

Emissions with Heavy-duty Diesel Engines and Vehicles using FAME, HVO and GTL Fuels with and without DOC+POC Aftertreatment

T. Murtonen and P. Aakko-Saksa
VTT Technical Research Centre of Finland

M. Kuronen and S. Mikkonen
Neste Oil Corporation

K. Lehtoranta
Ecocat Oy

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ABSTRACT

This study presents emission results measured with renewable and synthetic diesel fuels. Three engines and five city buses were studied. The efficiency of diesel oxidation catalyst combined to particle oxidation catalyst (POC®) was measured with two engines. The studied diesel fuels were EN590, FAME, HVO and GTL. In most cases all regulated emissions decreased with HVO and GTL fuels compared to conventional EN590 diesel fuel. With FAME, the NO_x emissions were higher compared to EN590, but other emissions were reduced. Alternative fuels had a positive effect on emissions, which are considered harmful to human health.

INTRODUCTION

There is an increasing pressure to find alternatives for fossil fuels in transportation. Motivation has shifted from energy security to reduce local pollution and lately to the climatic issues with emphasis on biofuels to reduce the greenhouse gas emissions. However, there are doubts on benefits of first generation biofuels regarding global warming. Sustainability of biofuels from edible feedstocks, or from feedstocks risking biodiversity are questionable.

The engine and emission control technologies for heavy-duty applications is incoherent today. Over the last few years a wide variety of different technologies, like

common-rail fuel injection systems, complex EGR systems, particle traps, flow through filters, oxidation catalysts, and urea based catalysts have been introduced. The latest technologies may increase the requirements on fuel cleanliness, and questions on component durability will rise when using new fuel alternatives.

New types of biofuels are coming in to the markets. One option to produce so called second generation biofuel is via gasification of biomass followed by Fischer-Tropsch synthesis. In this case fuel is called Biomass-to-Liquids (BTL) fuel. Another option is by hydrotreatment process of vegetable oils and animal fats (HVO). Both processes produce paraffinic diesel fuel, similar to GTL (Gas-to-Liquids) fuel. These totally different fuels, esters and paraffinic diesels, blended with sulphur-free fossil diesel, will set a challenging platform for engines and aftertreatment devices.

This study aims at generating information, which improves possibilities to evaluate risks and benefits of different combinations of biodiesel options, engines and exhaust aftertreatment devices with focus on the exhaust emissions and their health effects. The study concentrated on diesel fuels but as a reference also one CNG vehicle was measured.

REVIEW

FAME-TYPE TRADITIONAL BIODIESEL – Traditionally, biodiesel means fatty acid methyl esters (FAME). Neat vegetable oils are not suitable for high-speed diesel engines, and thus FAME esters are produced by transesterification of triglycerides and/or free fatty acids with alcohol using sodium or potassium hydroxide as catalyst. Side-product of process is glycerol [1-2]. Due to certain end-use problems with FAME, the current maximum concentration is limited, e.g. in European EN590:2009 specification for diesel fuel, up to 7.0%.

Ignition properties of FAME esters are acceptable with cetane numbers generally over 50. FAME contains practically no sulphur or aromatics. Lubricity of FAME is good. There are also drawbacks with FAME: viscosity is higher and cold properties worse than with the diesel fuel. Distillation range of esters is narrow and boiling point higher than those for diesel, which may lead to deterioration of oil quality. Higher viscosity of esters may affect injection performance and cold-start properties. FAME biodiesel may contain certain impurities, e.g. triglycerides, glycerol, alcohols and ash. Sodium or potassium can be present depending on the catalyst used in the esterification process. Phosphorus content of FAME depends on fertilizers used for growing plants and pressing process of vegetable oil [2-3]. FAME esters as polar compounds dissolve materials more efficiently than diesel fuel, which may lead to problems with materials. Storage stability of esters is challenging. Heat content of esters is lower compared to conventional diesel and thus volumetric fuel consumption higher and power output lower, but this is compensated to some extent with higher density of esters. Flash point of esters is high, but if there is any alcohol as impurity the flash point lowers rapidly [2-3].

FAME biodiesel generally reduces CO, HC and PM emissions, but increases NO_x emissions [4-6]. The reason for increase in NO_x emission with FAME is not clear even today. The role of density, high distillation area, oxygen content and double bonds has been considered as reasons [4]. Ignition delay with FAME can be shorter than with diesel, if cetane number of diesel is poor, but vice versa when FAME is compared to high-cetane diesel fuel. According to Graboski et al. [2], the effect of low soot emission on flame temperature may affect NO_x emission with FAME. In addition, possible changes caused by FAME's physical properties in e.g. spray behaviour, ignition delay and injection timing may cause unexpected effects to emissions.

Reduction of particulate matter emission is believed to be due to presence of oxygen in FAME [4, 7-9]. FAME reduces soot portion of particulate matter, but increases soluble organic fraction (SOF). In some cases, this can lead to higher PM emissions with FAME than with diesel fuel, e.g. at partial loads or at cold temperatures [10-12].

Oxidation catalyst removes SOF efficiently, and thus a combination of FAME and oxidation catalyst can result in substantial benefit in PM emission.

Particle number size distributions with FAME biodiesel depend on engine, aftertreatment, load and measurement conditions. Generally, number of particles in the accumulation, "soot" mode, is typically lower for FAME biodiesel than for conventional diesel. However, FAME may increase nuclei mode particles, especially at cold temperatures. [12-14]

Mutagenic effect tested with Ames strains tend to be lower for FAME than for conventional diesel fuel. This is believed to be due to differences in PAH content of exhaust gases, and thus only slight or no benefit with FAME is gained when compared to diesel fuel with very low aromatics content. [11, 15]

Typically oxygen containing fuels tend to increase aldehyde emissions. Krahel et al. [16] reported that aldehyde emissions increased with FAME biodiesel, but some studies report on reductions of aldehyde emissions with FAME (very low-cetane diesel fuel as reference fuel [e.g.17]).

PARAFFINIC DIESEL – Synthetic fuels offer an alternative route to convert a variety of feedstocks to liquid fuels, e.g. gasification to syngas (carbon monoxide and hydrogen), and Fischer-Tropsch process for liquefaction. When the feedstock is natural gas, the product is GTL (Gas-to-Liquid), in the case of coal, CTL (Coal-to-Liquid), and in the case of biomass, BTL (Biomass-to-Liquid) [18-19].

GTL and CTL are commercially produced already today. The first BTL plant is being built in Freiberg, Germany by CHOREN in co-operation with Shell, Daimler Chrysler, and VW. So called Beta-Plant will have production of 15,000 tons/year. Also other projects on BTL production are progressing. One option to produce high-quality paraffinic diesel resembling synthetic fuel is by hydrotreatment of oils and fats (HVO). Neste Oil in Finland developed the refinery-based NExBTL process [20]. NExBTL plant with a capacity of 170,000 tons/year started production in 2007 in Finland, a second plant will start in 2009, and 800 000 tons/a plants will be built up in Singapore and Rotterdam. Also other companies utilize hydrotreatment of oils and fats e.g. Petrobras of Brazil (H-Bio), Galp Energia in Portugal, UOP and Eni in Italy and Dynamic Fuels LLC in the U.S. [18, 21].

Conventional diesel fuel contains a number of hydrocarbons, aromatics, naphthens and paraffins, whereas in the most part GTL from low temperature Fischer-Tropsch process (Low temperature Fischer-Tropsch (LTFT) is GTL technology, which maximises production of paraffinic middle distillates. High temperature Fisher-Tropsch produces a mixture of

various types of hydrocarbons [22]) and HVO are paraffinic fuels with high cetane number, low sulphur and aromatics content. HVO and BTL are paraffinic and oxygen free fuels with high cetane number and practically free from sulphur and aromatics. Storage stability of these fuels is good and water solubility low. Density of paraffinic diesel fuels is lower compared to EN590, which leads to a slightly higher volumetric fuel consumption than with conventional diesel fuel even though mass-based fuel consumption and tailpipe CO₂ emissions decrease due to higher hydrogen to carbon ration and better heating value. Using HVO or BTL biofuel as a high-concentration blending component, or as such, requires no investments in the fuel distribution infrastructure or existing vehicle fleet. However, e.g. the current European EN590:2009 specification determines a lower density limit, which limits the blending ratio of paraffinic fuel into diesel in Europe. Up to ca 30 vol-% of paraffinic fuels can be blended to conventional summer diesel to fulfill EN590 limits.

Excellent fuel properties of paraffinic synthetic fuels lead to exhaust emissions benefits and good engine performance [23]. Substantial reductions in NO_x, PM, CO and HC emissions are reported with HVO and GTL [24-25]. Kitano et al. [26] reports of reduction of exhaust emissions of modern diesel engine equipped with advanced diesel aftertreatment system using GTL fuel. A significant impact on engine-out PM, HC and CO emissions was observed, but only little effect on the NO_x emission. Clark et al. [19] noticed that for light-duty vehicles, the effect of GTL on NO_x and PM results vary between cars. One EGR equipped car resulted in low PM, but slight NO_x disadvantage for GTL, which was deemed to be due to lower EGR rate for low-density fuel. Another car optimised for low NO_x showed significant NO_x reduction with GTL, but poor PM performance. Where as other cars low NO_x and low PM emissions with the GTL fuel. Schubert et al [27], Nord et al. [28] and Alleman et al. [23] reported of lower aldehyde emissions for Fischer-Tropsch diesel than for conventional diesel. Krahel et al. [29] did not find significant difference in mutagenicity of particulate extracts with GTL and diesel fuel.

Studies with paraffinic diesel fuels have been carried out mainly with engines and vehicles using factory settings. However, further benefits in engine performance, exhaust emissions and fuel consumption can be achieved by adjusting engine parameters to utilize properties of paraffinic fuels [30].

DIESEL EXHAUST EMISSIONS AND THEIR HEALTH EFFECTS – Diesel engine emissions consist of a number of emission components, which are harmful to human health, e.g. nitrogen oxides, aldehydes, particulate matter and polyaromatic hydrocarbons. The major concern with diesel engines is the NO_x and particulate matter emissions. Particulate matter refers to

everything emitted in the form of a condensed, liquid or solid phase [31]. Fine particles with a diameter smaller than 2.5 µm in urban atmospheres raise concern of extensive and severe health outcomes, e.g. shortened life-expectancy, in susceptible population groups such as elderly subjects with chronic respiratory or cardiovascular disease, asthmatic subjects of all ages and small children [32]. The legislation on the particulate matter emissions from diesel-engines is tightening. The small size of the particulates and the chemical composition of the soluble organic fraction in the particulates are considered to cause adverse health effects. The soluble organic fraction (SOF) includes compounds such as polycyclic aromatic hydrocarbons (PAH) and their derivatives. The particulate matter emission and particle associated compounds could be decreased with aftertreatment devices, especially when combined with biodiesel [11]. Therefore, the aftertreatment can be considered as a possible abatement method to decrease the harmful properties of particulates.

EXPERIMENTAL

FUELS

This study included two biofuels: hydrotreated vegetable oil (HVO) as renewable diesel and rapeseed methyl ester (RME) as FAME. In addition, two fossil fuels, Gas-to-Liquids diesel (GTL) and conventional diesel were studied. Biofuels were studied as neat, and restrictedly as a 30% blend with conventional diesel fuel.

The studied HVO was NExBTL supplied by Neste Oil and the GTL was supplied by Shell.

HVO, GTL and RME were compared to a sulphur-free fossil diesel fuel, fulfilling the EN590:2004 specification. Several batches of EN590 was used, however, all of these were the summer grade diesel.

All fuels were "sulphur-free" containing below 10 mg/kg of sulfur. RME ester was the only fuel containing oxygen. The European summer grade diesel fuel was the only fuel containing significant amount of aromatics (18 wt-%). However, polyaromatic content of the European grade fuel was very low (below 2 wt-%) when compared to limit value of European Directive 98/70/EC (11 wt-%). The low sulphur and aromatic content of EN590 fuel means that the reference emission levels were rather low.

When the physical fuel properties are screened the paraffinic fuels have the lowest densities and viscosities whereas RME has the highest density and viscosity. Cetane number of HVO and GTL fuels was high, 79 and 72, whereas cetane numbers of EN590 and RME were at the level of 51–55. (Table 1)

Table 1, Fuel properties.

		RME	HVO	GTL	EN 590 ^b
				winter	summer
Density at 15°C	kg/m ³	884	777	777	840
Viscosity at 40°C	mm ² /s	4.5	2.6	2.6	3.5
Sulphur content	mg/kg	8	< 5	< 5	8
Cetane number (DCN,IQT)			79	72	56
Cetane number (engine)		min. 51.0			56
Cloud point	°C	0...-5 ^a	-18	-19	<-5 ^b
CFPP	°C	-14	-19	-20	<-15 ^b
Lower heating value	MJ/kg	36 ^a	44.0	44.0 ^c	43.2
Distillation					
	IBP °C	300 ^a	172	202	197
	10 vol-% °C		234	230	236
	90 vol-% °C		290	305	348
	FBP °C	340 ^a	303	317	364
Oxygen	wt-%	10 ^a	0	0 ^c	0
Aromatics	wt-%	<0.02 ^a	0.2	0.1 ^c	18
Polyaromatics, di+	wt-%	bd	<0.1	bd ^c	1
Iodine number		<120			

^a Typical values, European standard EN 14214^b Results from several batches. Cold properties from product data sheet.^c Typical values for GTL

na = not analysed

bd = below detection limit

ENGINES AND VEHICLES

Engines

The engines used in this research represent different heavy-duty technologies and target applications. In many respect, there are critical differences in e.g. injection systems, combustion technologies and emission control solutions affecting formation and existence of emissions.

Three heavy-duty diesel engines were tested on engine dynamometer. Two of these were Euro 4 emission level engines for on-road applications, one bus and one truck engine. One engine was for non-road applications

representing a prototype for European Stage 3b emission limits. Table 2 presents the main characteristics of the engines. With on-road engines, measurements with DOC+POC aftertreatment system were performed.

Vehicles

In addition to engine dynamometer tests, five buses were studied on chassis dynamometer (Table 3). Two buses represented Euro 4 emission level and three buses EEV emission level technologies. One bus was a stoichiometric CNG bus.

Table 2, Main characteristics of the measured engines.

	Cummins ISBe4 160B Bus engine	Scania DT 12 11 420, Variant L01 Truck engine	Sisudiesel 74 CTA-4V (SCR) Non-road engine
Model year	2006	2005	2008
Cylinder capacity, liters	4.5	11.7	7.4
Cylinders	4 in-line	6 in-line	6 in-line
Fuel system	Common-rail, Bosch HPCR	Scania HPI	Common-rail
Engine type	Direct injection, turbocharged intercooled	Direct injection, turbocharged intercooled	Direct injection, turbocharged intercooled
Max. Power, kW	118 kW / 2500 min ⁻¹	310 kW / 1900 min ⁻¹	175 kW / 2200 min ⁻¹
Max. Torque, Nm	600 Nm / 1500 min ⁻¹	2100 Nm / 1100-1350 min ⁻¹	1070 Nm / 1500 min ⁻¹
Compression ratio	17,3:1	17:1	17,5:1
Emission control	SCR *	EGR	SCR, Bosch DENOX 2.0
Emission class	Euro 4	Euro 4	Stage 3A
Catalyst tested	DOC+POC	DOC+POC	-

* measurements were performed without SCR-system

Table 3, Main characteristics of the measured buses.

	Bus A	Bus B	Bus C	Bus D	Bus E
Model year	2006	2005	2008	2007	2008
Kilometers	14 900	155 000	100 000	12 300	206 000
Cylinder capacity, liters	7.2	8.9	8.87	7.8	11.90
Cylinders	6	5	5	6	6
Fuel system	Common rail	Unit injectors	Unit injectors	Unit injectors	Stoichiometric
Max. power, kW	213	169	169 kW / 1800 min ⁻¹	213	180 kW / 2200 min ⁻¹
Max. Torque, Nm	1200	1050	1050 Nm / 1100-1500min ⁻¹	1100	880 Nm / 1000-1200min ⁻¹
Emission control	SCR	EGR + DOC	EGR + DOC	SCRT (=CRT+SCR)	TWC
Emission class	Euro 4	Euro 4	EEV	EEV	EEV

AFTERTREATMENT DEVICES

Diesel oxidation catalyst (DOC), particle oxidation catalyst (POC®), EGR, SCR and SCRT® emission control technologies were represented in the engines and vehicles tested.

Selective catalytic reduction (SCR) is an aftertreatment system for reduce of NO_x emissions in exhaust gases. System is based on injecting e.g. urea or ammonia in the exhaust gas where it reacts with NO_x. The injection is located upstream of catalyst. Inside the catalyst chemical reactions take place and the outcome is reduced NO_x emissions.

SCRT® aftertreatment system is a combination of SCR and continuously regenerating technology (CRT®). CRT technology has been developed for particle emission reduction. CRT system includes passive filter and oxidation catalyst. Oxidation catalyst produces NO₂ which is used for regenerating the particle filter.

The DOC+POC catalyst combination was only non-OEM aftertreatment system used in this study. Particle oxidation catalyst (POC®) developed by Ecocat Oy is a

so called flow-through filter. POC is a specialized diesel oxidation catalyst that utilizes substrates with capacity to capture solid particles [33-34]. POC is used in combination with DOC. This oxidation catalyst produces NO₂ to oxidize the soot collected in the POC. Catalytic coating is also used in the POC substrate to enable continuous soot regeneration.

Cummins engine was originally equipped with the SCR system. In these measurements SCR system was removed to allow instrumentation for DOC+POC system. When engine was measured without DOC+POC catalyst, the backpressure of the exhaust system was adjusted with valve to achieve the same backpressure as with catalyst. A DOC+POC system was also studied with Scania engine.

TEST MATRIX

Table 4 presents the test matrix for the study. Matrix included four measurement period with engines and five with buses.

Table 4, Test matrix.

			RME	RME30	HVO	HVO30	GTL	EN590
ENGINES	cycle	number of measurements						
Engine, bus (Cummins)	with catalyst	ESC	6				6	8
	w/o catalyst	ESC	6				6	8
	with catalyst	Steady-state	4 loads					4 loads
	w/o catalyst	Steady-state	4 loads					4 loads
Engine, truck (Scania)	with catalyst	Braunschweig	4		13			14
	w/o catalyst	Braunschweig	5	4	9	8	3	10
	with catalyst	Steady-state	3 loads					3 loads
	w/o catalyst	Steady-state	3 loads					3 loads
Engine, non-road (SisuDiesel)	NRTC				4			4
	ISO8178				3			3
VEHICLES								
Bus A (SCR)	Braunschweig				3			5
Bus B (EGR)	Braunschweig				3			5
Bus C (EGR)	Braunschweig				4			4
Bus D (SCRT)	Braunschweig				4		2	6
Bus E, CNG	Braunschweig		25 measurements					

TEST METHODS

Engine and vehicle emission test laboratory at VTT is built and equipped according to valid standards. Laboratory has accreditation for several engine and vehicle test methods. The laboratories are equipped with engine and vehicle dynamometers, exhaust gas analysers, exhaust gas dilution systems for particle sampling and appropriate data-acquisition systems for controlling and monitoring the test runs.

The measurement and analysis of emissions covered the regulated emissions CO, HC, NO_x, PM plus unregulated emissions i.a. CO₂, NO, NO₂, NH₃, SO₂ and aldehydes. In addition, soluble organic fraction of particulate matter was analysed for PAH compounds and mutagenic activity was screened using Ames test.

Test equipment

Scania and Sisudiesel engines were measured in a transient dynamometer using a full-flow CVS system and an analyser set conforming to the requirements of Directive 1999/96/EC for the measurement of exhaust emissions of heavy-duty on-road engines.

Cummins engine was tested in a steady-state test bench in an eddy-current dynamometer, a computer based control system were used for running and controlling the test engine. Regulated gaseous emissions were measured with an analysis system which conforms the requirements of Directive 1999/96/EC. Mini Dilution Tunnel was used for particulate matter (PM) measurements.

Heavy-duty vehicles were tested on chassis dynamometer using a full-flow CVS system and an

analyser set conforming to the requirements of Directive 1999/96/EC for the measurement of exhaust emissions of heavy-duty on-road engines.

With each test bench the particulate filters for standard collection system were Pallflex TX40HI20WW Ø 70 mm and for high-capacity collection system Pallflex T60A20 Ø 142 mm filters or Fluoropore 30 µm FSLW filters.

Test cycle with heavy-duty vehicles

For the heavy-duty vehicle measurements there are no official standards or regulations. Tests were carried out using Braunschweig –test cycle, which is internationally recognized method for simulating city bus driving conditions (Figure 1).

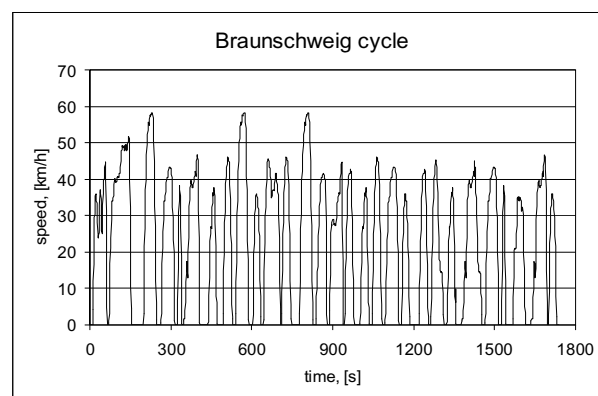


Figure 1, Vehicle speed profile of the Braunschweig test cycle.