High-quality paraffinic diesel from synthesis or hydrotreatment can be used to enhance diesel fuel quality (“preeming”), or alternatively when used as such, to deliver significant reductions of local emissions. The main objectives of the OPTIBIO project were to demonstrate the emission benefits of paraffinic HVO and to verify the general functionality of the new fuel.

5.2 Alternative routes to renewable diesel fuel

Esterification is the traditional way of processing biodiesel. The main advantage of this technology is relatively simple and inexpensive processing equipment. The processing of fatty-acid methyl esther (FAME) also generates glycerine as a by-product.

As mentioned in Chapter 1, conventional FAME biodiesel has a number of shortcomings regarding performance. Therefore, the current fuel Directive and the European standard EN590 limit FAME concentration in regular diesel fuel to 7 % (vol.) to ensure proper functionality. High-concentration FAME fuels have poor performance in low temperature conditions, e.g. poor cold flow properties. In addition, the high-boiling fuel delivers poor startability and causes fuel dilution of the engine oil. FAME is good for reduced particulate emissions, but regarding emissions, the backside is increased NO_x emissions. Impurities of FAME may also harm exhaust after-treatment devices. Figure 5.1 shows examples of trace element concentrations for various types of crude bio-oils and esterified biodiesel fuels. Calcium and phosphorus are especially troublesome for particulate filters. One additional drawback is that FAME has a short shelf-life, meaning that it is not suited for extended storage.

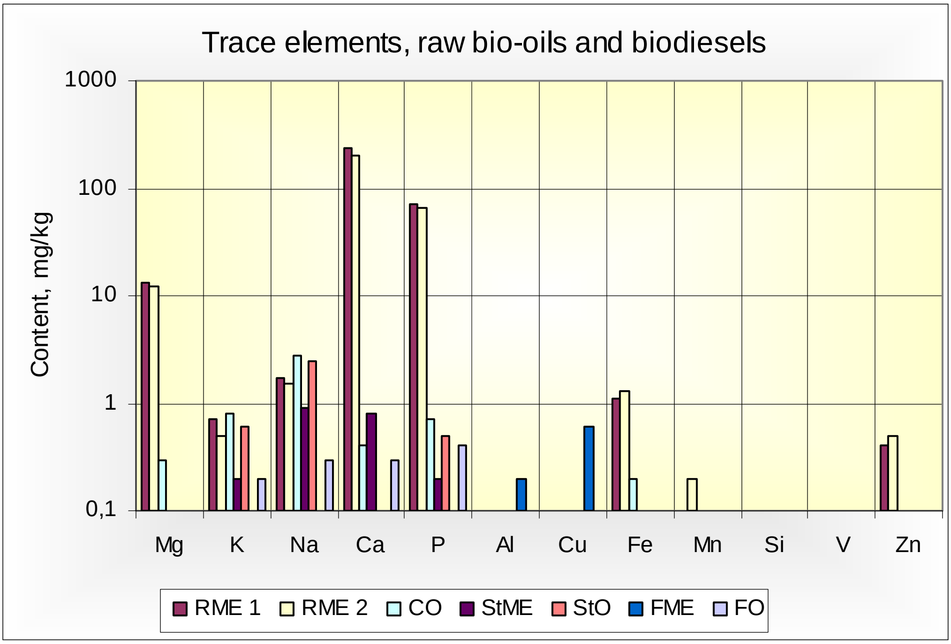


Figure 5.1. Trace elements for various types of crude bio-oils and esterified biodiesel fuels. RME = rapeseed methyl ester, CO = animal fat derived crude bio-oil, StME = fish based methyl ester, StO = fish based crude bio-oil, FME = animal fat derived methyl ester, FO = animal fat derived crude bio-oil. (Niemi 2011)

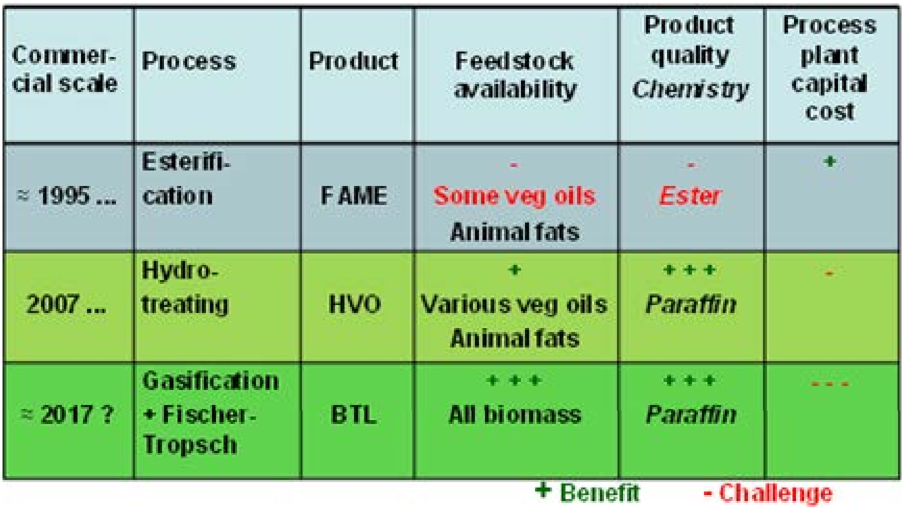
In the case of conventional biodiesel FAME, the properties of the fatty acids will affect the properties of the end product. Properties of vegetable oils vary widely, and those property differences in feedstocks can have profound effects on the properties of the finished biodiesel product, the fatty acid alkyl ester. Affected properties can cause large differences in performance in the areas of emissions (especially NO_x), cetane number, cold flow properties, and stability. Property variations are directly related back to the degree of saturation (number of double bonds between carbon atoms) of the feedstock (McGill et al. 2008).

When applying **hydrotreatment** and isomerisation on fatty acids, a technology which will be discussed in detail in the following paragraph, the processing decouples the dependence between feedstock and end-product quality, and this definitely is a major benefit. The end product is high quality paraffinic diesel. The processing equipment needed HVO is more sophisticated and expensive than for FAME production, and not suitable for small-scale production.

The third basic alternative is **gasification** of solid biomass and applying the Fischer-Tropsch **synthesis** to deliver liquid fuels (BTL). The crude Fischer-Tropsch waxes require additional processing for diesel. Fischer-Tropsch -based diesel is also paraffinic. Actual BTL is still in the development phase. BTL production will be very complicated and capital intensive. Neste Oil is also working on gasification based BTL fuels in a consortium with the pulp and paper company Stora Enso and VTT Technical Research Centre of Finland (NSE Biofuels 2009).

Table 5.1 presents a general overview of processes for renewable diesel.

Table 5.1. Characteristics of processes for renewable diesel. (Aatola et al. 2008).



Commercial scale	Process	Product	Feedstock availability	Product quality *Chemistry*	Process plant capital cost
≈ 1995 ...	Esterification	FAME	- Some veg oils Animal fats	- *Ester*	+
2007 ...	Hydrotreating	HVO	+ Various veg oils Animal fats	+ + + *Paraffin*	-
≈ 2017 ?	Gasification + Fischer-Tropsch	BTL	+ + + All biomass	+ + + *Paraffin*	- - -

+ Benefit - Challenge

5.3 Hydrotreated vegetable oil (HVO) processing and fuel properties

Hydrotreatment of fatty acids (vegetable oils and animal fats) is a new way of producing high-quality renewable diesel fuel. The HVO fuel can be used as such in the existing refuelling infrastructure and existing vehicles without adverse effects to fuel distribution, engines, exhaust after-treatment devices or exhaust emissions. Thus, HVO is a “drop-in” fuel, unlike FAME.

Hydrotreatment renders paraffinic hydrocarbons with zero sulphur, zero aromatics and high cetane. The end product is a clear liquid. Figure 5.2 presents the chemistry of hydrotreatment of fatty acids and Figure 5.3 shows the schematics of Neste Oil’s proprietary NExBTL process for hydrotreated vegetable oil (HVO). The NExBTL process combines oxygen removal from the fatty acid through hydrotreatment and isomerisation to form branched paraffins. Isomerisation is used to adjust the cold flow properties of the product. After isomerisation the product consists of a mixture of n- and isoparaffins. The NExBTL process can even be tuned to deliver aviation kerosene. The NExBTL process also delivers a small amount of bio-petrol and bio-LPG, but no low-value glycerine. When striving for good cold flow properties for the diesel fuel, the share of bio-petrol goes up and the yield of diesel goes down which means that for economic reasons, overdoing cold properties should be avoided. Diesel fuel from the NExBTL process has superior performance compared to regular diesel fuel, whereas the petrol stream does not deliver a corresponding quality advantage, although it is a biocomponent, and therefore has value. Thus the process is normally controlled to maximise diesel yield.

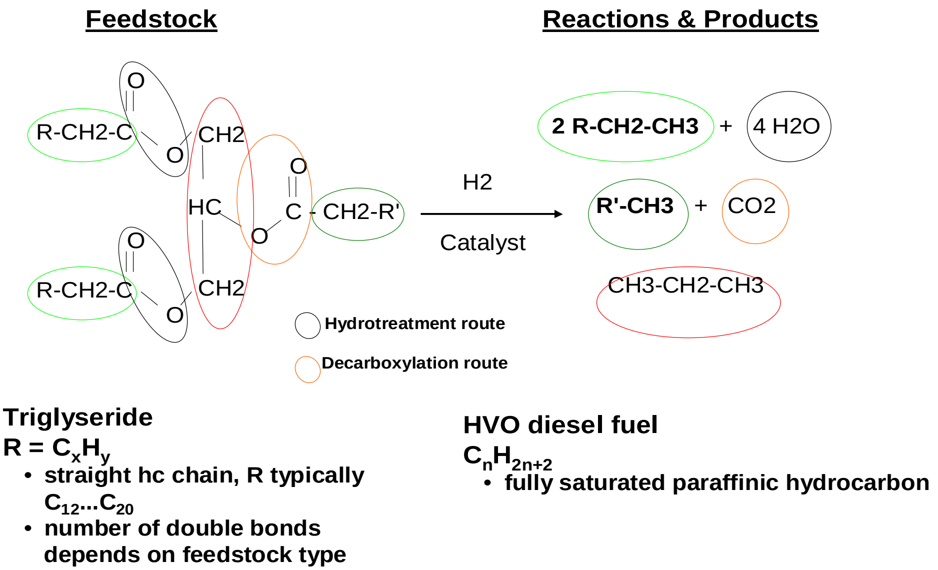


Figure 5.2. Chemistry of hydrotreatment of fatty acids. Figure by Seppo Mikkonen, Neste Oil.

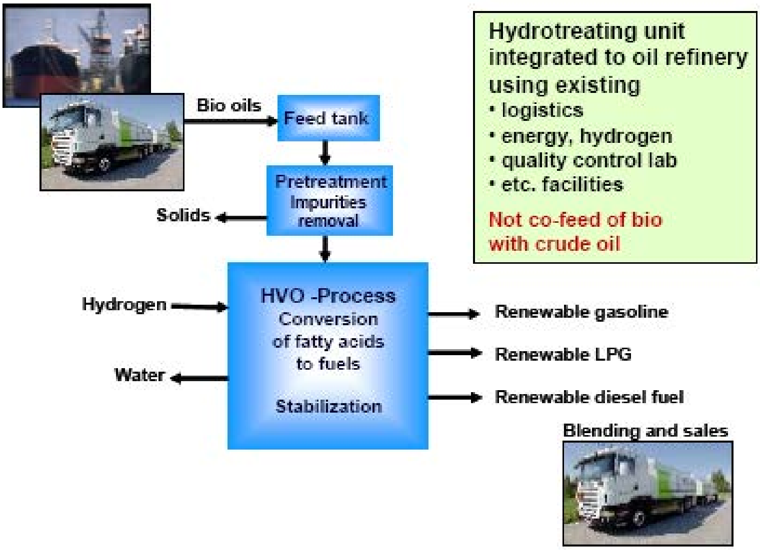


Figure 5.3. The schematics of Neste Oil's NExBTL process. (Aatola et al. 2008)

It can be said that the HVO processing combines the feedstock of FAME production with the end-use performance of high-quality synthetic fuels. However, as the interrelation between feedstock and end-product performance is broken using hydrotreatment, HVO processing deliver higher feedstock flexibility that conventional FAME processing.

NExBTL diesel, which is a clear liquid (Figure 5.4), has very high cetane number, above 80. As for other properties, NExBTL resembles synthetic fuels produced using the Fischer-Tropsch synthesis (BTL, CTL, GTL).

Figure 5.4. Appearance of NExBTL fuel.

During the period of the OPTIBIO project, CEN, the European Committee for Standardization launched a pre-standard, a so-called Workshop Agreement, on paraffinic diesel fuel. The CEN Workshop Agreement 15940 states as follows (CEN 2009):

> *"The Workshop Agreement has been laid down to define a specification for diesel fuel on the basis of synthesis gas (from natural gas, coal or biomass) or of hydrotreated vegetable or animal oils. Its main use is as diesel fuel in dedicated diesel vehicle fleets. Paraffinic diesel fuel does not meet the current diesel fuel specification, EN590. The main differences between paraffinic diesel fuel and automotive diesel fuel are in the areas of distillation, density, sulfur aromatics and cetane. Its low density is outside the regular diesel specification.*
>
> *From an environmental perspective, paraffinic diesel is a high quality, clean burning fuel with virtually no sulphur and aromatics. Paraffinic diesel fuel can be used in existing diesel engines*[1] *substantially reducing regulated emissions. In order to have the greatest possible emissions reduction, a specific calibration may be necessary."*

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[1] Engine warranty may require additional validation steps, dedicated pump marking is recommended

Figure 5.5, showing conventional diesel fuel and paraffinic diesel fuel burning in open beaker, illustrates the environmental benefits of paraffinic diesel fuel.

Figure 5.5. Diesel fuels burning in open beakers. Conventional diesel fuel on the left, paraffinic diesel fuel on the right. (ASFE 2006)

It should be noted that the Workshop Agreement covers end-use properties of fuels from synthesis (Fisher-Tropsch) as well as fuels made by hydrotreatment of fatty acids, and that it doesn't differentiate between feedstock or processing method. Therefore end-use experience generated with hydrotreated vegetable oil HVO will also be valid for synthesis gas based actual BTL fuels (biomass-to-liquids) and vice versa.

Neste Oil's NExBTL fulfils the requirements of CWA 15940 (Appendix 1). Since NExBTL or HVO is a 100 % hydrocarbon fuel, the fuel also fulfils the requirements in most diesel fuel standards and specifications, e.g. EN590, ASTM D975, Worldwide Fuel Charter Category 4 (WWFC 2006), with the exception of density. The density for HVO is typically 780 kg/m^3. A blend of regular diesel fuel and 30 % HVO fulfils all EN590 requirements (min. density 800/820 kg/m^3). Table 5.2 presents properties of various fuels (typical values). Hereinafter the generic acronym HVO will be used in the text.

Table 5.2. Typical properties of HVO, European EN590:2009 diesel fuel, GTL and FAME. Table compiled by Seppo Mikkonen, Neste Oil. Actual data for OPTIBIO test fuels (30 % and 100 % HVO) is presented later on in this report.

	HVO (NExBTL)	EN590 (summer grade)	GTL	FAME (from rape seed oil)
Density at 15 °C (kg/m^3)	775 ... 785	≈ 835	770 ... 785	≈ 885
Viscosity at 40 °C (mm^2/s)	2.5 ... 3.5	≈ 3.5	3.2 ... 4.5	≈ 4.5
Cetane number	≈ 80 ... 99	≈ 53	≈ 73 ... 81	≈ 51
Distillation range (°C)	≈ 180 ... 320	≈ 180 ... 360	≈ 190 ... 330	≈ 350 ... 370
Cloud point (°C)	−5 ... −35	≈ −5	−0 ... −25	≈ −5
Heating value, lower (MJ/kg)	≈ 44.0	≈ 42.7	≈ 43.0	≈ 37.5
Heating value, lower (MJ/l)	≈ 34.4	≈ 35.7	≈ 34.0	≈ 33.2
Total aromatics (wt-%)	0	≈ 30	0	0
Polyaromatics (wt-%)(1)	0	≈ 4	0	0
Oxygen content (wt-%)	0	0	0	≈ 11
Sulfur content (mg/kg)	< 10	< 10	< 10	< 10
Ash, metals	≈ 0	≈ 0	≈ 0	Challenge
Lubricity HFRR at 60 °C (μm)	< 460(2)	< 460(2)	< 460(2)	< 460
Storage stability	As for diesel	Good	As for diesel	Challenge

(1) European definition including di- and tri+ -aromatics

(2) With lubricity additive

The FAME ester specifications (EN14214, ASTM D6751) do not apply for HVO. FAME esters, on the other hand, do not fulfil CWA 15940.

In the spring of 2011 CEN started work to develop the CWA for paraffinic diesel fuel into an actual European standard. In order to be in congruence with the EN590 standard for regular diesel fuel, the oncoming standard for paraffinic diesel fuel will allow up to 7 % (vol.) of FAME.

There are no specific technical reasons that would prohibit the use of 100 % HVO. In an engine with standard settings 100 % HVO would lead to a small reduction in maximum power output and a slight increase in volumetric fuel consumption. The heating value per unit of weight (MJ/kg) is slightly higher for HVO compared to ordinary diesel fuel, whereas the heating value per unit of volume (MJ/l) is, due to lower density, some 4–6 % lower compared to regular diesel fuel.

The cold flow properties of HVO differ from conventional diesel fuel made from crude oil. HVO is a rather homogenous fuel, with hydrocarbons mainly in the range of C_{15} to C_{18}. Therefore cloud point (CP) and cold filter plugging point (CFPP) expressed in degrees centigrade are almost identical. This means that crystallization takes place throughout the fuel at a temperature just below the cloud point. Ordinary diesel fuels show a difference, typically 5–10 °C between cloud point and CPFF (CFPP being lower in temperature). Cloud point is indicative of the lowest long-time storage temperature and CFPP indicative of the lowest operating temperature. Regular cold flow additives do not necessarily work for HVO fuels, so the main way of adjusting HVO cold properties is controlling the isomerisation process parameters.

Most sulphur-free diesel fuels are treated with anti-wear lubricity additives. HVO fuels also need lubricity additives. The aromatic compounds in ordinary diesel fuel cause swelling of various kinds of gaskets and sealings. Paraffinic diesel does not induce this swelling effect. Therefore, there is a change that when switching from conventional diesel fuels to neat HVO fuel leakages could occur as a result of shrinking. This was one of the issues to be followed up in the OPTIBIO field test.

HVO delivers benefits regarding fuel quality and performance, toxic exhaust emissions and greenhouse gas emissions over regular diesel. In addition, HVO is excellent from the viewpoint of occupational safety. Mechanics working in vehicle maintenance and repair are exposed to diesel fuel. In this sense HVO, which is totally free of aromatics, is much less harmful than conventional diesel fuel. The safety data sheets of diesel fuel and HVO (NExBTL) state, among other things, the following (Neste Oil. Safety data sheets: Diesel fuel, sulphur free 14.10.2009, NExBTL Renewable Diesel 22.12.2010):

Irritation and corrosion:

- *Diesel fuel: Kerosine: slightly irritating on the skin (rabbit, 4 h) and to the eyes (rabbit). Straight run and hydrocracked gas oil streams: irritating on the skin (rabbit) but not to the eyes (rabbit). Alkanes*[2]*: No skin irritation, Non-irritating to the eyes (rabbit).*
- *HVO (NExBTL): No skin irritation, Non-irritating to the eyes (rabbit).*

Toxicity/subacute, subchronic and prolonged toxicity:

- *Diesel fuel: Straight run and hydrocracked gas oil streams: Oil mist has produced functional and structural changes in the lungs (rat). Repeated contact irritates the skin severely (mouse and rabbit). Long term contact has produced skin tumours in experimental animals (mouse). Genotoxic effects have been observed in bacterial cells and mouse lymphocytes in vitro. Alkanes: In vitro tests did not show mutagenic effects. Product is possibly carcinogenic to man (category 3).*

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[2] Alkanes = paraffinic compounds

Product contains hydrocracked gas oil streams, which are classified as category 3 carcinogens.

- *HVO (NExBTL): In vitro tests did not show mutagenic effects.*

Ecotoxicity and biodegradation:

- *Diesel fuel: Toxic (aquatic toxicity). Kerosine and gas oil hydrocarbons are slowly biodegradable (estimate). Degradation occurs extremely slowly under anaerobic conditions. Alkanes: Expected to be biodegradable.*
- *HVO (NExBTL): Very low toxicity (aquatic toxicity). Readily biodegradable.*

5.4 HVO in fuel distribution and logistics

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

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

Water separation from HVO is fast (low water solubility), and usually HVO 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 regular basis. Water promotes corrosion, and microbiological growth can occur at a fuel-water interface.

The flash point of HVO is above +55 °C, meaning that HVO can be stored and transported like standard diesel fuel.

As a pure component HVO is shipped with the exact shipping name Alkanes (C10-C26), linear and branched under MARPOL Annex II, Category Y and ShipType 3 (MARPOL 1983). This means that, at least in the current situation, HVO must be carried on chemical tankers with prewash requirements.

Regarding materials compatibility (e.g. seals, hoses, diaphragms, dry couplers, base swivel joints), HVO can be considered equivalent to petroleum diesel. Tank construction materials may include carbon and stainless steels 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 aluminium. Nitrogen blanketing can be used.

HVO is compatible with nitriles, fluoroelastomers, PTFE, vinyl ester resins and epoxy resins. As mentioned before, the lack of aromatic compounds could shrink elastomers that have already been swollen when used with aromatic containing fuels. This might be the case for both the fuel logistics system as well as for the system onboard the vehicle.

5.5 Feedstocks and greenhouse gas balance

HVO can be produced from a multitude of feedstocks, including virgin vegetable oils, various by-products from vegetable oil processing as well as vegetable and animal-based waste oils.

Currently the main feedstocks for Neste Oil's HVO (NExBTL) production are palm oil, rapeseed oil and waste animal fats. Neste Oil is continuously evaluating alternative feedstocks. Near-term options include soy, Camelina oil, waste oils from fish processing and Jatropha oil. Microbial oils and algae oils may become feasible in the future (Honkanen 2011, Lehtonen 2011). As mentioned earlier, Neste Oil is also involved in the development of wood-based BTL.

Companies producing renewable fuels need to be able to provide evidence that their production chain embodies the principles of sustainable development and actually reduces greenhouse gas (GHG) emissions. Although the framework is not yet fully established, some basic principles are already set in the Directive 2009/28/EC on the promotion of the use of energy from renewable sources. Regarding GHG emissions, Directive 2009/28/EC sets the following minimum requirements for GHG emission savings from the use of biofuels:

- initially, a minimum of 35 %
- as of January 2017 onwards, a minimum of 50 %
- as of January 2018 onwards, a minimum of 60 % savings are required for biofuels produced in installations in which production started on or after 1 January 2017.

The Directive also contains typical and default greenhouse gas emission saving values for various biofuel options, including products from hydrotreatment. Table

5.3 presents examples on these values. For equivalent feedstocks, Directive 2009/28/EC gives somewhat more favourable values for hydrotreated fuels than for esterified fuels.

In September 2010, Neste Oil supplied the EU Commission with a description of its current sustainability verification system, developed in accordance with the Directive on renewable energy. The system covers all parts of the production chain, and the verification is carried out by an independent certification company. Neste Oil's goal is to have the system approved by the EU and receive certification for its supply chain. (Neste Oil Annual Report 2010)

Table 5.3. Typical and default greenhouse gas emission saving values for various biofuel options according to Directive 2009/28/EC.

Biofuel production pathway	**Typical greenhouse gas emission saving**	**Default greenhouse gas emission saving**
Esterified fuels		
rape seed biodiesel	45	38
sunflower biodiesel	58	51
soybean biodiesel	40	31
palm oil biodiesel (process not specified)	36	19
palm oil biodiesel (process with methane capture at oil mill)	62	56
waste vegetable or animal oil biodiesel	88	83
Hydrotreated fuels		
HVO from rape seed	51	47
HVO from sunflower	65	62
HVO from palm oil (process not specified)	40	26
HVO from palm oil (process with methane capture at oil mill)	68	65

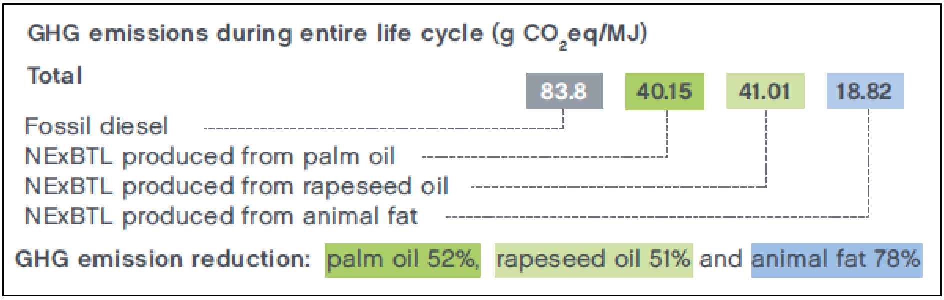
In November 2010, Neste Oil received an ISCC (International Sustainability & Carbon Certification) certificate for the NExBTL fuel produced at its Porvoo site, verifying that the fuel is suitable for use in meeting mandated bio-content requirements in Germany. Furthermore, the certification audit for the Singapore plant was completed in December 2010, and Neste Oil received its certificate at the beginning of 2011. Certification also verified the suitability of Neste Oil's method that it currently uses for calculating the reduction in greenhouse gases offered by NExBTL. The method covers the product's entire life cycle from production to end-use (Neste Oil Annual Report 2010).

Neste Oil has used several independent institutes to evaluate the greenhouse gas emissions from NExBTL production. The list includes, among others Helsinki University of Technology, now Aalto University (Nikander 2008) and the German institute IFEU (Reinhardt et al. 2006).

Neste Oil Annual Report 2010 contains a chapter called "Proven to be sustainably produced". The chapter presents the company's own estimates for greenhouse gas emission reductions for three different feedstocks: palm oil, rapeseed oil and animal fat (Table 5.4). For rapeseed oil and animal fat the stated values are rather well in congruence with the default values of Directive 2009/28/EC (but the Directive only presents figures for esterified waste oils, and not for hydrotreated waste oils). Neste Oil's value for palm oil, 52 %, is close to the mean value of the numbers listed in the Directive (process not specified 40/26 %, process with methane capture at the oil mill 68/65 %).

Palm oil is a very productive plant. The yield of oil is as high as 5,000 kg/hectare, whereas the yield of rape is only some 1,000 kg/hectare (Table 5.5).

Table 5.4. Neste Oil's figures for specific greenhouse gas emissions (g CO_2eq/MJ) and relative greenhouse gas emission reductions. (Neste Oil Annual Report 2010)

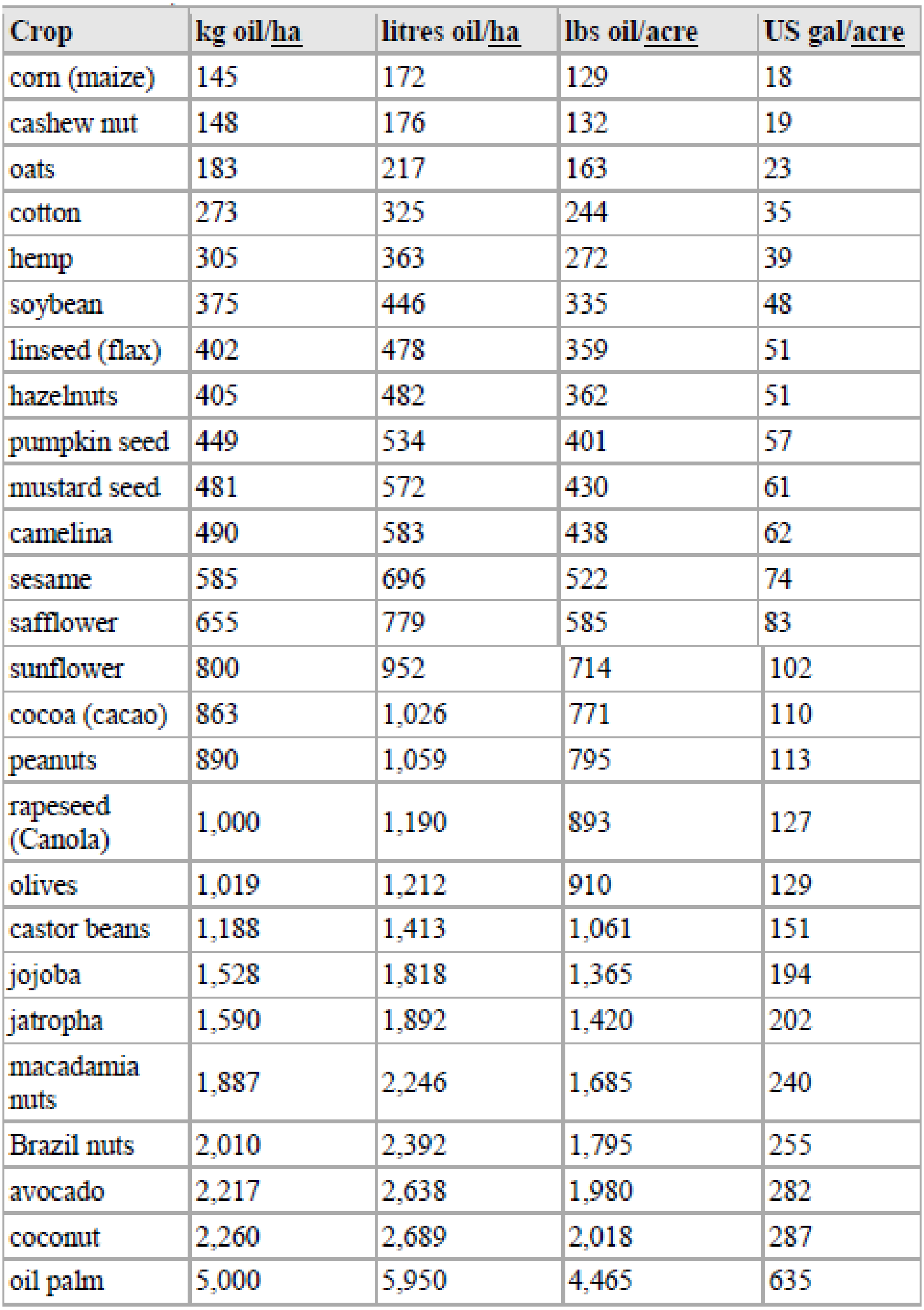


GHG emissions during entire life cycle (g CO_2eq/MJ)

	Total
Fossil diesel	83.8
NExBTL produced from palm oil	40.15
NExBTL produced from rapeseed oil	41.01
NExBTL produced from animal fat	18.82

GHG emission reduction: palm oil 52%, rapeseed oil 51% and animal fat 78%

Table 5.5. Yields for various vegetable oil sources. (McGill et al. 2008)



Crop	kg oil/ha	litres oil/ha	lbs oil/acre	US gal/acre
corn (maize)	145	172	129	18
cashew nut	148	176	132	19
oats	183	217	163	23
cotton	273	325	244	35
hemp	305	363	272	39
soybean	375	446	335	48
linseed (flax)	402	478	359	51
hazelnuts	405	482	362	51
pumpkin seed	449	534	401	57
mustard seed	481	572	430	61
camelina	490	583	438	62
sesame	585	696	522	74
safflower	655	779	585	83
sunflower	800	952	714	102
cocoa (cacao)	863	1,026	771	110
peanuts	890	1,059	795	113
rapeseed (Canola)	1,000	1,190	893	127
olives	1,019	1,212	910	129
castor beans	1,188	1,413	1,061	151
jojoba	1,528	1,818	1,365	194
jatropha	1,590	1,892	1,420	202
macadamia nuts	1,887	2,246	1,685	240
Brazil nuts	2,010	2,392	1,795	255
avocado	2,217	2,638	1,980	282
coconut	2,260	2,689	2,018	287
oil palm	5,000	5,950	4,465	635

5.6 HVO production capacity

Neste Oil is the world's leading producer of HVO. Neste Oil's production is based on stand-alone processing of neat HVO, whereas some producers are in favour of co-processing mineral oil and bio-oils.

Neste Oil's first NExBTL unit started up in 2007, and the second unit came on stream in 2009. The two first units, Porvoo 1 and Porvoo 2, with a capacity of approximately 190,000 t/a each, are located at Neste Oil's Porvoo refinery, some 50 km east of Helsinki.

Neste Oil's first HVO megaplant, Singapore with a capacity of 800,000 t/a, started up in November 2010. A second megaplant, placed in Rotterdam, is scheduled to commence operations in mid-2011.

In the United States, Dynamic Fuels started up a 220,000 t/a plant in Geismar, Louisiana in 2010 (Syntroleum 2010). Valero has announced a 405,000 t/a plant that is due to come on line in 2012 at their refinery in Norco, Louisiana. By the end of 2012, the U.S. will thus have a total capacity of 625,000 t/a of renewable paraffinic diesel from standalone hydrotreating process facilities (Darling International 2011).

Amyris has indicated that they will have 90,000 t/a of capacity on-line by 2012 using their proprietary biotechnology (sugars to hydrocarbons). The company states that the output will be paraffinic diesel. (Amyris 2009)

The Portuguese company Galp and the Brazilian company Petrobras have announced co-operation for 250,000 t/a HVO production. The scheme is to produce palm oil (300,000 t/a) in Brazil and to process the oil in Portugal. (Petrobras 2010)

Figure 5.6 presents an estimate of existing and projected HVO capacity.

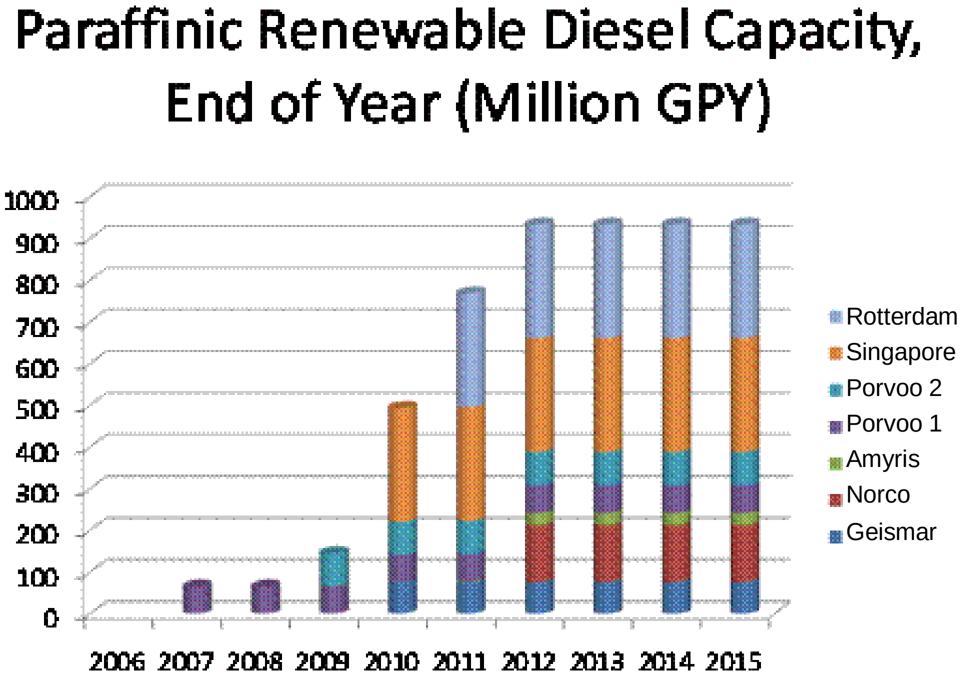


Figure 5.6. Estimate of existing and projected HVO capacity. Source Neste Oil. 1000 million gallons per year ~3 Mt/a.

Co-processing is applied at Conoco Phillips' refinery in Cork, Ireland, in BP's refinery in Bulwer, Australia and also in Sweden (Global Biofuels Center). The Swedish refiner Preem is co-processing mineral oil and crude tall oil. The mixture, with a content of 20 % hydrotreated tall oil, is sold under the brand "Evolution Diesel". The capacity for hydtrotreated tall oil (co-processed) is estimated at 90,000 t/a. (Preem 2011).

6. VTT's heavy-duty vehicle test facility and bus performance data base

The heavy-duty vehicle test facility at VTT was instrumental in determining the effects of HVO fuel on fuel consumption, exhaust emissions and exhaust emission stability.

VTT's test facility comprises a heavy-duty transient chassis dynamometer, a transient engine dynamometer and a full-flow CVS (Constant Volume Sampler) dilution and sampling system, as well as a full set of gas analysers for regulated emissions. The facility also has versatile instrumentation for special emission analysis, including detailed measurements of particles.

The chassis dynamometer, manufactured by Froude Consine, has a roller diameter of 2.5 metres and a power absorption capacity of 300 kW (continuous) at the driving wheels. The dynamometer has a very fast control system and electric inertia simulation making dynamic (transient) testing possible. Inertia can be simulated within the range from 2,500 to 60,000 kg.

The regulated emissions are measured using a full-flow CVS system (Pierburg CVS-120-WT) and an analyzer set (Pierburg AMA 4000) conforming to requirements of Directive 1999/96/EC for the measurement of exhaust emissions of heavy-duty on-road engines. As the testing is carried out using transient vehicle driving cycles, the emission measurements are basically performed in the same way as for passenger car chassis dynamometer tests.

At VTT, the need for an approved chassis dynamometer measurement procedure for heavy-duty vehicles was recognised. VTT developed its own in-house method based on existing elements (light-duty vehicles chassis dynamometer emission certification 70/220/EC, transient-type emission certification of heavy-duty engines 1999/96/EC, SAE J2711: Recommended Practice for Measuring Fuel Economy and Emissions of Hybrid-Electric and Conventional Heavy-Duty Vehicles, Figure 6.1).

The method covers both emission and fuel consumption measurements. In June 2003, FINAS, the Finnish Accreditation Service, granted accreditation for the method of VTT (T259, In-house method, VTT code MK02E). Figure 6.2 shows an emission test of a bus on the chassis dynamometer, including instrumentation for special emission analyses, and an insert showing the size of the dynamometer rollers.

Since start-up in 2002 VTT has measured close to 200 different buses, and thereby built up one of the most comprehensive databases on bus performance. To update this database, VTT continuously measures the performance of new vehicles as well as of vehicles that already have been in service. Some vehicles are subjected to measurements for emission stability over time. Thus VTT's bus performance data base formed an important reference for the OPTIBIO project.

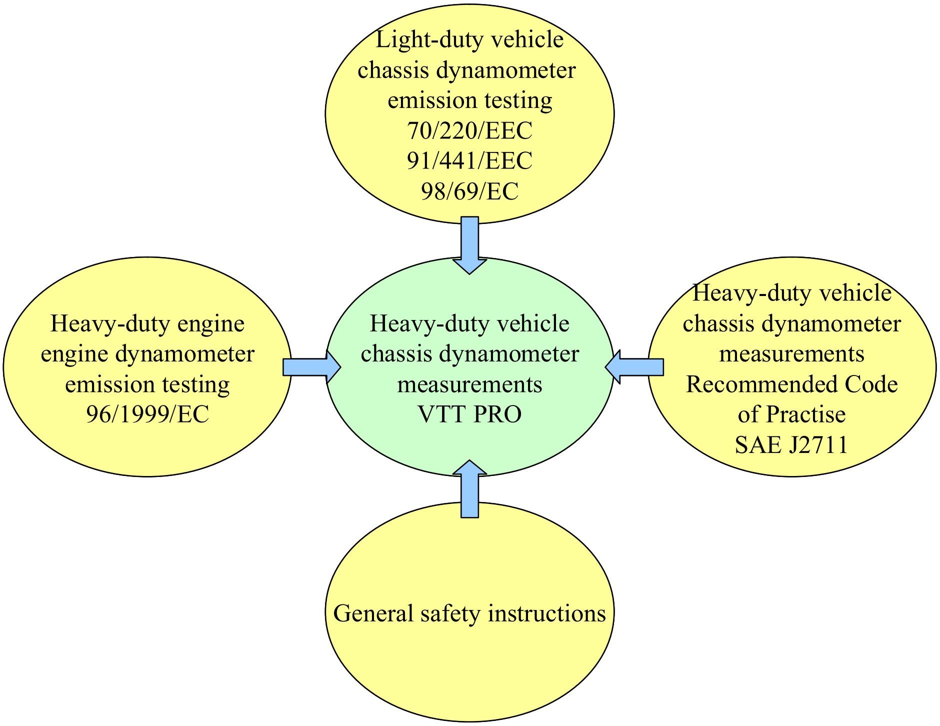


Figure 6.1. The elements of the accredited in-house method of VTT for measuring emissions and fuel economy of heavy-duty vehicles.

Figure 6.2. Emission testing of a bus on the chassis dynamometer and a detail of the dynamometer.

Table 6.1 presents average emission factors for buses representing Euro I to EEV emission certification (VTT's general data bank). The data has been generated using the Braunschweig bus cycle (Table 6.2, Figure 6.3), which has been found representative of bus operation in Helsinki, as well. The emission and fuel consumption measurements for the OPTIBIO project were also carried out using the Braunschweig cycle. VTT uses 3,000 kg (roughly half load) as default load for standard size two-axle city buses.

Table 6.1. Emission factors and fuel consumption figures for two-axle city buses. Braunschweig test cycle, half load (3,000 kg). (VTT 2010)

Braunschweig	*CO g/km*	*HC g/km*	*CH_4* g/km*	*NOx g/km*	*PM g/km*	*CO_2 g/km*	*CO_2 eqv** g/km*	*FC kg/100km*	*FC MJ/km*
Diesel Euro I	1.39	0.32	0.00	15.59	0.436	1219	1219	38.6	16.4
Diesel Euro II	1.48	0.19	0.00	12.94	0.202	1270	1270	41.0	17.4
Diesel Euro III	0.79	0.15	0.00	8.57	0.190	1182	1182	38.0	16.2
Diesel Euro IV	2.77	0.11	0.00	8.32	0.116	1197	1197	38.6	16.4
Diesel Euro V***	2.77	0.11	0.00	8.32	0.094	1197	1197	38.6	16.4
Diesel EEV	0.93	0.03	0.00	6.12	0.071	1126	1127	36.9	15.7
CNG Euro II	4.32	7.12	2.33	16.92	0.009	1128	1283	42.1	20.7
CNG Euro III	0.15	2.14	1.70	9.82	0.013	1222	1271	45.1	22.1
CNG EEV	2.73	1.08	0.91	3.34	0.007	1251	1272	45.0	21.9

* For CNG vehicles CH4 = THC * 0.95, for diesel CH4 = 0
** CO_2 eqv = CO_2 + 23 * CH4
*** Euro V emission factors are estimated by Euro IV results

Table 6.2. Data of the Braunschweig bus cycle. (Nylund et al. 2004)

Length (km)	Duration (s)	Av. Speed (km/h)	Max. speed (km/h)	Share of idle (%)
10.873	1740	22.5	58.2	25

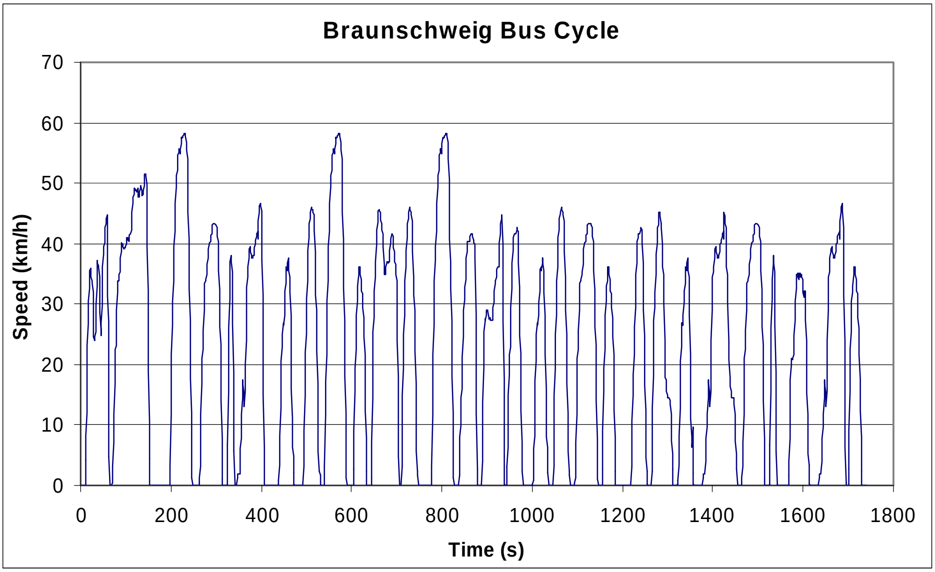


Figure 6.3. Speed vs. time of the Braunschweig bus cycle.

Fuel consumption can be gravimetrically measured very accurately, with only some +1 % of inaccuracy. However, the accuracy for emission measurements is not as good, due to the fact that several pieces of equipment and instruments are needed to form the results: chassis dynamometer, CVS for determining flow, analyzers to determine concentrations, calibration gases etc., and their individual inaccuracies are all summed up in the final result. Therefore, for emission measurements, inaccuracy is estimated to be at the level of ±15 %.

In the OPTIBIO project, all measured values are based on average values from at least two parallel measurements. In addition, ambient temperature during bus testing in laboratory conditions was kept approximately constant at +23°C.

7. Set-up of the field test with HVO

7.1 General

The large-scale field test with buses was the core activity of the OPTIBIO project. Carrying out extensive field testing is the only way to get feedback and verification of the true performance of a new fuel quality. The field test was supplemented by a comprehensive testing programme including, among other things, emission measurements, analysis of fuel and lubricating oil samples and inspections of fuel injection systems.

The project partners applied for public support for the project. This support in practise meant a tax reduction for the biocomponent as well as research funding from Tekes, the Finnish Funding Agency for Technology and Innovation. Within Tekes programme structure, OPTIBIO was part of the programme "BioRefine – New Biomass Products 2007 – 2012"

(http://www.tekes.fi/programmes/biorefine).

Good cooperation with the vehicle operators and the vehicle manufacturer was essential for the project. The public support made it possible to design the project so that it would not induce significant economic burden on the fleet operators. With the help of the biocomponent tax exemption Neste Oil committed to deliver the test fuels (diesel + HVO blend and neat HVO) at the same price (€/l) as regular diesel fuel. However, due to the lower volumetric heating value of HVO, volumetric fuel consumption will increase somewhat compared to regular fossil diesel fuels, especially when running on neat HVO. Therefore, the project provided compensation for the increased volumetric fuels consumption. The compensation was based on VTT's fuel consumption measurements and actual densities of fuels delivered (see Paragraph 7.2).

In addition, the project paid a compensation for the vehicles which were used in the emission measurements (compensation for vehicles being out of revenue-generating service). Naturally, the project and the actual partners covered all costs for the emission measurements, fuel and lubricant analysis, injection equipment inspections etc. The project also set up a reserve fund for possible engine failures or damages. However, no break-downs occurred, so there was no need to use these funds.

The OPTIBIO field test officially started 27.9.2007, when the Deputy Mayor for Public Works and Environmental Affairs in Helsinki Mr. Pekka Sauri performed the symbolic first refuelling of a test bus with a diesel/HVO blend. The experimental activities of the project were closed as planned on 31.12.2010.

7.2 Test fuels

The original test plan stated that testing would be carried out with a 30 % (vol.) HVO blend and neat HVO, the blended fuel being the principal test fuel. The reason for selecting the 30 % blend was that using this concentration of HVO, all EN590 requirements, including density, can be met in most cases. Furthermore, this blend still delivers a high share of bioenergy, 28.5 %, compared to only 6.5 % for B7 (7 vol.-% FAME, the highest content allowed by the fuel quality Directive 2009/30/EC and EN590). Fulfilling all fuel requirements and standards means that vehicle warranty terms are not an issue.

However, the most interesting and at the same time most challenging fuel option is 100 % HVO, a fuel delivering maximum environmental benefits. As neat HVO does not fulfil all current EN590 fuel standard requirements, engine warranty terms and possible durability issues have to be considered. As mentioned in the previous paragraph, the project set aside funds to compensate possible engine damages.

Neat HVO was introduced for testing in two ways, for new vehicles in cooperation with the vehicle manufacturer (see Paragraph 7.4) and for vehicles that already had been in service with the agreement that the OPTIBIO project would cover possible fuel-related problems (for vehicles still under warranty as well as for vehicles past the warranty period).

The first NExBTL process unit came on stream in the summer of 2007, just before the OPTIBIO field test started in September 2007. At that time it was not possible to fully control the cold flow properties of the HVO component. To begin with, there were also some issues in meeting the minimum EN590 density requirement of the blended fuel. For these reasons, field testing commenced with a 25 % blend. In the spring of 2008, HVO concentration of the blended fuel was increased to 30 %. For the rest of the project, 30 % was the blended fuel target HVO concentration. This target could be met most of the time, with the exception of brief transition periods when the conventional diesel part of the fuel switched from one seasonal grade to another. Neste Oil made a commitment to the fleet operators to deliver fuels with guaranteed cold-weather performance, not to endanger the commercial operations of the bus operators.

However, going slightly below the minimum density limit is not a real technical issue from the engine point of view, it is more a commercial contractual issue.

As of 2009, when the second NExBTL unit came on stream, Neste Oil had the possibility to diversify NExBTL grades, and produce HVO fuel with very good cold flow properties. The winters of 2009/2010 and 2010/2011 were quite severe in Finland and in the Helsinki region. However, despite ambient temperature dropping below -25 °C, even the buses running on 100 % HVO could be operated without any problems.

In the field test, the cold properties of the diesel part of the blended fuels varied normally during the course of the year.

In the screening-type emission and fuel consumption measurements at VTT, both summer and winter grade commercial mineral oil diesel fuels were used as reference. The test fuels were blends with 10, 30 and 50 % (vol.) HVO in summer grade diesel, a blend with 30 % HVO in winter grade diesel, and naturally also 100 % HVO. The original test plan included using FAME as one reference fuel, but this alternative had to be revoked as some bus manufacturers would not allow the use of neat FAME in sophisticated diesel engines.

It should also be mentioned that the base diesel fuel used as reference was of high quality, meaning sulphur below 10 mg/kg, polyaromatics well below the regulated value of max 8.0 weight-% (Directive 2009/30/EC), and in addition, with zero FAME content. In many other areas of the world diesel fuel may contain more aromatics or sulphur. In comparison with lower quality diesel fuels, the emission benefits of HVO might have been even larger.

For the engine test bench work at Aalto University, the fuels were regular EN590 diesel fuel, a blend with 30 % HVO and 100 % HVO. More data on the test fuels are given later on in the text (e.g. fuel analysis results from the storage tanks) and in the appendixes.

The base EN590 diesel fuel used in all testing, as such as a reference fuel and as blending component for the HVO blends, was without any biocomponents, meaning "EN590 B0" grade. Currently the fuel Quality Directive and EN590 allow up to 7 % (vol.) FAME in regular diesel, and the "B7" grade has become common in the European markets. This change in the common European fuel quality has to be taken account when results of the OPTIBIO project are interpreted. **All results presented later on in this report are HVO results in comparison to regular fossil diesel without biocomponents ("B0").**

As mentioned, the option of 100 % FAME could not be included in the test matrix, as some of the manufacturers do not allow the use of 100 % FAME in advanced vehicles.

Table 7.1 presents density and heat value figures for various fuels (see also Paragraphs 7.3.1 and 7.3.2). In comparison with regular fossil diesel fuel HVO has higher gravimetric heating value (MJ/kg) and lower density, whereas FAME, in comparison with regular diesel, has lower gravimetric heating value and higher density.

Table 7.1. Density and heat value figures for various fuels. EN590 and HVO values are actual data for OPTIBIO test fuels. "s" denotes summer grade and "w" winter grade diesel fuel. Bxx means FAME concentration (vol).

Fuel	**Density (kg/m^3)**	**Heating value (MJ/kg)**	**Heating value*) (MJ/l)**	**Rel. vol. based (%)**
EN590 "s BO"	844	43.1	36.4 (36)	-
EN590 "w BO"	827	43.1	35.6	-2.2
FAME	885	37.5	33.2 (33)	-8.8
EN590 "s B7"			36.2	-0.5
EN590 "w B7"			35.4	-2.7
HVO grade 1	780	44.1	34.4 (34)	-5.5
HVO grade 2	776	44.0	34.1 (34)	-6.3

*) Values in brackets from Directive 2009/28/EC (RES)

7.3 Preparatory measurements

7.3.1 General

In the initial phase of the project, VTT carried measurements to establish the effects of HVO on fuel consumption and vehicle performance (acceleration, traction power). Part of the emission measurements (screening) were also carried out upfront.

Neat HVO has lower volumetric heating value than regular fossil diesel fuel. This will have an impact on volumetric fuel consumption as well as on maximum power output. Most fuel systems are designed to deliver a certain volume of fuel, and when volumetric heating value goes down, so goes maximum power output.

Based on the numbers in Table 7.1, volumetric fuel consumption with neat HVO could be expected to increase some 4–6 % compared to neat fossil diesel fuel, and maximum power output to be reduced accordingly. In the case of neat FAME, the difference compared to neat fossil diesel would be some 9 %.

In traditional oil refining, the basic level of cold operability properties is set by distilling fuels to lighter and narrower fractions, and some additional help can be obtained from cold flow additives. For winter grade fuels, density and viscosity will be lower than for summer grade fuels. Isomerisation, which is used to adjust cold operability properties of HVO, has negligible effect on density and viscosity, since the process changes the structure of the molecules while keeping distillation characteristics practically constant.

In Finland, there are several grades of diesel fuel, depending on the season and the geographical area. Summer grade diesel has the highest density, arctic grade diesel the lowest. The difference mentioned above, 4–6 %, can be expected when comparing summer grade diesel without FAME (B0) with HVO. Compared to winter grade or even arctic grade diesel the difference will be smaller.

The information on fuel consumption was needed to settle the contractual matters between the OPTIBIO project and the fleet operators. All parties could agree that the compensation of additional volumetric fuel consumption should first and foremost be based on VTT’s chassis dynamometer measurements. In the chassis dynamometer, gravimetric fuel consumption can be measured with high accuracy, and volumetric fuel consumption can then be calculated using actual fuel density.

It was, however, also agreed that if the fleet operators’ own fuel monitoring systems for fuel consumption would show remarkably diverging results, these would be taken into account when setting the compensation. The outcome was that throughout the project, the fuel consumption figures recorded by the fleet operators were in congruence with VTT’s figures, so VTT’s figures, compensated for actual density, were use throughout the project.

In addition, some measurements of exhaust temperatures from buses en route were carried out. Devices for particulate reduction, wall-flow filters as well as flow-through filters, need a certain minimum temperature to ensure regeneration.

Proventia Emission Control wanted to find out which vehicle types and which bus routes would be most suitable for retrofitting (see Paragraph 7.6).

7.3.2 Results for fuel consumption

In the initial phase, altogether 11 city buses representing Euro II to EEV emission certification were tested to establish the effect of HVO on fuel consumption. The fuels tested were:

- summer grade EN590 “B0” diesel (density 836–844 kg/m^3)
- winter grade EN590 “B0” diesel (density 827–829 kg/m^3)
- 100 % HVO (density 776–780 kg/m^3)
- 10, 30 and 50 % (vol.) HVO in summer grade diesel
- 30 % (vol.) HVO in winter grade diesel.

Analyses of the laboratory test fuels used for the screening work (EN590 summer, winter, 100 % HVO) are presented in Appendix 2 (see also Table 7.1). The test fuels were actually from two different batches, but with critical parameters (heating value, density) very close from one batch to the other. The biggest difference was in HVO cetane: 89 for the first batch and 76 for the second batch (CWA 15940 Class A: minimum 70).

Figure 7.1 shows the effect of HVO concentration on energy consumption expressed as MJ/km. The outcome was that compared to regular diesel fuel, summer grade as well as winter grade, 100 % HVO reduces energy consumption by some 0.5 %. The variation for 100 % HVO is from +1 % to -2.5 %. In practise it can be said that HVO has no significant effect on energy consumption in vehicles using standard calibration. As show in Chapter 12, optimising engine calibration for constant NO_x emission can deliver improvements in fuel efficiency.

Figure 7.2 correspondingly shows the effect of HVO concentration on volumetric fuel consumption. Neat (100 %) HVO increases volumetric fuel consumption 5.2 % compared to summer grade fossil diesel fuel (not 6 % as indicated by the volumetric heating values) and 3.5 % compared to winter grade fossil diesel fuel. Thus it can be concluded that volumetric fuel consumption first and foremost is determined by volumetric heating value. It should be noted that Figure 7.2 is valid for a certain set of values for density (see values listed above). Lowest allowable density for winter grade diesel fuel is 800 kg/m3. In comparison with such a fuel quality the difference in volumetric fuel consumption would have been even smaller than the value of 3.5 %, which was now recorded. The summer grade reference fuels (836–844 kg/m^3) were close to the border of the highest permissible density of 845 kg/m^3 and were neat fossil “B0” grade fuels meaning that difference between diesel and HVO shown here is the largest one possible.

At the end of the day, in total 17 buses were screened for exhaust emissions as well as fuel consumption within the OPTIBIO project. The final outcome on fuel consumption was that 100 % HVO reduced energy consumption by 0.3 % compared to regular diesel fuel, so the conclusions drawn from the first 11 buses remain unchanged.

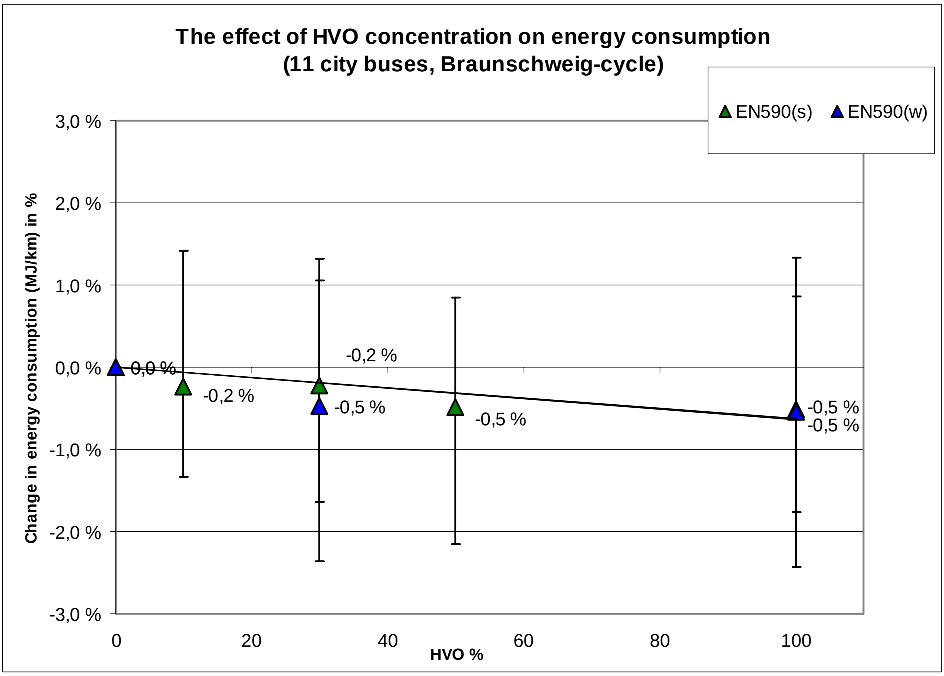


Figure 7.1. The effect of HVO concentration on energy consumption. 11 buses tested over the Braunschweig cycle. Denotation “s” means summer grade diesel fuel, “w” winter grade diesel fuel. EN590 base fuels are “B0” grades without FAME.

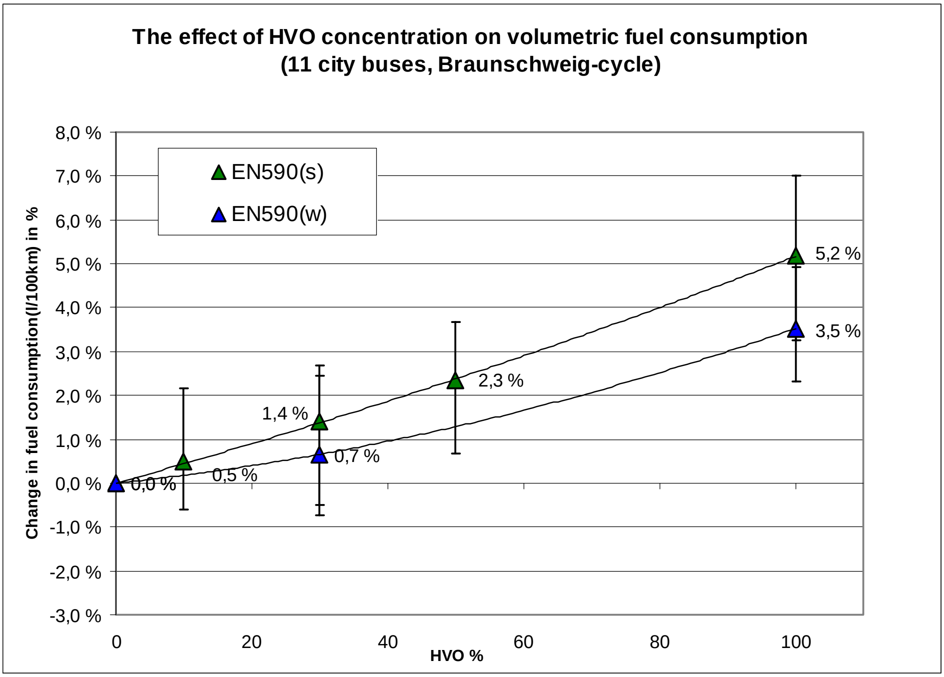


Figure 7.2. The effect of HVO concentration on volumetric fuel consumption. 11 buses tested over the Braunschweig cycle. Denotation "s" means summer grade diesel fuel, "w" winter grade diesel fuel. Fuel densities: EN590(s) 836–844 kg/m^3, EN590(w) 827–829 kg/m^3 and HVO 780 kg/m^3. EN590 base fuels are "B0" grades without FAME.

7.3.3 Acceleration and traction power

The measurements on a chassis dynamometer allow determination of acceleration against simulated driving resistances and inertia, as well as determination of maximum traction power. Several bus types were screened for performance. Figure 7.3 (acceleration) and 7.4 (traction power) show results for two buses, an older Euro II certified bus and a newer EEV certified bus. The fuels were summer-grade EN590 diesel and 100 % HVO. The Figure on traction power (7.4) clearly shows the variations in power caused by the gear shifting of the automatic gearboxes.

For the older bus, equipped with an in-line injection pump, the results were as expected: the difference in performance was roughly equivalent to the differences in volumetric heating value. Reaching 50 km/ h took 17 s with summer grade EN590 and 18 s with 100 % HVO, a difference of some 5 %. At 50 km/h, traction power was 115 kW with EN590 and 108 kW with 100 % HVO, so a difference of 6 % was observed.

In the case of the EEV bus, equipped with a common-rail injection system, the differences in both acceleration and traction power were negligible. The EEV bus reached 50 km/h in some 15 s with both fuels, and the traction power at 50 km/h was some 150 kW, about 30 % higher compared to the Euro II certified bus. Here it should be noted that current city buses have plentiful of power, and a loss of maximum power in the order of 5 % has no consequences whatsoever for the vehicle's ability to carry out its normal functions.

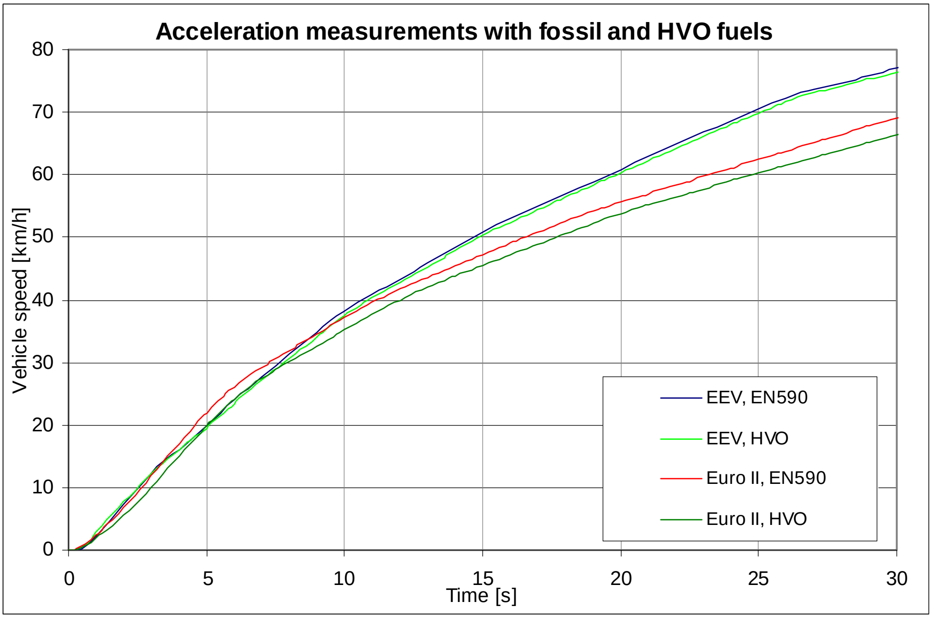


Figure 7.3. Acceleration with summer-grade EN590 and 100 % HVO.

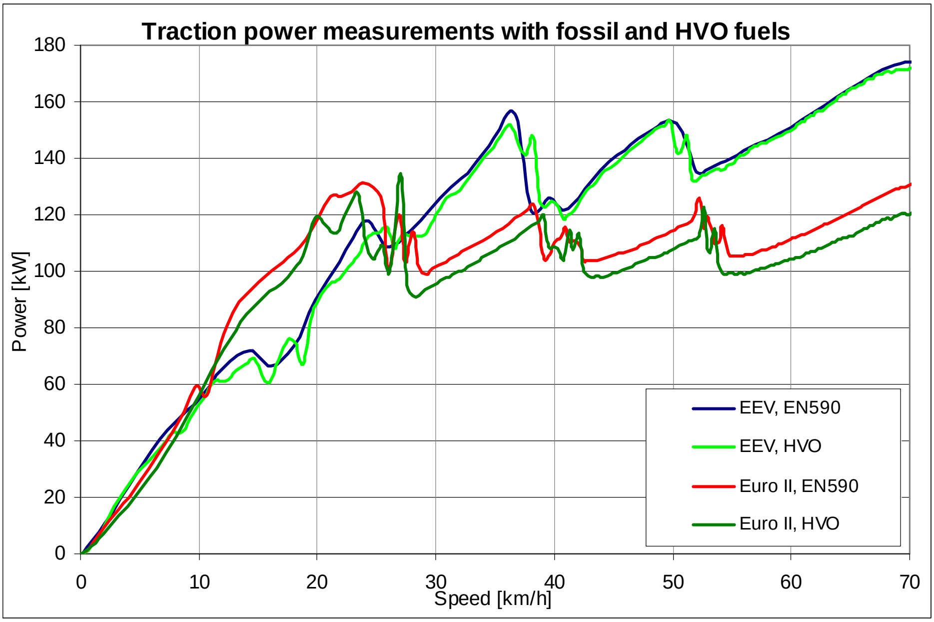


Figure 7.4. Traction power with summer-grade EN590 and 100 % HVO.

7.4 Fleet operators, vehicle types and vehicle numbers

Two bus fleet operators, Pohjolan Liikenne and Veolia Transport Finland, joined the project right from the start in September 2007. Testing started with blended fuel (initially 25 % HVO) in six buses at Pohjolan Liikenne and some 40 buses at Veolia Transport. This meant that only part of the fleet at respective depot was using test fuel.

The first expansion took place in March 2008, when Helsingin Bussiliikenne entered the project with six new EEV certified Scania buses, four of them running on 100 % HVO and two control vehicles on regular diesel fuel. This part of the project was carried out in cooperation with the manufacturer, Scania. The agreement was such that Scania would, after inspecting the engines at the end of the test, deliver information (relative, qualitative) of the effects of 100 % HVO on engine wear and cleanliness in comparison with regular diesel fuel.

The OPTIBIO project reached full volume in the fall of 2008. Then a fourth bus operator, Porvoon Liikenne, part of the Koiviston Auto -group, joined the project. In addition, the number of buses using HVO fuels increased at the other three operators. The total number of buses participating in the OPTIBIO project peaked at some 300 units. The numbers of vehicles were as follows (rounded figures):

- Pohjolan Liikenne, Ilmala depot: 50 buses (3 on 100 % HVO)
- Veolia Transport, Suomenoja depot: 80 buses
- Veolia Transport, Kerava depot: 3 buses (all on 100 % HVO)
- Helsingin Bussiliikenne, Koskela depot: 90 buses (4 on 100 % HVO)
- Porvoon Liikenne, Porvoo depot: 70 buses.

The buses represented a large spectrum of technologies:

- emission certification class from Euro II to EEV
- injection systems: in-line pumps, unit injectors, common-rail
- NO_x control strategy: no specific, exhaust gas recirculation (EGR), selective catalytic reduction (SCR)
- PM control strategy: no specific, oxidation catalysts, flow-through filter FTF, wall-flow DPF.

In 2009, three older Euro III certified Scania vehicles started operation on 100 % HVO, and three EEV certified Iveco buses on 100 % HVO were added to the fleet in 2010. All vehicles running on 100 % HVO had equivalent control vehicles running on standard EN590 diesel fuel. The total number of buses running on 100 % HVO was thus 10:

- 4 new EEV certified Scania buses starting 2008 (high-pressure common-rail injection systems)
- 3 older Euro III certified Scania buses starting 2009 (conventional in-line injection pumps)
- 3 fairly new EEV certified Iveco buses starting 2010 (unit injectors).

7.5 Refuelling infrastructure

In principle, HVO fuels do not require modifications to the refuelling infrastructure. However, the introduction of one or two new fuel qualities (HVO blend and neat HVO) at the bus operators required some additional installation work and equipment. For reasons of operational security, in a situation when e.g. the actual low-temperature performance of HVO fuels was still unknown, testing of HVO fuels started in only part of the vehicle fleets at the individual depots. Thus either the existing fuel storages had to be divided into blocks, or additional tanks had to be installed.

At Veolia Transport’s Suomenoja depot the existing storage and refuelling system was split into two separate parts when testing began; one part for regular diesel and one part for blended fuel.

In the case of Pohjolan Liikenne, the test started with blended fuel in six buses. A new fuel storage tank (7 m^3) with meter and associated data acquisition equipment was installed at the Ilmala depot. Later, when the test expanded, the main refuelling system at the depot was used for blended fuel and the new fuel storage tank was used for 100 % HVO. Pohjolan Liikenne uses an advanced system called EcoSmart to monitor refuelling. This system automatically identifies the vehicles being refuelled and the amount of fuel dispensed to each vehicle.

At the Koskela depot of Helsingin Bussiliikenne, on the other hand, testing started with 100 % delivered from a new 5 m^3 fuel storage. When the rest of the buses at this depot later on switched to blended fuel, the depot’s main refuelling system was used.

7.6 Exhaust after-treatment devices

All in all, 10 field test vehicles were equipped with retrofit exhaust treatment devices. Three main technologies were tested: flow-through filter (FTF, partial diesel particulate filter), wall-flow filter (actual filter, diesel particulate filter DPF) and a combination of SCR catalyst (selective catalytic reduction) and DPF. The original project plan focused on flow-through filters, and in a way, the DPF and the SCR/DPF combination were “add-ons”.

All devices were installed on Euro II and Euro III certified vehicles in the following manner:

Euro II:

- 3 vehicles upgraded with FTF

Euro III:

- 5 vehicles upgraded with FTF
- 1 vehicle upgraded with DPF
- 1 vehicle upgraded with SCR/DPF combination.

In the screening phase for FTF devices, Proventia Emission Control varied geometry (e.g. cell density) as well as chemistry to optimize design parameters before entering field testing.

Some of the FTF devices accumulated more than 400,000 km. However, the PDF and SCR/DPF devices were not installed before the fall of 2010, so actual durability data is not available for these devices. The reason for this was that Proventia Emission Control first wanted to get feedback on the performance of the FTF devices and on operational parameters, mainly exhaust temperatures in varying conditions and duties.

7.7 Monitoring programme

7.7.1 Fuel analyses

Fuel quality and condition was monitored in the course of the whole field test. Sampling focused on fuel storages at the bus depots of the fleet operators. Analyses included parameters such as density, flash point, cloud point, CFPP, water content, lubricity (high frequency reciprocating rig HFRR), cetane number, corrosion and filter blocking tendency. Fuel monitoring covered blended fuels as well as neat HVO. The results of the fuel analyses are presented later on in Paragraph 14.3.2.

7.7.2 Lubricant analyses

Lubricant analyses focused on vehicles running on 100 % HVO. The vehicle manufacturer, Scania, was responsible for the lubricant analyses of the new Scania EEV buses put into service at Helsingin Bussiliikenne. Lubricant sampling was also done at Pohjolan Liikenne and Veolia Transport, the two operators that put 100 % HVO into service in existing vehicles. At Pohjolan Liikenne, sampling was carried out for one reference bus on regular diesel and one vehicle on 100 HVO, the same vehicles which were subjected to injection equipment monitoring (see Paragraph 7.7.3). At Veolia Transport, lubricant oil sampling was done from 3 buses on 100 % HVO and 2 reference buses on regular diesel.

A summary of the results will be presented in Paragraph 14.3.3.

7.7.3 Fuel injection equipment

It was concluded that the 30 % blend could not possibly have any negative effects on injection equipment. Thus monitoring of injection equipment was limited to vehicles running on 100 % HVO.

The follow-up of the brand new EEV certified vehicles was carried out by the manufacturer, Scania. At the end of the testing, the four plus two engines were removed from the buses and sent to Sweden for inspection. The inspection was not limited to fuel injection equipment only, other parts and systems of the engine were also checked thoroughly.

In the case of the Euro III certified Scania buses running on 100 % HVO, the injection systems of one test vehicle and one reference vehicle were inspected and refurbished before the test, and then inspected again after the test.

In the case of the EEV certified Iveco vehicles, the check-ups were limited to inspection of one of the vehicles after completed testing.

7.7.4 Emission stability (including performance of exhaust after-treatment devices)

All in all, 33 different vehicles were selected for recursive emission measurements to monitor general vehicle performance as well as emission stability (see Paragraph 14.5.1 for more details). As in the case of the preparatory measurements and screening measurements, follow-up testing was carried out using the Braunschweig bus cycle on VTT's chassis dynamometer.

Most vehicles were tested three times: one initial test, one intermediate test and then a final test at the end of 2010. However, all vehicles were not subjected to full three follow-up measurements for various reasons: some vehicles were moved from one depot to another, some vehicles broke down (other than engine problems) and some were involved in collisions.

The follow-up testing was done using the fuels the vehicles were actually running on in the field.

7.7.5 Operator feedback

VTT was responsible for acquiring operator feedback on issues related to test fuel, such as impact on fuel consumption, general operability, possible problems and vehicle maintenance. Operator feedback was collected steadily during the course of the field tests and in the form of a dedicated campaign after completion of the test.

Operators have different policies and systems to manage their vehicle fleets, and therefore the available data differs from operator to operator. Systems to monitor fuel and report consumption, for example, varied significantly, from manual record-keeping to fully-automated systems.

Some of the vehicles subjected follow-up of emission stability occasionally showed abnormal deviations in emission performance. In these cases it was important to try to diagnose the reasons, and, e.g., go through the service history of respective vehicle.

Results and discussion

Photo: Helsinki Region Transport HRT.

8. General

The following chapters will present the outcome on the OPTIBIO project. The six main tasks of the OPTIBIO project were listed in Chapter 4:

1. Field testing of diesel/HVO blends and neat HVO
2. Analysis of fuels, lubricants and fuel injection equipment
3. VTT's emission and fuel consumption measurements on heavy-duty vehicles
4. A Thesis for a Master's Degree on the effects of HVO fuel and various engine parameters on the emissions of a diesel engine equipped with a common-rail fuel injection system
5. Testing of retrofitted exhaust gas after-treatment devices (laboratory measurements as well as field testing)
6. Testing of low temperature operability and low temperature exhaust emissions (using diesel passenger cars).

For the presentation of the outcome and the results a somewhat modified schedule will be used.

The preparatory laboratory measurements for fuel consumption and performance were already reported in Paragraph 7.3. In this section, the order for presentation of the other results will be as follows:

Studies of the effect of HVO on emissions:

- VTT's screening measurements with heavy-duty vehicles (regulated exhaust emissions, chassis dynamometer)
- The effect of HVO on unregulated emissions (chassis dynamometer)

- Emission results with HVO in combination with exhaust gas after-treatment devices (chassis dynamometer)
- Effects of varying engine calibration (engine dynamometer).

Studies related to cold weather performance:

- Correlation between standardized laboratory test methods, rig tests and real vehicle operability (passenger cars)
- Emission performance of HVO in cold conditions (passenger cars).

Results of the field test:

- General
- Feedback from the operators
- Fuel analyses (ensuring fuel quality, e.g., fuel stability and tendency for water pick-up, throughout fuel logistics)
- Lubricant analyses
- Inspection of fuel injection equipment and engines
- Emission stability (fuel as well as exhaust after-treatment devices).

9. Emission screening (HVO effects on regulated emissions and CO_2)

9.1 General

In the initial phase, 11 buses and 2 trucks were used for determining the effects of HVO fuels on emissions (screening). During the course of the project, 7 more buses were subjected to screening. However, one of the buses in the first batch delivered irregular emission results. As no reason for this anomaly could be found, the results for this bus were omitted from the aggregated emissions analysis. Still, the results for this vehicle individual are included in the fuel consumption results (see Paragraph 7.3.2). For the regulated emissions, the final number of buses included in the results was 10 + 7 = 17.

The idea of screening was to determine the fuel effects on emissions for vehicles of varying degree of sophistication (emission certification from Euro II to EEV) and different types of fuel injection and exhaust after-treatment systems. For obvious reasons, emphasis was on buses. For buses, the screening was done using the Braunschweig bus cycle (see Chapter 6), for trucks with one cycle representing waste collection and one representing general truck operation (interchangeable platform operation).

The OPTIBIO results for emissions, regulated as well as unregulated emissions, were presented in a technical paper at the JSAE/SAE Powertrains, Fuel and Lubricants Meeting in Kyoto, Japan, September 2011. (Erkkilä et al. 2011b)

9.2 Test vehicles

The buses were chosen to represent the buses in Helsinki area. The average age of the current bus fleet is approximately 7 years. According to the rules of Helsinki Region Transport, the maximum permissible age is 16 years. Therefore, older buses were also included in the programme. The bus matrix comprised 10 buses which were tested with 6 to 7 fuels (first batch of buses) and 7 buses, which were tested with 2 or 3 fuels. Table 9.1 presents the bus matrix.

The trucks used for screening were a Euro III certified vehicle without any specific exhaust emission reduction system and a Euro IV certified vehicle with common-rail, EGR as well as FTF.

9.3 Test fuels

The emission screening for both buses and trucks were carried out with same fuels as listed in Paragraph 7.3.2, meaning altogether 6 to 7 fuels or fuel blends for most of the 10 buses of the first test set. The 7 buses added later on were tested on 2 to 3 fuels. For fuels characteristics see Appendix 2.

Table 9.1. Characteristics of the buses used for emission screening.

Emission cert. class	Year mod.	Mileage (1000 km)	Eng. size (l)	After treat.	Inject. syst.
1. Euro II	1998	951	9.6	Oxycat	In-line pump
2. Euro II	1998	1126	9.6	Oxycat	In-line pump
3. Euro III	2005	336	9.0	Oxycat	In-line pump
4. Euro III	2003	277	9.0	Oxycat	In-line pump
5. Euro III	2004	852	9.0	Oxycat	In-line pump
6. Euro III	2002	652	9.0	Oxycat	In-line pump
7. Euro III*	2002	786	9.0	Oxycat	In-line pump
8. Euro III	2004	391	9.0	DPF	In-line pump
9. Euro IV	2006	128	8.9	EGR + Oxycat	Unit-injectors
10. Euro IV	2007	141	8.9	EGR + Oxycat	Unit-injectors
11. Euro IV*	2007	173	8.9	EGR + Oxycat	Unit-injectors
12. Euro V	2006	158	12.1	SCR	Unit-injectors
13. EEV	2007	1	7.1	SCR	Common-rail
14. EEV*	2008	45	7.1	SCR	Common-rail
15. EEV	2007	79	7.8	SCR + DPF	Unit-injectors
16. EEV	2008	24	8.9	EGR+ FTF	Common-rail
17. Euro IV hybrid	2007	3	4.5	SCR	Common-rail

*) vehicles 7, 11 and 14 were used to evaluate regulated as well as unregulated emissions

9.4 Results – buses

9.4.1 General

Regarding urban air quality and health effects, nitrogen oxides (NO_x) and particulate matter (PM) are the most critical emission components. Neat HVO fuel can reduce both these critical emission components. Figure 9.1 presents an indicative summary of the emission results for NO_x and particulates for various vehicle categories.

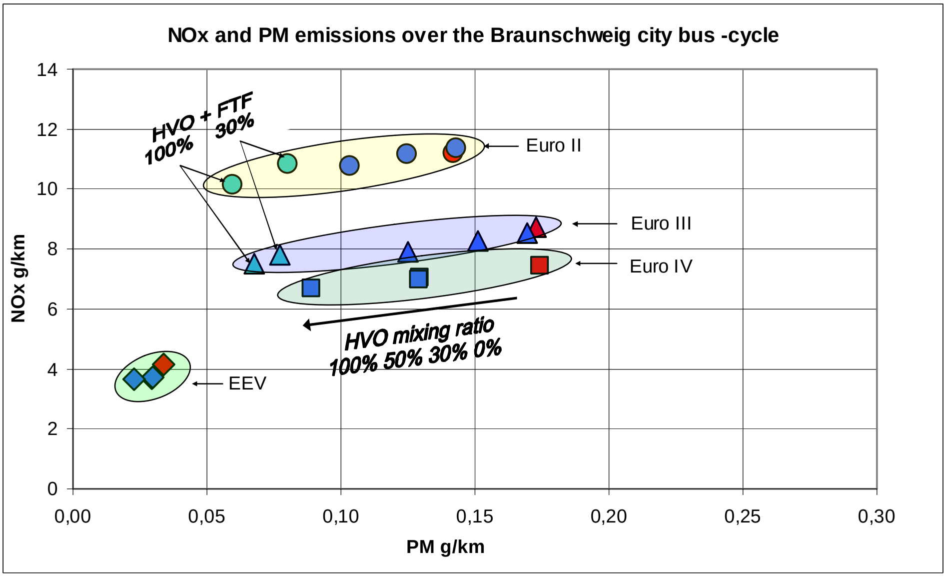


Figure 9.1. Effect of HVO on NO_x and PM emissions. Red marks EN590 diesel fuel. Blue marks 30, 50 and 100 % HVO. For Euro II and III vehicles, results are also shown with retrofitted FTF (30 and 100 % HVO).

The outcome is consistent for most of the vehicles. In comparison with high quality sulphur-free diesel 100 % HVO will on average reduce NO_x emissions by some 10 % and PM emissions by some 30 %. A relatively simple device like the FTF helps to enhance emission performance even further: the PM level of an old Euro II bus can be brought down close to EEV level.

However, in reality the response to paraffinic fuel depends on the vehicle type, and there are variations from one vehicle type to another. The differences arise from variations in fuel injection principles, as well as differences in exhaust emission control strategies. This will be discussed in the next paragraph.

9.4.2 NO_x and PM emissions

The response of older Euro II and Euro III engines to HVO is quite straightforward, as both NO_x and PM emissions are reduced when switching to neat HVO. For the newer Euro IV, Euro V and EEV certified vehicles, there are more variables affecting the response to HVO fuel, e.g.:

- type of injection system (in-line vs. unit-injector or common-rail)
- NO_x control strategy (EGR or SCR)
- PM control strategy (in-cylinder, FTF, DPF).

In the year 2005, Europe adopted Euro IV emission regulations for heavy-duty engines. From Euro III to Euro IV, the NO_x limit value went down from 5.0 g/kWh to 3.5 g/kWh. The PM limit value was lowered more drastically: from 0.16 g/kWh to 0.03 kWh (ETC limits). This forced all manufacturers to develop more advanced emission control strategies, like high-rate EGR systems, SCR-systems and different particle reduction devices.

Changes in engine-out NO_x and PM emissions can be attributed to physical as well as chemical phenomena. For example retardation of start of injection will reduce the share of premixed combustion, and lower combustion temperature, and thus decrease NO_x emissions, while at the same time increase the emissions of unburned components and particulates.

Fuel chemistry affects pollutant formation in many ways. Paraffinic hydrocarbons render lower flame temperatures than aromatic hydrocarbons (Ekelund et al. 1989), and thus switching from a regular diesel fuel containing aromatics to neat paraffinic fuel results in lower combustion temperatures and lower NO_x emissions. Aromatics are also soot precursors, and therefore, a fuel switch to paraffinic fuel suppresses particulate formation (see Figure 5.5).

Fuel injection systems can be divided into two main classes depending on the operation principles. In-line injection pumps and unit-injector systems are volume controlled systems, in which the physical piston movement forces the defined fuel amount through the injector nozzle. For these systems, part of the NO_x effects can be explained by retarded start of injection due to lower fuel density, viscosity and especially bulk modulus of the HVO fuel. Additional NO_x reductions are due to fuel chemistry. Although start of injection is slightly delayed, PM emissions are reduced considerably, as the benefits of paraffinic fuel in particulate suppression clearly overrule the effects of retarded injection.

The effect of compressibility on injection timing has been studied by several researchers. Rakopoulos & Hountalas (1996) and Arcoumanis et al. (1997) modelled in-line pump-line-nozzle fuel injection systems. In these studies, the only fuel property that had noticeable effect on the pressure as a function of time was the bulk modulus of compressibility. A less compressible fuel results in a faster pressure increase, higher maximum pressures and faster pressure pulsations inside the injector, which then leads to earlier injection. The effect is opposite with more compressible (paraffinic) fuels. With esterified biodiesel (high bulk modulus), a 1 ^{o}CA advancement has been noted, whereas paraffinic diesel (low bulk modulus) has resulted in a 0.5 ^{o}CA retardation. This supports the observation that paraffinic fuels (HVO and FT-diesel) generally yield lower and esterified biodiesel higher NO_x emissions compared to regular diesel fuel, if no changes to the engine are implemented.

In the case of common-rail injection systems, the fuel amount is controlled by rail pressure and injector activation time. Density, viscosity and compressibility do not affect start of injection as much, because pressure is pre-built-up, and the lift of needle immediately starts injection (Zhang & Boehman 2007, Tilli et al. 2009).

Taking into consideration the differences in injection systems, combustion strategies and exhaust gas after-treatment of the vehicles screened, the effects of HVO on NO_x as well as PM emissions are readily explained.

Conventional diesel vehicles (Euro II & Euro III with in-line injection pumps)

Euro II and Euro III certified buses, the oldest vehicles covered in this study, can be considered to represent the most robust technologies. They have in-line –type fuel injection pumps and simple oxidation catalyst. In other projects, VTT has found out that the service life of the oxidation catalyst used on Euro II and Euro III buses is rather limited (Erkkilä et al. 2004, Nylund & Erkkilä 2005, Kytö et al. 2009, Erkkilä et al. 2011a). This means that in the screening process, the tailpipe emissions of these vehicles in fact corresponded to engine-out emissions. Because of simple fuel injection systems, ineffective exhaust after-treatment devices and open loop control systems, this group of vehicles was less prone to secondary factors affecting emission results. However, one tested Euro III vehicle was retrofitted with a particulate filter.

Figures 9.2 and 9.3 show NO_x and PM emissions as a function of HVO content in regular EN590 summer-grade diesel fuel for eight individual Euro II and Euro III buses (2 Euro II buses of the same brand and 6 Euro III buses of another brand). As can be seen in Figure 9.2, both bus types and all bus individuals tested show relatively congruent NO_x results. For this group of buses, 100 % HVO reduced NO_x emission by 9 % on an average. PM-emission reductions were also consistent, 100 % HVO delivering on an average 23 % PM reduction (Figure 9.3).

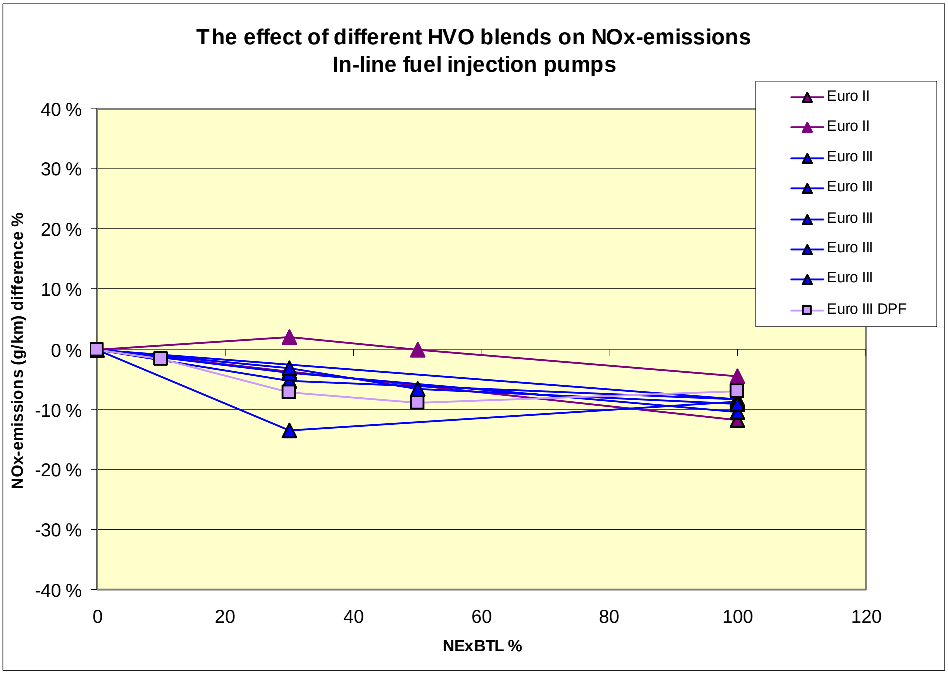


Figure 9.2. The effect of HVO content on NO_x emissions (Euro II and Euro III vehicles with in-line fuel injection pumps).

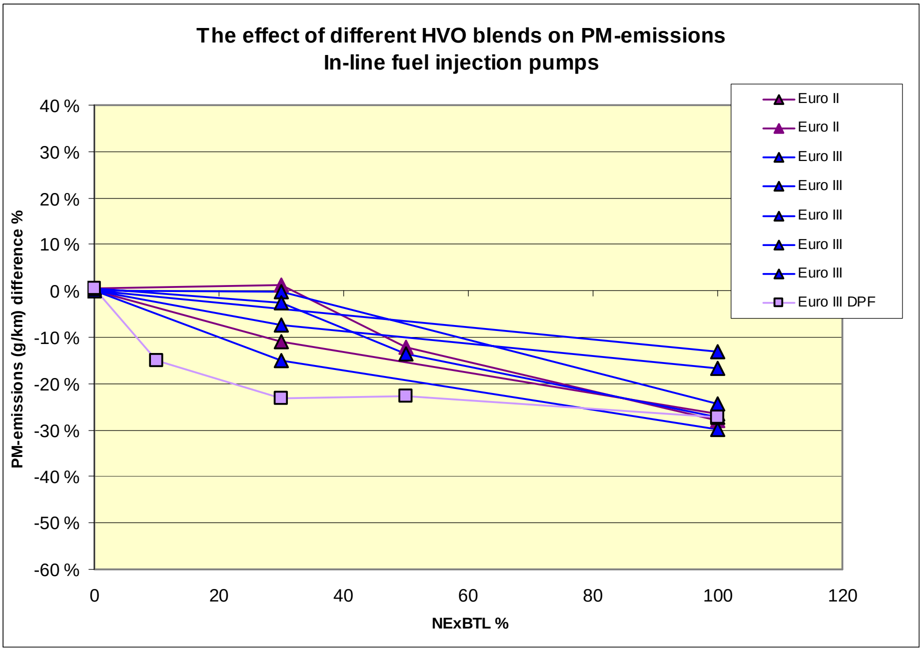


Figure 9.3. The effect of HVO content on PM emissions (Euro II and Euro III vehicles with in-line fuel injection pumps).

Advanced diesel vehicles (Euro IV & EEV with common-rail injection systems)

Figures 9.4 (NO_x) and 9.5 (PM) show the effect of HVO content on emissions for newer Euro IV and EEV buses equipped with common-rail injection systems. In this group, the effect on NO_x emissions varied significantly by bus type and even by bus individual (Figure 9.4). Only one case of increased NO_x emissions was found: for the EGR-technology based EEV bus NO_x emissions increased by 16 %, but on the other hand, for this bus particulate mass was reduced by as much as 47 %. Two other common-rail buses showed no effect at all, and one bus showed a reduction of 14 %.

High rate of EGR retards start of combustion and slows down combustion suppressing NO_x formation, but at the expense of elevated PM emissions. For the high EGR rate EEV certified engine the effect of HVO could be explained as follows: the high-cetane fuel shortens ignition delay and speeds up combustion, resulting in an increase in combustion temperature and NO_x, and, on the other hand, a significant reduction of particulates. The difference in fuel chemistry (fuel containing aromatics vs. paraffinic fuel with lower combustion temperature) is in this case not enough to reduce or even stabilize NO_x emissions. PM emissions, on the other hand, were significantly reduced. It should be noted that all measurements were done with standard engine calibrations. In the case of the high EGR rate engine, injection timing should probably have been retarded somewhat to trade-off high PM reductions for comparable or reduced NO_x emissions.

On an average, HVO did not render any NO_x benefits for the tested common-rail buses (+1 %), but then the reduction of PM emissions was higher than for the Euro II and Euro III certified buses, being 36 % on an average (Figure 9.5). In the case of the EGR technology based EEV bus, the only vehicle to show an increase in NO_x, HVO reduced PM emissions significantly, 47 %. The EGR EEV bus was equipped with a FTF device for particulate reduction.

For common-rail buses without any PM after-treatment devices, HVO on an average delivered 31 % lower PM emissions than regular diesel. This was slightly higher than the average for in-line pump or unit-injector engines. This in combination with a smaller NO_x reduction could be explained by the non-retarded start of injection and combustion in engines using common-rail injection (compared to volume based systems using HVO).

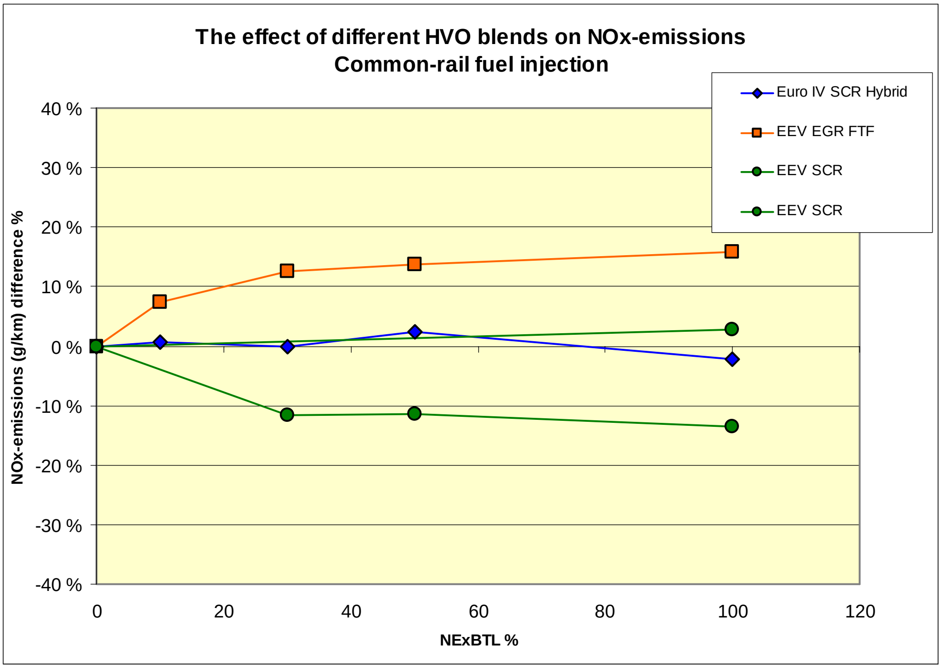


Figure 9.4. The effect of HVO content on NO_x emissions (Euro IV and EEV vehicles with common-rail injection systems).

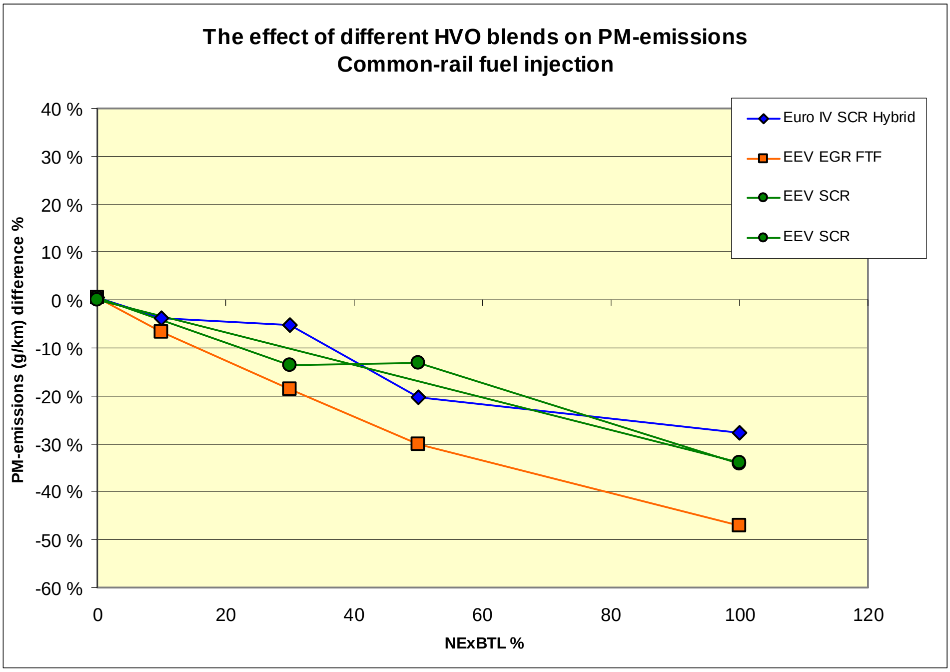


Figure 9.5. The effect of HVO content on PM emissions (Euro IV and EEV vehicles with common-rail injection systems).

Advanced diesel vehicles (Euro IV, Euro V & EEV with unit injectors)

On buses with unit injectors, HVO delivered the highest combined NO_x and PM reductions. Average reduction was 16 % for NO_x and 45 % for PM (Figures 9.6 and 9.7). The bus equipped with both SCR and DPF after-treatment devices presented the highest reduction rates for all vehicles, 31 % for NO_x and 53 % for PM.

When excluding results with SCR after-treatment systems for NO_x emission control and FTF or DPF for PM reduction, the reduction for all vehicles with volume based injection system (in-line pumps and unit injectors), was a steady 9 % (sd. 2.7 %) for NO_x and 24 % (sd. 6.2 %) for PM.

HVO in vehicles with SCR systems

SCR systems using urea injection for NO_x control are sensitive to, among other things, actual exhaust temperatures during the test cycle. This leads to a relatively unstable NO_x performance, which can be seen from the scattered results of two identical common-rail SCR buses in Figure 9.4. Another specimen of SCR buses was a parallel diesel-electric hybrid, but for this case the emission behaviour with HVO was also in congruence with the rest of the common-rail SCR vehicles.

Current SCR-systems control the amount of injected urea using pre-programmed injection maps, based on engine torque and rpm. Running on neat HVO, the fuel flow is, due to the lower density of HVO, slightly higher than for regular diesel fuel. The engine will interpret the increased injection volumes as higher loads, thus increasing urea injection. This makes it harder to draw conclusions on fuel effects for the SCR equipped vehicles.

Two SCR buses, one in the category of vehicles with common-rail injection systems and one in the category of vehicles with unit injectors, showed high NO_x reductions, 14 % (Figure 9.4) and 31 % (Figure 9.6). These two vehicles in fact used some 10 % more urea than the other SCR vehicles. This means that variations in NO_x emission can be attributed to fuel and injection system effects as well as to SCR system performance.

Vehicles with PM reducing devices

Comparing PM results in Figures 9.3, 9.5 and 9.7, it is evident that vehicles with PM after-treatment devices, FTF or DPF, were showing higher PM reduction rates for HVO than vehicles without these devices. This could be related to a more favourable engine out NO_x/PM ratio with respect to the operation of particle oxidation devices. In proportion, PM is reduced more than NO_x, and NO_2 again acts as an oxidizing agent for PM. This may also have positive long-term advantages when using HVO fuel in vehicles with particle reducing exhaust after-treatment systems.

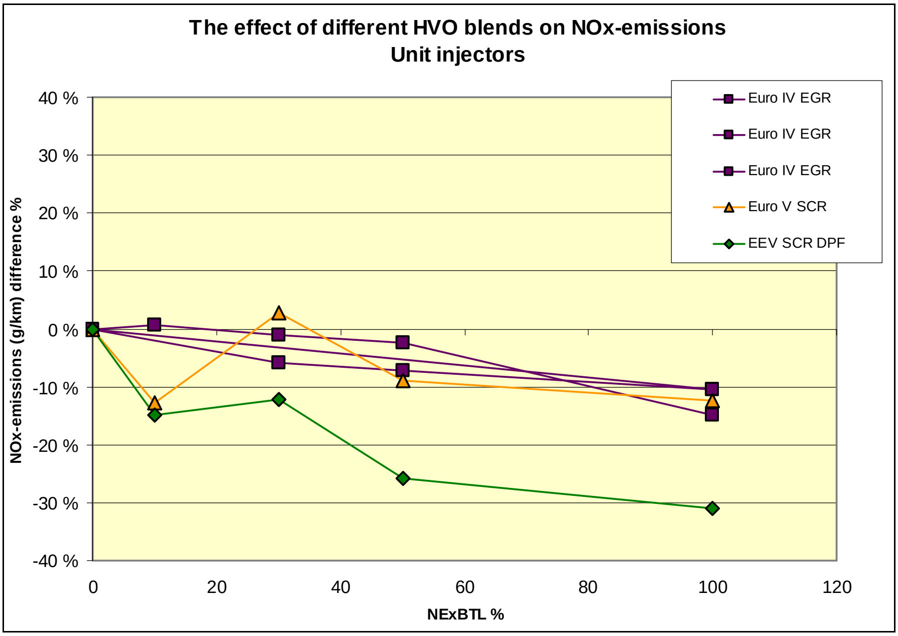


Figure 9.6. The effect of HVO content on NO_x emissions (Euro IV, Euro V and EEV vehicles with unit injectors).

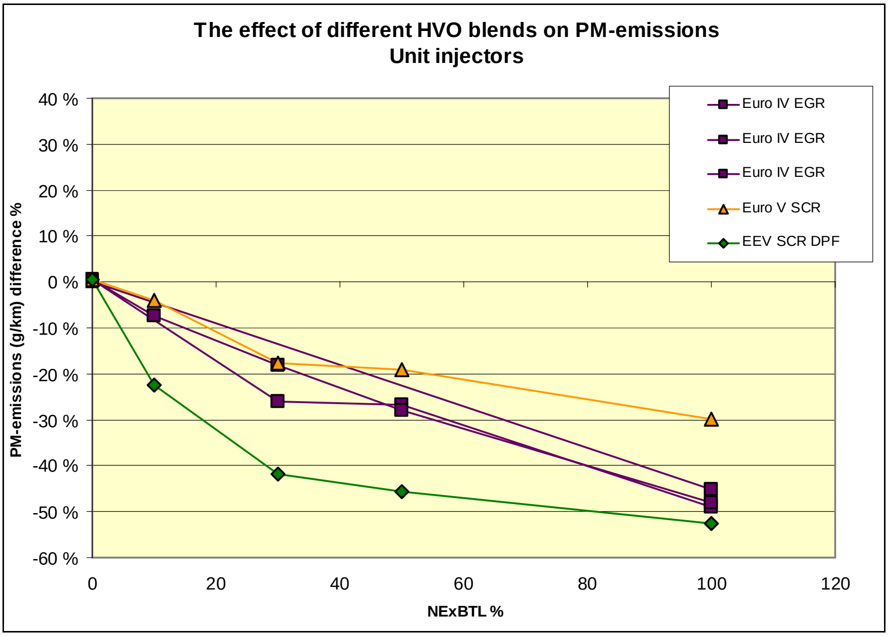


Figure 9.7. The effect of HVO content on PM emissions (Euro IV, Euro V and EEV vehicles with unit injectors).

Average effect of HVO fuel on NO_x and PM emissions

It can be concluded that the effects of HVO fuel on NO_x and PM emissions depend on the injection systems as well as on the exhaust control strategies, and that the response to HVO fuel will vary depending on technology. In most cases it is more practical to report average effects than vehicle specific results. In addition to the dense summer grade EN590 diesel fuel, lighter winter grade diesel fuel was also included in the test matrix (Paragraph see 7.3.2). The average effect of HVO fuel on NO_x and PM emissions, compared to the two reference EN590 diesel fuels, are shown in Figures 9.8 and 9.9. Individual results are included in grey colour to illustrate the variation. The average effect was -10 % for NO_x and -30 % for PM (see also Paragraph 9.4.1).

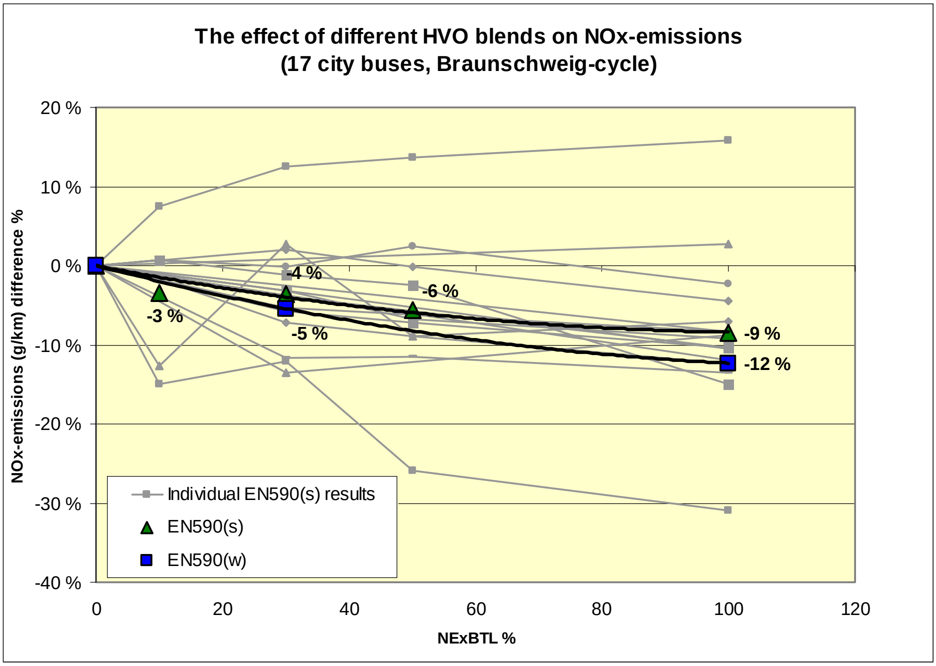


Figure 9.8. Average effect of HVO fuel on NO_x emissions.

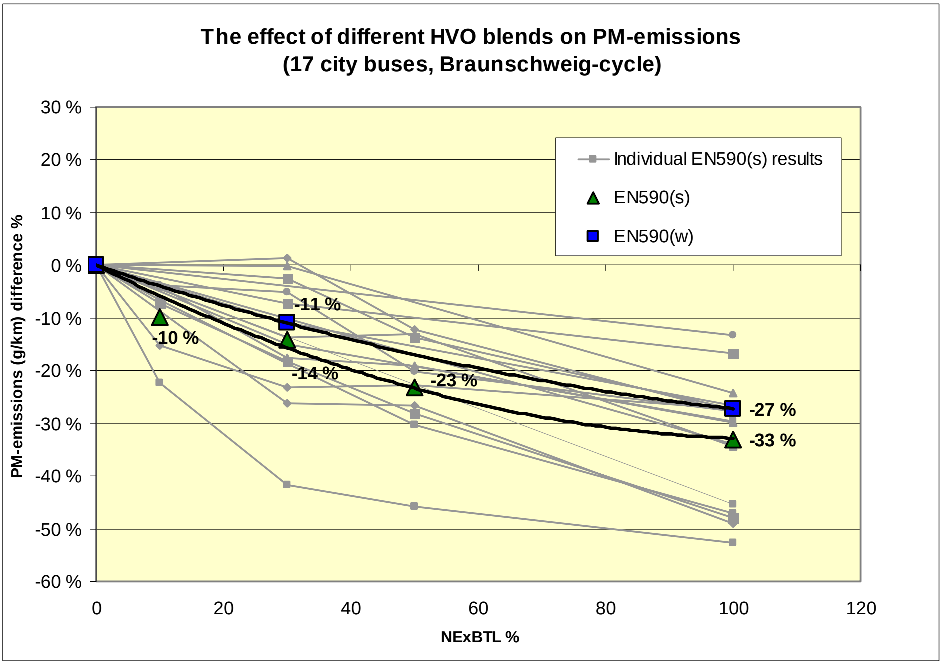


Figure 9.9. Average effect of HVO fuel on PM emissions.

9.4.3 CO and THC emissions

For diesel engines, carbon monoxide (CO) and total hydrocarbons (THC) are not as problematic emission components as NO_x and PM are. However, both CO and THC are regulated as they are unwanted emissions with health effects, but the regulatory limit values are normally easily met. Figures 9.10 and 9.11 show average CO and THC reductions with HVO fuel. The error bars in the pictures illustrate the variation of individual results (min and max). The results of two EEV buses with particulate oxidation devices were ignored, because the emission levels were at the detection limit of the emission analyzers. Low absolute CO and THC levels explain the variations in Figures 9.10 and 9.11. The reductions in CO and THC emissions indicate improved and more complete combustion process with HVO (Aatola et al. 2008). Average reductions were 29 % for CO and 39 % for THC.

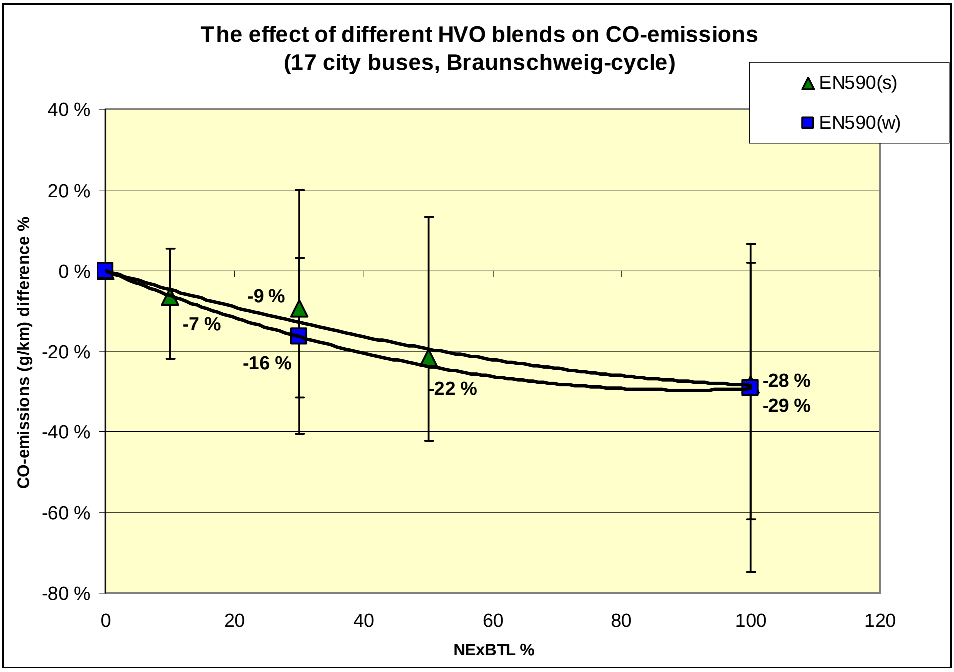


Figure 9.10. The effect of HVO content on CO emissions.

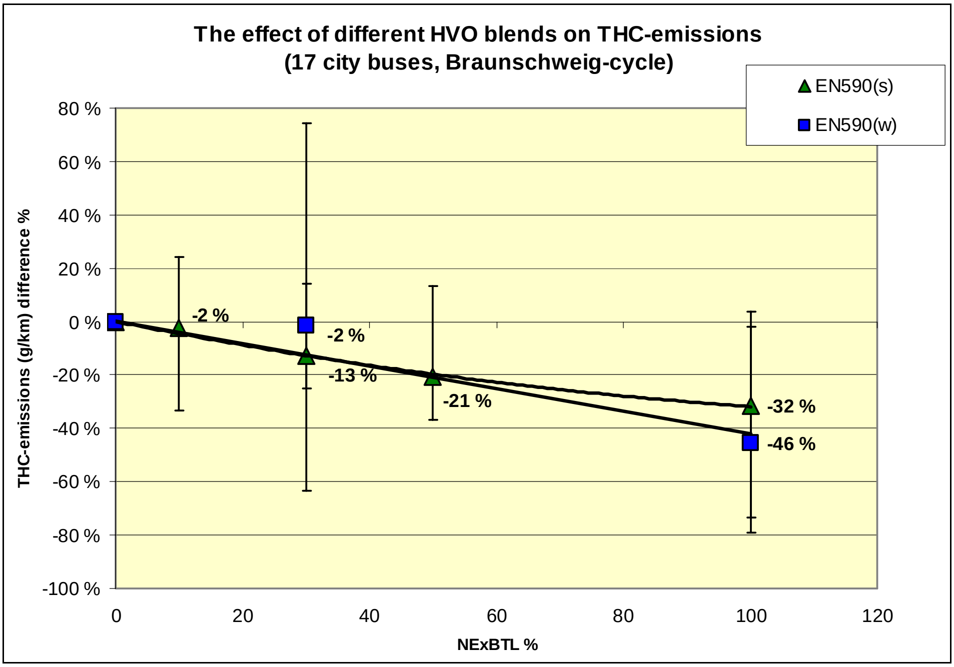


Figure 9.11. The effect of HVO content on THC emissions.

9.4.4 Tailpipe CO_2 emissions

Switching from regular diesel fuel to neat HVO also affects tailpipe carbon dioxide (CO_2) emissions. There are two factors influencing CO_2 emissions, energy use (e.g. MJ/kg) and specific CO_2 emission (g CO_2/MJ). The fuel consumption measurements reported in Paragraph 7.3.2 showed that the effect of ne at HVO on energy consumption is quite small, in the order of -0.5 % (results for 10 buses). For all 17 buses screened, the reduction was -0.3 %.

Calculated from the carbon content of the fuels, with equal energy consumption a switch from regular diesel to neat HVO should reduce tailpipe CO_2 emissions some 3.3 %. The average measured CO_2 emission reduction with neat HVO was 4.6 % (Figure 9.12). Thus the CO_2 measurements also indicate a small decrease in energy consumption when switching to neat HVO. However, it should be noted that fuel consumption can be measured with high accuracy (sd. 1.1 %), whereas the accuracy for CO_2 measurements as well as emission measurements in general is estimated at some ±15 %.

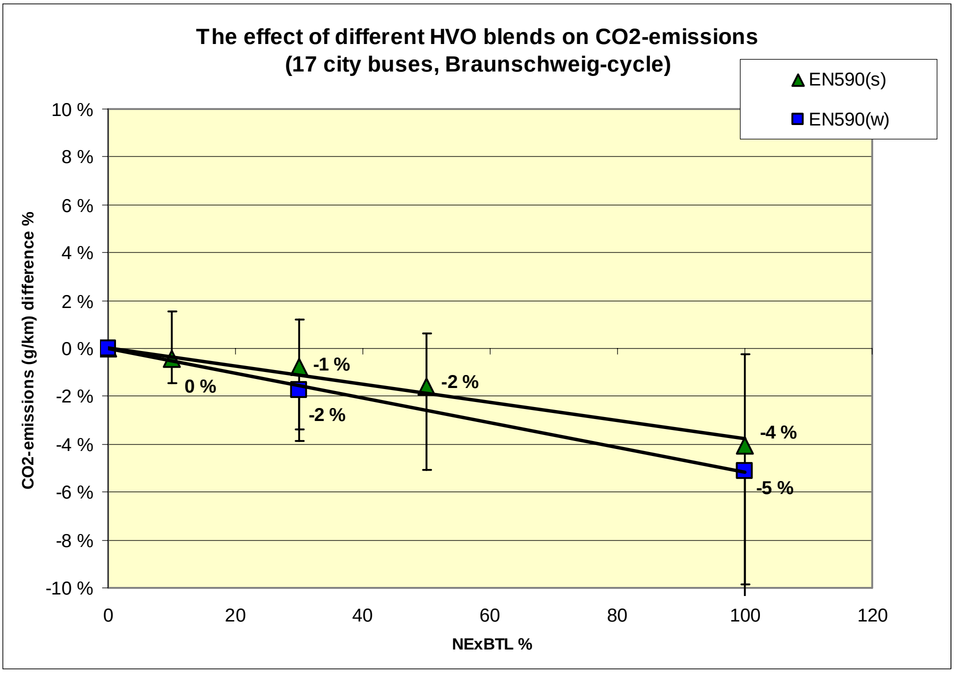


Figure 9.12. The effect of HVO content on tailpipe CO_2 emissions.

9.4.5 Summary – buses

HVO undoubtedly reduces the emission of products of incomplete combustion. The physical properties of HVO (e.g., low density, low bulk modulus, low viscosity and low end of distillation temperature) lead to wide fuel spray angles, smaller droplets, early evaporation and thus short liquid penetration, good mixing and less spray-wall interactions. This reduces CO, THC and PM emissions. The effect on NO_x depends on several factors, injection system, combustion scheme and exhaust after-treatment system. However, 100 % HVO has a potential to reduce aggregate NO_x and PM emissions. In an engine, which delivers little or no reductions for NO_x with HVO, PM emissions will be substantially reduced. This applies, when using standard engine calibration. The balance between NO_x and PM will be discussed in detail in Chapter 12. Tailpipe CO_2 emissions will be reduced somewhat when switching from regular diesel to 100 % HVO. The primary reason for this is a more favourable hydrogen-to carbon ratio for HVO, whereas the marginally improved efficiency on HVO is only a secondary factor.

The average reductions in regulated emissions, CO_2 emission and fuel consumption when switching from regular diesel to 100 % HVO are (round figures, results based on 11–17 vehicles):

- CO: -30 %
- THC: -40 %
- PM: -30 %
- NO_x: -10 %
- CO_2: -5 % (tailpipe)
- energy consumption: -0.5 % (volumetric fuel consumption: +4.5 %).

9.5 Results – trucks

The results of the emission measurements on the two trucks are summarized in Figure 9.13 (NO_x and PM emissions). Although the duty cycles differ significantly from the Braunschweig cycle used for buses, the results for 100 % follow the same pattern as for buses. HVO reduced both NO_x and PM emissions for the Euro III vehicle, whereas HVO slightly increased NO_x but significantly reduced PM emissions for the Euro IV vehicle:

- Euro III, in-line injection pump: NO_x – 7 % and PM – 23 %
- Euro IV, common-rail, EGR, FTF: NO_x +3 % and PM – 62 %.

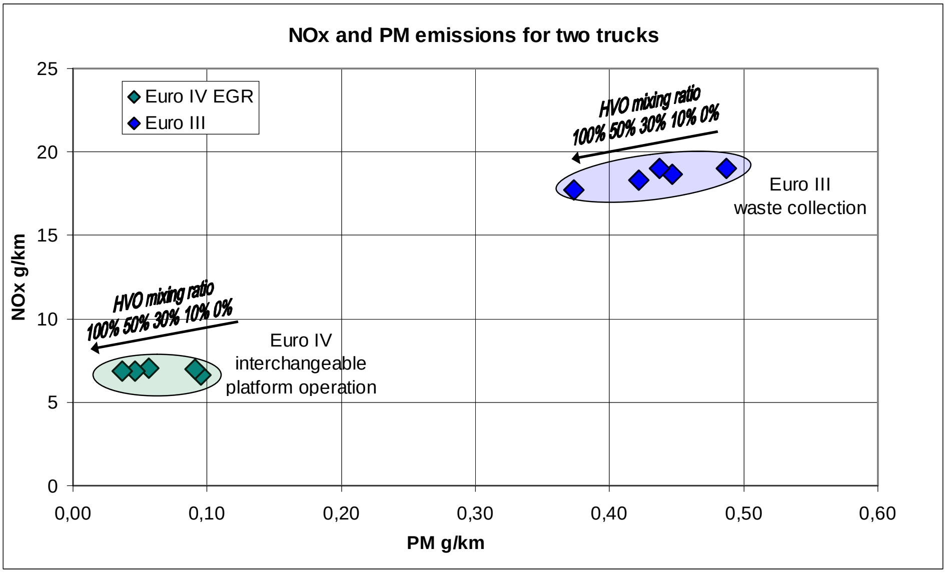


Figure 9.13. Effect of HVO on NO_x and PM emissions from trucks. Euro III vehicle with in-line injection pump, no exhaust after-treatment. Euro IV vehicle with common-rail injection, EGR and FTF. Red marks EN590 diesel fuel. Blue and green marks 10, 30, 50 and 100 % HVO.

10. The effect of HVO on unregulated emissions

10.1 General

As shown in Chapter 9, switching from regular diesel to 100 % HVO will on an average deliver emission benefits in the for m of reduced regulated emissions (NO_x, PM, CO, THC). As for NO_x, the response to 100 % HVO depends on the vehicle type (mainly injection system and combustion scheme).

The methodology and the limit values set for regulated components have originally been developed for regulatory purposes, for type approvals and for engine-to-engine or vehicle-to-vehicle comparisons using closely defined reference fuels. Therefore, when evaluating the performance of new fuel qualities, unregulated emissions should also be accounted for. This to ensure that a fuel switch does not lead to unwanted effects regarding, e.g., toxicity or health effects.

VTT has carried out measurements of unregulated emission components in several earlier projects. One example of such a project is the 2004 project “Transit Bus Emission Study: Comparison of emissions from diesel and natural gas buses”. The final report of this project contains information on methodology, as well as on the significance of various emissions components (Nylund et al. 2004).

For the measurements of unregulated components within the OPTIBIO project, basically the same principles were applied as for the Transit Bus Emission Study.

Analysing unregulated emission components can be both expensive and time consuming. To determine the unregulated emissions for all vehicles and all fuel options covered in the screening process would have been too costly. Therefore, for the OPTIBIO project, three representative vehicles were chosen for the measurements of unregulated emissions (see Table 9.1):

- Euro III (in-line injection pump, oxidation catalyst, vehicle 7)
- Euro IV (unit-injectors, EGR, oxidation catalyst, vehicle 11)

- EEV (common-rail, SCR catalyst, vehicle 14).

As stated in Paragraph 9.4.2, VTT has found that the durability of simple diesel oxidation catalysts is quite limited. The assumption is therefore that the tailpipe emissions of the Euro III and Euro IV vehicles selected for measurement of unregulated emissions were quite close to engine-out emissions.

The number of fuels was limited to two, regular summer-grade diesel fuel and 100 % HVO, as these two options represent the “extreme ends” of the fuel matrix.

10.2 Components analysed and instrumentation

The analysis of unregulated emission components covered the following measurements (a full list of the components analysed is presented in Appendix 3):

Gaseous phase:

- hydrocarbon speciation up to C_8 hydrocarbons (GC)
- aldehydes (DNPH sampling, HPLC)
- ammonia (FTIR).

Particulate phase:

- particulate number size distribution (ELPI)
- PAH compounds (polyaromatic hydrocarbons, collected on filters, GC/MS-SIM)
- Ames mutagenicity of the extracted particle matter.

In its 2007 rulemaking, the U.S. Environmental Protection Agency (EPA) lists mobile source air toxics (MSAT). The 8 components or groups of compounds of particular concern are (EPA 2007):

- benzene
- 1,3-butadiene
- formaldehyde
- acetaldehyde
- acrolein
- polycyclic organic matter (POM)
- naphthalene
- diesel exhaust.

EPA has identified seven polynuclear aromatic hydrocarbons as probable human carcinogens (often called priority PAHs):

- (benz(a)anthracene
- benzo(b)fluoranthene
- benzo(k)fluoranthene
- benzo(a)pyrene
- chrysene,
- 7,12-dimethylbenz(a)anthracene
- indeno(1,2,3-cd)pyrene.

Nitro substituted PAHs were not analysed in the OPTIBIO project.

Ammonia was measured from raw exhaust using an on-line FTIR instrument by Gasmet. For this instrument, detection limit for ammonia is 3 ppm.

Particle number size distribution was measured using an on-line ELPI instrument by Dekati Ltd. The instrument's electrical low pressure impactor classifies particles by size based on aerodynamical diameter. The raw exhaust sample has to be diluted for the device. This was done in two steps, the first step being a porous tube diluter and the second step being an ejector type diluter. The instantaneous dilution ratio was measured from CO_2, and the dilution ratio was used for the calculations.

The Ames test is used as a bioassay for indicating a substance's short-term mutagenicity in the *Salmonella* bacteria cells (Maron & Ames 1983). It has been an established and simple cell test for more than 20 years, but it is not a substitute for tests with animal or human cell lines or tests using living animals or epidemiological studies.

In the Ames test bacteria strains are subjected to extracts from the particle matter. With reserve, the test can also be applied to samples from the semivolatile phase. The number of mutations in the bacteria is used as an indication of the mutagenicity of the particle matter. Different kinds of bacteria strains, responsive to different kinds of compounds can be used.

Nitro-PAHs are direct acting mutagens and react in *Salmonella typhimurium* cells without metabolic activation (TA98-S9). With metabolic activation (+S9), the mutagenicity of nitro-PAH's is overruled, and therefore the result indicates indirect mutagenicity of the sample. Typically diesel exhaust gas contains more direct acting mutagens than indirect acting ones.

The outcome of the Ames test is normally given in the form revertants/mass, typically krev/mg indicating specific mutagenicity of the material analysed. Mutagenicity can also be correlated to work, meaning that the results are expressed as krev/km or krev/kWh. This approach takes into consideration both the specific mutagenicity of the particle matter and the amount of particle mass emitted. (Nylund et al. 2004)

The Ames testing was carried out using the same particulate samples, which had been used for PAH analysis. The analysis were performed for the extracted samples and reference samples, using 5 different concentration levels and 2–3 parallel Petri dishes per concentration level. The bacteria strains used were *Salmonella typhimurium* TA98 (±S9 mix) and *Salmonella typhimurium* TA98 NR (-S9 mix).

As will be seen later on from the results, the non-responsive Ames tests and the zero results for priority-PAHs indicate probable errors in particle sample extractions. Therefore Ames results from a parallel study (IEA Bus project, Munack et al. 2010) will be presented.

10.3 Results

10.3.1 General

Already the term "unregulated emission components" indicates that there are no legislative limits for these components. Therefore, the evaluation must be based on comparative analysis. In the case of the OPTIBIO project this was done between regular EN590 diesel fuel vs. 100 % HVO. In addition, most of the analyses are rather complicated, meaning that the margins of errors might be quite high. Therefore, the results for unregulated components should first and foremost be considered indicative only.

10.3.2 Speciated light hydrocarbons

The total THC levels of the tested vehicles are as follows (round figures):

- Euro III: 0.3 g/km
- Euro IV: 0.15 g/km
- EEV: 0.03 g/km.

Figures 10.1 to 10.3 show speciated light hydrocarbons for the three test vehicles. The Euro III vehicle and the Euro IV vehicle showed similar patterns and similar component levels. The dominating non-methane hydrocarbons are ethene (C_2H_4) and propene (C_3H_6). Neat HVO tends to decrease methane (CH_4), benzene (C_6H_6) and toluene (C_7H_8) and increase ethane and propene emissions. The trend for 1,3-butadiene (C_4H_6) is not unambiguous. In the case of the SCR equipped EEV vehicle, only methane and benzene were detected. With 100 % HVO, the benzene emission dropped below detection limit.

The individual hydrocarbons constitute the following relative shares of THC (round figures):

- Euro III: methane 5 %, ethene 15 %, propene 5 %, benzene 2 %
- Euro IV: methane7 %, ethene 17 %, propene 5 %, benzene 3 %
- EEV: methane 30 %, benzene 7 %.

The overall conclusion is that the fuel effects are rather small, but that 100 % HVO consistently reduces benzene and toluene emissions.

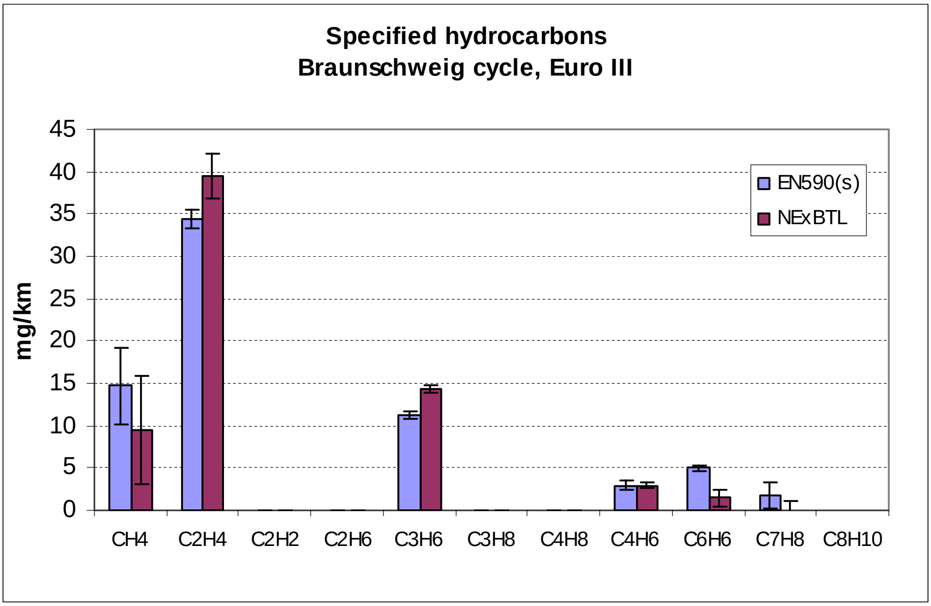


Figure 10.1. Speciated light hydrocarbons for the Euro III vehicle. Vehicle equipped with oxidation catalyst (ineffective).

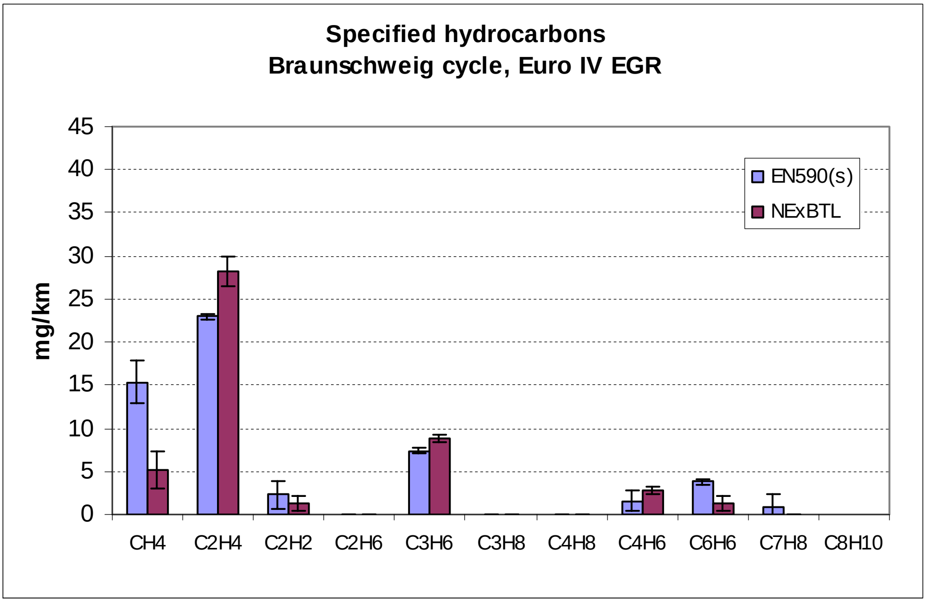


Figure 10.2. Speciated light hydrocarbons for the Euro IV vehicle. EGR vehicle with oxidation catalyst (ineffective).

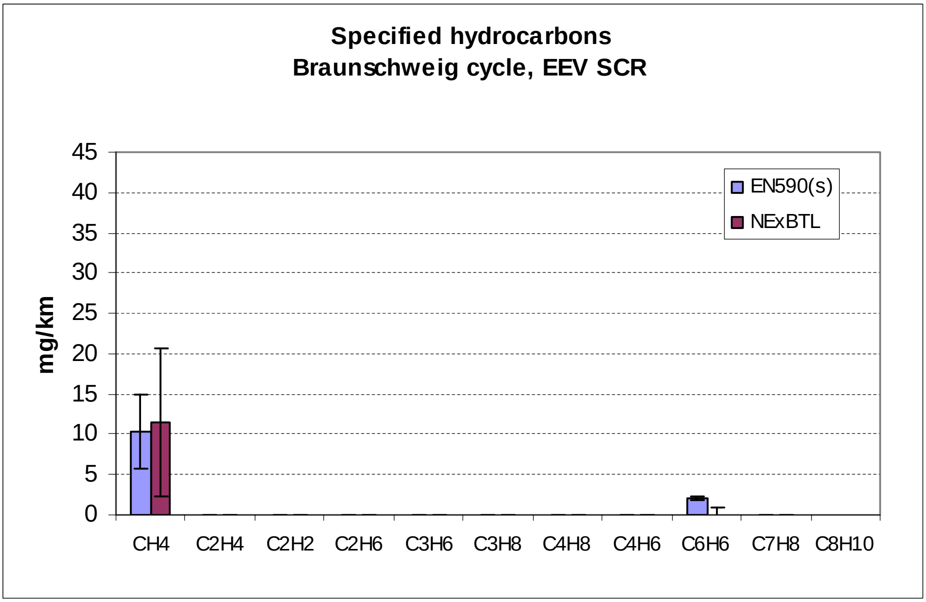


Figure 10.3. Speciated light hydrocarbons for the EEV vehicle. SCR catalyst.

10.3.3 Aldehydes

Figure 10.4 shows the aggregate emission of aldehydes (sum of 10 compounds), formaldehyde emission and acetaldehyde emission. Formaldehyde is the dominating component, some two thirds of aggregate aldehyde emissions. Formaldehyde and acetaldehyde together make up some 85 % of total aldehyde emissions. The fuel has negligible effects on the aldehyde emissions of the Euro IV and the EEV vehicle. In the case of the Euro III vehicle, 100 % HVO increases aldehyde emissions somewhat (some 15 %). This is in line with the findings of Munack et al. (2010). Switching fuel doesn't affect the ratio between formaldehyde and acetaldehyde. Vehicle technology, on the other hand, has a major impact on aldehyde emissions. The EEV vehicle delivers some 80 % lower aldehyde emissions compared to the Euro III vehicle.

Both the Euro III vehicle and the Euro IV were equipped with an oxidation catalyst. An oxidation catalyst should in principle effectively reduce carbonyl emissions. The relatively high carbonyl emissions of the vehicles indicate that the oxidation catalysts were more or less inactive, as indicated earlier.

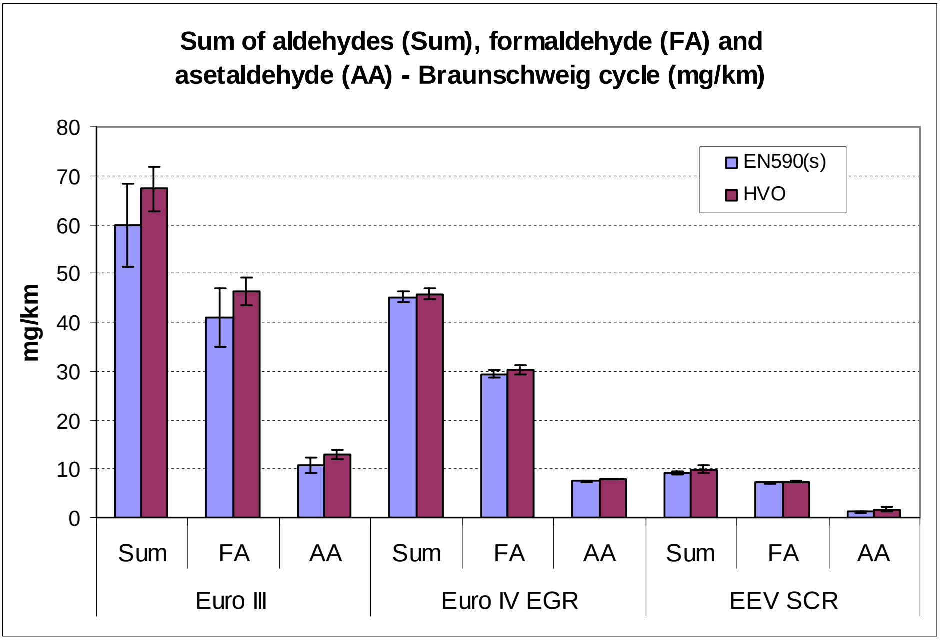


Figure 10.4. Aggregate aldehyde emissions, formaldehyde emissions and acetaldehyde emissions.

10.3.4 Ammonia

The EEV vehicle was equipped with an SCR catalyst system using urea as a reducing agent. With such a system, ammonia slip is possible. Slip means that the urea injection is not in balance with the actual load condition and NO_x formation, leading to ammonia in the exhaust after the SCR system due to overdosing of urea. Typically slip occurs in conjunction with rapid load changes from high to low.

Figure 10.5 shows ammonia concentration in raw exhaust for the SCR equipped EEV vehicle with regular diesel fuel and with 100 % HVO. Ammonia levels were low, even the peaks were below the actual detection limit of 3 ppm, and thus no fuel related differences could be detected.

As described in Paragraph 9.4.2, an SCR system might interpret 100 % HVO as increased load, due to the increased fuel with 100 % in comparison with regular diesel. The measurements confirmed that this has no consequences for ammonia slip.

As can be expected, ammonia levels were also low for the two other vehicles evaluated.

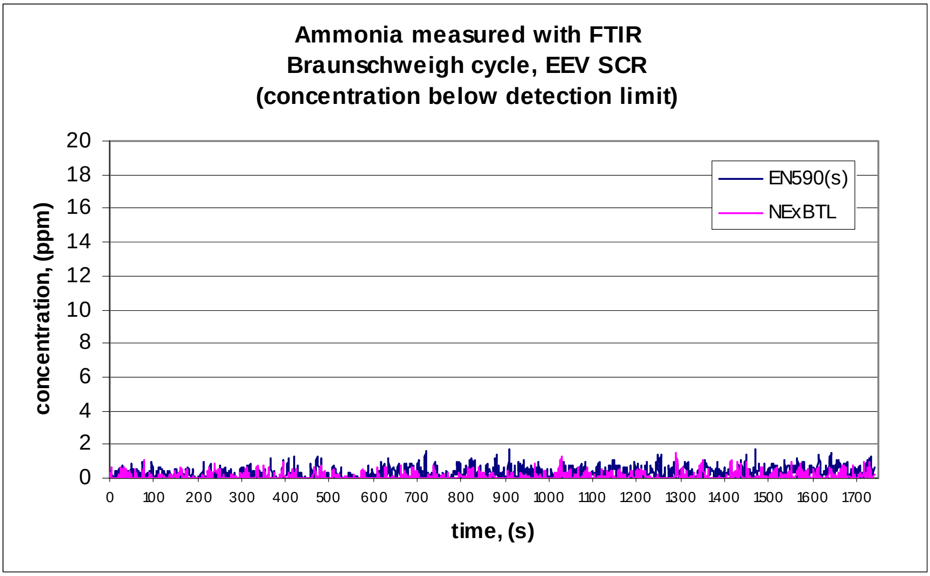


Figure 10.5. Ammonia concentration in raw exhaust for the SCR equipped EEV vehicle.

10.3.5 Particle sizes and numbers

Figures 10.6 to 10.8 show particle number size distribution for the individual vehicles (linear scale for particle sizes). Markings for scatter of the results have been included to depict repeatability.

In the case of the Euro III vehicle, fuel had negligible effects on particle size distribution and particle numbers in the different particle size categories, despite the fact that particle mass, expressed as g/km, was reduced 7 % when going from regular diesel fuel to 100 % HVO.

For the Euro IV vehicle and the EEV vehicle fuel had a clear effect on particle numbers. Compared to regular diesel, 100 % HVO reduced particle numbers in all size classes by 17–40 %. For these two vehicles, the reduction in particle mass (in g/km) was particularly high, some 40 %.

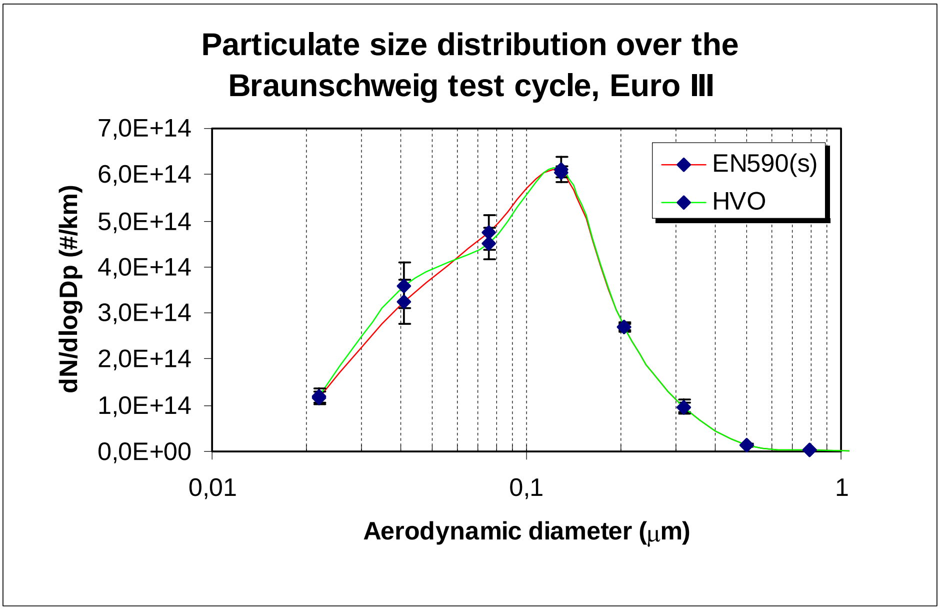


Figure 10.6. Particle number size distribution for the Euro III vehicle.

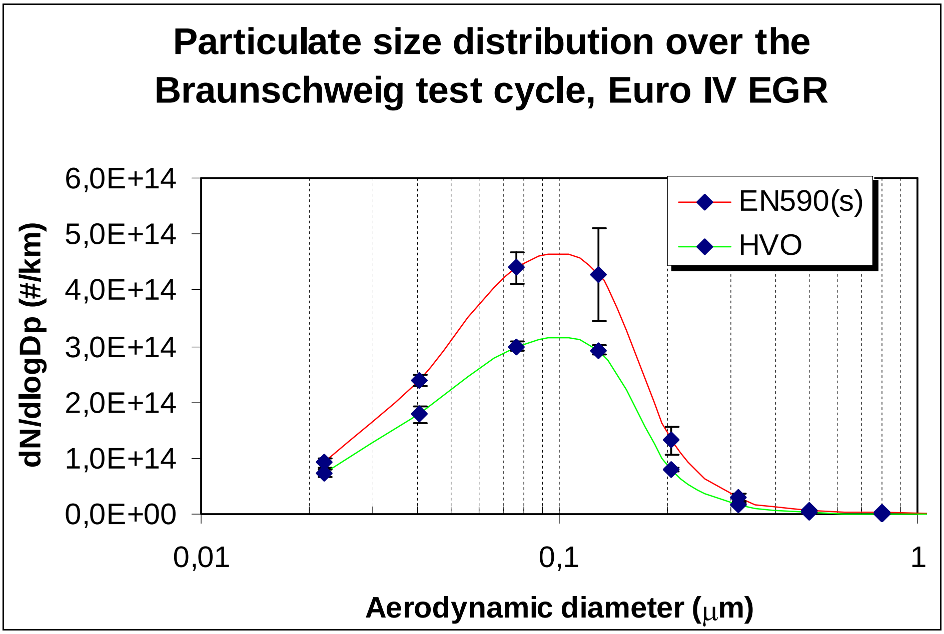


Figure 10.7. Particle number size distribution for the Euro IV vehicle.

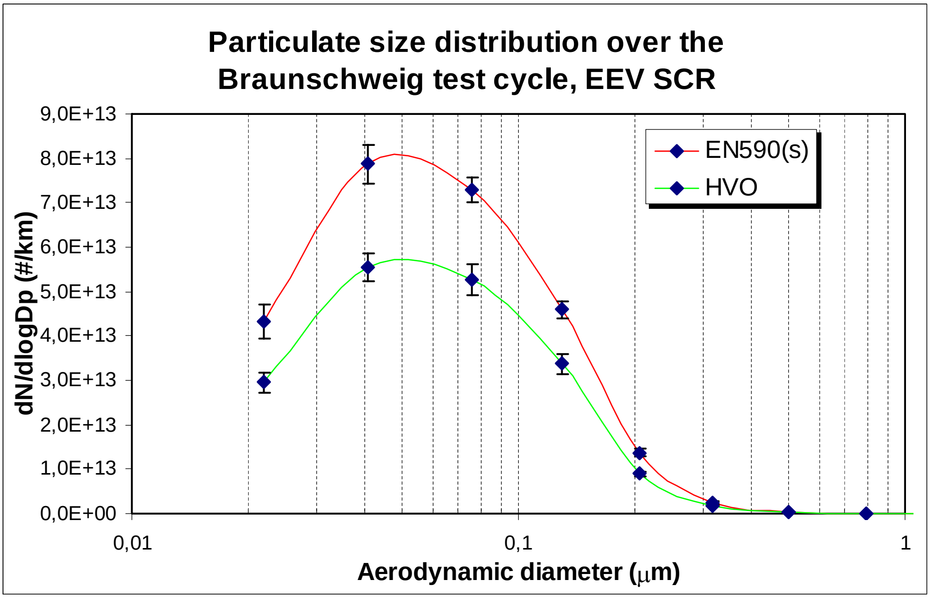


Figure 10.8. Particle number size distribution for the EEV vehicle.

Switching from regular diesel to 100 % HVO did not significantly change the profile of the particulate number size distribution curves. This is true for all three vehicles tested. This means that HVO does not affect the distribution between small and large particle in an adverse way (the numbers of small particles remain constant or decreases). This is important, since small particles are considered more harmful than larger particles.

Figure 10.9 shows a comparison of the particle number emissions for the three vehicles. In this case the scale for particle size is logarithmic to make it possible to show the results of all three vehicles in the same figure. The Euro III and the Euro IV vehicle show almost identical results, whereas particle numbers are reduced approximately with one order of magnitude for the EEV vehicle. However, in comparison with the two other vehicles, the EEV vehicle shows a slightly different size distribution profile with, in relative terms, higher numbers of small and lower numbers of large particles.

Although HVO reduces particulate mass and in most case also particle numbers, the results on particle number size distribution demonstrate that particle numbers first and foremost depend on vehicle technology, not fuel.

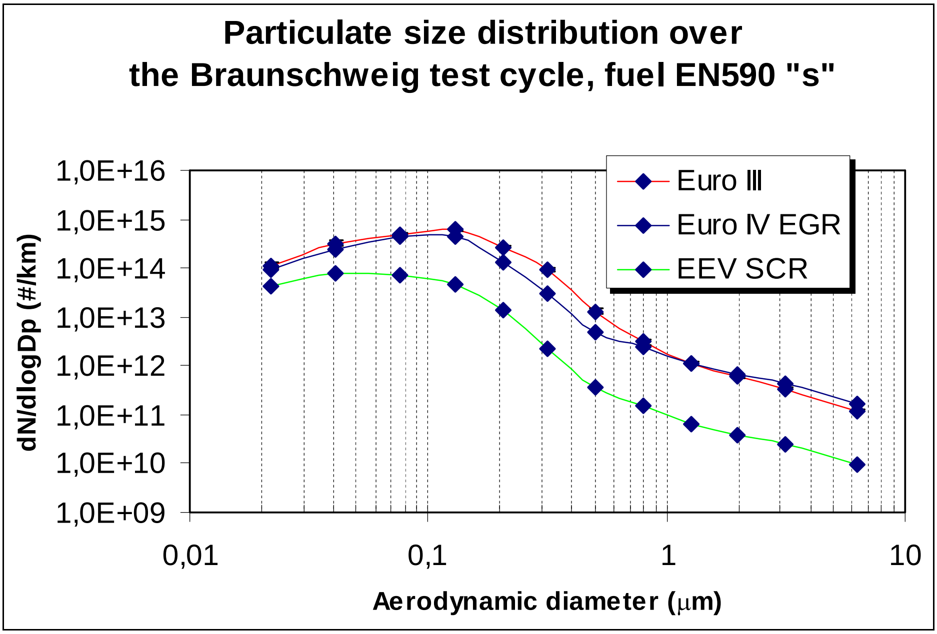


Figure 10.9. Comparison of particle numbers of the three vehicle individuals (Euro III, Euro IV and EEV) using regular diesel fuel.

10.3.6 PAH emissions

A wide range of PAH compounds were analysed, in total 30 compounds. The results are grouped as follows:

- compounds with 2 to 3 rings
- compounds with 4 or more rings
- priority PAHs
- total PAH.

It is evident vehicle technology as well as fuel affect PAH emissions significantly (Figure 10.10). Aggregate PAH emission with regular diesel fuel varied from 87 to 4 µg/km, depending on vehicle technology. However, fuel also had a major impact on PAH emissions, especially in the case of the Euro III and Euro IV vehicles. For these two vehicles, a switch from regular diesel to 100 % HVO reduces PAH emissions as follows:

- compounds with 2 to 3 aromatic rings: -55 %
- compounds with 4 or more aromatic rings: -83–-88 %
- total PAH: -60–-68 %

This means that the effects of HVO on PAH emissions, and therefore probably on exhaust toxicity, are more significant than the effects on regulated emissions discussed in Chapter 9 (range -10–-40 %).

In the case of the EEV vehicle, the PAH levels were low, and the relative fuel effects were smaller than for the older vehicles. The level of priority PAHs was below detection limit for all cases, indicating that there might have been an error in the extraction of the particle samples.

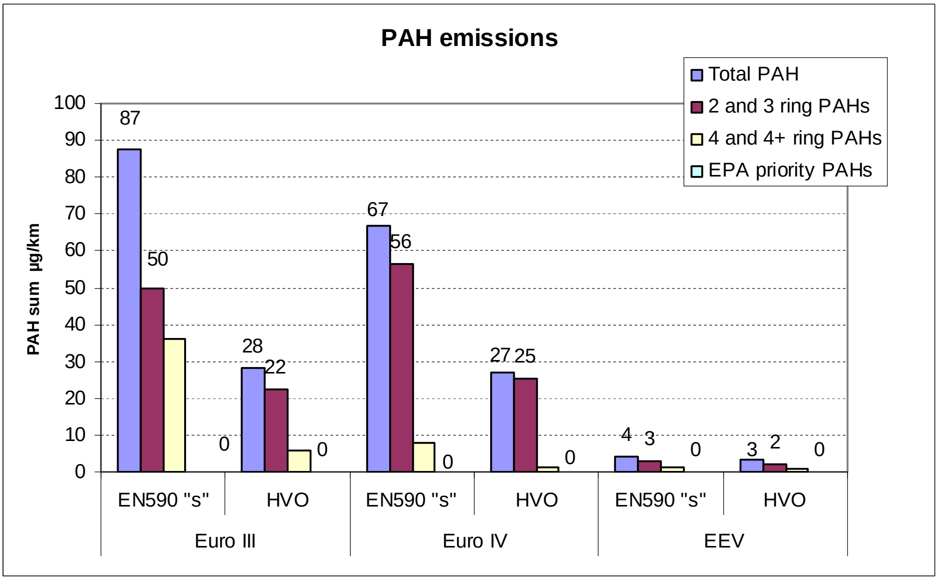


Figure 10.10. Summary of PAH emissions (extracted particulate phase).

10.3.7 Mutagenicity (Ames)

In the 2004 Transit Bus Study, testing delivered logical responses and values for specific mutagenicity. Fuels (diesel, methane) as well as different exhaust after-treatment devices could be differentiated. However, in the case of the OPTIBIO project, for reasons unknown, the response of the bacteria to different concentration levels was not explicit, and no distinct conclusion on mutagenicity could be drawn. Therefore the Ames analysis had to be deemed unsuccessful.

VTT is participating in a large International Energy Agency Technology Network programme called “Fuel and technology options for buses”. Within this project, the German research organization von Thünen Institute (vTI) of Braunschweig has conducted emission testing, including unregulated emissions, for several types of biodiesel fuels (Munack et al. 2010). vTI carried out the testing using a Euro III level heavy-duty engine (Mercedes-Benz OM 906) installed in an engine test bench. Ames testing was part of vTI’s work programme. vTI used strains TA98 and TA100, detecting mutagens that cause frameshift mutations and base-pair substitutions.

In the summary, Munack et al. 2010 state as follows:

> *“In comparison to diesel fuel, NExBTL (HVO) showed similar or better results except for the carbonyl emissions. In particular, NExBTL exhibited a very low mutagenicity of the exhaust and had the lowest PAH emissions compared to the three other fuels (diesel fuel and two vegetable oil esters). This trend of lower emissions had also been found for GTL fuel, which has comparable properties.”*

Figures 10.11 (TA98) and 10.12 (TA100) show vTI’s Ames results. The results are presented as number of mutations for a sample collected at equivalent engine conditions of a 28 minute period of the ESC (European Steady Cycle) emission certification cycle. This means that the results (relative) are comparable on a revertants/kWh or revertans/km basis.

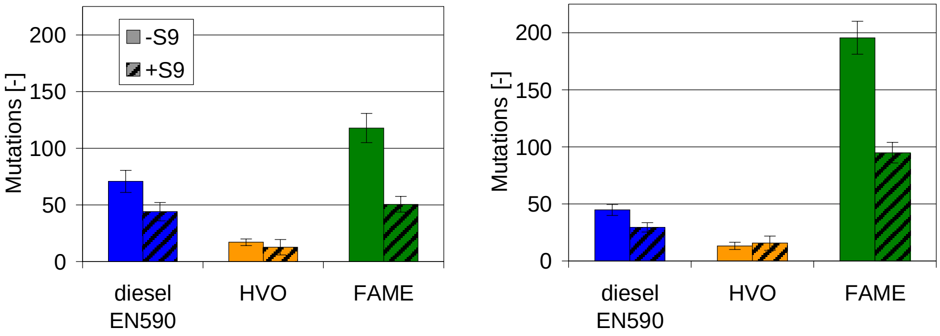


Figure 10.11. Mutagenicity of PM extracts/particulate phase (left) and condensates/ semivolatile phase (right) in strain TA98. (Munack et al. 2010)

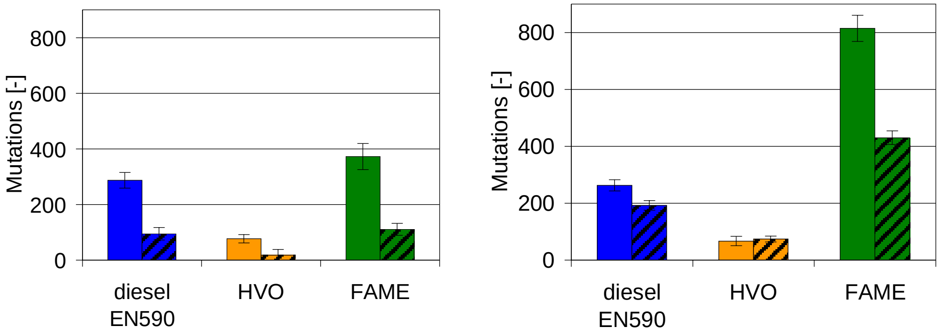


Figure 10.12. Mutagenicity of PM extracts/particulate phase (left) and condensates/semivolatile phase (lower) in strain TA100. (Munack et al. 2010)

NExBTL (HVO) shows a significant reduction in mutagenicity compared to diesel fuel (DF), whereas rape seed methyl ester (RME) shows significant increase in mutagenicity. As esterified biodiesel reduces particulate mass more effectively than HVO, the differences in specific mutagenicity (revertants/mg) would be even greater.

In a scientific article from 2009, VTT reports on the effects of various fuels on emissions. Included in the fuel matrix were, among others, HVO and GTL. Both HVO and GTL reduced Ames mutagenicity some 65 % compared to regular EN590 diesel. (Murtonen et al. 2009)

10.4 Summary – unregulated components

In Paragraph 9.4.5 it was concluded that HVO undoubtedly reduces the emission of products of incomplete combustion, that is to say CO, THC and PM.

As for unregulated emissions, the main conclusion is that paraffinic HVO reduces the harmfulness of exhaust significantly. This is indicated by substantial reductions in PAH emissions, emissions of lighter aromatic components such as benzene and toluene and ultimately, prominent reductions in exhaust mutagenicity. Lowered toxicity of the exhaust, with reductions in indicator values even up to 85 %, must be considered the main advantage of paraffinic HVO fuel. As stated in Paragraph 9.4.5, the reductions for regulated emission components typically range from 10 to 40 %.

Based on the analysis performed, HVO doesn't seem to affect particle number size distribution profiles significantly. For the Euro IV and EEV vehicles HVO reduced particle numbers evenly in all size classes.

The only unregulated emission indicator which is adversely affected by HVO is aldehydes. In the case of the Euro III vehicle, total aldehyde emissions increased some 15 % when switching from regular diesel to 100 % HVO.

Switching to paraffinic HVO fuel is a viable way of reducing the harmfulness of exhaust gases in particular from older diesel vehicles. However, it should be noted that improved diesel technology and exhaust after-treatment also deliver significant reductions. This goes for PAH emissions, aldehydes as well as particle numbers.

11. HVO in conjunction with exhaust after-treatment devices

11.1 General

Normally retrofitting means changing or adding hardware. However, switching from regular diesel fuel to HVO could also be considered a kind of retrofit operation for reduced emissions. As a matter of fact one of the starting points of the OPTIBIO project was, indeed, to demonstrate the feasibility of lowering emissions and extending the service life of older city buses by switching fuel and by adding a relatively simple exhaust after-treatment device such as a flow-through filter.

As described in Chapters 1 and 5, FAME can harm exhaust after-treatment devices as well as engines equipped with after-treatment systems. HVO, on the other hand, present no challenges to exhaust after-treatment devices, actually quite the contrary.

This Chapter will describe screening of various after-treatment systems in laboratory conditions, as well as data of operating conditions in the field. Data on emission stability in the field will be presented in Chapter 14 in connection with the results of the field test.

There are two parameters which are crucial for the operation and performance of exhaust after-treatment devices: exhaust temperature and pressure build-up over the device. Catalysts need a certain minimum temperature to activate, and therefore particle reducing devices with active coatings also need a certain minimum temperature, typically 250 ^{o}C, to enable regeneration. If exhaust temperature is too low for regeneration to take place every now and then, soot build-up occurs and backpressure will eventually increase, leading to reduced vehicle performance and in the worst case, even engine damages. In the case of FTF and DPF devices, exhaust temperature should exceed 250 ^{o}C at least occasionally to enable regeneration. Wall-flow actual DPF devices are naturally more prone to blocking than flow-trough type devices.

Engine out particulate mass emission level also affects blocking tendency: the higher PM emissions, the higher risk for FTF or DPF blockage. Thus a fuel reducing PM emissions by default will improve the operational preconditions of PM reducing devices.

11.2 Preparatory measurements

In preparation for the initial screening work of FTF devices, exhaust temperature measurement and logging was performed for several types of vehicles on various routes. Figures 11.1 (Euro II vehicle) and 11.2 (Euro III) vehicle show examples of exhaust temperature distribution.

The temperature distribution shown in Figure 11.1 is safe for the installation of both FTF and DPF devices (some 30 % of the time above 250 °C), whereas the distribution shown in Figure 11.2 is critical even for a FTF device (only some 5 % of the time above 250 °C).

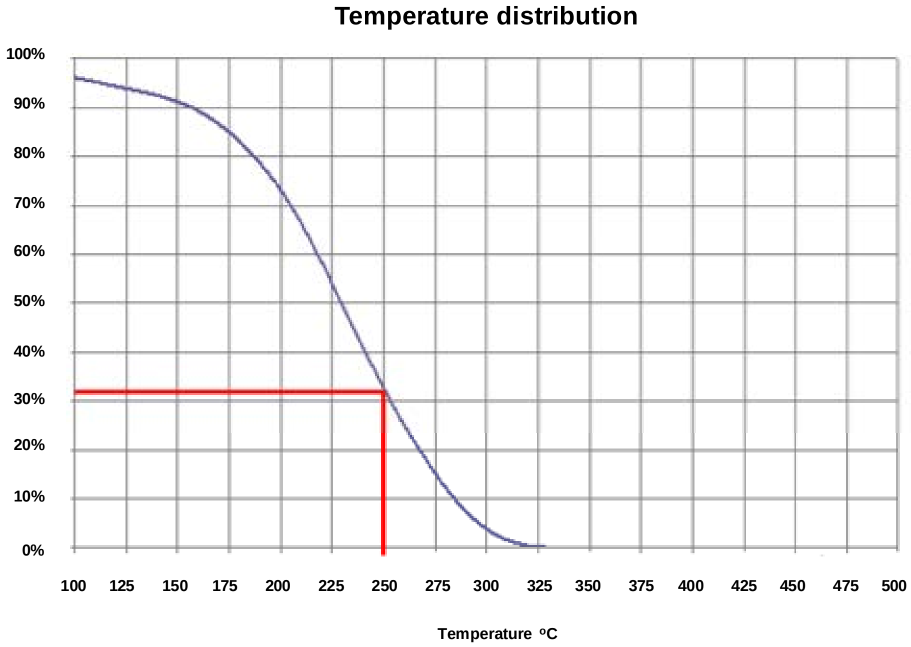


Figure 11.1. Example of a temperature distribution profile for a Euro II vehicle. X-axis temperature (°C), Y-axis cumulative percentile.

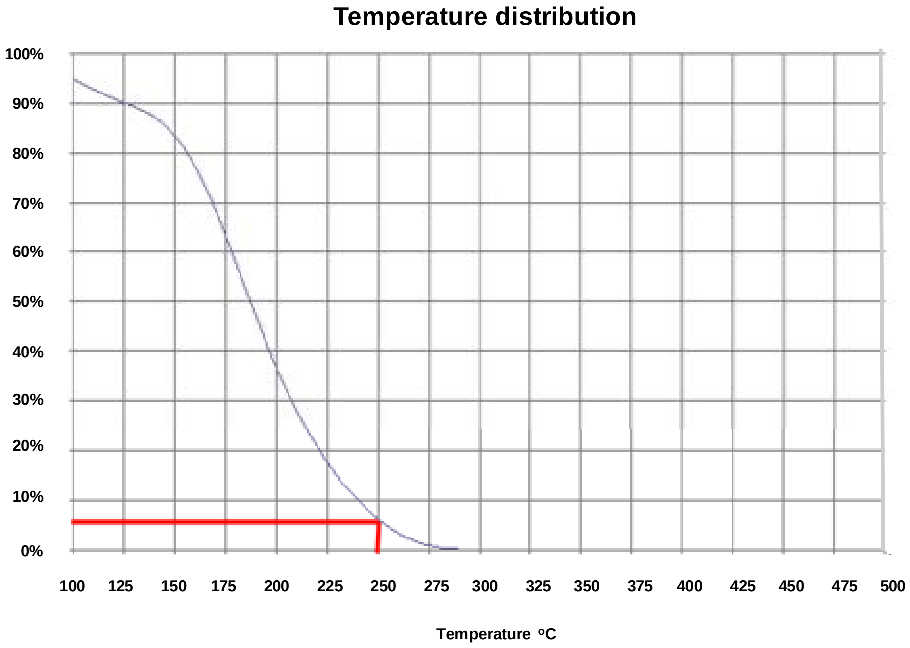


Figure 11.2. Example of a temperature distribution profile for a Euro III vehicle. X-axis temperature (°C), Y-axis cumulative percentile.

11.3 Screening of exhaust after-treatment devices

In the initial testing phase, a matrix consisting of a total of 29 different combinations of exhaust after-treatment device, vehicle type and fuel was evaluated. Emphasis was on FTF (flow-through filter) type devices. The test vehicles represented Euro II and Euro III emission certification, as retrofitting is best suited for older vehicles. The test vehicles were originally equipped with oxidation catalysts, but as discussed earlier, the devices were practically inactive.

Most of the testing was done with a 30 % HVO blend, the principal fuel for the field test. However, EN590 as well as 100 % HVO was used in some measurements.

In a FTF type device, particulates adhere on the surfaces and on a netlike structure with rather coarse mesh, but the exhaust gases do not pass through any kind of actual filtering wall. The design of FTF devices was varied for layout, geometry and chemistry. Both single and twin block layouts were evaluated. Three different matrixes were tested for the single block designs: coarse, dense and "mixed". The dimensions were 285 mm by 170 mm and 285 mm by 195 mm. The coarse and the dense matrixes differed in the degree of foil corrugation. The dense structure delivered higher PM reductions, but at the expense of elevated back pressure, +15 % compared to the coarse design. In the mixed design, two different patterns for foil corrugation was used, one for the front end and one for the rear end. The coating chemistry was also differentiated for the front and rear ends. The idea of the divided structure was to generate oxidation promoting NO_2 in the front end, and to collect and oxidize particulate matter in the rear end.

The twin block designs had a diameter of 320 mm, and a total length of some 350 mm.

The concepts for the various FTF devices were:

- FTF1: twin-block design
- FTF2: single-block design 1
- FTF3: single-block design 2
- FTF4: single-block design 3, zone coated
- FTF5: single-block design 4, zone coated.

Figure 11.3 shows PM emissions for various FTF configurations for a certain Euro II bus type. The fuel was a 30 % HVO blend. Two vehicles of the same brand and model were used for testing (corresponding to vehicles 1 & 2 in Table 9.1). The reference levels were measured with the original more or less inactive oxidation catalysts. It should be noted that there was a significant difference in the PM emissions of the two vehicle individuals. One FTF device, FTF2, was tested on both buses. PM reductions were in the range of 40–60 %, FTF1 giving the highest PM reduction when installed on the high-emitting vehicle. FTF2 delivered a reduction rate of 48 % for the vehicle with high PM emissions and a reduction rate of 40 % for the vehicle with lower PM emission.

Figure 11.4 shows emission results for two other Euro II vehicles, of two different brands which were not covered in the emission screening measurements. These two vehicles were tested with the same FTF1 and FTF2 units as the two other Euro II buses. In this case FTF1 on an average delivered a PM reduction rate of 65 % and FTF2 a reduction rate of 49 %. For all four buses the measured PM reductions were from 60 to 69 % for FTF1 and from 40 to 54 % for FTF2, depending on the vehicle. On EN590, FTF1 delivered a PM reduction rate of 75 %. It was deemed that the collection efficiency of FTF1 might be too high in real service. If exhaust temperature is not sufficiently high for proper regeneration, there might be a risk of blocking due to carbon build-up.

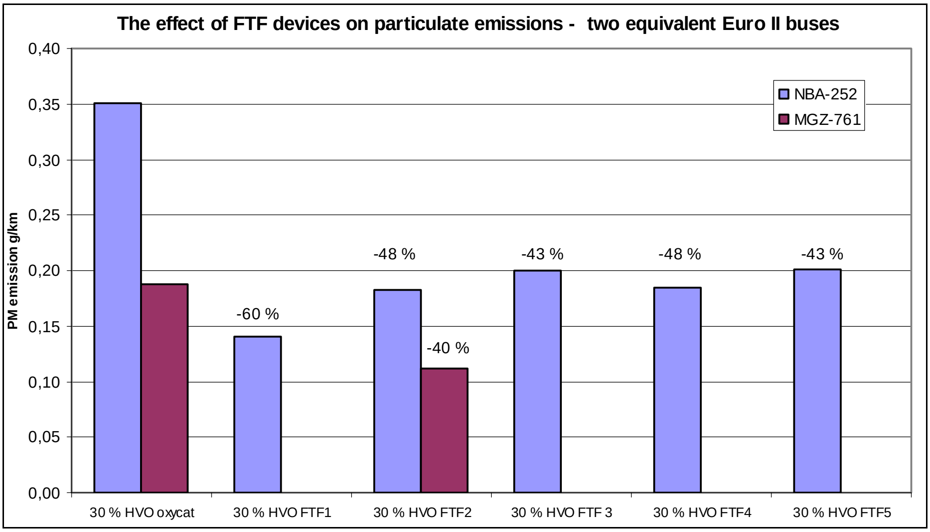


Figure 11.3. The effect of FTF devices on PM emissions. Two Euro II vehicles of the same brand and model. NBA-252 and MGZ-761 vehicle registration numbers. Tests with a 30 % HVO blend.

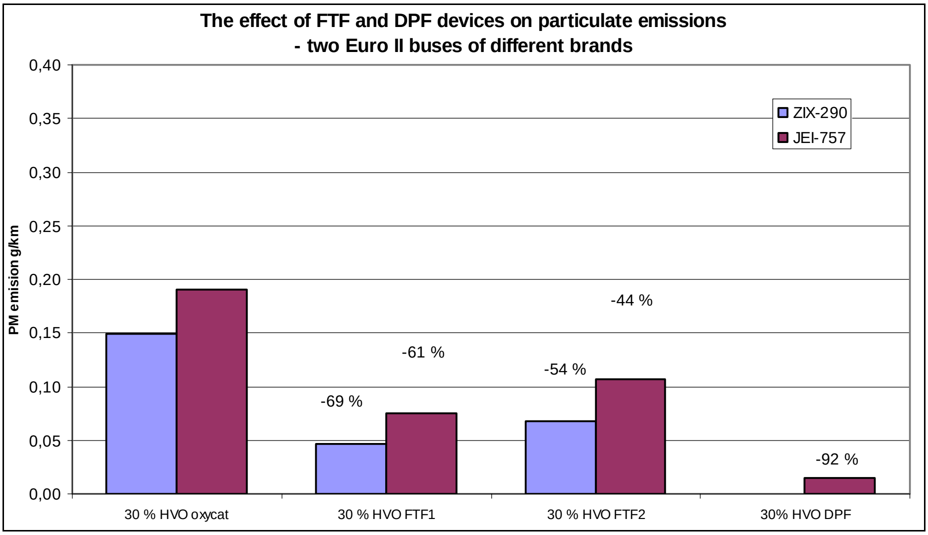


Figure 11.4. The effect of FTF and DPF devices on PM emissions. Two Euro II vehicles of different brands. FTF devices the same as in Figure 11.3. ZIX-290 and JEI-757 vehicle registration numbers. Tests with a 30 % HVO blend.

One of the vehicles not included in the screening program was also tested with an actual wall-flow DPF device delivering a PM reduction of 92 %. This particular DPF device was approved for the Copenhagen diesel retrofit program, for which the requirement for PM reduction rate is 80 %.

(http://www.proventia.com/sivu/en/emission_control/retrofit_projects/_dpf/)

Figure 11.5 shows results for a Euro III vehicle (corresponding to vehicles 3–6 in Table 9.1). In this case two fuels were used, a 30 % HVO blend and 100 % HVO. The reference PM level of this particular vehicle was lower than for the Euro II vehicles in Figures 11.3 and 11.4. For the Euro III vehicle, the FTF concepts tested were:

- FTF6 single-block design 5
- FTF1 twin-block design
- FTF2 single-block design 2.

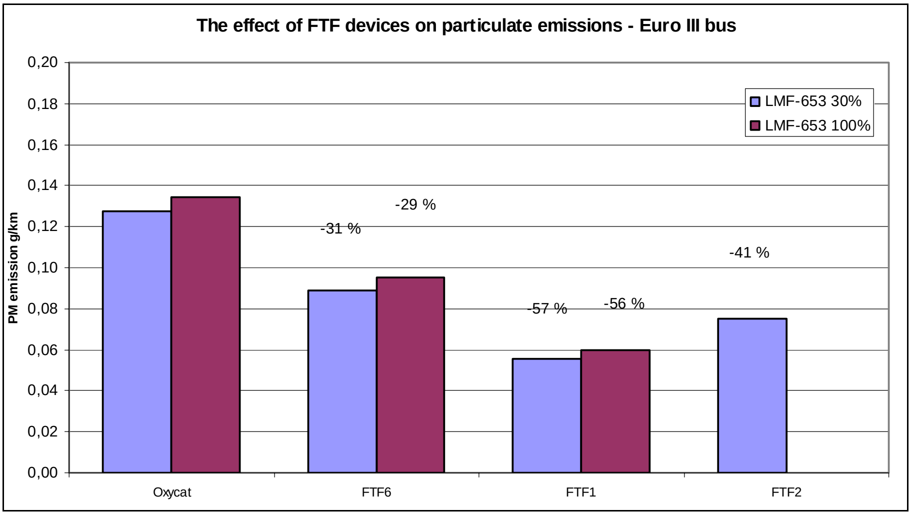


Figure 11.5. The effect of FTF devices on PM emissions. Euro III vehicle. LMF-653 registration number. Tests with a 30 % HVO blend and 100 % HVO. Note the different y-scale compared to Figures 11.3 and 11.4.

For the Euro III vehicle, PM reduction rate varied from 29 to 57 %. For this particular vehicle, 100 % HVO gave slightly higher PM emissions than the 30 % blend, which normally is not the case. As for the effectiveness of the FTF devices, the presumption was that the PM reduction rate might be lower with 100 % HVO than with either EN590 or the 30 % blended fuel. The reason for this presumption was that 100 % HVO might produce drier particles (less readily oxidised semivolatiles) than regular diesel fuel. However, the reduction rates for the blended fuel and 100 % HVO were almost identical (31 and 29 % for FTF6 and 57 and 56 % for FTF1).

Another Euro III vehicle of the same brand and model was also tested with FTF2. The second vehicle had slightly higher initial PM emissions. In the first vehicle (LMF-653, Figure 11.5) FTF2 reduced PM emissions 41 %, for the second vehicle PM reduction rate was 55 %. Both vehicles had roughly the same PM emission level after the FTF device, some 0,075 g/km.

Figure 11.6 shows the effect of a combined SCR/wall-flow DPF retrofit system on NO_x and PM emissions. In this case a Euro III level bus is brought to Euro VI emission level by retrofitting, meaning a very significant reduction in emissions.

The Figure shows “boxes” for the various emissions classes. These estimates have been generated by multiplying the engine test stand limit values for NO_x and PM by a factor of 1.8, as in the Braunschweig bus cycle the approximate amount of work on the engine crankshaft is 1.8 kWh/km. Thus, e.g., the NO_x limit value of Euro III, 5 g/kWh translates into 9 g/km (5 * 1.8 = 9). See also Figure 9.1.

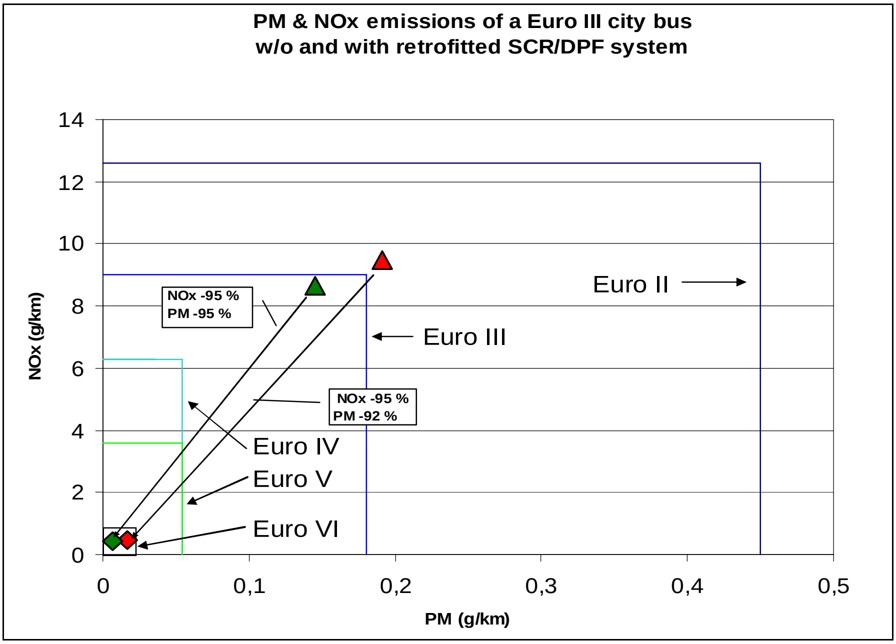


Figure 11.6. NO_x and PM reductions with a retrofitted SCR/DPF system. Red triangle: Euro III bus with EN590 diesel fuel. Green triangle: Euro III bus with 100 % HVO. Red rhomb: SCR/DPF retrofit with EN590. Green rhomb: SCR/DPF retrofit with 100 % HVO.

In optimising FTF devices, a balancing of cell density (blocking tendency), loading of precious metals (cost) and physical size has to be made. For the field test, the following devices, deemed efficient enough and commercially viable, were installed (see 7.6):

Euro II:

- 3 vehicles with FTF.

Euro III Euro II:

- 5 vehicles with FTF
- 1 vehicle with DPF
- 1 vehicle with SCR/DPF combination.

The feedback from the exhaust after-treatment devices is reported in Paragraph 14.5.3.

12. The effect of HVO on emissions when varying engine calibration

12.1 General

For diesel engines, there is normally a trade-off between NO_x, PM emissions and fuel consumption. This means that changing engine parameters and settings for lower NO_x emissions will increase PM emissions, as well as fuel consumption, and vice versa. As discussed in Chapter 9, HVO makes it possible to reduce aggregate NO_x + PM emissions. All the results on emission performance of HVO shown in Chapter 9 were generated using standard calibration for the engines

Changing engine calibration parameters such as injection timing makes it possible to optimize performance on HVO. E.g., if NO_x reductions are not needed, the engine could be tuned to retain the original NO_x output level, while at the same time delivering significantly reduced PM emissions and improved fuel efficiency.

The research on the effects of engine calibration (in practise injection timing) when using HVO was conducted at Aalto University in 2008, using a diesel engine installed in an engine dynamometer. The work has been reported in a Master's Thesis (Aatola 2008) and in a SAE Technical Paper (Aatola et al. 2008).

12.2 Experimental setup

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

The test engine was a turbocharged 8.4 litre 6-cylinder 4-stroke direct injection heavy-duty diesel engine. Nominal power of the engine was 225 kW at 2200 r/min. The engine was equipped with a common-rail fuel injection system and a charge air cooler. The fuel injection system and its control system allowed flexible timing and multiple injections per working cycle. No EGR or exhaust after-treatment devices were used. This was to eliminate any secondary effects arising from changes in injection timing.

The measured emission parameters were CO, THC, NO_x, and in addition, filter smoke number (FSN). The analysers were Hartmann & Brown Uras 3G for CO, J.U.M. Engineering Model VE 7 for THC, Eco Physics CLD 822 Sh for NO_x and AVL-415S variable sampling smoke meter for filter smoke number. The system for measuring fuel consumption comprised AVL 733 dynamic fuel meter with AVL balance control 7030-A04.1 and AVL fuel calculator 7030-A05.

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

12.3 Test fuels

Three test fuels were used:

- EN590 diesel fuel (summer grade)
- 100 % HVO
- a blend of 70 % (vol.) EN590 and 30 % (vol.) HVO (denotation EN590-30).

The characteristics of the test fuels are presented in Appendix 4.

12.4 Test programme

During the tests, performance and emissions of the test engine were recorded under steady-state conditions with a warmed engine. The engine was run at three speeds and two loads:

- 2200 r/min, 1500 r/min, and 1000 r/min
- 50 % and 100 % load (1000 r/min only on 50 % load).

Main injection timing was changed from the default setting of the engine (D) to 6 crank angle degrees (°CA) earlier (D-6°CA) and to 6°CA later than the default setting (D+6°CA) with intervals of 2°CA.

Pilot injection was used at 50 % load at 1500 r/min and 1000 r/min. Post injection was used at 50 % load and 1000 r/min. Timing of pilot and post injection was constant in time units in relation to the main injection timing. At 1500 r/min the start of pilot injection was 5°CA and at 1000 r/min 4°CA earlier than the start main injection. The start of post injection was 6.5°CA later than the end of main injection. To achieve equal brake power of the engine for all fuels, the amount of injected fuel was adjusted. With neat HVO duration of the main injection was increased because of the lower density of HVO compared to EN590 diesel fuel. Injected fuel mass was still lower with neat HVO due to the higher mass based heating value (see Appendix 4).

12.5 Results and discussion

12.5.1 Results with standard settings

Figure 12.1 shows relative changes in emissions (CO, HC, NOx, smoke number), as well as volumetric and mass based fuel consumption of the test engine when using standard injection settings for the different fuels. The results, relative to EN590 diesel, are averaged results calculated without any weighting factors from absolute emission values (g/kWh, FSN) of all measured engine speed and load configurations. At each speed, the test engine was run under same load with all test fuels. This was achieved by modifying the injected fuel amount until same load was obtained.

As it can be seen from Figure 12.1, 100 % HVO reduced all emission components. The largest reduction, 35 %, was found for filter smoke number. The relative reductions in CO and THC were some 30 %. The blended fuel reduced smoke by some 10 %. In this common-rail engine 100 % HVO delivered a small but measurable reduction in NO_x, about 6 %.

Compared with the EN590 fuel, gravimetric specific fuel consumption (SFC) was reduced with 100 % HVO because of the higher mass based effective heating value of the HVO (see Appendix 4). Volumetric fuel consumption increased some 5 % with 100 % HVO because of the lower volumetric effective heating value of the HVO fuel. The effects of the blended fuel were negligible, within ±1.5 %.

The results are well in line with the results of VTT's emission screening and fuel consumptions.

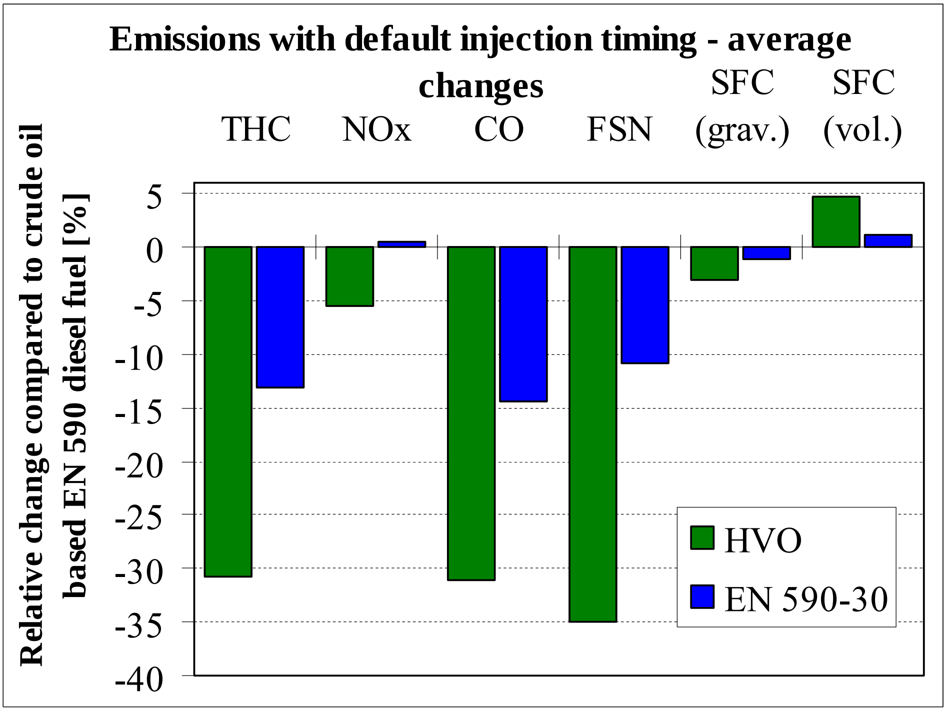


Figure 12.1. Relative emissions and fuel consumption for 100 % and blended fuel (30 % HVO in diesel). Reference EN590 fuel. Average of all speeds and loads with standard injection timing.

12.5.2 Results with modified injection timing

For diesel engines, the trade-off between NO_x and particulate emissions or alternatively NO_x and fuel consumption are well known phenomenon. Adjusting the injection timing for low NO_x (retarding injection) normally increases particulate emissions as well as fuel consumption. The switch from regular EN590 diesel fuel to 100 % HVO allows a reduction of aggregate NO_x plus PM, meaning that the trade-off curve in a NO_x vs. PM diagram moves towards origo.

Figure 12.2 shows NO_x-PM (smoke) trade-off curves for the various operating points of the test engine and Figure 12.3 correspondingly NO_x-fuel consumption trade-off curves (specific fuel consumption in g/kWh). The forms of the NO_x vs. PM (smoke) curves vary significantly with engine load point, whereas the NO_x vs. fuel consumption trade-off curves have a more uniform shape. In fact, at 2200 r/min there is no clear NO_x vs. PM (smoke) trade-off effect. This is due to the fact that charge air pressure increased as main injection timing was retarded. This resulted in increased air-fuel ratio of the engine. As the air-fuel ratio increased, the smoke number decreased. Figure 12.4 presents a synthesis of the NO_x-PM (smoke) trade-off curves.

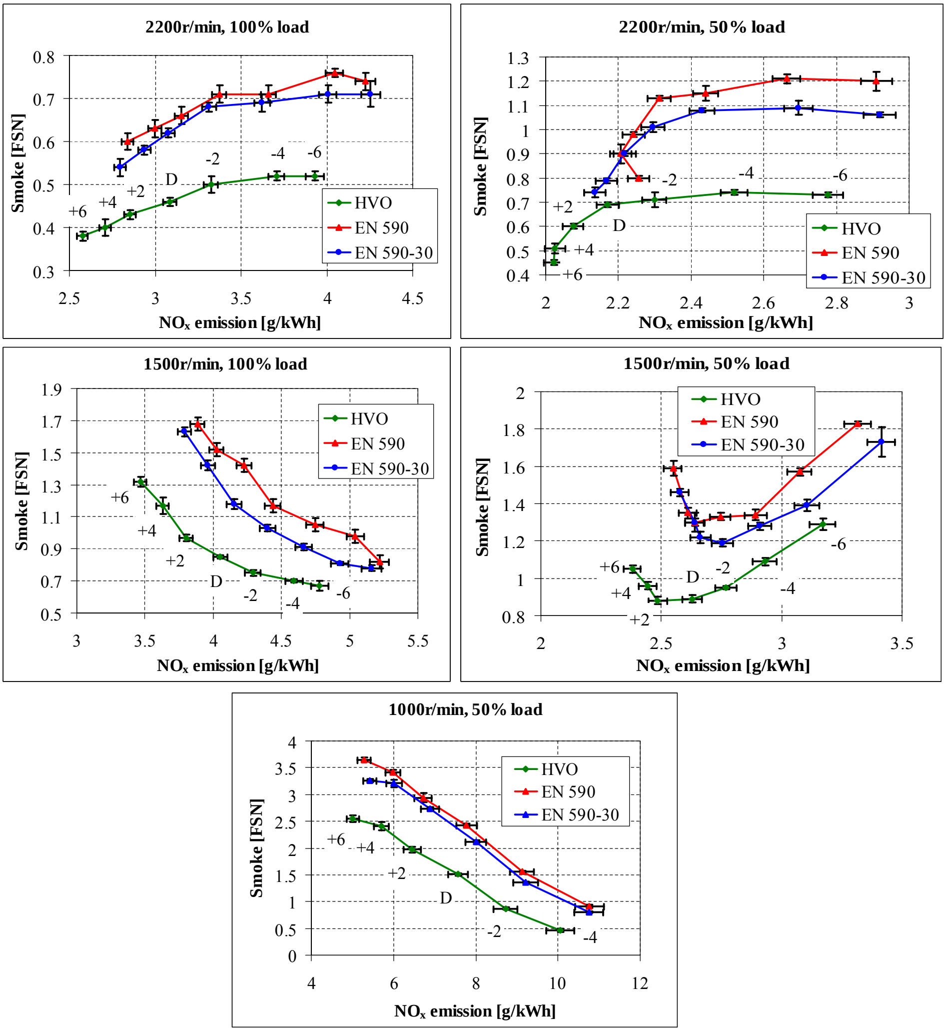


Figure 12.2. Trade-off between NO_x and smoke. “D” means the default main injection timing. + or – sign and a number means the start of main injection in °CA after or before the default setting.

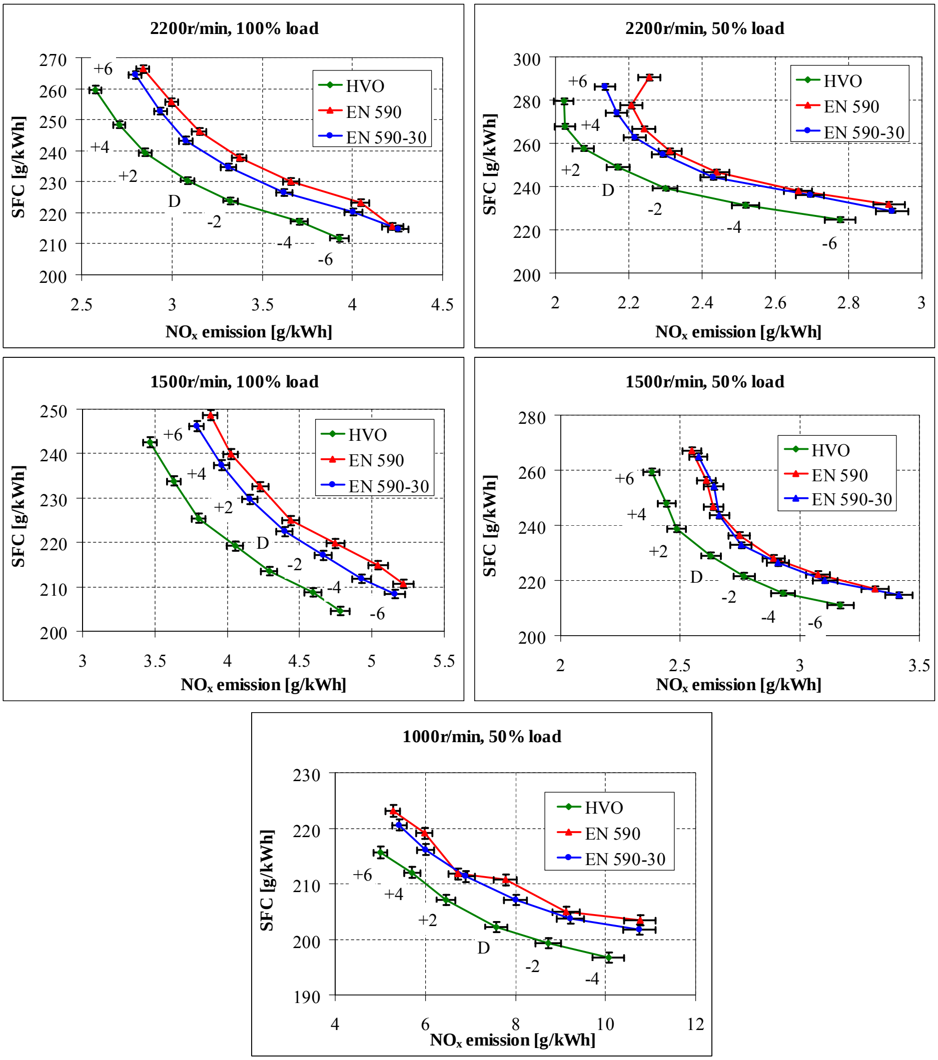


Figure 12.3. Trade-off between NO_x and specific fuel consumption (SFC). “D” means the default main injection timing. + or – sign and the number means a start of main injection in °CA after or before the default setting.

For all load points, HVO delivers more favourable combined NO_x vs. smoke or NO_x vs. fuel consumption numbers than EN590 fuel.

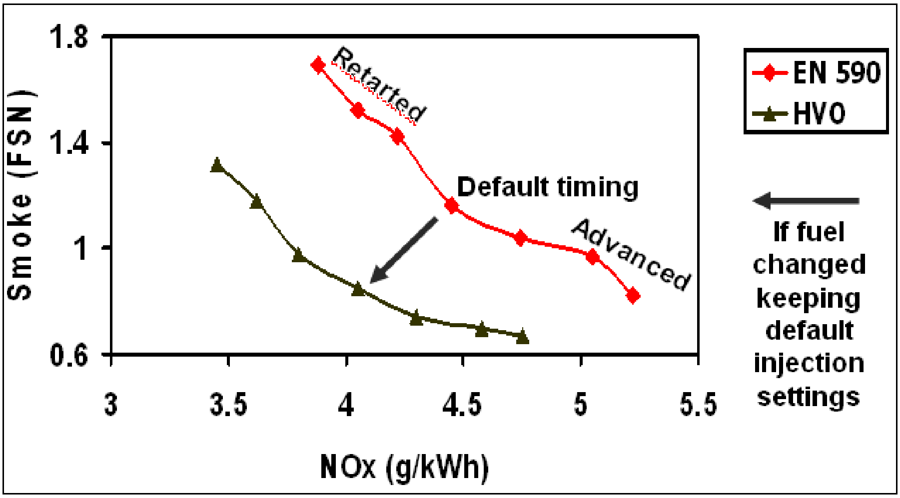


Figure 12.4. Synthesis of HVO effects on NO_x-PM trade-off.

It is also of interest to evaluate, what advantages 100 % HVO can deliver either when keeping NO_x emission or fuel consumption constant by adjusting fuel injection timing. Figure 12.5 shows smoke numbers and specific fuel consumption when keeping the NO_x levels equal to those obtained with EN590 fuel. For this case, smoke number was reduced by 37 % on an average, only marginally more than with standard injection timing.

However, trading the 6 % reduction in NO_x for reduced fuel consumption in fact means 6 % lower gravimetric fuel consumption compared to EN590, which is a double of the figure of 3 % for standard engine settings (Figure 12.1). Taking into account the differences in heating value (43.13 MJ/kg for EN590 and 44.04 MJ/kg for HVO, Appendix 4) means that when running on constant NO_x, HVO will reduce the energy consumption of the engine by some 4 %. With standard settings HVO increased the volumetric fuel consumption by some 5 % over EN590 (Figure 12.1), while with constant NO_x the increase in volumetric fuel consumption was only 1.5 %.

Figure 12.6 correspondingly shows smoke numbers and NO_x emissions while maintaining constant gravimetric fuel consumption. Constant gravimetric fuel consumption means that energy consumption is slightly higher, some 2 %, with HVO than with EN590. With these settings, HVO on an average delivered a 23 % reduction in smoke number (less than with standard settings) and a 16 % reduction in NO_x (more than with standard settings).

Table 12.1 presents a summary on how injection timing affects engine performance with HVO. The overall conclusion was that HVO is beneficial in reducing emissions. The NO_x vs. PM "calibration" line moves towards lover NO_x/PM combinations. Dedicated engine calibration makes it possible to optimise either emissions or fuel efficiency. When adjusting the engine for constant NO_x, HVO will increase volumetric fuel consumption over EN590 only marginally, despite of the lower density of HVO (843 kg/m^3 for EN590 and 780 kg/m^3 for HVO).

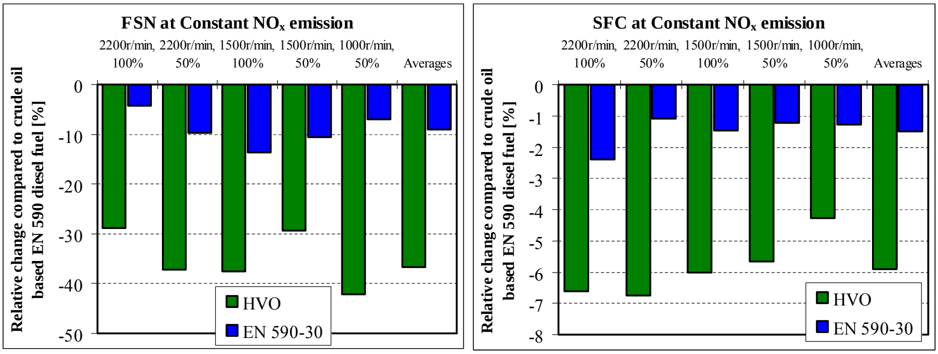


Figure 12.5. Filter smoke number (FSN) and specific fuel consumption (SFC) when NO_x is equal with all fuels.

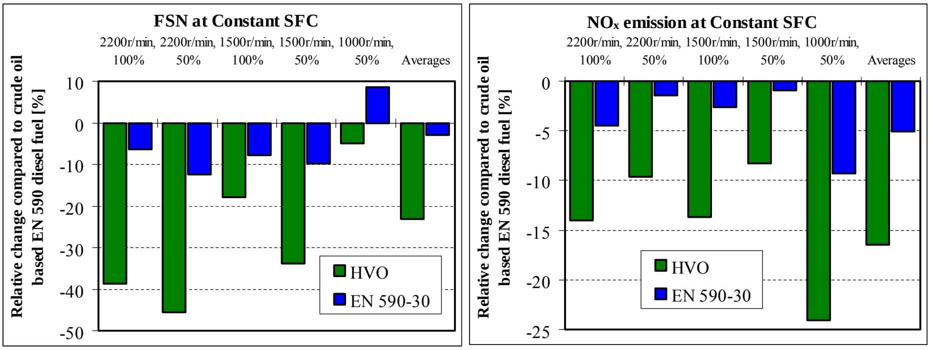


Figure 12.6. Filter smoke number (FSN) and NO_x emission when specific fuel consumption (SFC) is equal with all fuels.

Table 12.1. Possibilities to optimize engine for HVO by changing injection timing. Baseline EN590 fuel.

	Default	**Advanced**	**Remarkably advanced**	**Retarded**
NO_x	- 6 %	0 %	+ 4 %	- 16 %
Smoke	- 35 %	- 37 %	- 32 %	- 23 %
Fuel cons (mass)	- 3 %	- 6 %	- 8 %	0 %
Fuel cons (vol.)	+ 5 %	+ 1.5 %	-0.5 %	+ 8 %
Energy consumption	-1 %	-4 %	-6 %	+2 %

13. Studies related to cold weather performance

13.1 General

As discussed in Paragraph 5.3, the cold flow properties of HVO differ from conventional diesel fuel made from crude oil. For HVO, cloud point and CFPP (cold filter plugging point) expressed in degrees centigrade are almost identical. This means that crystallization takes place throughout the fuel at a temperature just below the cloud point, and that regular cold flow additives do not necessarily work for HVO fuels. Since crystallization takes place predictably, standardized analyses for cold flow properties should give quire realistic results for neat HVO. As for cold star emissions, the high cetane number of HVO could improve engine running and reduce emissions.

A double-barrelled test programme for cold weather performance was set up. The first task was establishing the lower limit for cold weather operability by comparing actual vehicle performance, rig test results and laboratory analysis results. The second one was studying the effects of HVO on low-temperature emissions. For practical reasons and limitations in test facilities, both tasks were carried out using passenger cars. The first task was carried out in Neste Oil's vehicle laboratory, the second one in VTT's light-duty testing facilities. Both facilities are equipped with cooling equipment.

13.2 Limits for cold weather operability

13.2.1 General

The evaluation of cold weather operability was carried out at Neste Oil. Four different methods were used, two of them standardized laboratory analyses:

- CP (cloud point)
- CFPP (cold filter plugging point)
- an in-house test rig for cold weather operability
- vehicle testing in a chassis dynamometer facility with cooling equipment.

13.2.2 Test fuels

Rig and vehicle tests were performed with the following fuels (CFPP values in brackets):

Neat fuels:

- summer grade diesel fuel (-14 °C)
- winter grade diesel fuel (-43 °C)
- 100 % HVO of two different batches with different cold flow properties;
    - HVO1 (-15 °C)
    - HVO2 (-24 °C).

Blended fuels

- 10 % HVO1 in summer grade diesel (-20 °C)
- 30 % HVO1 in summer grade diesel (-18 °C)
- 50 % HVO1 in summer grade diesel (-18 °C)
- 30 % HVO in winter grade diesel (-34 °C).

13.2.3 Rig testing

The test rig consists of a rotary-type injection pump driven by an electric motor, a fuel filter and a fuel tank with piping. The instrumentation covers temperature and pressure (vacuum) after the filter. The whole system is installed in a temperature controlled chamber.

The idea of the testing is to run the pump according to a specified scheme, corresponding to the vehicle cycle described Paragraph 13.2.4 (2000 seconds), and to monitor the pressure after the fuel filter. As the filter starts to get blocked, pressure after the filter drops. The empirical cut-off pressure for operability has been determined to be 0.7 bar vacuum for this particular set-up.

The test procedure is as follows. The starting temperature is above +20 °C. The previous fuel sample is removed from the system, and the fuel filter is replaced with a new one. The system is topped up with 10 litres of the fuel to be tested. The system is started up, and 1 litre of the test fuel is drained from the return flow line to remove any residual fuel.

During the cooling down, the system is in stand-still condition. To start with, the test chamber is cooled down to 0 ^{o}C and kept at this temperature for two hours. Then the chamber is cooled down linearly to the desired test temperature over a period of 19 hours. After reaching the desired test temperature, temperature is kept constant for four hours before commencing testing, i.e., switching on the electric motor. Maximum vacuum after the filter during the 2000 second test is recorded. If maximum vacuum is less than 0.7 bar, the fuel is considered to be operable at the test temperature.

Figure 13.1 describes the methodology. The figure contains data for several fuels and temperatures. The results for one test fuel, code 10/146, at five different temperatures are highlighted. The data points for this fuel are connected with a line. At -34 ^{o}C, maximum vacuum was over 0.7 bar, and the fuel is deemed non-operable. Four tests at -32, -28, -27 and -25 ^{o}C resulted in a maximum vacuum of less than 0.2 bar, and the fuel is operable. Therefore, limit temperature for operation is considered to be around -33 ^{o}C. Neste Oil always carries out a minimum of three tests to establish the borderline temperature for operation.

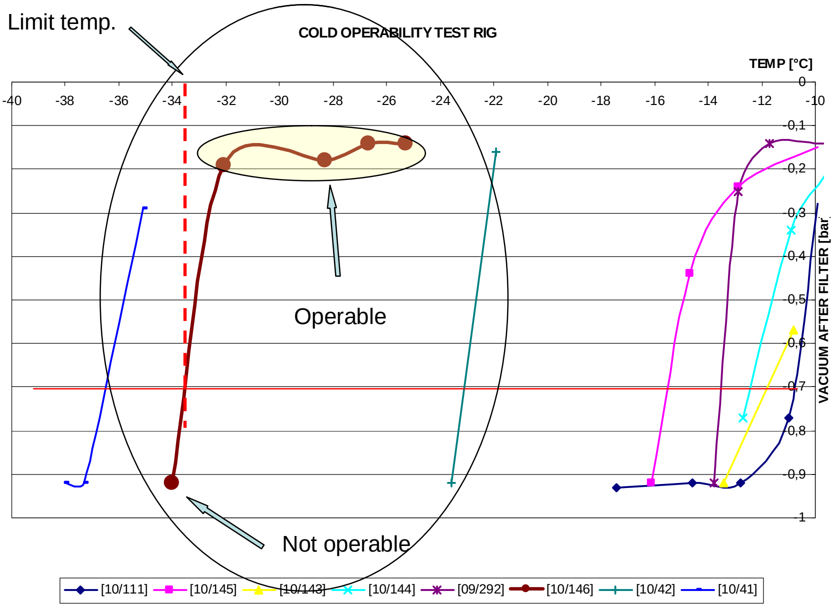


Figure 13.1. The principle for determining the limit temperature for operability in the rig test. The Figure contains results for several fuels, with limit temperatures of some -36, -33, -23 and around -12 ^{o}C. The highlighted example has a limit temperature of some -33 ^{o}C.

13.2.4 Vehicle testing

In principle, the methodology for vehicle testing resembles the methodology for rig testing. The amount of test fuel is 20 litres, and the amount of flushed fuel is 2 litres. Cooling-down period is 12 hours instead of 19 hours. Figure 13.2 shows the driving cycle used for the testing.

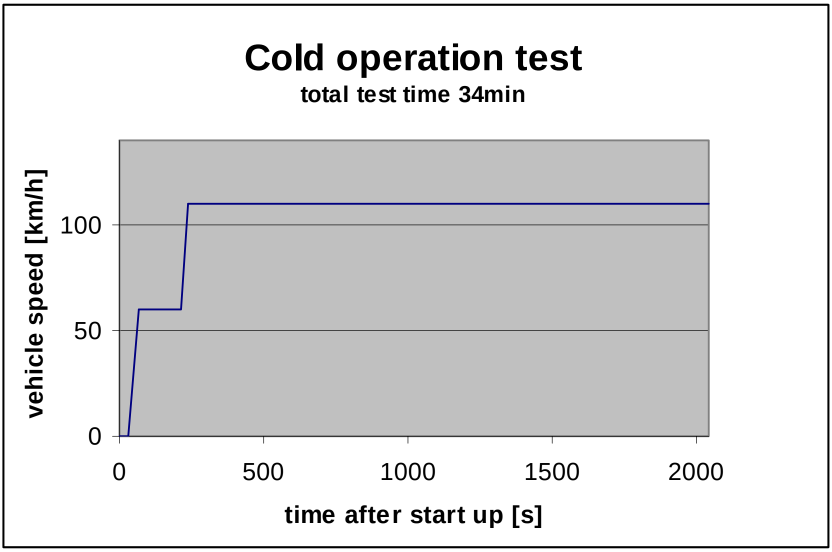


Figure 13.2. The vehicle test cycle for the cold operability test.

In vehicle testing, the evaluation is based on the behaviour of the vehicle, not pressure measurements. The fuel is considered operable if the vehicle operates normally and no problems can be detected. On the other hand, the fuel is considered non-operable if, e.g.:

- the vehicle doesn’t start due to fuel related problems
- the vehicle cannot keep the stipulated speed.

Two diesel passenger cars were used as test mules.

13.2.5 Results for cold weather operability

A comparison between CP, CFPP, rig results and vehicle results are shown in Table 13.1 and Figure 13.3.

Table 13.1. Results for cold weather operability.

	Diesel "s"	Diesel "s" + 10 % HVO1	Diesel "s" + 30 % HVO1	Diesel "s" + 50 % HVO1	HVO1	Diesel "w"	Diesel "w" + 30 % HVO2	HVO2
CP	-4,1	-5	-7	-10	-11,8	-26,4	-28	-23,8
CFPP	-14	-20	-18	-18	-15	-43	-34	-23,8
rig	-10,5	-12	-12,5	-15	-13	-36	-33,5	-22,5
Vehice A	-15	n/a	-23	n/a	-15	-32	n/a	n/a
Vehicle B	-10	n/a	-13	n/a	-12	-35	-31	-23

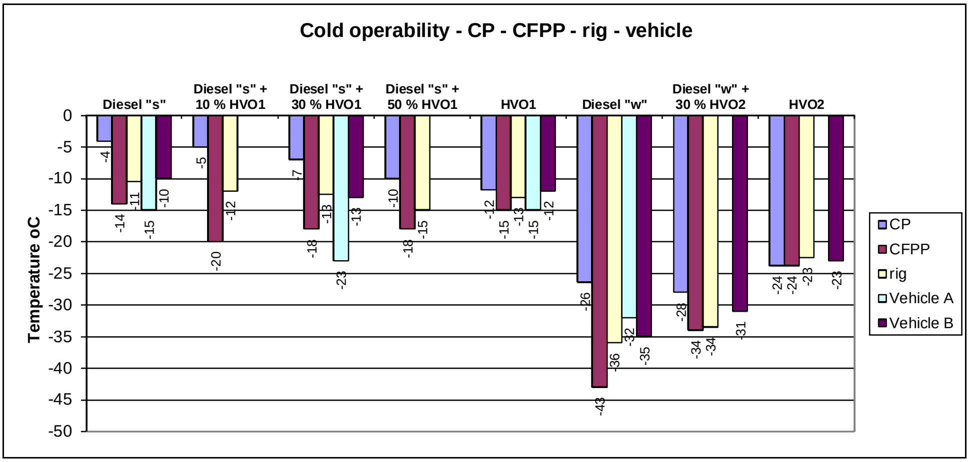


Figure 13.3. Results for cold weather operability. Comparison between CP, CFPP, rig results and vehicle results. Order of fuels: summer grade diesel, blends of summer grade diesel and HVO1, neat HVO1, winter grade diesel, blend of winter grade diesel and HVO2, neat HVO2.

A number of observations could be made:

- for neat HVO, CP and CFPP were quite close, as expected (a difference of 0–3 °C for HVO and 10–17 °C for diesel)
- the rig test was more severe than CFPP
  - difference for neat diesel 4–7 °C
  - difference for neat HVO 1–2 °C
  - difference for blended fuels 1–8 °C
- vehicle “B” was more critical than vehicle “A” except for winter grade diesel fuel
- vehicle “A” gave values close to CFPP, except for winter grade diesel, in with case CFPP gave an overestimate of cold operability by some 10 °C

- in the case of vehicle “B”, CFPP gave an overestimate of cold operability for all fuels by 1–8 °C
- the rig was more severe than vehicle “A”, with the exception of winter grade diesel fuel
- the rig gave roughly equivalent values compared to vehicle “B”, the difference being within ±2 °C
- at roughly same CFPP, HVO1 delivered equivalent or better performance than summer grade diesel in the rig and in the vehicles
- the blends of summer grade diesel and HVO1 delivered better low-temperature performance than either of the neat fuels
- the performance of 30 % HVO2 in winter grade diesel delivered performance in between the neat fuels.

All in all, CP, CFPP, rig and vehicle test results were well in congruence with HVO (within 2–3 °C, Figure 13.4). As for blends of summer grade diesel fuel and HVO1, the blends performed better than either of the neat fuels. In the case of 30 % HVO2 in winter grade diesel fuel, the actual lower limit of operation was within ±3 °C of the performance calculated from the performance of the neat fuels.

This means, that CFPP or the rig test or even CP could be used to estimate the lowest temperature of operability for HVO, without the risk of overestimating low-temperature performance of HVO.

The HVO batches used in this study originated from the start-up phase of commercial HVO production. Since that period, fuels with enhanced cold-flow properties have been produced, with cloud points down to -35–-40 °C. This means that HVO in fact can deliver operability equivalent to winter grade diesel fuels, and that when implementing biofuels, using HVO instead of FAME, operability problems at low temperatures can be avoided.

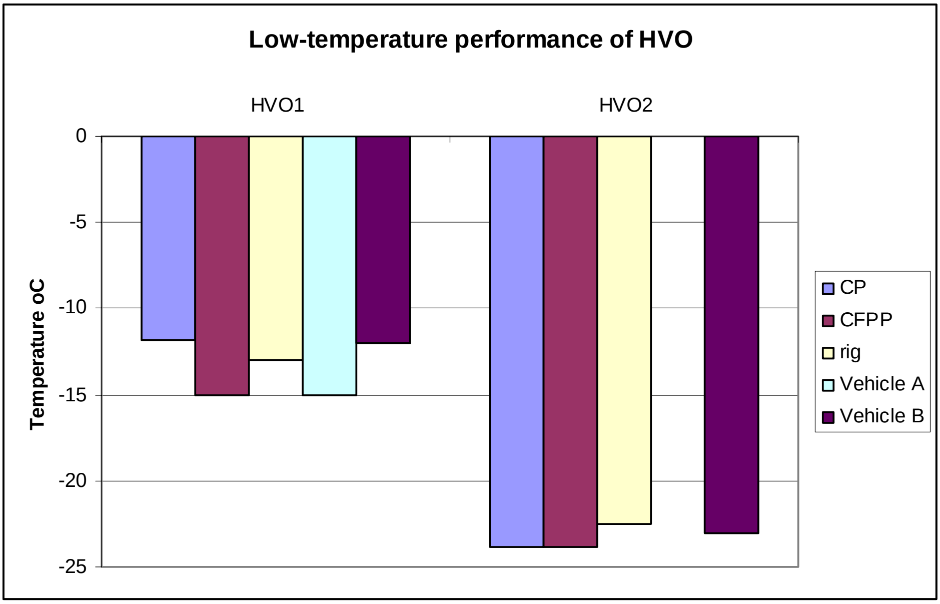


Figure 13.4. Comparison of CP, CFPP, rig test results and vehicle test results for two HVO grades.

13.3 Low-temperature emissions

13.3.1 General

The low-temperature emission testing was carried out in VTT's light-duty test facility. The equipment and methodology complies with ECE Regulation No. 83, Revision 3 – Amendment 2 (Supplement 7 to the 05 series of amendments). The test method is described in Annex 4 of the documentation. VTT's measurements of exhaust emissions and fuel consumption of light-duty vehicles are accredited (FINAS T259, VTT code MK01). Figure 13.5 shows the test facility.

Figure 13.5. VTT's accredited light-duty vehicle test facility.

The general expectation was that HVO would, due to its high cetane number, improve startability and reduce emissions of unburned components at low temperatures.

13.3.2 Test procedures and test fuels

Two diesel passenger cars were used for the low-temperature emission testing:

- Toyota Corolla D-4D, 1.4 litre, MY 2007
- Volkswagen Golf TDI, 1.9 litre, MY 2008.

The cars were tested using the European NEDC test cycle (the EC2000 implementation that is in use since Euro 3 level). Testing was carried out both with an actual cold start, and also by running the test with a fully warmed-up engine. The latter method of testing brings out possible effects of the ambient temperature on vehicle operation, with the cold-start portion eliminated.

The vehicles were tested at three different temperatures, +23, -7 and -20 ^{o}C. The fuels were chosen so that operation at -20 ^{o}C was possible. The test fuels were winter grade diesel fuel, 100 % HVO (with adequate cold flow properties) and a blend with 30 % HVO in winter grade diesel.

13.3.3 Results for low-temperature emissions

The temperature effects with a fully warmed-up engine were rather small, and therefore only results for tests including cold start are presented. When cold starting is included, the effects of both temperature and fuel on emissions were substantial. The results are presented in Figures 13.6 (for CO), 13.7 (for THC), 13.8 (for NO_x) and 13.9 (for PM).

Lowering of the ambient temperature from +23 to -20 °C increased emissions in the following way:

- CO and THC by a factor of close to 10
- NO_x and PM by a factor of up to 3.

According to the results, HVO, both as a blend and as neat, lowered CO and THC emissions at all temperatures, at the most 70–90 % for neat HVO. Fuel effects were of the same order of magnitude as the temperature effect. Maximum reduction was for the Volkswagen car in THC at -20 °C, in which case 0.34 g/km went down to 0.03 g/km, a reduction of 91 %. In the case of PM, the use of 100 % HVO at -20 °C brought down PM emission to the level of regular diesel at +23 °C, -70 % in the case of the Volkswagen. This confirmed that HVO is beneficial for low-temperature emissions.

The fuel effects on NO_x were small, and no unambiguous trend could be seen. Especially in the case of the Toyota, fuel had very little effects on NO_x emissions.

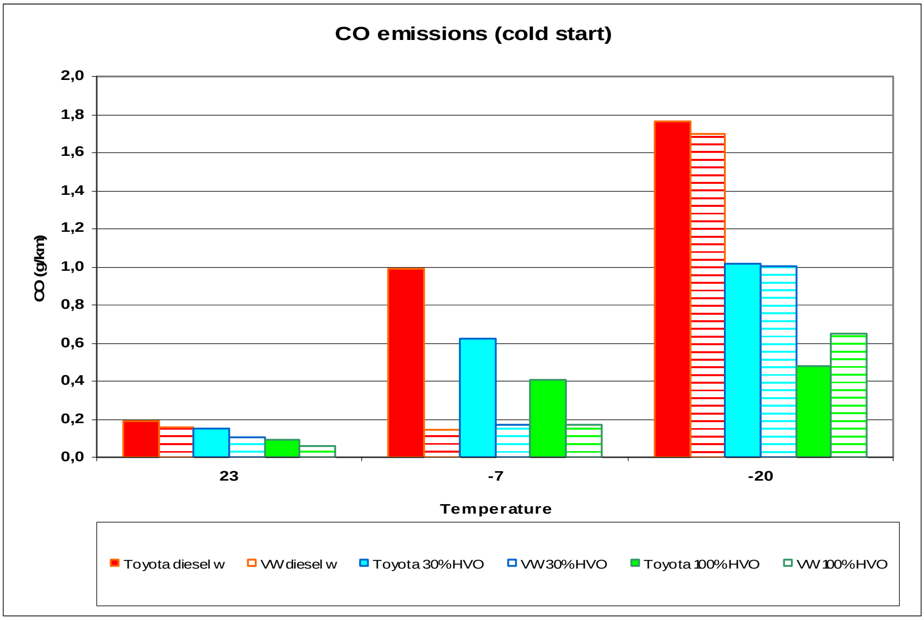


Figure 13.6. The effect of temperature and fuel on CO emissions.

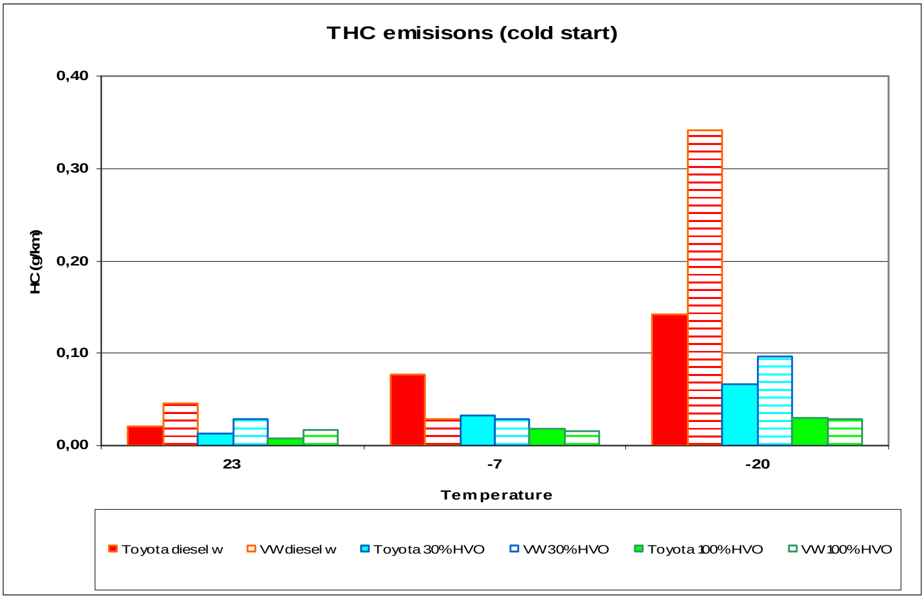


Figure 13.7. The effect of temperature and fuel on THC emissions.

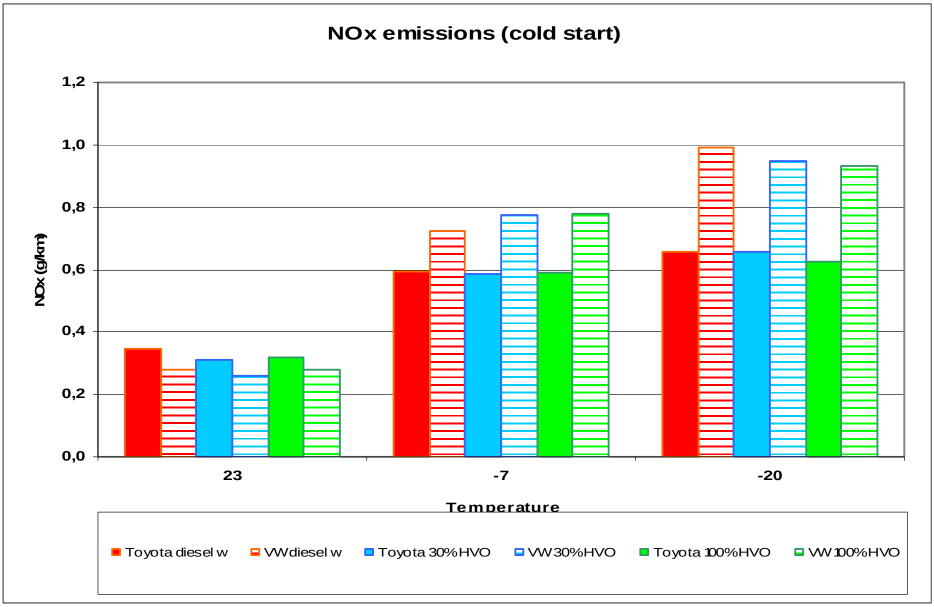


Figure 13.8. The effect of temperature and fuel on NO_x emissions.

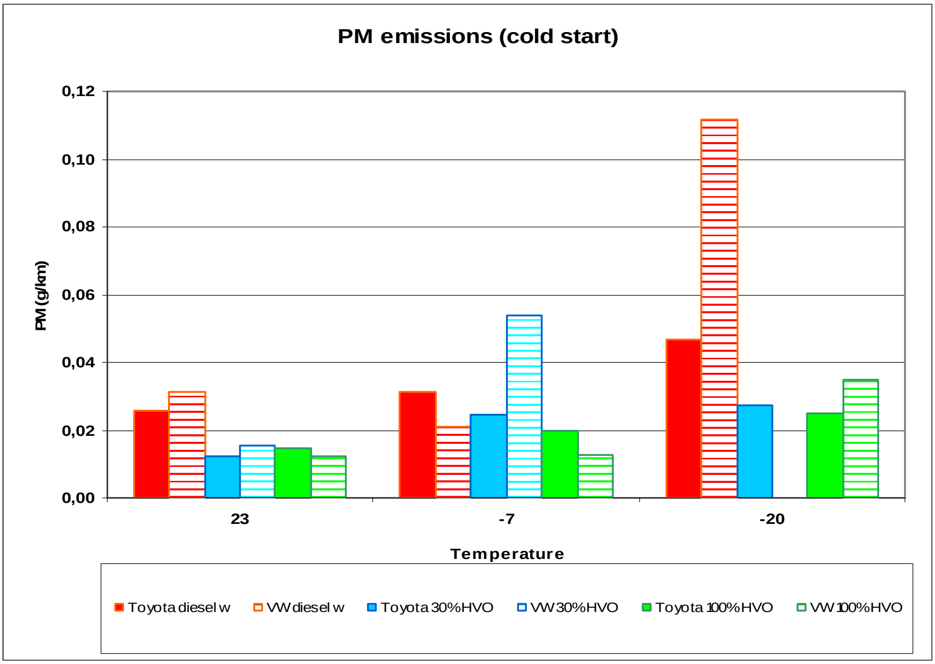


Figure 13.9. The effect of temperature and fuel on PM emissions.

14. Results of the field test

14.1 General

The 3.5 year field test was completed successfully at the end of 2010. Although the test officially ended on December 31st, some minor activities continued into the spring of 2011.

The general outcome of the field test was that that the test fuels didn't cause any problems whatsoever in everyday service. A de-briefing workshop for the bus operators was arranged in February 2011, and none of the operators reported any fuel-related problems. One of the operators made a comment that the project was "invisible", meaning no problems in everyday operation.

It should be noted that the winters 2009/2010 and 2010/2011 were exceptionally cold in the Helsinki region. At the lowest, minimum temperature was below -25 °C. Figure 14.1 presents minimum temperatures in Helsinki for the duration of the test and Figure 14.2 a scene from the Helsinki area in January 2010.

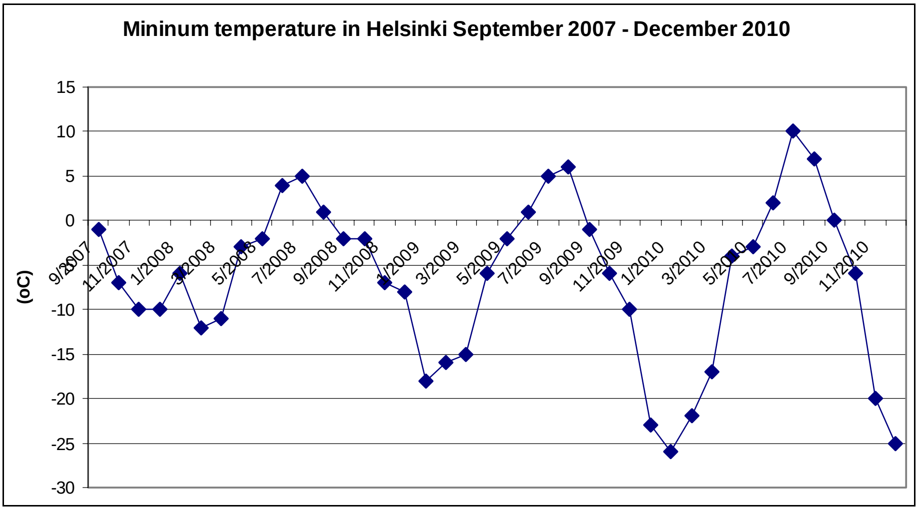


Figure 14.1. Minimum monthly temperature in Helsinki during the test. (http://freemeteo.com/)

All in all, the vehicles accumulated some 50 million kilometres, of which some 1.5 million kilometres on 100 % HVO. Average distance per vehicle was some 170,000 km. The amounts of fuel were some 22 million litres of blended fuel and 1 million litres of straight HVO.

Figure 14.2. Winter conditions in the Helsinki area.

The overall outcome of the OPTIBIO field test was presented in a technical paper at the JSAE/SAE Powertrains, Fuel and Lubricants Meeting in Kyoto, Japan, September 2011. (Mäkinen et al. 2011)

14.2 Operator feedback

14.2.1 General

The buses participating in the OPTIBIO field test were in normal revenue service in metropolitan Helsinki. Operator feedback was collected mainly by interviewing operators during and after the field test. Operators were encouraged to give feedback on any problems or performance related issues which could be attributed to the test fuels, either the blended fuel or the neat HVO fuel. Validation for the feedback given by the operators was acquired by collecting data on vehicle service history and fuel consumption records.

Operators have different policies and systems to manage their vehicle fleets, and therefore the available data differs from operator to operator. As a result the amount of data obtained from different operators also varies. The primary parameters to be observed were fuel consumption and maintenance needs in the fuel and engine systems. The formation of any reoccurring patterns in these parameters was charted.

As for fuel consumption monitoring, one problem is that the bus fleets are not static, vehicles are exchanged and operation modes are changed. Therefore it can be really difficult to obtain good reference data to be compared to the data of the test vehicles.

14.2.2 Fuel consumption

Fuel consumption data was collected from three operators, Helsingin Bussiliikenne, Pohjolan Liikenne and Veolia Transport. All mentioned operators have systems in place to follow the refuelling of individual vehicles, some of them fully automated. The operators pay for the fuel by the litre, so they naturally are interested in volumetric fuel consumption. As described in Paragraph 7.3.2, VTT did preparatory fuel consumption measurements on the chassis dynamometer. The additional volumetric fuel consumption recorded by VTT was (for a certain set of densities for summer grade diesel, winter grade diesel and HVO, diesel fuels without biocomponents “B0”):

- 0.7 to 1.4 % for the 30 % HVO blend
- 3.5 to 5.2 % for 100 % HVO.

Again it should be noted that the diesel fuels used within the OPTIBIO project didn't contain any FAME. Compared to "B7", the increase in volumetric fuel consumption with HVO fuels would have been slightly smaller.

For reasons of competition, the bus operators are reluctant to publish absolute fuel consumption data. Therefore only relative fuel consumption is reported.

Helsingin Bussiliikenne

Helsingin Bussiliikenne was able to deliver refuelling records of approximately 90 vehicles for the year of 2008. At the end of 2008, new software was introduced for the automated system for collecting refuelling data. The new software did not function as reliably as expected, and the records are considered unreliable from December 2008 onwards. The 90 vehicles at Helsingin Bussiliikenne included six new EEV Scania buses, four of which used 100 % HVO fuel and two EN590 control fuel.

Pohjolan Liikenne

Pohjolan Liikenne has a sophisticated refuelling data system including automatic vehicle detection. Pohjolan Liikenne was able to deliver accurate fuel consumption data for six model year 2006 Euro IV certified Scania vehicles. Before the field test period, all vehicles ran on regular EN590 "B0" diesel fuel. Within the test, to begin with three vehicles operated on regular diesel fuel and three on the 30 % HVO blend, and later on all six vehicles on blended fuel. All vehicles operated on the same bus route.

The results of the comparison are presented in Table 14.1. The results accentuate the difficulties in making accurate comparisons. Vehicles are individuals, and differences between the two groups of three vehicles each could be found even when running on the same fuel (regular diesel to start with and later on 30 % HVO). The second group consistently consumed some 1.3 % more fuel than the first group. When the first group was running on regular diesel and the second group on 30 % HVO, the second group consumed some 2.6 % more fuel than the first group. However, when eliminating the difference between the vehicles themselves, the fuel effect on fuel consumption was only some 1.4 %, a number which is congruence with VTT's figures from in-laboratory measurements.

Table 14.1. Results for fuel consumption (relative values, smallest figure = 100). Regular diesel and 30 % HVO at Pohjolan Liikenne in Euro IV certified Scania buses. Yellow regular diesel, green 30 % HVO. At a given time, all six buses operated on the same route. Until 9/07 the route was different than for the period 9/07–2/09.

Veh. number/ Time period	1/06-9/07	10/07-1/08	2/08-9/08	10/08-2/09
855	102	113	112	113
865	102	111	115	112
882	100	112	113	112
889	105	116	118	116
890	100	111	113	110
891	102	117	118	115
Avg. group 1	101	112	113	112
Avg. group 2	102	115	116	114
Total difference rel.	1,2	2,5	2,7	1,4
Difference from vehicles rel.		1,3	1,3	
Difference from fuel rel.		**1,2**	**1,4**	

Veolia Transport

Veolia Transport delivered refuelling records for the entire test vehicle fleet at Suomenoja depot running on the blended fuel. The records date back to 2007, and extend to the end 2010. This fleet included nearly 80 vehicles. Data is not available for all vehicles for the whole test period as new vehicles entered the fleet at Suomenoja and some were taken out of service or transferred.

Data from 2007, prior to the start of the test, gives a rough basis for the estimation of changes in fuel consumption when switching from regular diesel to the blended HVO fuel. It should, however, be noted that only significant changes could be noticed by comparing fuel consumption data on a yearly basis.

In 2010, Veolia Transport operated three fairly new EEV certified Iveco Crossway buses on 100 % HVO at the Kerava depot. Good fuel consumption data is available for these three vehicles and two reference vehicles on regular diesel fuel (Figure 14.3, average monthly values for the two vehicle groups). The data actually covers the period from February 2010 to April 2011, as the three HVO buses continued operation after closing on the main project at the end of December 2010. The average increase in volumetric fuel consumption over the 15 month test period with 100 % HVO was +3.9 %. In this case the actual increase in volumetric fuel consumption was also in accordance with VTT's estimates.

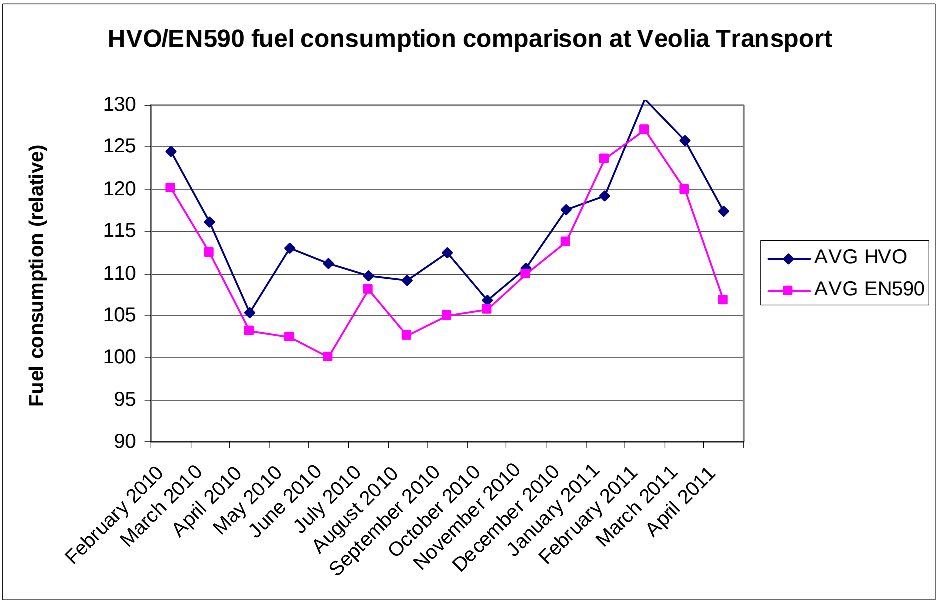


Figure 14.3. Veolia Transport's data on fuel consumption. HVO average of three buses on 100 % HVO, EN590 average of two buses on regular diesel fuel.

At some point it was noticed that the on-board computers (based on CAN bus data) showed increased fuel consumption, even though the refuelling records showed no significant changes. VTT carried out some additional chassis dynamometer measurements in an effort to clarify the reason for this phenomenon (see Paragraph 14.4.4, inspection of fuel injection equipment).

Outcome

The compensation for increased volumetric fuel consumption to the bus operators was based on VTT's chassis dynamometer measurements with corrections for actual densities of the delivered fuel batches. No case in which the refuelling data records of the operators would have indicated higher fuel consumption was brought forward, and thus the compensation to the operators was based on VTT's measurements throughout the project.

14.2.3 Service history – general

Service history data was requested from the same three operators mentioned above. Service history information was collected in various ways, depending on operator and e.g., whether the vehicles had service contracts or not (service provided by an external organisation). Generally, service history data includes an extensive amount of detailed information on performed maintenance work. In addition, the exporting of this information out of the system used may be complicated or impossible without paper printouts. This led to a slight unwillingness to deliver data for the study.

Typically, data is collected in a more systematic way for those vehicles which are covered by service contracts. Unfortunately, in some cases the repair shops were reluctant to deliver service records, and in some cases, actually refused to deliver data.

Helsingin Bussiliikenne

Service data was received for the six new EEV Scania buses at Helsingin Bussiliikenne. The operation of the vehicles was closely monitored by the manufacturer. After completion of the field test, all engines (four 100 % HVO engines and two reference engines on regular diesel) were returned to the manufacturer for an in-depth control.

Pohjolan Liikenne

Pohjolan Liikenne delivered service records for the three Euro III Scania buses which were using 100 % HVO and the three corresponding control vehicles on diesel fuel. This information was in the form of printouts from individual maintenance visits. Service history information was also received for four EEV certified Volvo buses on 30 % HVO involved in the emission follow-up measurements. These vehicles were under a service contract, and a complete service history was received from Volvo. As a reference for these four vehicles, the service histories of four similar buses not included in the field test were also received.

Veolia

In the case of Veolia Transport, data on service mainly relate to vehicles showing abnormalities in emission performance. Most of these vehicles had accumulated significant mileage, and suffered from faults which were not related to the fuel in any way, e.g., turbocharged break-downs. The service history for these vehicles goes back as far as 2003, providing a good background for finding out reasons for irregular performance.

14.2.4 Fuel related problems and maintenance

When analysing service history data, several fuel related problems could be found. However, most of the problems were rather vehicle or fuel system specific than directly fuel specific, and the problems occurred in vehicles operating on HVO fuels as well as in vehicles on regular diesel fuel. One batch of vehicles suffered from failing turbochargers. The first failure, resulting in elevated emissions, gave rise to suspicions about fuel related problems. However, it soon became apparent that this problem was again a vehicle specific problem, and not related to fuel type.

Another batch of vehicles suffered from clogging (paraffinization) of the suction filter inside the fuel tank during the winter season. The issue was resolved through suction filter modifications, but the modification, on the other hand, caused some problems with the fuel level sensor. However, these suction filter problems occurred regardless of the fuel type.

The third observed batch of vehicles had only two fuel related problems, and both occurred in reference vehicles on regular diesel fuel.

Based on the observations it can be concluded that HVO fuel didn’t cause any particular problems in the test fleet. Three years of field testing is perhaps not enough to bring out all potential problems, but at least the results are indicative.

The observed fuel related problems are listed in Table 14.2. The vehicles with a numerical code without letters only used regular fossil diesel, and are added as reference vehicles. Some of the vehicles operated on regular diesel as well as test fuels. These vehicles are denoted with a number plus an additional marking of F or HVO.

As stated above, most of the problems are actually more related to the vehicle itself than to the fuel. The listed problems are problems that required some maintenance to keep the vehicle in normal operating condition (for example "fuel level sensor not working", "engine malfunction light lit" or "vehicle starts poorly"). Some problems required several workshop visits before they were finally sorted out, but each visit to the maintenance was counted. Many problems were minor problems and they didn't cause breakdowns, but at least once the need for towing was reported (all operators didn't report the need for towing in their maintenance history so the actual amount might be higher).

Table 14.2. Fuel related problems in the field test. Number of incidents/100,000 km.

Vehicle batch 1		
Vehicle	Problems/ 100,000km	Fuel
1	3.2	EN590 100 %
2	1.5	EN590 100 %
3	3.6	EN590 100 %
4	2.9	EN590 100 %
12F	3.8	EN590 100 %
13F	1.2	EN590 100 %
14F	4.6	EN590 100 %
Average	3.0	
11HVO	7.6	EN590 70 % + HVO 30 %
12HVO	2.9	EN590 70 % + HVO 30 %
13HVO	3.6	EN590 70 % + HVO 30 %
14HVO	2.0	EN590 70 % + HVO 30 %
Average	4.0	

Vehicle batch 2		
Vehicle	Problems/ 100,000km	Fuel
15F	0.4	EN590 100 %
16F	0.3	EN590 100 %
17F	0.4	EN590 100 %
18F	0.4	EN590 100 %
Average	0.4	
15HVO	0.0	EN590 70 % + HVO 30 %
16HVO	0.4	EN590 70 % + HVO 30 %
17HVO	1.3	EN590 70 % + HVO 30 %
18HVO	0.5	EN590 70 % + HVO 30 %
Average	0.5	

Vehicle batch 3		
Vehicle	Problems/ 100,000km	Fuel
5	1.6	EN590 100 %
6	1.6	EN590 100 %
7	0.0	EN590 100 %
Average	1.1	
8HVO	0.0	HVO 100 %
9HVO	0.0	HVO 100 %
10HVO	0.0	HVO 100 %
Average	0.0	

One issue which received special attention was possible fuel leaks. Aromatic compounds in diesel fuel tend to cause swelling in various types of seals and gaskets. Paraffinic fuels could, especially when replacing conventional diesel fuel cause shrinking, and thereby induce fuel leaks. This could be the case when 100 % HVO is applied to vehicles that already have been in service. However, none of the bus operators reported any fuel leaks, not for blended fuels and not for 100 % HVO.

14.3 Fuel and lubricant analyses

14.3.1 General

Neste Oil was responsible for fuel and lubricant analyses. One exception was the lubricant analyses for the six new EEV certified Scania buses at Helsingin Bussiliikenne.

14.3.2 Fuel analyses

Fuel quality and condition was monitored in the course of the whole test, at intervals of two to four weeks. Sampling focused on the fuel storages at the bus depots of the different operators taking part in the field test. All in all, more than 150 fuel samples were analyzed.

Analyses included parameters such as density, flash point, cloud point, CFPP, water content, lubricity (high frequency reciprocating rig HFRR), cetane number, corrosion and filter blocking tendency (FBT). FBT is a test method intended for use in evaluating the cleanliness of middle distillate fuels, and biodiesel and biodiesel blends for specifications and quality control purposes. Conventional biodiesel (FAME) often delivers poor performance in the FBT test.

Most of the analyses were performed on the blended fuels, which contained 25 to 30 % HVO in regular diesel fuel. Testing started with a 25 % blend, and as of 2008, the target HVO for the blended fuel was 30 % (see Paragraph 7.2). The cold flow properties of the diesel part of the blended fuel varied normally according to the time of the year. All the samples of the blend fuels fulfilled the EN590 specification for diesel fuel. The water content of the blended fuels was low, and so was the filter blocking tendency.

Similar analyses were also performed on the 100 % HVO fuel. The neat HVO fuel was used throughout the winters, and for this reason, HVO was also produced in different grades depending on the time of the year. In the case of 100 % HVO, all samples fulfilled the requirements of the CEN Workshop Agreement CWA 15940 for paraffinic fuel. The water content as well as the filter blocking tendency were low also in this case. Cetane numbers were very high

Table 14.3 presents a summary of the fuel analyses. All fuel parameters were within the specifications, and the target parameters for cold operability (CP and CFPP), which were adjusted according to the time of the year, could be met at all times.

The large variation in the parameters is due to the fact that summer as well as severe winter grade fuels were covered. CFPP is not reported for neat HVO, since CFPP (expressed in degrees centigrade) is very close to the cloud point, and because cloud point is sufficient to describe cold operability of HVO (see Paragraph 13.2.5). At its lowest, the cloud point of neat HVO was -32 ^{o}C, meaning that the vehicles could still have been operated on 100 % biofuel at -30 ^{o}C.

Table 14.3. Summary of the fuel analyses.

	Blended fuel 30 % HVO	**EN590 specification**	**Neat HVO**	**CWA 15940 specification**
Cetane number	55–67	min 51	76–96	min 70
Density kg/m^3	803–825	800–845	778–785	770–800
Cloud point ^{o}C	-3 – -29	As locally needed	-4 – -32	As locally needed
CFPP ^{o}C	-13 – -45	As locally needed	Not relevant	As locally needed
Lubricity HFRR μm	191–390	max 460	264–440	max 460
Water mg/kg	10–58	max 200	13–67	max 200

At the end of the test, one of the fuel cisterns that had carried 100 % HVO was inspected. Left-over fuel had intentionally been left in the cistern for some 8 months. There was no sign of fungus or other biological activity, and the fuel was still completely clear (Figure 14.4). Fuel stability is one major benefit of HVO. Oxygen containing FAME has a limited “shelf life”, and is not suitable for prolonged storage.

In the beginning of the OPTIOBIO project, Neste Oil carried out two 1000 hour lubricity tests according to the method CEC-PF-032 using a diesel injection pump (rotary-type Bosch VE). The fuels were a blend of 25 % HVO in diesel and 100 % HVO. Both fuel were treated with anti-wear additives, and screened for lubricity using the HFRR test. The objective was to adjust the dosing of the additive to achieve a wear scar as close as possible to the EN590 limit value of 460 µm. This way the test is as critical as possible for the pump, but still with a fuel that meets the EN590 specification. After additive treatment, the test fuels rendered the following wear scars:

- 25 % HVO blend: 424 µm
- 100 % HVO: 446 µm.

After the 1000 test run the pump is dissembled and inspected, both visually and by measurements according a procedure defined by Bosch. All in all 10 different parts of the pump are inspected and rated. The calculated numerical limit value for the test is 3.5 (maximum value). The results for the two test fuels were:

- 25 % HVO blend: 2.5
- 100 % HVO: 3.0.

Figure 14.4. The inside of a 100 % HVO storage tank. The fuel is still completely clear after 8 months. The surface rust on the tank walls existed already before switching to HVO.

Both pumps showed normal wear rates for all parts, and both fuels passed the test. Neste Oil has been running these rig tests since the beginning on the 90's, and therefore has solid experience in this kind of testing and in evaluating different grades of wear.

14.3.3 Lubricant analyses

Lubricant analyses (engine oil) focused on vehicles running on 100 % HVO. The new EEV vehicles at Helsingin Bussiliikenne were handled by the manufacturer, Scania. Neste Oil analysed oil samples from the other buses running on 100 % HVO, namely the Euro III certified Scania buses of Pohjolan Liikenne and the EEV certified Iveco buses of Veolia Transport.

In the case of Pohjolan Liikenne, samples were taken from one bus running on 100 % HVO and from one control vehicle on regular diesel. These were the same two vehicles which had their fuel injection systems checked (see Paragraph 7.7.3). The results of the oil analyses are presented in Table 14.4. All the results are normal, except one sample with increased molybdenum level for the control bus on regular diesel fuel. Otherwise, the two buses gave very congruent results.

In the case of Veolia Transport, samples from all three buses running on 100 % HVO and three reference buses were analyzed. Unused oil was analyzed as well. The results are presented in Table 14.5. Two samples, one from a 100 % HVO vehicle and one from a reference vehicle showed elevated copper levels (139 and 88 mg/kg). In the case of 100 % HVO this occurred in the first sample. All the other indicators like additive metals, TAN (total acid number), TBN (total base number), fuel dilution and soot content were in order, and at the same level for 100 % HVO as well as for normal diesel fuel. As for the last sample, all vehicles on 100 % HVO showed excellent results. In the case of Veolia Transport, the vehicles on 100 % HVO accumulated mileage quite rapidly.

The conclusion is that there were no significant differences in the samples from the vehicles on 100 % HVO compared to the reference vehicles. In all cases the engine oil change interval was in accordance with the manufacturer's recommendation (varying from one vehicle type to another).

Table 14.4. Oil analyses results for Pohjolan Liikenne. N.B.: The first sample of the HVO vehicle is for regular diesel fuel before entering the test.

		NExBTL 100 %					**EN590 DIESEL FUEL**				
Samples taken		14.4.2009	21.7.2009	21.9.2009		10.6.2010	20.4.2009	13.7.2009	30.9.2009		9.6.2010
Total km of vehicle		281820	296613	309130	324736	340000	282014	297791	312179	328636	343628
oil used km		~15 000	14793	12517	15606	15264	~15 000	15777	14388	16457	14992
Wear metal analysis											
Aluminium	mg/kg	1	2	1	1	1	0	1	1	1	1
Cromium	mg/kg	0	1	0	1	1	0	1	0	0	0
Copper	mg/kg	4	5	3	3	7	3	8	8	7	6
Iron	mg/kg	5	8	6	6	7	3	9	6	5	5
Molybdenum	mg/kg	0	1	0	0	0	67	8	1	0	0
Nickel	mg/kg	0	0	0	0	0	0	0	0	0	0
Leed	mg/kg	2	3	3	2	2	2	3	3	2	2
Tin	mg/kg	0	0	0	0	0	0	1	0	0	0
Sodium	mg/kg	0	2	4	0	4	5	6	4	1	1
Potassium	mg/kg	0	0	0	2	2	0	1	1	2	3
Silicon	mg/kg	2	3	2	2	2	3	5	3	3	3
Additive metals											
Barium	mg/kg	0	1	0	0	0	1	0	0	0	0
Calsium	mg/kg	2882	2911	2785	2947	3167	2717	2671	2640	2972	2942
Magnesium	mg/kg	0	1	3	3	4	7	4	4	5	3
Phosphorous	mg/kg	1046	1005	1007	986	1102	954	922	954	997	1017
Zinc	mg/kg	1191	1162	1157	1121	1228	1138	1100	1101	1134	1150
Boron	mg/kg	0	1	0	0	1	77	8	1	1	1
Total acid number, TAN	mgKOH/g	3,48	3,86	3,31	3,45	2,97	2,97	3,21	2,86	4,73	3,39
Total buffer number, TBN	mgKOH/g	10,95	10,95	10,59	10,56	10,84	11,55	10,49	11,29	10,64	0,3
Viscosity +100 ºC	mm2/s	11,26	11,08	11,43	11,1	11,3	12,8	11,43	11,52	10,78	10,62
Fuel dilution	%	1,25	2,86	2,51	3,17	2,56	1,25	2,1	2,18	3,39	2,52
Soot content	%	0,3	0,3	0,3	0,5	0,5	0,2	0,3	0,3	0,4	0,3
Flash point	ºC	201	195	194	192	197	205	203	200	192	200

Table 14.5. Oil analyses results for Veolia Transport. N.B.: The first samples of the HVO vehicles are for regular diesel fuel before entering the test.

		NExBTL 100%								
		490			**491**			**492**		
Samples taken		16.2.2010	9.8.2010	20.12.2010	17.2.2010	11.8.2010	20.12.2010	17.2.2010	12.8.2010	20.12.2010
Total km of vehicle		59000	109 668	152247	67525	124002	163843	66007	121182	163332
oil used km		40tkm	50 668	42 579	40tkm	56477	39841	40tkm	55175	42150
Wear metal analysis										
Aluminium	mg/kg	5	16	12	4	12	7	1	6	6
Cromium	mg/kg	1	3	2	1	3	2	0	1	1
Copper	mg/kg	24	139	18	27	9	3	6	11	14
Iron	mg/kg	13	30	25	15	38	23	5	19	23
Molybdenum	mg/kg	0	0	0	0	0	0	0	0	0
Nickel	mg/kg	0	0	0	0	0	0	0	0	0
Leed	mg/kg	2	17	4	2	32	5	0	5	5
Tin	mg/kg	1	0	0	0	1	0	0	0	0
Sodium	mg/kg	8	9	16	8	9	16	9	8	17
Potassium	mg/kg	10	26	18	8	11	8	3	5	7
Silicon	mg/kg	7	13	8	6	13	7	3	11	8
Additive metals										
Barium	mg/kg	0	0	0	0	0	0	0	0	0
Calsium	mg/kg	3677	4709	4408	3670	4721	4344	3721	4532	4437
Magnesium	mg/kg	19	31	25	20	32	24	21	31	24
Phosphorous	mg/kg	809	1033	918	823	1035	897	801	969	924
Zinc	mg/kg	924	1152	1059	939	1160	1041	909	1102	1066
Boron	mg/kg	14	4	1	13	3	1	3	2	1
Total acid number, TAN	mgKOH/g	6,74	5,53	5,22	6,66	5,49	4,95	4,67	5,09	4,78
Total buffer number, TBN	mgKOH/g	15,09	15,98	15,57	14,91	15,75	15,29	16,17	16,43	15,68
Viscosity +100 ºC	mm2/s	11,66	11,57	11,5	11,79	11,7	11,42	11,81	11,54	11,8
Fuel dilution	%	0,42	0,7	0,71	<0,3	1,34	1,78	0,34	0,45	<0,3
Soot content	%	0,1	<0,1	<0,1	<0,1	<0,1	<0,1	0,1	<0,1	<0,1
Flash point	ºC	210	208	209	213	203	203	211	209	213

		EN590 Diesel			New Oil
		493	494	495	5W30
Samples taken		20.12.2010	20.12.2010	16.2.2010	1.10.2010
Total km of vehicle		166734	165400	n.80tkm	0 km
oil used km		n.40tkm	n. 40tkm	40tkm	0 km
				*note different engine oil	
Wear metal analysis					
Aluminium	mg/kg	6	9	10	2
Cromium	mg/kg	2	3	1	0
Copper	mg/kg	3	5	88	0
Iron	mg/kg	21	25	33	3
Molybdenum	mg/kg	0	0	0	0
Nickel	mg/kg	0	0	0	0
Leed	mg/kg	4	15	7	0
Tin	mg/kg	0	0	0	0
Sodium	mg/kg	15	16	6	15
Potassium	mg/kg	9	9	17	4
Silicon	mg/kg	7	8	10	5
Additive metals					
Barium	mg/kg	0	0	0	0
Calsium	mg/kg	4411	4246	3244	4468
Magnesium	mg/kg	24	23	3	28
Phosphorous	mg/kg	924	914	1017	964
Zinc	mg/kg	1059	1050	1222	1071
Boron	mg/kg	1	1	9	1
Total acid number, TAN	mgKOH/g	5,68	5,68	3,68	3,69
Total buffer number, TBN	mgKOH/g	15,82	14,74	10,04	17,26
Viscosity +100 ºC	mm2/s	11,71	11,63	12,02	11,85
Fuel dilution	%	0,65	1,78	<0,3	<0,3
Soot content	%	<0,1	<0,1	<0,1	<0,1
Flash point	ºC	212	203	212	214

14.4 Inspections of fuel injection equipment and engines

14.4.1 General

As mentioned in Paragraph 7.7.3, monitoring of injection equipment was limited to vehicles running on 100 % HVO. These vehicles were:

- four new EEV certified Scania buses at Helsingin Bussiliikenne
  - high-pressure common rail injection system
- three older Euro III certified Scania buses at Pohjolan Liikenne
  - in-line injection pumps
- three fairly new EEV certified Iveco buses at Veolia Transport
  - unit-injectors.

All these vehicles had control vehicles running on regular diesel fuel.

14.4.2 Scania EEV buses

The follow-up of the new EEV certified Scania buses at Helsingin Bussiliikenne was carried out by the manufacturer, Scania. At the end of the testing, the four HVO engines and the two control engines on regular diesel fuel were removed, and sent to Sweden for inspection. The engines were equipped with the high-pressure XPI fuel injection system.

The initial analysis done by Scania summarizes following findings:

- *Generally: Very few incidents were reported for both the diesel and NExBTL buses. No degradation of polymeric materials, e.g., sealings. No corrosion, cavitation or wear of metallic material except in the fuel system.*
- *Combustion system: No reported significant differences between NExBTL and diesel.*
- *Oil system: Low-ash oil was used. No reported significant differences between NExBTL and diesel. It can be noted that the soot levels and fuel dilution were lower in the NExBTL engines than in the diesel engines (indicates lower degradation of the oil and lower wear of lubricated parts).*
- *After-treatment: No reported significant differences between NExBTL and diesel.*
- *Fuel system: The injectors from the NExBTL engines showed deterioration: the pilot valve seats had abrasive wear compared to the diesel engine. The wear on the fuel pump was minimal and no loose debris that might have damaged the pilot valve seats was found.*

The injectors were then subjected to more detailed analysis. The outcome was that the abrasive wear was not caused by the paraffinic fuel, but rather by a materials problem in the valve. Thus, based on the findings of the OPTIBIO project, in August 2011 Scania approved the use of 100 % HVO, or rather NExBTL, in its city and intercity buses with DC9 engines.

14.4.3 Scania Euro III buses

In this case, the injection systems of one test vehicle and one reference vehicle were inspected and refurbished before the test, and then inspected again after the test. The refurbishing and inspection was carried out by Diesel-Oteko Oy, an authorised Bosch repair workshop. Before entering the test, the vehicles had travelled some 270,000 km on regular diesel fuel. The distance on 100 % HVO was some 60,000 km.

The parts replaced were:

- pump elements
- pressure valves
- camshaft bearings
- roller tappets.

The injection nozzles were simply checked for opening pressure (with possible adjustment) and function (spray pattern).

Diesel-Oteko delivered a written inspection report. The comments were:

Vehicle on 100 % HVO:

- practically no change in pump delivery volumes
- a small increase in the variation of idle delivery volumes
  - this was considered normal
- the visual inspection of the pump elements revealed some scratches on the sliding surfaces
  - this was also considered normal
- no marks of seizure in the tips of the injector nozzles
- the opening pressures of the injection nozzles had fallen some 5 bar, but the functioning and the spray formation were normal.

Vehicle on regular diesel fuel:

- the visual inspection of the pump elements revealed no abnormal wear or scratched
  - the condition of the elements was slightly better than in the case of the 100 % HVO vehicle
- no marks of seizure in the tips of the injector nozzles
- the opening pressures of the injection nozzles had fallen some 5 bar, but the functioning and the spray formation were normal.

The conclusion was that although the injection pump elements were in slightly better condition in the reference vehicles, the wear of the injection pump and the injection nozzles with 100 % HVO were within normal limits. However, it should be noted that only one vehicle for each fuel was checked, and that 60,000 km is quite a short distance for a bus.

14.4.4 Iveco EEV buses

Fuel injection system

In the case of the EEV certified Iveco vehicles, the check-ups were limited to inspection of one of the HVO vehicles after completed testing. The vehicles had travelled some 60,000 km on regular diesel fuel entering the HVO testing. Accumulation of mileage with HVO was rapid, and in less than one year the vehicles accumulated some 100,000 km on 100 % HVO. Thus the total mileage at the time of the inspection was some 160,000 km.

For the Iveco, the check-up was carried out by another authorised Bosch repair workshop, Diesel-Asennus Oy. In this case, the written report also contains photos of the various parts of the injection system.

The report presents the following statements:

- the unit-injectors were tested in a rig, and the delivery volumes were congruent with the guideline values
- no signs of abnormal wear in the unit injectors
    - no signs of abnormal wear in the pistons or valves
    - no sign of abnormal wear in the injector nozzle tip
- no signs of fuel related deposits.

Figures 14.5 and 14.6 show parts of the unit-injector fuel injection system.

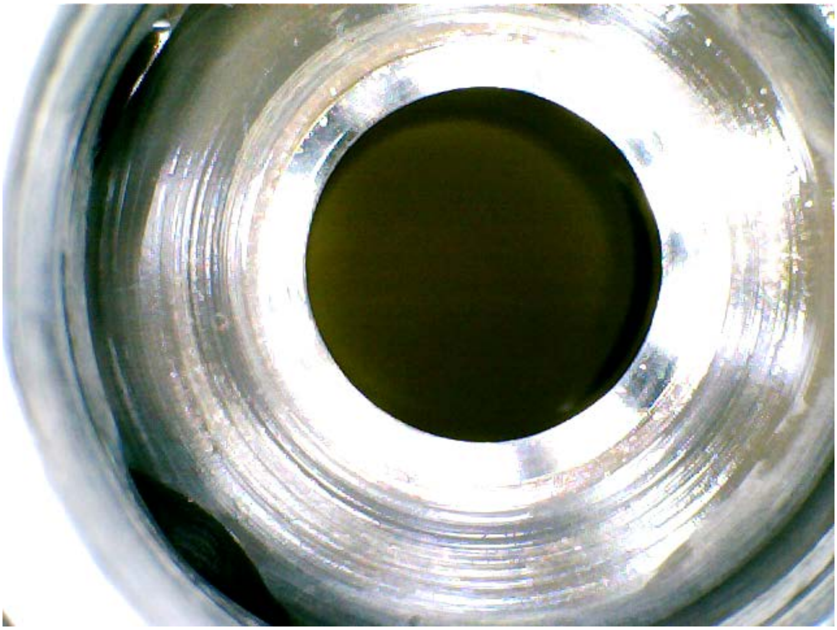


Figure 14.5. Tapered valve seat on the unit injector system.

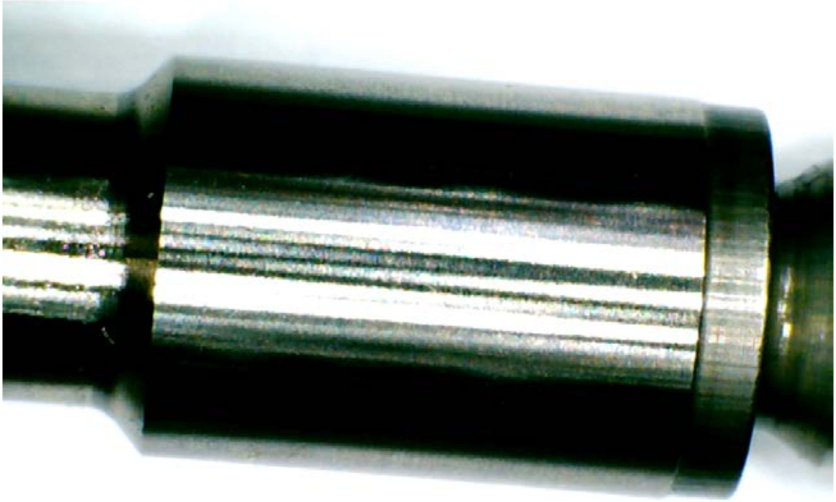


Figure 14.6. Surface of the piston stem.

Discrepancy between actual fuel consumption and CAN bus fuel data

Veolia Transport monitors fuel consumption both from actual refuelling (Figure 14.3) and by an automated data logging system from the data on the on-board computer. During the course of the test it was noted that the data from the vehicle systems indicated a significant increase in fuel consumption for the vehicles running on 100 % HVO over the vehicles on regular diesel fuel (Figure 14.7), while the actual refuelling data showed no significant changes.

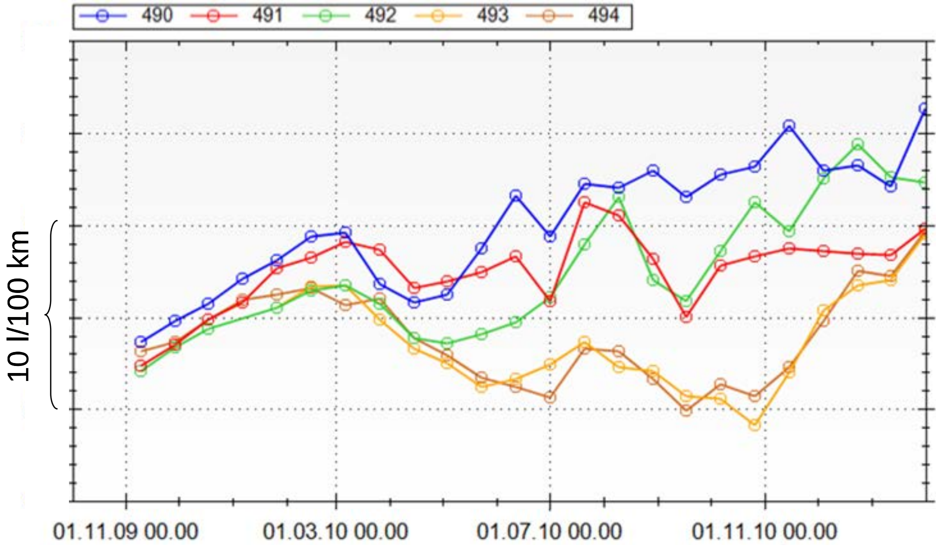


Figure 14.7. Fuel consumption data from the on-board computers on the Iveco buses at Veolia Transport. Vehicles 490, 491 and 492 on 100 % HVO, vehicles 493 and 494 on regular diesel fuel.

An obvious mechanical fault in the injection system leading to, e.g., excessive bypass could have explained the phenomenon. However, as described above, the one injection system inspected was in perfect working order. The self-learning capabilities of the control system might be one explanation. Neat HVO increases volumetric fuel consumption and fuel dosing for a given power level, and this may somehow distract the control system. Additional testing to clarify the situation was carried out on VTT's chassis dynamometer. It remains unsolved exactly what caused the fuel consumption indicated by the CAN on-board system to be higher than the true fuel consumption. No consistent link between the difference and relevant fuel properties or parameters was found.

14.5 Emission stability

14.5.1 General

Altogether 33 vehicles were selected for recursive emission measurements to monitor general vehicle performance as well as emission stability. The following vehicles were selected for follow-up measurements:

Vehicles on 30 % HVO:

- Euro II: 5 units (including 3 units with retrofitted FTF devices)
- Euro III: 6 units (including 1 unit with retrofitted FTF device)
- Euro IV: 2 units
- EEV: 6 units.

Vehicles on 100 % HVO:

- EEV Scania: 4 units (new vehicles)
- Euro III Scania: 3 units (including 1 unit with retrofitted FTF device)
- EEV Iveco: 1 unit.

Reference vehicles on EN590 diesel:

- EEV Scania: 2 units (new vehicles)
- Euro III Scania: 3 units (including 1 unit with retrofitted FTF device)
- EEV Iveco: 1 unit.

Most vehicles were tested three times, meaning that the total number of follow-up measurements, including some repeats, approached 100. VTT's general data base on bus emissions (see Chapter 6) served as a good reference for the emissions measurements in the OPTIBIO project.

14.5.2 Results for vehicles

The results will be presented in the order from older vehicles to newer vehicles. Euro II and Euro III vehicles are rather stable for emissions, on the condition that the vehicles are in good mechanical order. As explained earlier in Paragraph 14.2.3, e.g., some turbocharger failures caused some confusion in interpreting emission results.

Figure 14.8 shows NO_x stability and Figure 14.9 PM stability for Euro II and Euro III vehicles. The NO_x levels are extremely stable. PM shows more variation, but the variations relate to general faults in the engines, not the fuel.

Even the blended fuel seems to deliver a small reduction in both NO_x and PM.

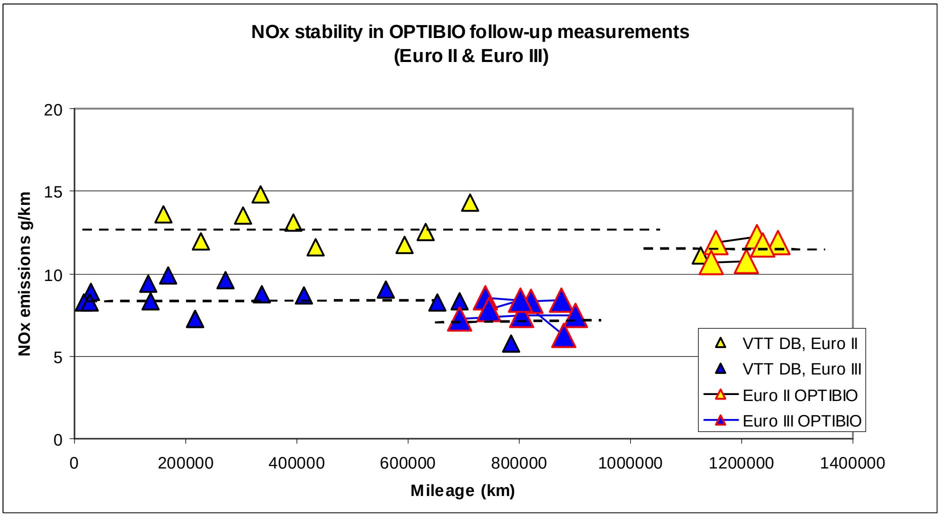


Figure 14.8. NO_x emission stability for Euro II and Euro III buses. Triangles with red edge OPTIBIO results for blended fuel (30 % HVO), other data points VTT's bus data base.

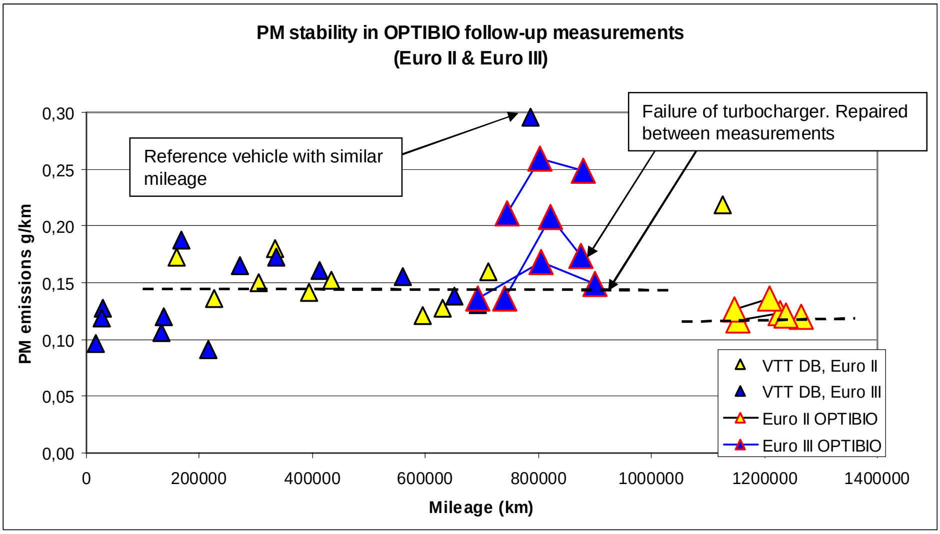


Figure 14.9. PM emission stability for Euro II and Euro III buses. Triangles with red edge OPTIBIO results for blended fuel (30 % HVO), other data points VTT's bus data base.

Figures 14.10 and 14.11 correspondingly show results for Euro IV EGR and EEV SCR vehicles.

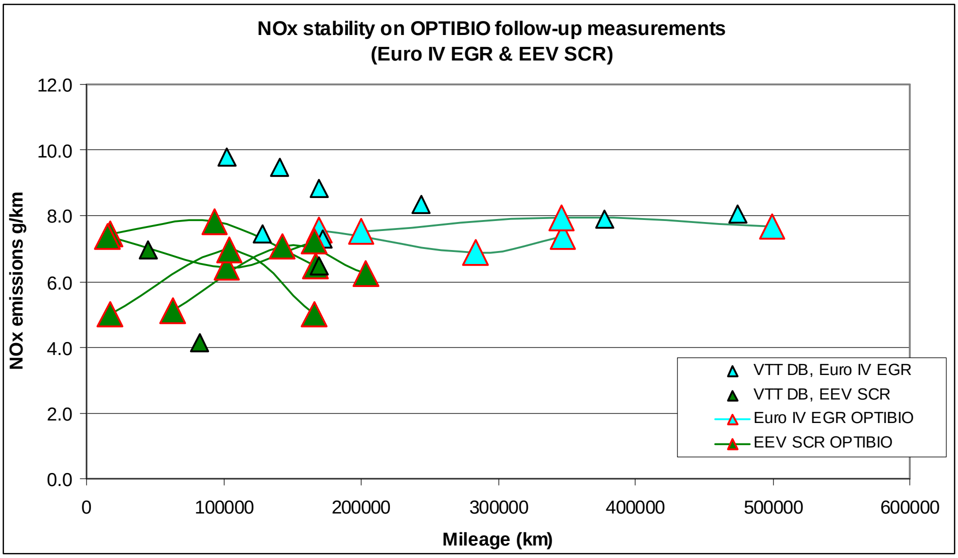


Figure 14.10. NO_x emission stability for Euro IV EGR and EEV SCR buses. Triangles with red edge OPTIBIO results for blended fuel (30 % HVO), other data points VTT's bus data base.

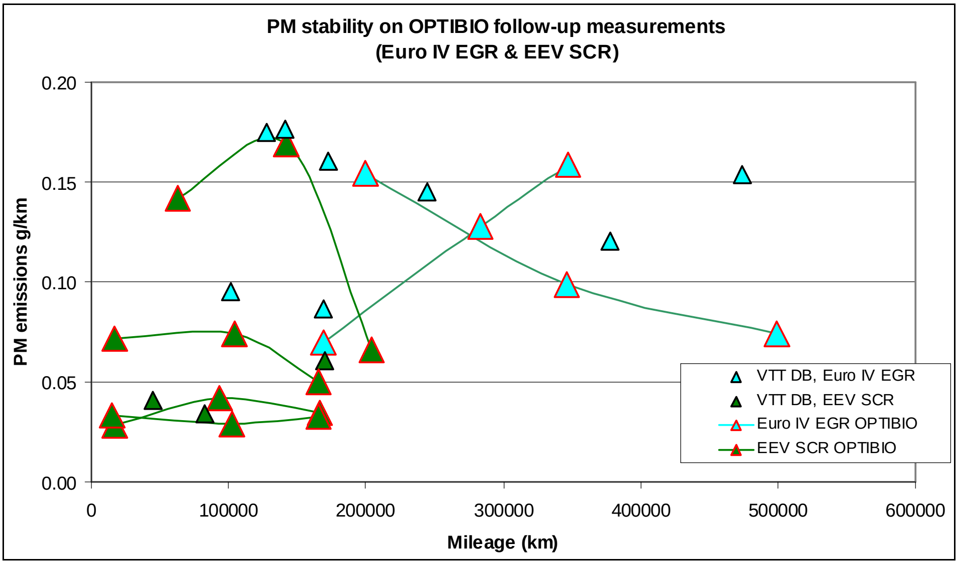


Figure 14.11. PM emission stability for Euro IV EGR and EEV SCR buses. Triangles with red edge OPTIBIO results for blended fuel (30 % HVO), other data points VTT's bus data base.

In Euro IV EGR vehicles, the blended fuel seems to deliver a small reduction in NO_x. SCR systems for NO_x reduction are rather unstable, and therefore it's impossible to say anything about fuel effects on NO_x emissions for SCR vehicles.

As in the case of Euro II and Euro III vehicles, there is significantly more variation in PM emissions than in NO_x emissions. One of the SCR buses showed large variation in PM emissions over time, starting quite high and then increasing, only to end up at normal level in the last measurement. Two EGR vehicles gave quite diverging results for PM, one vehicle showed a steady increase in PM emissions, the other vehicle a steady decrease over time.

Figures 14.12 (NO_x) and 14.13 (PM) show results for EEV EGR buses. Again, the NO_x levels are stable, but there are huge variations in PM emissions.

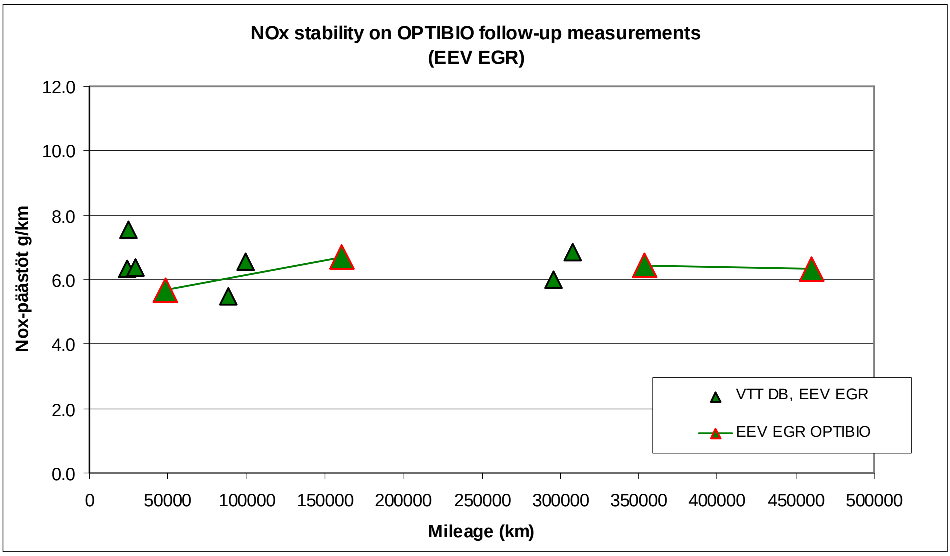


Figure 14.12. NO_x emission stability for EEV EGR buses. Triangles with red edge OPTIBIO results for blended fuel (30 % HVO), other data points VTT's bus data base.

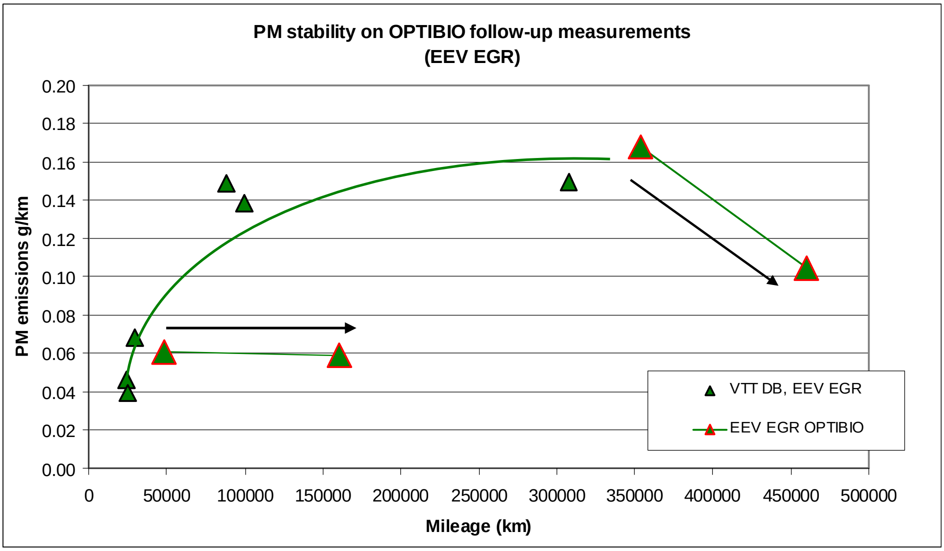


Figure 14.13. PM emission stability for EEV EGR buses. Triangles with red edge OPTIBIO results for blended fuel (30 % HVO), other data points VTT's bus data base.

The 30 % blended fuel delivered very interesting PM results. When applied to one rather new vehicle, the HVO blend prevented increase in PM over time, a phenomenon often seen. When applied to vehicle with higher mileage (some 350,000 km) and high PM emissions, the blended fuel brought down PM emissions by some 40 % over the next 100,000 km.

Figures 14.14 (NO_x) and 14.15 (PM) show emission stability for the three Scania Euro III vehicles on 100 % HVO and two control vehicles. Unfortunately, the distances driven were quite low, only some 60,000 km per vehicle. In the case of NO_x, two vehicles on 100 % HVO showed an increase and one vehicle a decrease in NO_x, while the control vehicles showed no changes. It should be noted that in comparison with VTT's bus database, all three plus two OPTIBIO vehicles produced NO_x emissions in the lower range of Euro III vehicles.

As for PM emissions, two of the vehicles on 100 % HVO showed a decrease and one vehicle an increase in PM, while both control vehicles showed an increase in PM. The short driven distance prevents drawing any definite conclusions from the results.

Figures 14.16 (NO_x) and 14.17 (PM) shows results for two EEV certified Iveco SCR + DPF vehicles within the OPTIBIO project, one running on EN590 and one on 100 % HVO. In this case the driven distance was some 100,000 km.

Both vehicles delivered extremely stable NO_x values. As for PM, both vehicles showed a reduction in PM emissions over time. The vehicle on 100 % HVO started from a higher level, but due to a sharper decrease ended up at the same level as the control vehicles. Here it should be noted that the PM level, due to the actual DPF device, is significantly lower than for the Euro III vehicles (final level only some 10 % of the Euro III vehicles).

In the case of the Iveco buses, only one vehicle on 100 % HVO was measured, so in this case the sample size is too small to draw definite conclusions.

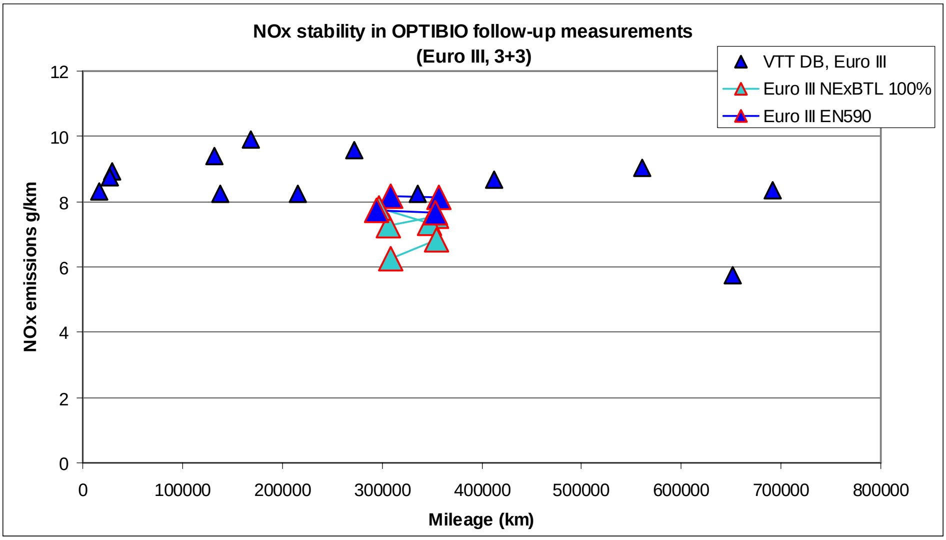


Figure 14.14. NO_x stability for three plus two Euro III Scania buses on EN590 and 100 % HVO.

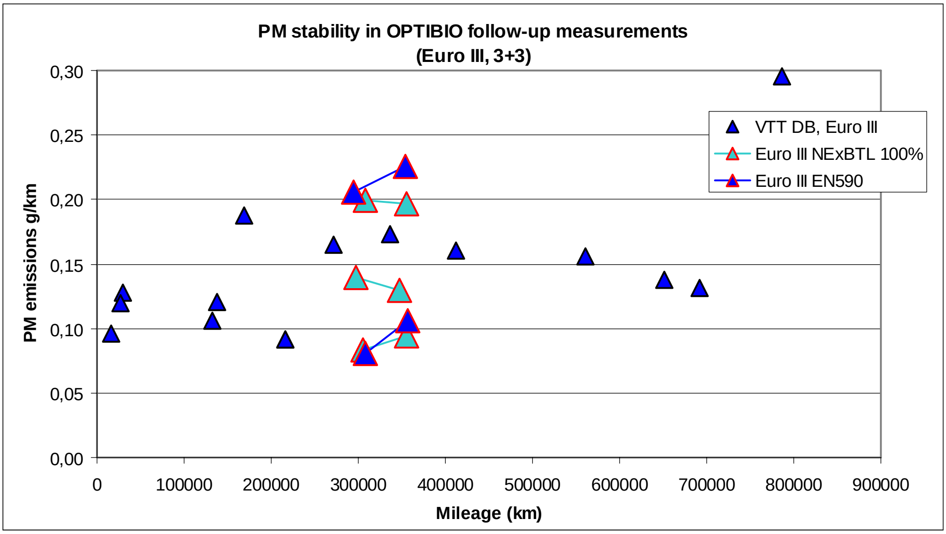


Figure 14.15. PM stability for three plus two Euro III Scania buses on EN590 and 100 % HVO.

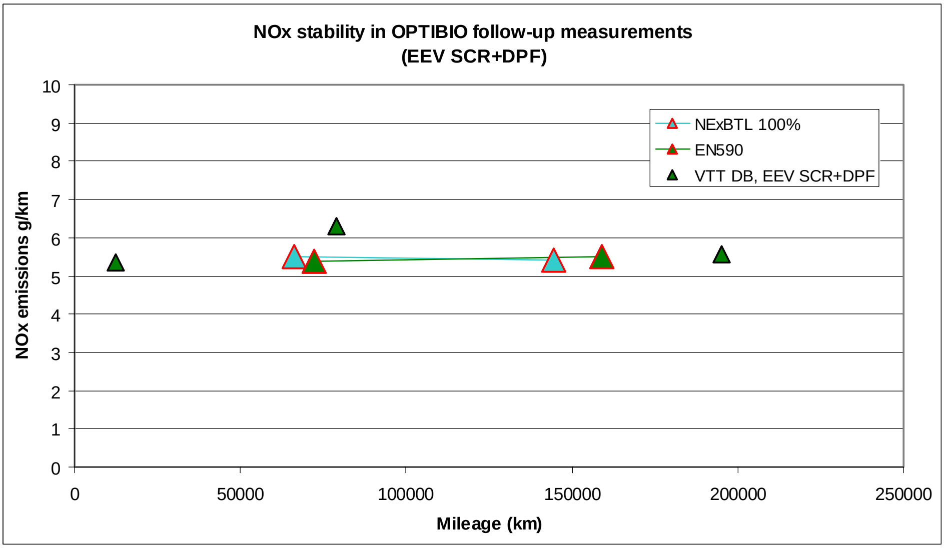


Figure 14.16. NO_x stability for two Iveco EEV SCR/DPF buses, one on EN590 and one on 100 % HVO.

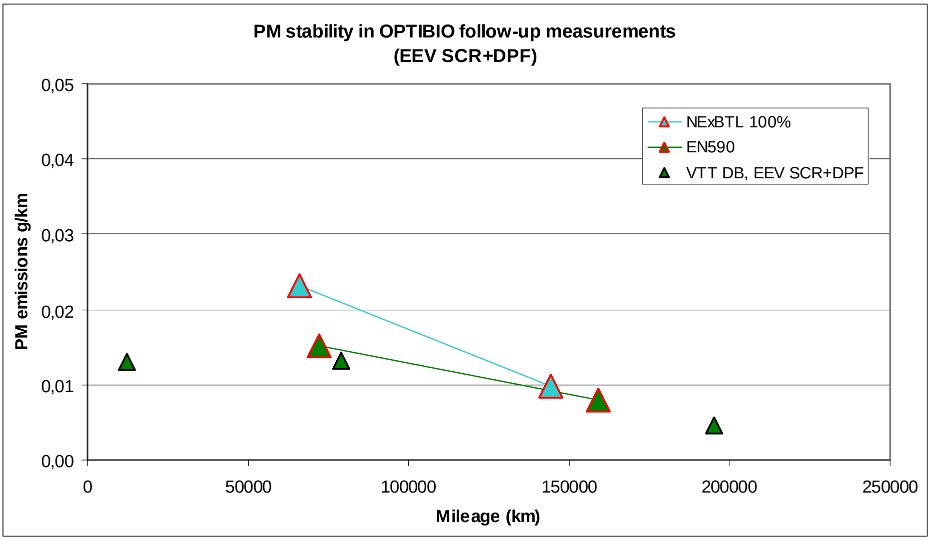


Figure 14.17. NO_x stability for two Iveco EEV SCR/DPF buses, one on EN590 and one on 100 % HVO.

14.5.3 Results for retrofitted exhaust after-treatment devices

Only FTF type devices were subjected to long-term testing, as the actual DPF device and the SCR/DPF combination were not installed in vehicles before the fall of 2010. Some FTF devices accumulated more than 400,000 km, but by an unfortunate mistake there is no emission data available for these units.

Figure 14.18 shows PM emissions for two Euro II level buses retrofitted with a FTF device and running on a 30 % HVO blend. The reference trendline is from VTT's general bus emission database. The Figure shows that when running on the HVO blend, for one vehicle aging of the FTF follows roughly the same trend as for the vehicle itself without exhaust after-treatment, and the other vehicle actually shows decreasing PM emissions over time. However, it should be noted that in these particular cases the distances driven with the FTF systems were rather limited, and that the variation from vehicle to vehicle is significant.

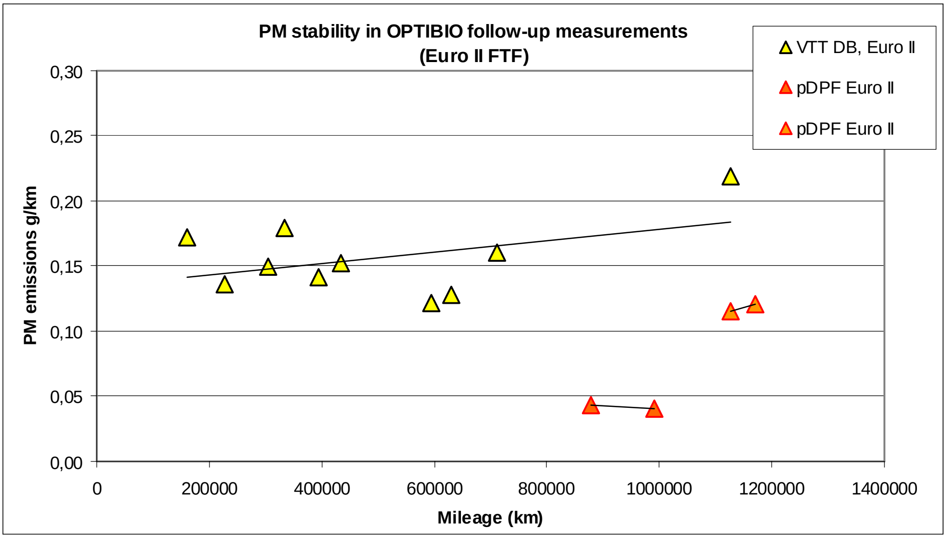


Figure 14.18. PM emissions of a Euro II bus retrofitted with p-DPF and running on 30 % HVO. The reference line is from VTT's general bus emission database.

Proventia Emission Control has concluded that HVO has no negative effects on exhaust after-treatment devices. On the contrary, while in proportion reducing PM emissions more than NO_x, the conditions for regeneration of PM reducing devices are more favourable with HVO than with ordinary diesel fuel.

FAME biodiesel, on the other hand, may endanger the performance and durability of exhaust after-treatment devices. Therefore Proventia Emission Control sets limitations on the use of FAME containing fuels.

Proventia Emission Control collected some general data regarding the performance of the retrofitted exhaust after-treatment devices. One of the FTF devices was inspected visually after some 400,000 km in a Euro III certified bus. The device was intact and in good working order, judging from the clean exhaust pipe. Figure 14.19 shows logged temperature and pressure data for this particular device. Average back-pressure is some 50 mbar to start with, but increases somewhat over time. The same trend applies to maximum back-pressure, increasing from some 230 mbar to 320 mbar. Average exhaust temperature is just below 200 °C, with peaks at some 300 °C. Lower exhaust temperature or a denser matrix would probably have caused blocking.

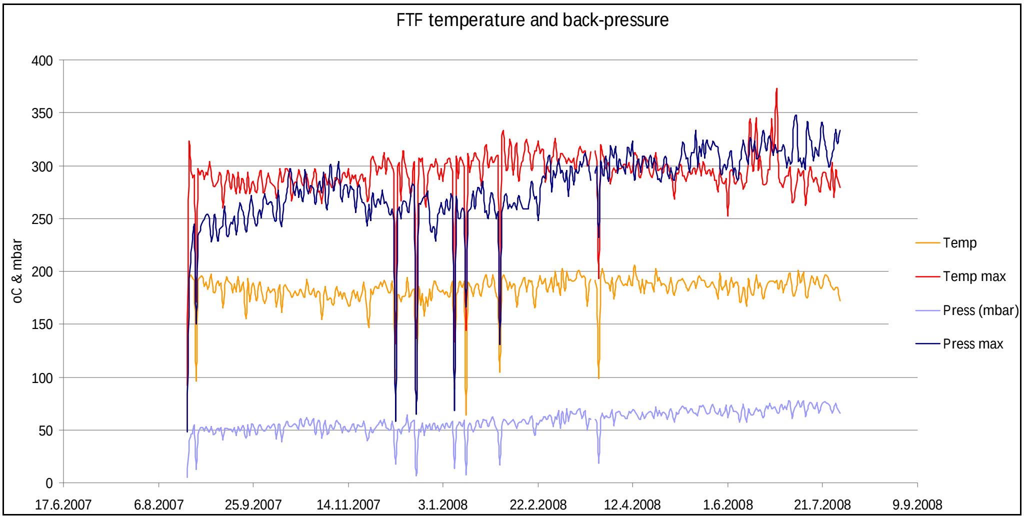


Figure 14.19. Temperature and back-pressure data for one of the FTF devices.

The actual wall-flow DPF device was installed in October 2010, on a Euro III certified bus that had run some 280,000 km. In April 2011, the device had accumulated some 30,000 km at an average driving speed of 21 km/h. The severe winter had kept exhaust temperatures down. Figure 14.20 shows exhaust temperature distribution for this particular device in December 2010, with temperatures over 250 °C less than 5 % of total time (see also Paragraph 11.2). Over the 30,000 km, maximum back-pressure had increased from 100 to 250 mbar, but the filter was still not blocked, which was somewhat of a surprise with respect to the low exhaust temperatures.

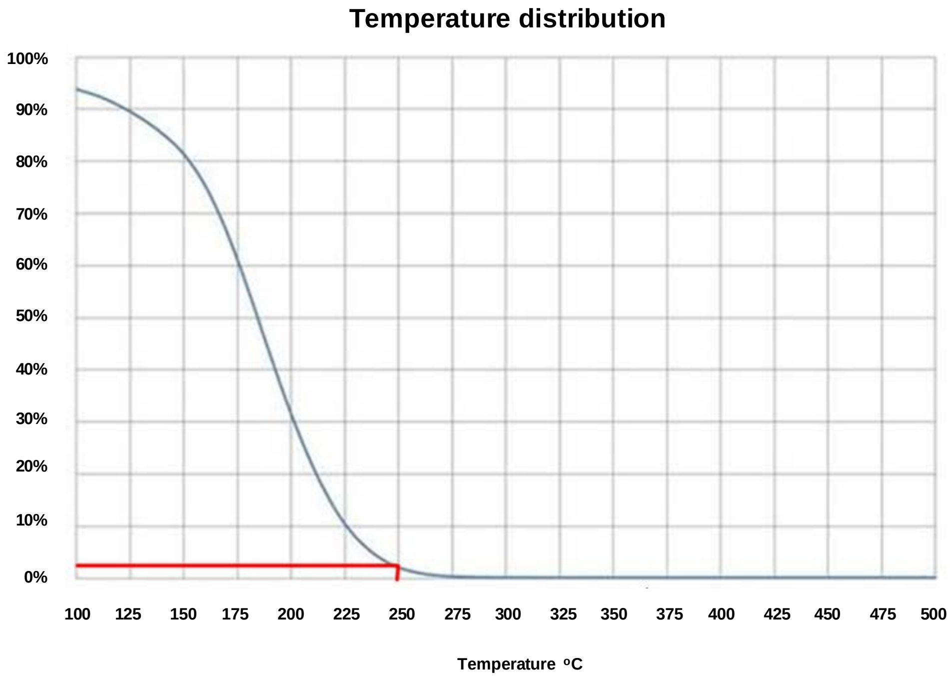


Figure 14.20. Exhaust temperature distribution for the DPF device in December 2010.

The combined SCR/DPF device was also installed in late 2010. In February 2011, it had accumulated some 30,000 km. The system includes a data logging system, with various kinds of alarms.

Over the period of 30,000 km, the system had recorded in total 36 faults, of which 21 happened during the first 11 hours of operation. These 21 faults were related to the installation and commissioning of the system (loose contacts, urea tank empty etc.). The remaining 15 faults/alarms were:

- 1 time blocked urea nozzle
- 4 times blocked return line
- 10 times urea tank empty.

Return line blockage was caused by freezing. The system is fitted with heated lines, but after a standstill at low temperature it takes a while for the system to melt frozen urea lines. The duration of the alarms was 24 seconds up to 240 seconds. The duration of the blocked urea nozzle alarm was only 58 seconds, and might also have been caused by freezing. The alarms for empty urea tank have been false alarms, since the duration of the alarms has been short, from some seconds up to a couple of minutes.

The system didn't record a single alarm for low NO_x conversion or any other serious malfunction.

The distance of 30,000 km was equivalent to 1400 hours of engine operation. Out of these 1400 hours, the urea injection was active 1080 hours, e.g., 77 % of the total time. Total urea consumption for 30,000 km was 300 litres, so urea consumption was 1 litre/100 km.

15. Summary and conclusions

The goal of the OPTIBIO project was to verify the feasibility of high quality, high concentration biofuels as fuels for captive urban fleets. Focused use of high quality renewable diesel fuel will not only reduce greenhouse gas emissions, but most important, also reduce harmful local emissions, especially particulates and oxides of nitrogen. The high quality biofuel also guarantees flawless operation of the sophisticated exhaust after-treatment systems on new diesel buses.

The OPTIBIO project is an example of a successful public-private partnership. Helsinki Region Transport, Neste Oil and Proventia Emission Control joined forces to demonstrate hydrotreated vegetable oil (HVO) in an extensive field test, lasting 3.5 years and involving some 300 buses. The project also received support from the Finnish public administration. The project was the largest of its kind in the world. VTT Technical Research Centre of Finland and Aalto University provided technical support and research services to the project. The bus manufacturer Scania also contributed to the project.

The OPTIBIO project comprised three main blocks with subtasks:

The field test itself:

- Running some 300 buses on test fuels in everyday service
- Feedback from the operators
- Fuel analyses (ensuring fuel quality, e.g., fuel stability and tendency for water pick-up, throughout fuel logistics)
- Lubricant analyses
- Inspection of fuel injection equipment and engines
- Emission stability (fuel as well as exhaust after-treatment devices).

Studies of the effect of HVO on emissions:

- VTT's screening measurements with heavy-duty vehicles (regulated exhaust emissions, chassis dynamometer)
- The effect of HVO on unregulated emissions (chassis dynamometer)
- Emission results with HVO in combination with exhaust gas after-treatment devices (chassis dynamometer)
- Effects of varying engine calibration (engine dynamometer).

Studies related to cold weather performance:

- Correlation between standardized laboratory test methods, rig tests and real vehicle operability (passenger cars)
- Emission performance of HVO in cold conditions (passenger cars).

Field test

The fuels in the field test were a 30 % HVO blend (periodically 25 %) fulfilling all EN590 requirements and 100 % HVO fulfilling CEN CWA 15940. The latter option was used in 10 vehicles. The test vehicles were running in everyday operation at the four bus operators. The emission certification of the vehicles ranged from Euro II to EEV, meaning vehicles from the late 1990's to brand new vehicles. The buses represented a large spectrum of technologies. The field testing started in the fall of 2007 with some 40 vehicles running on blended fuels, and the first buses on 100 % HVO started operation in the spring of 2008. At the end of the summer 2008 the project had reached full volume involving some 300 buses.

All in all, the vehicles accumulated some 50 million kilometres, of which some 1.5 million kilometres on 100 % HVO. Average distance per vehicle was some 170,000 km. The amounts of fuel were some 22 million litres of blended fuel and 1 million litres of straight HVO.

The project confirmed that HVO actually works as a drop-in fuel, meaning that HVO can replace diesel fuel 100 % without any modifications to the refuelling system or to the vehicles, without causing any operational problems. The test fuels didn't cause any problems whatsoever in the field. It should be noted that the winters 2009/2010 and 2010/2011 were exceptionally cold in the Helsinki region. At the lowest, minimum temperature was below -25 °C. A debriefing workshop for the bus operators was arranged in February 2011, and none of the operators reported any fuel related problems. One of the operators made a comment that the project was “invisible”, meaning no problems in everyday operation.

Due to its low density, HVO increases volumetric fuel consumption compared to regular fossil diesel fuel. In the beginning of the project, VTT carried out fuel consumption measurements with 11 different buses. VTT concluded that maximum increase in volumetric fuel consumption was 1.4 % for the 30 % HVO blend and 5.2 % for 100 %. The actual differences depend on fuel densities (diesel as well as HVO). In no case the refuelling data records of the operators indicated higher fuel consumption than the original VTT’s estimates.

In the OPTIBIO project, the base reference fuel was dense (836 to 844 kg/m^3) summer grade diesel fuel without biocomponents (“B0”). Therefore the recorded increases in volumetric consumption with HVO fuels represent maximum values. Compared to the current European “B7” grade containing 7 % FAME the differences would have been somewhat smaller. Comparing neat HVO and neat FAME, FAME would increase volumetric fuel consumption some 4 % over HVO and some 9 % over fossil diesel.

Fuel quality and condition was monitored in the course of the whole test, at intervals of two to four weeks. Sampling focused on the fuel storages at the bus depots of the different operators taking part in the field test. Altogether, more than 150 fuel samples were analyzed. All fuel parameters were within the specifications throughout the test.

Lubricant analyses and monitoring injection equipment focused on vehicles operating on 100 % HVO. The conclusion of the lubricant analyses was that there were no significant differences in the samples from the vehicles on 100 HVO compared to the reference vehicles.

In-line and unit injector fuel injection systems showed no signs of abnormal wear with 100 % HVO. However, the preliminary inspection the injector pilot valve seats in the high-pressure common-rail fuel injection system used by Scania in EEV buses showed signs of abrasive wear with 100 % HVO. The injectors were then subjected to more detailed analysis. The outcome was that the abrasive wear was not caused by the paraffinic fuel, but rather by a materials problem in the valve. Thus, based on the findings of the OPTIBIO project, in August 2011 Scania approved the use of 100 % HVO, or rather NExBTL, in its city and intercity buses with DC9 engines.

All in all 33 vehicles were subjected to regular emission follow-up. For obvious reasons, most part of the emission stability data is for vehicles that operated on blended fuel. VTT's comprehensive general data bank on bus emissions was used as a reference. Even the blended fuel seems to deliver a small reduction in both NO_x and PM over time in Euro II and Euro III certified vehicles. In the case of more sophisticated vehicles (Euro IV, V, EEV) variation in PM emissions was high. The variation cannot be attributed to the fuel, but rather to instable vehicles. Some EEV vehicles often show a rapid increase in PM emissions over time. In one relatively new EEV vehicle, the 30 % HVO fuel prevented the increase in PM emissions over time, and in another vehicle of the same type but with higher mileage, the 30 % blend actually brought forward a decrease in PM emissions.

As for retrofitted exhaust after-treatment devices, Proventia Emission Control concluded that HVO has no negative effects on the devices. On the contrary, while in proportion reducing PM emissions more than NO_x, the conditions for regeneration of PM reducing devices are more favourable with HVO than with ordinary diesel fuel.

The effect of HVO on regulated and unregulated emissions

All in all 17 buses representing different emission certification classes from Euro II to EEV were tested to demonstrate the effect of HVO fuel on exhaust emissions and fuel consumption. The vehicle matrix included buses with different fuel injection and exhaust after-treatment systems. All tests were carried out with standard engine calibration.

Average emission reductions for 100 % HVO fuel were 10 % for NO_x, 30 % for PM, 30 % for CO and 40 % for THC (round figures). The older Euro II and III buses demonstrated consistent emission reductions for HVO. However, for newer buses the direct fuel effects are obscured by variations in fuel injection equipment as well as in exhaust after-treatment systems.

In common-rail engines, no NO_x benefits were seen, but PM emissions were reduced as much as 36 % on an average. For these engines, start of injection is not retarded, as is the case in engines with volume controlled injection systems.

Particle after-treatment devices (FTF and DPF) seemed to reduce particles even more effectively with HVO than with regular diesel fuel. One reason could be a more favourable (higher) engine out NO_x to PM ratio, which is beneficial for particle oxidation.

EGR engines also showed higher PM reduction with HVO in general, compared to non-EGR engines. For one bus, in which NO_x emission increased by 16 %, PM emissions were reduced as much as 46 %. One possible cause for this is that the high cetane number of HVO will advance the actual start of the combustion and speed up the combustion, whereas high EGR rates normally retard combustion lowering NO_x but increasing PM emissions.

As for unregulated emissions, the main conclusion is that paraffinic HVO reduces the harmfulness of exhaust significantly. This is indicated by substantial reductions in PAH emissions, emissions of lighter aromatic components such as benzene and toluene and ultimately, prominent reductions in exhaust mutagenicity. Lowered toxicity of the exhaust, with reductions in indicator values even up to 85 %, must be considered the main advantage of paraffinic HVO fuel. HVO doesn't affect particle number size distribution profiles significantly. For the Euro IV and EEV vehicles HVO reduced particle numbers evenly in all size classes. The only unregulated emission indicator which is adversely affected by HVO is aldehydes. In the case of the Euro III vehicle, total aldehyde emissions increased some 15 % when switching from regular diesel to 100 % HVO.

HVO in combination with exhaust gas after-treatment devices

In the initial testing phase, a matrix consisting of a total of 29 different combinations of exhaust after-treatment device, vehicle type and fuel was evaluated. Emphasis was on FTF (flow-through filter) type devices. The test vehicles represented Euro II and Euro III emission certification, as retrofitting is best suited for older vehicles.

In optimising FTF devices, a balancing of cell density (blocking tendency), loading of precious metals (cost) and physical size has to be made. For the field test devices deemed efficient enough and commercially viable were installed. The average PM reduction was about 50 %. The combination of 100 % HVO and a relatively simple FTF device can bring down the PM emissions of Euro II and Euro III vehicles by some 60 to 70 %.

The actual wall-flow DPF device tested delivered a PM reduction of more than 90 %, and the combined SCR/DPF system reduced the emissions of a Euro III level vehicle to Euro VI level. Proventia Emission Control sees that HVO enhanced the performance and durability of exhaust after-treatment devices.

Optimizing injection timing for HVO

HVO makes it possible to reduce aggregate NO_x + PM emissions, as demonstrated by the emission testing of buses. When running on 100 % HVO, changing engine calibration parameters such as injection timing makes it possible to optimize performance on HVO.

The effects of injection timing on exhaust emissions and fuel consumption was studied at Aalto University with an engine equipped with an adjustable common-rail fuel injection system. The overall conclusion of the testing was that HVO is beneficial in reducing emissions. The NO_x/PM "calibration" line moves towards lover NO_x/PM combinations. Dedicated engine calibration makes it possible to optimise either emissions or fuel efficiency. Choosing a calibration that delivers NO_x at the same level as with regular diesel fuel results in a 4 % reduction in energy consumption and a reduction of some 40 % in filter smoke number. If a slight increase (4 %) in NO_x can be allowed, energy consumption can be reduced as much as 6 %. Engines running on 100 % HVO would benefit from detection of fuel grade and flexibility in engine settings.

Low-temperature performance

The work in this block was divided into two parts. The first task was establishing the lower limit for cold weather operability by comparing actual vehicle performance, rig test results and laboratory analysis results. The second one was studying the effects of HVO on low-temperature emissions. For practical reasons and limitations in test facilities, both tasks were carried out using passenger cars.

The evaluation of cold weather operability was carried out at Neste Oil. Four different methods were used, two of them standardized laboratory analyses:

- CP (cloud point)
- CFPP (cold filter plugging point)
- an in-house test rig for cold weather operability
- vehicle testing with two vehicles in a chassis dynamometer facility with cooling equipment.

The tested fuels were summer and winter grade diesel fuel, two grades of HVO and blended fuels. Some interesting observations were made. For the two grades of HVO, CP, CFPP, rig and vehicle test results were well in congruence, within 2–3 ^{o}C. This means, that CFPP or the rig test or even CP can be used to estimate the lowest temperature of operability for HVO, without the risk of overestimating low-temperature performance of HVO. In the case of neat winter grade diesel fuel, CFPP clearly overestimated the actual low-temperature performance.

As for blends of summer grade diesel fuel and the HVO with moderate cold performance, the blends actually performed slightly better than either of the neat fuels. In the case of 30 % HVO with good cold weather performance in winter grade diesel fuel, the actual lower limit of operation falls in between the neat fuels.

The results of the low-temperature emission testing were interesting as well. Going from +23 to -20 °C significantly increases CO, THC and PM emissions on regular diesel fuel. HVO, both as a blend and as neat, lowers CO, THC and PM emissions at all temperatures. Maximum reduction recorded was -91 % for THC at -20 °C. All in all, HVO can almost nullify the impacts of low temperature, meaning that 100 % HVO at -20 °C delivers roughly equivalent emission performance as regular diesel at +23 °C.

Conclusion and outlook

High quality paraffinic HVO is the fast track to biofuels implementation. HVO can be implemented without any “blending wall” limitations in existing refuelling infrastructure and vehicles overnight, delivering significant emission reductions especially for particulate matter, PAH and exhaust toxicity. From the operator’s point of view, HVO is an easy solution, not causing additional maintenance or operational problems at low temperatures.

The widespread use of high concentration paraffinic fuels is possible on condition that the fuel is covered by fuel standards, and that the vehicle manufacturers approve the fuel. Within the timeframe of the OPTIBIO project, CEN launched a pre-standard, CWA, for paraffinic diesel fuel, and is now in the process of developing an actual standard for paraffinic diesel. As of August 2011, Scania has approved the use of 100 % HVO (NExBTL) in its city and intercity buses with DC9 engines.

After the OPTIBIO demonstration phase, the markets will determine the future of high concentration HVO fuels in Finland. Low-level blending is already used commercially to fulfil the general biofuels obligation.

The outlook for high concentration paraffinic fuel is good as well. Starting as of 1.1.2011, a new taxation scheme for transport fuels was implemented in Finland. Taxation of fuels is based on energy content and CO_2 emissions. Biofuels receive a deduction of the CO_2 tax component based on their ability to reduce well-to-wheel CO_2 emissions. The evaluation is based on the default values given in the Directive 2009/28/EC. In addition, paraffinic diesel and methane receive a bonus for reduced local emission. The bonus is based on calculations according to the Directive 2009/33/EC on the promotion of clean and energy-efficient road transport vehicles In the case of paraffinic diesel (HVO, GTL, BTL) the bonus is 0.05 €/litre, or some 10 % of the total amount of taxes. For paraffinic biodiesel, the additional CO_2 tax benefit is 0.065 €/litre (fuel fulfilling minimum 2009/28/EC sustainability requirements) or 0.13 €/litre (fuels based on non-food feedstocks and eligible for double counting according to 2009/28/EC).

Helsinki Region Transport, on the other hand, has modified its procurement system for bus services. Already earlier, NO_x and PM were taken into account. Now CO_2 emissions have also been included in the system. Vehicles with low CO_2 emissions, whether from general fuel efficiency, hybridization or the use of biofuels, will receive credits. One bus operator will now start commercial operation on animal fat based HVO.

References

Aatola, H. (2008). Vetykäsitelty kasviöljy työkonedieselmoottorin polttoaineena. Diplomityö 26.3.2008. Teknillinen korkeakoulu, Insinööritieteiden ja arkkitehtuurin tiedekunta, Energiatekniikan laitos. Espoo, maaliskuu 2008. 117 p. (Master Thesis, in Finnish).

Aatola, H., Larmi, M., Sarjovaara, T. & Mikkonen, S. (2008). Hydrotreated Vegetable Oil (HVO) as a renewable diesel fuel: Trade-off between NO_x, particulate emission, and fuel consumption of a heavy duty engine. SAE Technical Paper 2008-01-2500. 12 p.

Amyris. (2009). Amyris press release October 1, 2009.

Arcoumanis, C., Gavaises, M., Yamanishi, M. & Oiwa, J. (1997). Application of FIE computer model to an in-line pump-based injection system for diesel.

ASFE. (2006). Strategic EU energy review. Note for consideration – Synthetic fuels. Alliance for Synthetic Fuels in Europe.

ASTM D975. (2011). ASTM D975 – 11. Standard Specification for Diesel Fuel Oils..

ASTM D6751. (2011). ASTM D6751 – 11a. Standard Specification for Biodiesel Fuel Blend Stock (B100) for Middle Distillate Fuels

CEN. (2009). CEN Workshop Agreement CWA 15940:2009. Automotive fuels – Paraffinic diesel from synthesis or hydrotreatment – Requirements and test methods. February 2009.

Darling International. (2011). Press Release January 20, 2011.

Directive 70/220/EC of the Council of 20 March 1970 on the approximation of the laws of the Member States on measures to be taken against air pollution by emissions from motor.

Directive 1999/96/EC EC of the European Parliament and of the Council of 13 December 1999 on the approximation of the laws of the Member States relating to be taken against the emissions of gaseous and particulate pollutants from compression ignition engines for use in vehicles, and the emissions of gaseous pollutants from positive ignition engines fuelled with natural gas or liquefied petroleum gas for the use in vehicles and amending Council Directive 88/77/EEC.

Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC .

Directive 30/2009/EC of the European Parliament and of the Council of 23 April 2009 amending Directive 98/70/EC as regards the specification of petrol, diesel and gas-oil and introducing a mechanism to monitor and reduce greenhouse gas emissions and amending Council Directive 1999/32/EC as regards the specification of fuel used by inland waterway vessels and repealing Directive 93/12/EEC.

Ekelund, M., Egnell, R. & Gabrielsson, R. (1989). Naturgas som kolvmotorbränsle. STU Information nr 751–1989.

EN590. (2009). Automotive fuels – Diesel – Requirements and test methods. CEN/TC 19. Date: 2009-04.

EN14214. (2008). Automotive fuels – Fatty acid methyl esters (FAME) for diesel engines – Requirements and test methods. November 2008.

EPA. (2007). Federal register. Part II. Environmental protection agency. 40 CFR Parts 59, 80, 85, and 86 Control of Hazardous Air Pollutants From Mobile Sources; Final Rule. Monday, February 26, 2007. http://www.epa.gov/fedrgstr/EPA-AIR/2007/February/Day-26/a2667a.pdf.

Erkkilä, K., Hartikka, T., Laine, P., Ahtiainen, M., Rahkola, P. Nylund, N.-O., Mäkelä, K., Lappi, M., Noponen, K. & Liimatainen, H. (2011a). Energy-efficient and Intelligent Heavy-duty Vehicle (HDENIQ). Annual report 2009. VTT report VTT-R-02704-11.

Erkkilä, K., Nylund, N.-O., Hulkkonen, T., Tilli, A., Mikkonen, S., Saikkonen, P., Mäkinen, R. & Amberla, A. (2011b). Emission performance of paraffinic HVO diesel fuel in heavy duty vehicles. JSAE/SAE Technical Paper JSAE 20119239. SAE 2011-01-1966. 12 p.

Erkkilä, K., Nylund, N.-O., Ikonen, M. & Laurikko, J. (2004). Evaluating exhaust emission performace of urban buses using transient heavy-duty chassis dynamometer. Proceedings of DEER 2004. 10th Diesel Engine Emission Reduction Conference. August 28-September 2, Coronado, California, USA. http://www1.eere.energy.gov/vehiclesandfuels/pdfs/deer_2004/session2/2004_deer_erkkila.pdf.

Fukuda, K. et al. (2008). Impact study of high biodiesel blends on performance of exhaust aftertreatment systems. SAE Technical Paper 2008-01-2494.

Global Biofuels Center. Capacity Database. http://www.globalbiofuelscenter.com/.

Honkanen, S. (2011). Tulevaisuuden biopolttoaineteknologiat ja raaka-aineet. Optibio-seminaari 10.2.2011. Helsingin seudun liikenne HSL. (In Finnish). http://www.hsl.fi/FI/mikaonhsl/Documents/Optibioseminaari%2010.2.2011/Optibio_Honkanen.pdf.

Jääskeläinen, H. (2010). Compatibility of Biodiesel with Petroleum Diesel Engines. DieselNet 2010. http://www.dieselnet.com/.

Kytö, M., Erkkilä, K. & Nylund, N.-O. (2009). Heavy-duty vehicles: Safety, environmental impacts and new technology "RASTU", Summary report 2006-2008, VTT-R-04084-09. http://www.motiva.fi/files/2279/RASTU_Summary_Report_2006-2008.pdf.

Lehtonen, J. (2011). Leviä, jätteitä ja mikrobeja? Uusia vaihtoehtoja uusiutuvan dieselin raaka-aineeksi. Kansainvälisen kemian vuoden toimittajatapahtuma. Liikenteen vaihtoehtoiset energialähteet. 3.5.2011. (In Finnish).

Maron, D.M. & Ames, B.N. (1983). Revised methods for the *Salmonella* mutagenicity test. Mutation Res. 113(3–4):173–215.

MARPOL. Annex II Regulations for the Control of Pollution by Noxious Liquid Substances in Bulk (entered into force 2 October 1983. International Convention for the Prevention of Pollution from Ships (MARPOL). http://www.imo.org/About/Pages/Default.aspx.

McGill, R., Aakko-Saksa, P. & Nylund, N.-O. (2008). Final Report. Annex XXXIV: Biomass-Derived Diesel Fuels. Task 1: Analysis of Biodiesel Options. IEA Advanced Motor Fuels. http://www.iea-amf.vtt.fi/pdf/annex34_report_final.pdf.

Munack, A., Pabst, C., Schaak, J., Schröder, O. & Krahl, J. (2010). Fuel and technology alternatives for buses – Measurements with NExBTL and Jatropha Oil Methyl Ester in a Euro III Heavy Duty Engine. Report for IEA Advanced Motor Fuels Annex XXXVII: Fuel and technology options for buses. Institute of Agricultural Technology and Biosystems Engineering, Johann Heinrich von Thünen Institute, Braunschweig, Germany. June 2010.

Murtonen, T., Aakko-Saksa, P., Kuronen, M., Mikkonen, S. & Lehtoranta, K. (2009). Emissions with Heavy-duty Diesel Engines and Vehicles using FAME, HVO and GTL Fuels with and without DOC+POC Aftertreatment. SAE Technical Paper 2009-01-2693. 20 p.

Mäkinen, R., Nylund, N.-O., Erkkilä, K., Saikkonen, P. & Amberla, A. (2011). Bus Fleet Operation on Renewable Paraffinic Diesel Fuel. JSAE/SAE Technical Paper JSAE 20119172/SAE 2011-01-1965. 8 p.

Neste Oil Annual Report. (2010). http://www.nesteoil.com/default.asp?path=1;41;540;1259;1261;16768;17113

Neste Oil. Safety data sheet. Diesel fuel, sulphur free; Neste Green -diesel. Date 14.10.2009.

Neste Oil. Safety data sheet. NExBTL Renewable Diesel; Neste 100 % NExBTL -diesel; Neste Green 100 -diesel. Date 22.12.2010.

Niemi, S. (2011). Polttoaine- ja työkonedieseltutkimuksia Vaasan yliopistossa (VY) ja Turun ammattikorkeakoulussa (TuAMK). Moottoritekniikan seminaari ”Tulevaisuuden moottori- ja polttoaineteknologiat”. 5.5.2011. Teknologiateollisuus, Dieselmoottorit ja kaasuturbiinit -toimialaryhmä. (In Finnish). http://www.teknologiateollisuus.fi/fi/ryhmat-ja-yhdistykset/seminaariaineisto-5-5-2011.html.

Nikander, S. (2008). Greenhouse gas and energy intensity of product chain: Case transport biofuel. Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Engineering. Helsinki, Finland, May 9, 2008.

NSE Biofuels. (2009). NSE Biofuels joint venture. http://www.storaenso.com/products/product-stories/2009/Pages/nse-biofuels-joint-venture.aspx.

Nylund, N.-O., Aakko-Saksa, P. & Sipilä, K. (2008). Status and outlook for biofuels, other alternative fuels and new vehicles. VTT Tiedotteita - Research Notes 2426. http://www.vtt.fi/inf/pdf/tiedotteet/2008/T2426.pdf.

Nylund, N.-O., Erkkilä, K., Lappi, M. & Ikonen, M. (2004). Transit bus emission study: Comparison of emissions from diesel and natural gas buses. Research report PRO3/P5150/04. http://www.vtt.fi/inf/pdf/jurelinkit/VTT_Nylund.pdf.

Nylund, N.-O. & Erkkilä, K. (2005). Bus Emission Evaluation. 2002–2004 Summary Report. Research report: PRO3/P3015/05. VTT Processes, April 2005. 51 p. http://www.vtt.fi/inf/julkaisut/muut/2005/BusEmissionEvaluation.pdf.Parsons, G.M. (2009). Clean diesel and after-treatment systems. Chevron Oronite. http://sustainable-biodiesel.org/assets/dpf_chevron.pdf.

Parsons, G.M. (2009). Clean diesel and after-treatment systems. Chevron Oronite. http://sustainable-biodiesel.org/assets/dpf_chevron.pdf.

Petrobras. (2010). Petrobras press release May 3, 2010.

Preem. (2011). Evolution Diesel – the world’s first standard diesel fuel based on residue from the Swedish forest industry. http://evolution.preem.se/assets/upload/zip/English,%20Background%20Evolution%20Diesel.pdf.

Rakopoulos C. & Hountulas, D. (1996). A Simulation Analysis of a DI diesel engine fuel injection system fitted with a constant pressure valve. Energy Convers. Manage 37(2):135–150.

Reinhardt, G., Gärtner, S.O., Helms, H. & Rettenmaier, N. (2006). An assessment of energy and greenhouse gases of NExBTL. Final Report. ifeu – Institute for Energy and Environmental Research Heidelberg GmbH. Heidelberg, June 2006.

SAE J2711. (2002) SAE Standard J2711 Recommended Practice for Measuring Fuel Economy and Emissions of Hybrid-Electric and Conventional Heavy-Duty Vehicle, Society of Automotive Engineers, Document No. J2711, 2002.

Serves de, C. (2009). Marknasanalys för drivmedel. Miljöstyrningsrådet Rapport 2009. (In Swedish). http://www.ecotraffic.se/getpublikfile.asp?publikid=39&file=file1

Syntroleum. (2010). Press Release. Syntroleum Corporation On Monday November 8, 2010, 8:00 am EST.

Tilli, A., Kaario, O., Imperato, M. & Larmi, M. (2009). Fuel injection system simulation with renewable diesel fuels. SAE Technical Paper 2009-24-0105.

VTT. (2010) Update of VTT's bus data base. 27.12.2010.

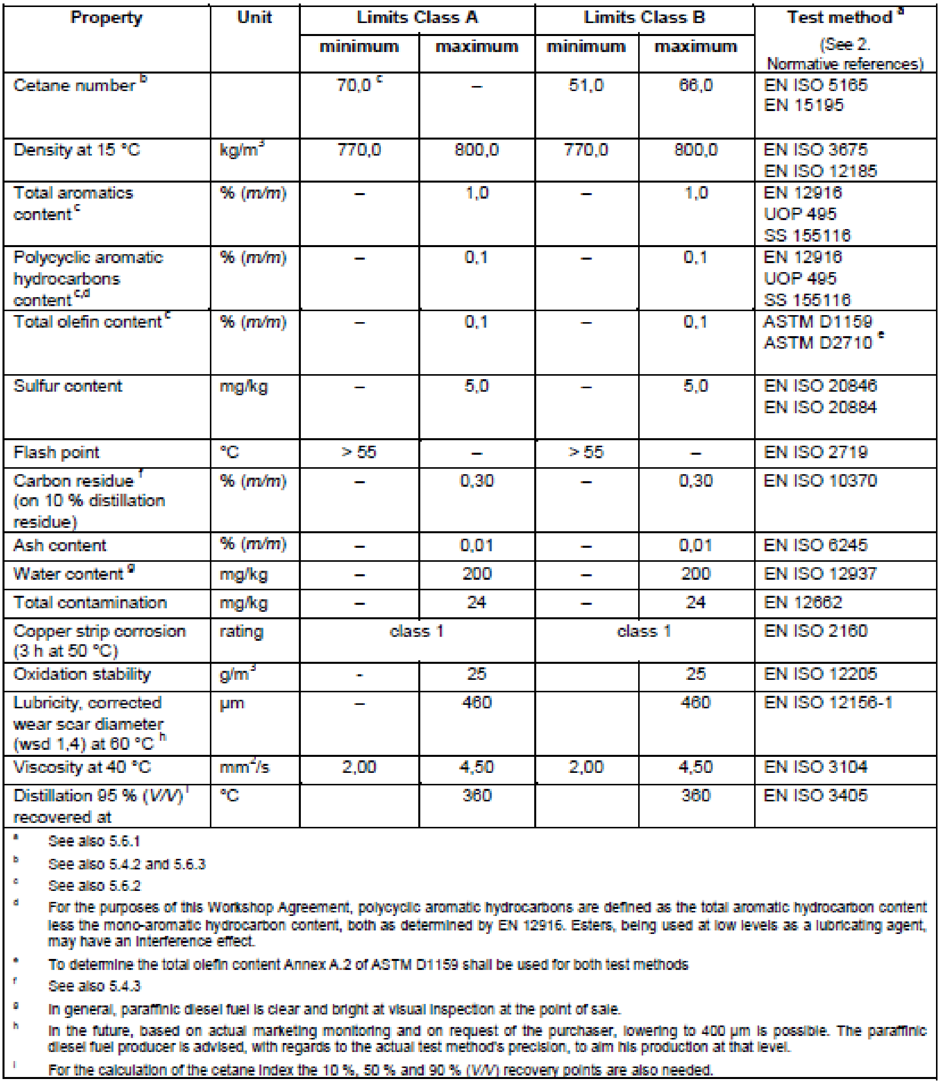
WWFC. (2006). Worldwide fuel charter. Fourth Edition, September 2006. http://www.oica.net/htdocs/fuel%20quality/WWFC%20Final%204%20Sep%202006.pdf

Zhang ,Y. & Boehman, A. (2007). Impact of Biodiesel on NOx emissions in a common rail direct injection diesel engine. Energy Fuels 21(4):2003–2012.

1420/2010. (2010). Laki biopolttoaineiden käytön edistämisestä liikenteessä annetun lain muuttamisesta. Annettu Helsingissä 30 päivänä joulukuuta 2010. (In Finnish).

Appendix 1: CEN Workshop Agreement CWA 15940:2009: Requirements

Table 1/1.Generally applicable requirements and test methods. The references refer to the CWA document itself.



Property	Unit	Limits Class A		Limits Class B		Test method [a] (See 2. Normative references)
		minimum	maximum	minimum	maximum	
Cetane number [b]		70,0 [c]	–	51,0	66,0	EN ISO 5165 EN 15195
Density at 15 °C	kg/m^3	770,0	800,0	770,0	800,0	EN ISO 3675 EN ISO 12185
Total aromatics content [c]	% (*m/m*)	–	1,0	–	1,0	EN 12916 UOP 495 SS 155116
Polycyclic aromatic hydrocarbons content [c,d]	% (*m/m*)	–	0,1	–	0,1	EN 12916 UOP 495 SS 155116
Total olefin content [c]	% (*m/m*)	–	0,1	–	0,1	ASTM D1159 ASTM D2710 [e]
Sulfur content	mg/kg	–	5,0	–	5,0	EN ISO 20846 EN ISO 20884
Flash point	°C	> 55	–	> 55	–	EN ISO 2719
Carbon residue [f] (on 10 % distillation residue)	% (*m/m*)	–	0,30	–	0,30	EN ISO 10370
Ash content	% (*m/m*)	–	0,01	–	0,01	EN ISO 6245
Water content [g]	mg/kg	–	200	–	200	EN ISO 12937
Total contamination	mg/kg	–	24	–	24	EN 12662
Copper strip corrosion (3 h at 50 °C)	rating	class 1		class 1		EN ISO 2160
Oxidation stability	g/m^3	-	25		25	EN ISO 12205
Lubricity, corrected wear scar diameter (wsd 1,4) at 60 °C [h]	µm	–	460		460	EN ISO 12156-1
Viscosity at 40 °C	mm^2/s	2,00	4,50	2,00	4,50	EN ISO 3104
Distillation 95 % (*V/V*) [i] recovered at	°C		360		360	EN ISO 3405

[a] See also 5.6.1

[b] See also 5.4.2 and 5.6.3

[c] See also 5.6.2

[d] For the purposes of this Workshop Agreement, polycyclic aromatic hydrocarbons are defined as the total aromatic hydrocarbon content less the mono-aromatic hydrocarbon content, both as determined by EN 12916. Esters, being used at low levels as a lubricating agent, may have an interference effect.

[e] To determine the total olefin content Annex A.2 of ASTM D1159 shall be used for both test methods

[f] See also 5.4.3

[g] In general, paraffinic diesel fuel is clear and bright at visual inspection at the point of sale.

[h] In the future, based on actual marketing monitoring and on request of the purchaser, lowering to 400 µm is possible. The paraffinic diesel fuel producer is advised, with regards to the actual test method's precision, to aim his production at that level.

[i] For the calculation of the cetane index the 10 %, 50 % and 90 % (*V/V*) recovery points are also needed.

Appendix 2: Fuel analyses – Test fuels at VTT

Test fuel properties

Table 2/1. Fuel properties, fuel set 1.

	HVO	**EN590 (s)**	**EN590 (w)**
Density at 15 °C (kg/m^3)	780	844	829
Cetane number	89	55	53
Distillation 5 vol-% (°C)	266	204	185
Distillation 50 vol-% (°C)	286	290	238
Distillation 95 vol-% (°C)	302	359	311
Heating value, lower (MJ/kg)	44.1	43.1	43.1

Table 2/2. Fuel properties, fuel set 2.

	HVO	**EN590 (s)**	**EN590 (w)**
Density at 15 °C (kg/m^3)	776	836	827
Cetane number	76	57	54
Distillation 5 vol-% (°C)	215	207	197
Distillation 50 vol-% (°C)	275	283	242
Distillation 95 vol-% (°C)	293	349	315
Heating value, lower (MJ/kg)	44.0	43.2	43.1

Appendix 3: List of unregulated emission components measured at VTT

Aldehydes:

- Formaldehyde
- Acetaldehyde
- Acrolein
- Propionaldehyde
- Crotonaldehyde
- n-Butyraldehyde
- Benzaldehyde
- Valeraldehyde
- m-Tolualdehyde
- Hexanal.

PAHs:

NAF	naphthalene	2fNAF	2-phenylnapthalene	BePYR	*benzo[e]pyrene
2mNAF	2-methyl-naphthalene	FLUT	*fluoranthene	**BaPYR**	***benzo[a]pyrene**
1mNAF	1-methyl-naphthalene	PYR	*pyrene	PERY	perylene
BiF	biphenyl acenaphtyl	BaFLU	benzo[a]fluorene	**IPYR**	***Indeno[1,2,3-cd]pyrene**
ANAF	acenaphthene	BbFLU	benzo[b]fluorene	dBahA	*dibenzo[a,h]anthracene
diBzFUR	dibenzofuran	**BaANT**	***benz[a]anthracene**	BghiPER	*benzo[g,h,i]perylene
FLU	*fluorene	**KRY**/TRI	***chrysene**/triphenylene	KOR	coronene
diBzTIO	dibenzothiophene	**BbFLUT**	***benzo[b]fluoranthene**	**7,12-dimethylbenz(a)anthracene**	
FEN	*phenanthrene	**BkFLUT**	***benzo[k]fluoranthene**		
ANT	*anthracene				
PAH(14) is the sum of PAH-compounds marked with asterisk					
PAH(7) is the sum of bold PAH- compounds					

Hydrocarbons:

Methane	CH_4
Ethylene	C_2H_4
Acetylene	C_2H_2
Ethane	C_2H_6
Propylene	C_3H_6
Propane	C_3H_8
Isobutylene	C_4H_8
1,3-Butadiene	C_4H_6
Butane	C_4H_{10}
Isopentane	C_5H_{12}
Benzene	C_6H_6
Toluene	C_7H_8
Ethylbenzene	C_8H_{10}
m-/p-/o-xylene	C_8H_{10}.

Appendix 4: Fuel analyses – Test fuels at Aalto University

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

(1) Calculated from carbon and hydrogen content

(2) Calculated from the analysis of components (EN 590 and HVO)

(3) Sum of di- and tri+ aromatics according to the European regulation

(4) Can be adjusted from -5 to -25 °C for different climate zones

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Title

Optimized usage of NExBTL renewable diesel fuel OPTIBIO

Abstract

Helsinki Region Transport, Neste Oil, Proventia Emission Control, VTT Technical Research Centre of Finland and Aalto University carried out a 3.5 year PPP venture “OPTIBIO” to demonstrate the use of paraffinic renewable diesel (hydrotreated vegetable oil HVO) in city buses. The project cooperated with the bus manufacturer Scania. The fleet test in Metropolitan Helsinki, involving some 300 buses at four bus operators, was the largest one in the world to demonstrate this new fuel. The fuels were a 30 % HVO blend and 100 % HVO. The field test was supplemented by a comprehensive in-laboratory research programme on fuel effects on exhaust emissions and low-temperature operability.

All in all, the vehicles accumulated some 50 million kilometres between September 2007 and December 2010, of which some 1.5 million kilometres on 100 % HVO. Average distance per vehicle was some 170,000 km. The amounts of fuel used were about 22 million litres of blended fuel and 1 million litres of neat HVO.

The project confirmed that HVO actually works as a drop-in fuel, meaning that HVO can replace diesel fuel 100 % without any modifications to the refuelling system or to the vehicles, without causing any operational problems. The emission testing, both the screening and the follow-up measurements, demonstrated significant and permanent emission benefits. Based on the findings of the OPTIBIO project, Scania has approved the use of 100 % HVO (NExBTL) in its city and intercity buses with DC9 engines. After the demonstration phase, the markets will determine the future of high concentration HVO fuels in Finland. Low-level blending is already used commercially to fulfil the general biofuels obligation.

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• • • VTT RESEARCH NOTES 2604 Optimized usage of NExBTL renewable diesel fuel. OPTIBIO

Buses are the backbone of many public transport systems, and as buses are centrally refuelled, they are ideal for the introduction of new fuel qualities. Concentrating the use of high quality biofuels to urban fleets makes sense, because this not only delivers biofuel penetration but more important, also reductions in local pollution. Helsinki Region Transport, Neste Oil, Proventia Emission Control, VTT Technical Research Centre of Finland and Aalto University carried out a 3.5 year project to demonstrate the use of paraffinic renewable diesel (HVO) in city buses. The fleet test in Metropolitan Helsinki involved some 300 buses.

The project confirmed that HVO actually works as a drop-in fuel, meaning that HVO can replace diesel fuel 100 % without any modifications to the refuelling system or to the vehicles, without causing any operational problems. The comprehensive emission testing by VTT demonstrated significant and permanent emission benefits. As a result of the project, Scania has approved the use of 100 % HVO (NExBTL) in its DC9 bus engines.

The report provides a solid documentation of the performance of HVO, and will be useful for all parties interested in the implementation of high quality renewable diesel fuel.

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