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Alternative fuels with heavy-duty engines and vehicles

VTT's contribution

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Abstract

The report at hand is documentation of the results from VTT on emissions and performance of heavy-duty engines and vehicles using hydrotreated vegetable oil, ester-type biodiesel, GTL diesel, CNG and selected blends in reference to fossil diesel fuel. Report combines result form three different projects which are closely related to each other.

Three engines and five city buses were used for the study. In addition, the efficiency of diesel oxidation catalyst combined to particle oxidation catalyst (POC®) was measured with two engines and a long term test was performed with diesel oxidation catalyst using EN590 and RME fuels.

Extensive exhaust gas emission measurements were carried out over the measurement periods. In addition to regulated emissions (HC, CO, NO, PM) a number of unregulated emission compounds were measured and analyzed e.g. CO_2, aldehydes, particle size distribution and total number, polyaromatic hydrocarbons, mutagenicity of particles and several gaseous compounds with FTIR.

Results show that in most cases all regulated emissions decrease with HVO, GTL and RME fuels compared to conventional EN590 diesel fuel. Alternative fuels have also a positive effect on emissions, which are considered harmful to human health. The selected results of the whole study are presented in this paper.

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Preface

There are strong efforts for introducing new alternative fuels to act against global warming and to increase independency from fossil fuels. This report enlightens how different biodiesels as fuel alternatives change the exhaust emissions of modern heavy-duty engines and vehicles. In-depth knowledge of emissions is needed before the alternative fuels can be introduced in large scale to avoid unintentional drawbacks. Information of operational performance with new fuels is also essential. This report aims at increasing understanding of these phenomenon and technical development.

The report at hand is documentation of the results from VTT on emissions and performance of heavy-duty engines and vehicles using hydrotreated vegetable oil, ester-type biodiesel, GTL diesel and selected blends in reference to fossil diesel fuel.

The research project on biodiesel was applied from Tekes in 2005, but after several turns the proposed work was divided in two separate projects. In addition, due to tight time-frame for required changes, one partner of the original application was left out and that work was carried out as bilateral project by two partners. As a result, the following three projects are reported here.

1) Alternative biofuels for compression ignition engines. Influence of fuel on emissions and health, coordinator University of Kuopio, partners are VTT, Technical University of Tampere, Ecocat Oy, Preseco Oy, AGCO SISU POWER (former SISU Diesel Oy). A project concentrating on particle emissions started in 2006, Tekes decision 40227/06.

2) Alternative biofuels for compression ignition engines. Influence of fuel on health effects. Coordinator The National Institute for Health and Welfare[1], partners are VTT, University of Kuopio, Neste Oil, Ecocat Oy, Helsinki Metropolitan Area Council and Helsinki City Transport. A project concentrating on health effects started in 2007, Tekes decision 40131/07.

[1] The National Public Health Institute.

3) Alternative biofuels for compression ignition engines. Biodiesel. Partners are Neste Oil and VTT. A project concentrating on vehicles as bilateral work between Neste Oil and VTT. Neste Oil is a member of Steering Group and the vehicle tests are an integrated part of the first project concentrating on particle emissions.

The literature part of these projects is covered by an international project "Evaluation of Biodiesel Options" (Annex XXXIV), within the Advanced Motor Fuels Agreement of the International Energy Agency (http://virtual.vtt.fi/virtual/amf/annex-xxxiv.html). In addition, a short review is included in the introduction of this report.

This report summarises the results obtained by VTT within these three projects with an Agreement by Steering Committee. The results obtained by all partners will be reported in several publications separately, and also as co-authored scientific articles and papers. In addition to national distribution of the results, the results are available internationally via conferences, articles and the IEA Advanced Motor Fuels activities.

Authors would like to aknowledge participants of the projects: University of Kuopio, Technical University of Tampere, Ecocat Oy, Preseco Ltd., AGCO SISU POWER, National Institute for Health and Welfare, Neste Oil, Helsinki Metropolitan Area Council (YTV) and Helsinki City Transport (HKL). Tekes is acknowledged for support for this work. Neste Oil is acknowledged for providing EN590 and NExBTL fuels for the emission project. Shell is acknowledged for providing the Gas-to-Liquids, GTL diesel.

Espoo 4.6.2009

Authors

Contents

List of symbols

Abbreviations

BMEP	Break mean effective pressure
BTL	Biomass to liquid
CFPP	Cold filter plugging point
CO	Carbon monoxide
CO_2	Carbon dioxide
CPC	Condensation particle counter
CRT®	Continuously regenerating trap, registered trademark owned by Johnson Matthey
CTL	Coal to liquid
DNPH	Dinitro phenyl hydrazine
DOC	Diesel oxidation catalyst
dr	Dilution ratio
EEV	Enhanced environmentally friendly vehicle, emissions limits between Euro 5 and 6
EGR	Exhaust gas recirculation
ELPI	Electrical low pressure impactor
ESC	European stationary cycle
FT	Fisher-Tropsch process
GTL	Gas to liquid
HVO	Hydrotreated vegetable oil
HC	Hydrocarbons
HTFT	High temperature Fischer-Tropsch
IEA	International Energy Agency
lpm	Liters per minute
LTFT	Low temperature Fischer-Tropsch

NExBTL	Neste Oil's proprietary hydrotreatment process and product using vegetable oil or animal fat as feedstock
NRTC	Non road transient cycle
nm	Nanometer
NO_3	Nitrates
NO_x	Nitrogen oxides (NO and NO_2)
PAH	Polyaromatic hydrocarbons
PM	Particulate matter
POC®	Particle oxidation catalyst, registered trademark owned by Ecocat Oy
RME	Rapeseed methyl ester
SCR	Selective catalytic reduction
SCRT®	Combination of SCR and CRT, registered trademark owned by Johnson Matthey
SO_4	Sulphates
SOF	Soluble organic fraction of particulate matter
TWC	Three-way catalyst
XTL	GTL, BTL and CTL

1. Introduction and background

1.1 General

There is an increasing pressure to find alternatives for fossil fuels in transportation. Alternative fuels have been under discussion several times with emphasis on different aspects. In the 70's, and other oil crises, the fuel substitutes were considered to improve energy security and to stabilize prices. Later on, the possibility to improve local pollution, especially reduction of noxious exhaust emissions, was the driving force. Lately, the focus has changed to the global environmental problems and climatic issues, which has brought emphasis on biofuels due to their ability to reduce the greenhouse gases. When biofuels are considered, the policy related to agriculture and labour has a strong position.

International organisations, such as IEA, forecast that the oil will be increasingly consumed in transportation. Transport sector would account for 54 % of global primary oil consumption in 2030 compared to 47 % in 2002 (IEA WEO 2004). Nearly 25 % of energy-related CO_2 emissions originate from transport sector (IEA ETP 2008). The transport sector is considered as a potential area to achieve reductions in greenhouse gases and global warming.

Biofuels in transport sector are believed to be capable in reducing the growth in carbon dioxide (CO_2) emissions, which supports commitment of European Union to fulfil the requirements of Kyoto Protocol. The European Union is strongly promoting biofuels, e.g. by an ambitious target of having 10 % substitution of transport fuels by renewable energy by 2020. However, serious doubts on benefits of first generation biofuels regarding global warming have been raised. In addition, sustainability of biofuels from edible feedstocks, or from feedstocks risking biodiversity is questionable.

There has been continuous research work on biofuels world-wide, but as far as biodiesel is considered, the programs have mainly concentrated on the fatty acid esters. In addition, the focus tends to be rather on production than on end-use side.

The engine and emission control technologies develop continuously. Especially, over the last few years a wide variety of different engine/aftertreatment technologies, like common-rail fuel injection systems and flow-through filters, have been introduced in the heavy-duty applications. The latest technology with complex control systems may increase the requirements on fuel cleanliness. There may be also questions on component durability especially when using new fuel alternatives.

In the following years, the traditional ester-type fuel will probably stay at the biodiesel market. However, gradually other options will be increasingly used in transportation. One option to produce second generation renewable diesel is via gasification of biomass followed by Fischer-Tropsch synthesis, in this case fuel is called Biomass-to-Liquids (BTL). Another option is by hydrotreatment of vegetable oils and animal fats with a process, such as NExBTL process developed by Neste Oil. Both processes produce paraffinic diesel fuel, resembling GTL (Gas-to-Liquids) fuel with superior properties. These totally different fuels, esters and paraffinic diesels, blended with sulphur-free fossil diesel, will set a challenging platform for engines and aftertreatment devices.

1.2 Particle emissions and their health effects

Diesel engine emissions consist of e.g. carbon monoxide, carbon dioxide, nitrogen oxides, hydrocarbons and particulate matter. Properties and composition of diesel exhaust depend on e.g. engine technology, engine operating conditions and fuel composition. The emissions from engines and vehicles have reduced significantly over the past years driven by tightening emission legislation. However, the major concerns with diesel engine still are the NO_x and particulate matter emissions.

Particulate matter emission from diesel applications traditionally refers to everything that is collected on the filter according to standardised measurement protocol. This material includes soot, unburned or partly burned hydrocarbons originating from fuel and lube oil, sulphates, metals and other elements. The chemical composition of particulate matter depends on e.g. engine technology, aftertreatment devices and fuel properties.

Diesel particulate matter consists primarily of elementary carbon (soot), which is formed in combustion at temperatures higher than 550 °C. Share of inorganic carbon may vary from 33 % to 90 %. With modern engines particulate matter tend to be “dry” and share of soot is typically over 75 %. (HEI 2003, Aakko et al. 2006.) Share of organic carbon with modern engines tend to be below 20 %. Aftertreatment devices, such as oxidation catalyst, can oxidize organic carbon efficiently leading to very dry particles. On the other hand, oxidation catalysts can generate sulphates from sulphur existing in fuel and lube oil. (Aakko et al. 2006.) Combination of effective oxidation catalyst and diesel fuel with 5 mg/kg sulphur level may result in the same sulphate emissions as diesel engine without catalyst using diesel fuel with 120 mg/kg sulphur content. (Rickeard 2000.) Metallic compounds originate from engine component wear, and from fuel and lubricant (e.g. Ca and Zn). Ash from oil combustion may occur as trace amounts.

Human lungs are exposed to ambient air particles originated from various sources, and particles appear in various size classes. Coarse particles are removed e.g. by swallowing or coughing. Smaller particles can reach the surface of the lung. These particles can be removed by scavenging cells (macrophages), but they may also drift into lymphatic vessels, and possibly further into the blood. The smallest, <0.1 µm, particles may play important role as source of the toxicity of ambient particles. (DEFRA 2001.) Diesel particles are small in size, typically more 90 % of the particle mass emission is below 0.1 µm. Depending on conditions, also nanoparticles in the size class below 50 nm may occur. Diesel particles have a large surface area, which may adsorb various compounds that can be toxic, mutagenic and carcinogenic (e.g. PAHs, nitro-PAHs, oxy-PAHs).

The health effect studies so far have found adverse effects in diesel exhaust. Short-term exposure can cause acute irritation (e.g. eye, throat, bronchial), neurophysiological symptoms (e.g. lightheadedness, nausea), and respiratory symptoms (cough, phlegm). In addition, there is evidence of an increase in responses to known allergens and asthma-like symptoms (immunologic effect). Chronic-exposure includes e.g. dose-dependent inflammation and histopathological changes in the lung. An estimate of so called reference concentration, which does not cause adverse non-cancer respiratory effects is 5 $\mu g/m^3$ for diesel PM. (US EPA 2002.)

The US EPA concludes that diesel exhaust is "likely to be carcinogenic to humans by inhalation" and that this hazard applies to environmental exposures. Diesel exhaust has also potential for "a nonthreshold mutagenic effect". The estimated higher environmental exposure levels are close to, or overlapping, the lower limits of exposures for which lung cancer increases are reported. Altogether, there is support to deem diesel exhaust as cancer hazard at environmental levels of exposure, even though there is not confidence in understanding the exposure/dose-response relationship. (US EPA 2002.)

Due to the health effects related to the fine particles, the legislation concerning the particulate emissions from combustion processes, such as diesel-engines, are tightening. The small size of the particles and the chemical composition of the soluble organic fraction in the particulate matter are considered to cause the main health effects of the particulates. Combination of biofuel and aftertreatment device can reduce particle mass emission and harmfulness of particles (McGill et al., 2003). Therefore, the aftertreatment devices should be tested as a possible abatement method to decrease the harmful properties of particulates.

1.3 FAME-type traditional biodiesel

Traditionally, biodiesel means fatty acid methyl esters (FAME). Neat vegetable oils are not suitable for high-speed diesel engines (light- and heavy-duty vehicles), and thus transesterification process is required to produce FAME, which is suitable for diesel engines. However, due to certain end-use problems with FAME, the current European EN 590:2004 specification for diesel fuel limits the maximum concentration of FAME to 5 % (7 % proposed in the update). European standard EN 14214:2003 sets requirements for quality of FAME used for automotive fuels.

FAME esters are produced by a reaction of triglycerides and/or free fatty acids with alcohol using sodium or potassium hydroxide as catalyst. Side-product of process is glycerol. Methanol gives better yield than e.g. ethanol, and thus it is used predominantly as alcohol. Various vegetable oils, even animal fats or tall oil, can be esterified. When using rapeseed oil as feedstock, the product is rapeseed methyl ester, RME. (Ma & Hanna 1999, Graboski & McCormick 1998.)

Ignition properties of FAME esters are good: cetane numbers are generally over 50. In addition, sulphur content of esters is low, they do not contain aromatics and lubricity is good. However, the FAME biodiesel has also drawbacks. High viscosity of esters may affect injection performance and cold-start properties. Distillation range of esters is narrow and boiling point high, which may lead to dilution effect of engine oil. FAME biodiesel may contain certain impurities, e.g. triglycerides, glycerol and alcohols. Triglycerides and glycerol are viscous molecules, which can lead to carbon deposits in engine. 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. (Graboski & McCormick 1998, WWFC 2006.)

FAME esters as polar compounds dissolve materials more efficiently than diesel fuel, which may lead to problems on sealing, paint, rubber and other materials with older vehicles. FAME also dissolves deposits from fuel system. Storage stability of esters is not good due to e.g. affinity of double bonds for oxidation. FAME should be used within six months after it is produced. Aged FAME can contain acids, water, peroxides, and polymerization products.

Heat content of esters is low and thus volumetric fuel consumption higher and full load characteristics of the engine lower than for diesel fuel, but this is compensated to some extent with higher density of esters. Esters are in the same hazard class as diesel, but if there is any alcohol as impurity the flash point lowers rapidly, which can lead tighter transportation and storage regulations. (Graboski & McCormick 1998, WWFC 2006.)

Sem (2004) reported that deposits formed on injectors with RME in the long-term test consisted of carbon, oxygen, some metals, chlorine, phosphorus and sulphur. Many of the metals were originating from engine-wear. Deposits might be caused by decomposition of the methyl ester or glycerin molecule, thus a limit for glycerin is important. The effect of phosphorus of FAME on catalyst has been studied e.g. by Krahl et al. (2006).

FAME biodiesel generally reduces CO, HC and PM emissions, but increases NO_x emissions (McCormick et al. 2001, Sharp et al. 2000a, Chang & Gerpen 1997). However, these trends are not consistent as the engine, load conditions, diesel fuel used for comparison, and properties of FAME affect the results.

McCormick et al. (2001) concludes that the reason for increase in NO_x emission with FAME is not clear even today, especially when considering low aromatic content of FAME. The role of density, high distillation area, oxygen content and double bonds has been considered as reasons for the increase of NO_x emission with FAME. Start of injection is earlier, and ignition delay longer when FAME is compared to high-cetane diesel fuel (McCormick et al. 2001, Senatore et al. 2000). However, ignition delay with FAME can be shorter, if cetane number of conventional diesel is poor. Grimaldi et al. (2002) reported that for common-rail engine, BMEP decreases, pilot injection is smooth and main injection combustion is steep leading to high local thermal peaks contributing on generation of NO_x. Graboski & McCormick (1998) commented that FAME lowers soot emission, which may increase flame temperature. In addition, changes in e.g. spray properties may cause unexpected effects. Many of the studies of 90's used low-cetane diesel as a reference fuel and thus the results do not represent today's situation, when cetane number of conventional diesel is typically higher than cetane number of FAME, especially in Europe.

Reduction of particulate matter emission is believed to be due to presence of oxygen in FAME. (Durbin & Norbeck 2002, Grimaldi et al. 2001 & 2002, McCormick et al. 2001.) 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. (Akasa et al. 1997, McGill et al. 2003, Aakko & Nylund 2003.) 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 are typically lower for FAME biodiesel than for conventional diesel. However, number of accumulation mode particles in some conditions, especially at cold test temperatures, may increase due to excessive soluble organic fraction in PM. FAME diesel may increase also nuclei mode particles (Tsolakis 2006, Aakko et al. 2002, Aakko & Nylund 2003).

Mutagenic effect tested with Ames strains are typically lower for FAME than for fossil 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. (McGill et al. 2003, Bünger et al. 2007.)

As concerns exhaust toxicity, opposite results have been observed. Eckl (1997) reported that genotoxicity of exhaust tested with hepatocyte assay was not lower for FAME than for diesel fuel. Prieur et al. (2000) reported that FAME increases cytotoxicity as measured with viability parameters (ATP and GSH). On the other hand, RME prevented apoptotic phenomenon (TNF-α, nucleosome). Bünger et al. (2000b) reported of increased toxicity of exhaust on mouse fibroblasts at idling, but not at rated power, when compared to diesel fuel. Also rat tests have been conducted with exhaust obtained with biodiesel as fuel (Finch et al. 2000).

Typically oxygen containing fuels tend to increase aldehyde emissions, and many studies, e.g. Krahl et al. (2001), report of increase in aldehyde emissions with FAME biodiesel. Some studies report also on reductions of aldehyde emissions with FAME, but in these cases (e.g. Sharp et al. 2000b) very low-cetane diesel fuel has been used as reference fuel.

1.4 Synthetic and renewable diesel

FAME biodiesel originates from edible feedstock, and thus other renewable options for diesel replacement are explored. Synthetic fuels offer an alternative route to convert a variety of feedstocks to liquid fuels, e.g. combination of gasification to syngas (carbon monoxide and hydrogen), and Fischer-Tropsch process for liquefaction. When the feedstock for Fischer-Tropsch process 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). (Nylund et al. 2008, Clark et al. 2006.)

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. (www.choren.com). Also other projects on BTL production are progressing, e.g. in Finland by Neste Oil and Stora Enso, UPM and Andritz plus Vapo. (www.nesteoil.com, http://www.upm-kymmene.com/en/.) There are also options other than Fischer-Tropsch for liquefaction of syngas, e.g. conversion of syngas to methanol and then via olefins to distillates.

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, which benefits from refinery's infrastructure including energy, blending facilities, logistics and laboratories (Rantanen et al. 2005). 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, ENI/UOP in Italy and Dynamic Fuels LLC in the U.S. (www.nesteoil.com, Nylund et al. 2008).

Conventional diesel fuel contains a number of hydrocarbons, aromatics, napthens and paraffins, whereas in the most part GTL[2] and HVO are paraffinic, oxygen-free, sulphur-free and aromatics-free fuels with high cetane number. Storage stability of these fuels is good and water solubility low. The current European EN 590:2004 specification for

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[2] Predominant GTL technology today is low temperature Fischer-Tropsch (LTFT), which maximises production of paraffinic middle distillates. High temperature Fisher-Tropsch produces a mixture of various types of hydrocarbons. (Clark et al. 2009.)

diesel fuel can be met with paraffinic synthetic fuel except for density. In February 2009, the CEN Workshop Agreement, CWA 15940, was published. CWA is not an official standard, but a document agreed by a Workshop. According to CWA 15940, density of paraffinic diesel should be 770–800 kg/m^3. Using BTL or hydrotreated biofuel as a high-concentration blending component, or as such, requires no investments in the fuel distribution infrastructure or existing vehicle fleet.

Excellent fuel properties of paraffinic synthetic fuels lead to exhaust emissions benefits and good engine performance (Alleman et al. 2003). Substantial reductions in NO_x, PM, CO and HC emissions are reported with NExBTL and GTL (Kuronen et al. 2007, ASFE). Kitano et al. (2007) reports of reduction of exhaust emissions of modern diesel engine equipped with advanced diesel aftertreatment system using GTL fuel. According to Kitano et al. (2007) distillation range of GTL fuels has a significant impact on engine-out PM. HC and CO emissions were low due to high cetane number, while these fuel properties have little effect on the NO_x emissions.

Clark et al. (2006) 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. Some cars behaved as expected: low NO_x and PM emissions were observed with the GTL fuel.

Schubert et al. (2002), Nord & Haupt (2002) and Alleman et al. (2003) reported of lower aldehyde emissions for Fischer-Tropsch diesel than for conventional diesel. Munack et al. (2006) found lower mutagenicity of particulate extracts with GTL than with diesel fuel, but this is not the case in all studies (Munack et al. 2007).

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 (Aatola et al. 2008).

2. Experimental

2.1 Fuels

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

RME is a traditional first generation biodiesel produced from rapeseed oil and methanol. RME was purchased from Lantmännen Ecobränsle AB. The properties analysed by manufacturer of RME are shown in Table 1. NExBTL is Neste Oil's proprietary hydrotreatment process and product using vegetable oil or animal fat as feedstock (Rantanen et al. 2005). NExBTL is non-oxygenated, paraffinic, high-quality renewable diesel fuel with similar chemistry to Fischer-Tropsch fuels. Properties of NExBTL are shown in Table 1.

One option to produce high-quality diesel from various feedstocks is via gasification followed by Fischer-Tropsch synthesis (FT). In this study, GTL (Gas-to-Liquids) diesel fuel represented FT fuels, for which also biomass could be used as feedstock (BTL). NExBTL, GTL and RME were compared to a sulphur-free fossil diesel fuel, which fulfills 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-%). When the physical fuel properties are screened the densities and viscosities of the paraffinic fuels are the lowest, whereas RME has the highest density and viscosity. Cetane numbers of HVO and GTL fuels were high, 83 and 72, whereas cetane numbers of EN590 and RME were at the level of 51–55.

Summer grade diesel fuel was used as reference. Typical cloud point of this quality is below –5 °C and typical CPFF below –15 °C. Difference between cloud point and CFPP is high for conventional diesel fuel consisting of various types of hydrocarbons. In the opposite, there is not much difference between cloud point and CFPP for RME and paraffinic fuels. For RME, CFPP was –14. For NExBTL and GTL fuels cloud point and CFPP were close to –20 °C. Metal analysis of fuels showed that RME contained higher amount of some metals than NExBTL or EN590. The highest concentrations were observed for potassium, tin, zinc, sodium and copper, altogether 4.2 mg/kg for RME, whereas sum of these metals was below 0.6 mg/kg for NExBTL fuel and below 0.9 for EN590 fuel. These originate from production process of RME, fertilizers, pesticides and soil. Selected properties of test fuels are shown in Table 1.

Table 1. Properties of the test fuels.

		RME	**NExBTL**	**GTL winter**	**EN 590 [b] 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	<1,0	1[c]	7.9
Cetane number (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]	18.4
Polyaromatics, di+	wt-%	bd	<0.1	bd[c]	1.1
Iodine number		<120			
Ash	wt-%	<0.001	0.001	na	<0.001
Metal analyses					
Ca	mg/kg	0.20	<0.1	na	<0.1
K	mg/kg	1.30	0.30	na	0.60
Na	mg/kg	0.47	0.08	na	0.08
Zn	mg/kg	0.90	<0.1	na	0.09
Si	mg/kg	0.04	0.18	na	0.50
Cu	mg/kg	0.24	<0.1	na	0.09
B	mg/kg	0.30	<0.1	na	<0.1
Sn	mg/kg	1.30	<0.05	na	<0.05
V	mg/kg	0.06	0.03	na	0.03
P, Ti	mg/kg	<0.2	<0.2	na	<0.2
Al, Cr, Pb	mg/kg	<0.1	<0.1	na	<0.1
Fe, Mo, Ni, Mg, Mn	mg/kg	<0.05	<0.05	na	<0.05

[a] Typical values, European standard EN 14214

[b] Results from several batches. Cold properties from product data sheet.

[c] Typical value for GTL.

na = not analysed

bd = below detection limit

Engines, vehicles and aftertreatment devices

The engines used in this research represented 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.

Engines

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. The third engine was for non-road applications representing a prototype for upcoming Stage 3B emission regulations.

Vehicles

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

Aftertreatment devices

Oxygenating catalyst, particle oxidation catalyst, EGR, SCR and SCRT emission control technologies were represented in the engines and vehicles tested Table 2 and 3.

Particle oxidation catalyst (POC®) developed by Ecocat Oy is a so called flow-through filter. Flow-through filters are specialized diesel oxidation catalysts that utilize substrates with capacity to capture solid particles. In POC the substrate is made from metal screen which can act as trapping material for diesel soot particles. The substrate channels are tortuous and direct the exhaust gas to either follow the channels or to go through the substrate walls i.e. the metal screen (Lylykangas et al. 2002, Lehtoranta et al. 2007).

The advantage of the POC compared to a conventional diesel particle filter (DPF) is that it does not have a blocking risk similar to DPF. If the POC substrate is saturated with soot the exhaust gas can still go through the POC following the channels similarly to a conventional flow through catalyst. Of course the POC substrate is not aimed to be saturated and in normal engine driving conditions it is not expected to happen. This is ensured by using a separate catalyst upstream of the POC substrate. This oxidation catalyst produces NO_2 to oxidize the soot collected in the POC. In addition a catalytic coating is also used in the POC substrate. These together enable continuous soot regeneration that keeps the collecting substrate clean allowing additional soot collection during the engine performance. Depending on diesel application, POC sizing and loading, PM conversions of 30–70 % can be achieved by the POC (Lehtoranta et al. 2007).

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 the catalyst. For Cummins engine the DOC had a length of 120 mm and a diameter of 240 mm. The cell density of the substrate was 350cpsi. Platinum was used as a precious metal with loading of 1.43 g/dm^3. The POC had a length of 300 mm and a diameter of 240 mm. The cell density was 300 cpsi. Platinum with loading of 0.35 g/dm^3 was used in substrate.

Scania engine was equipped with an EGR system. In addition, part of the fuels were measured also with DOC+POC system. For the Scania the DOC had a length of 150 mm and a diameter of 334 mm. The cell density of the substrate was 120cpsi. Platinum and Palladium were used as precious metals with total loading of 1.09 g/dm^3. The POC had a length of 150 mm and a diameter of 334 mm. The cell density was 300 cpsi. Platinum with loading of 0.35 g/dm^3 was used in substrate.

Exhaust Gas Recirculation (EGR), oxidation catalyst, Selective Catalytic Reduction (SCR) and a combination of SCR and particulate trap (SCRT) were used as emission control devices in buses. EGR is a NO_x reduction technology based on by recirculating a part of exhaust gas back to the cylinders. In the SCR system, urea is used as reductant to convert NO_x to nitrogen and water[3]. The engine/aftertreatment combinations studied at VTT are shown in Table 2 and vehicle/aftertreatment combinations in Table 3.

Table 2. Engines, application areas and emission classifications.

	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 capasity, 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
	direct injection, turbocharged, intercooled	direct injection, turbocharged, intercooled	direct injection, turbocharged, intercooled
Max. power	118 kW / 2500 min-1	310 kW (420 hp) / 1900 min-1	175 kW / 2200 min-1
Max. torque	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 oxidation catalyst	DOC+POC oxidation catalyst	-

* measurements were performed without SCR-system

[3] Reactions: Production on ammonia $OC(NH_2)_2 + H_2O \rightarrow CO_2 + 2\ NH_3$; Reduction nitrogen oxides: $4\ NO + 4\ NH_3 + O_2 \rightarrow 4\ N_2 + 6\ H_2O$: If too much ammonia is feeded: $4\ NH_3 + 3\ O_2 \rightarrow 2\ N_2 + 6\ H_2O$.

Table 3. Heavy-duty vehicles, application areas and emission classifications.

	Volvo B7RLE/680 Bus A	Scania K230 UB4x2LB Bus B	Scania K9 UB-B Bus C	IVECO CITELIS LINE Bus D	MAN CNG LION'S CITY Bus E
Model year	2006	2005	2008	2007	2008
Odometer	14 908	155 079	99 698	12 337	206 470
Cylinder capasity, 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	213	169	169 kW@1800 min^{-1}	213	180 kW@2200 min^{-1}
Max. torque	1200	1050	1050 Nm@1100-1500min^{-1}	1100	880 Nm@1000-1200min^{-1}
Emission control	SCR	EGR + oxdation cat.	EGR	SCRT (=CRT+SCR)	TWC
Emission class	Euro 4	Euro 4	EEV	EEV	EEV

2.2 Test Matrix

The measurement matrix included the following regulated and unregulated emissions:

- regulated emissions: total hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NO_x) and particle mass (PM)
- carbon dioxide (CO_2) and fuel consumption
- aldehyde analysis, eg. formaldehyde and acetaldehyde
- individual hydrocarbons (limited tests with buses)
- particulate analysis (SOF, anions with restricted matrix)
- the polyaromatic hydrocarbon analysis from particulate matter (PAH) (restricted matrix)
- Ames test from extract of particulate matter (restricted matrix)
- particle size distribution and number measurements.

In addition to emission tests, also a long-term test with one engine equipped with an oxidation catalyst was conducted.

Samples were collected with truck engine (Scania) and CNG bus for health effect study at the National Institute for Health and Welfare. University of Kuopio and Technical University of Tampere conducted also measurements from bus engine (Cummins). Those results will be reported on separate reports by University of Kuopio and Technical University of Tampere. A summary of engines/vehicles/fuels studied is shown in Table 4.

Table 4. Test matrix. Number of measurements includes regulated emissions. Limited number of unregulated emissions were measured.

		RME	RME30	NExBTL	NExBTL3C	GTL	EN590
ENGINES							
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
with catalyst	long-term test	350 h					350 h
Engine, truck (Scania)							
with catalyst	Brauncshweig	4		13			14
w/o catalyst	Brauncshweig	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 (SisuDiese	NRTC (transient)			4			4
	ISO8178			3			3
VEHICLES							
Bus A (SCR)				3			5
Bus B (EGR				3			5
Bus C (EGR+cat)				4			4
Bus D (SCRT)				4		2	6
Bus E, CNG		25 measurements					

2.3 Measurement methods

2.3.1 Heavy-dyty engine and vehicle tests

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

The measurement and analysis of emissions covered the regulated emissions CO, HC, NO_x, PM plus unregulated emissions i.a. CO_2, NO, NO_2, NH_3, SO_2 and aldehydes. In addition, soluble organic fraction of particulate matter was analysed for PAH compounds and mutagenic activity was screened using Ames test. Measurement equipment for regulated emissions is linked to test bench used.

Test facilities

Scania and SisuDiesel engines were measured in a transient dynamometer using a full-flow CVS system (Pierburg CVS-120-WT) and an analyser set (Pierburg AMA 4000) conforming to the requirements of Directive 1999/96/EC for the measurement of exhaust emissions of heavy-duty on-road engines (Table 3). Particulate filters for standard collection system were Pallflex TX40HI20WW ∅ 70 mm filters. For Scania engine, a high-capacity collection system was used with Pallflex T60A20 ∅ 142 mm filters (Chapter 2.4.3).

Cummins engine was tested in a steady-state test bench in a eddy-current dynamometer by Zöllner (Zöllner B-300 AD, 260 kW) "PUMA Test Assistant" control system by AVL were used for running and controlling the test engine. Regulated gaseous emissions were measured with an analysis system by BOO Instrument AB. This system includes several analysers from different manufacturers. Particles for the measurement of particulate matter emission (PM) were collected using AVL Mini Dilution Tunnel 474. Particulate filters for standard collection system were Pallflex TX40HI20WW ∅ 70 mm, and for high-capacity collection system Pallflex T60A20 ∅ 142 mm filters (Chapter 2.4.3).

Heavy-duty vehicles were tested on chassis dynamometer using a full-flow CVS system (Pierburg CVS-120-WT) and an analyser set (Pierburg AMA 4000) conforming to the requirements of Directive 1999/96/EC for the measurement of exhaust emissions of heavy-duty on-road engines. The equipment used for the emission measurements are listed in Table 5. Particulate filters for standard collection system were Pallflex TX40HI20WW ∅ 70 mm. and for high-capacity collection system Pallflex T60A20 ∅ 142 mm filters or Fluoropore 3.0 µm FSLW filters (Chapter 2.4.3).

Table 5. The basic measurement equipment.

Engine dynamometer (transient) **Manufacturer: *Froude Consine, UK* Model: Froude *AC 570 F***	**Chassis dynamometer** **Manufacturer: *Froude Consine, UK***	**Analyzers** **Manufacturer: *Pierburg, Germany***
Max power: 570 kW (at 1 700–4 000 rpm) Max torque: 3200 Nm (range 150–1 700 rpm) Fast and accurate IGBT control for transient cycles Texel V6 data collection / control system	Max. power: ± 300 kW (speed range 54–110 km/h) Overload capacity: 120 % / 300 s Increased power absorption possible with separate AC dynamometer Max. wheel force: ± 20 000 N (speed range 0–54 km/h) Inertia: 2 500–30 000 kg Roller diameter: 2 500 mm Max. axle load: 20 000 kg Fast and precise IGBT control for good transient load response Driver's aid with different drive cycles	Exhaust gas sampling system CVS-120-WT – Multiple (3) CFV-venturi system – High flow capacity 120m3/min – Dimensions of tunnel 8000 * 450 mm – Secondary tunnel VT-458 – Particle collector PS2000 C Analyzer system AMA 4000 – HFID THC 0–1000 ppm – HFID CH4 0–3000 ppm – HCLD NOx 0–10 000 ppm – NDIR CO2 0–20 % – NDIR CO 0–2500 ppm – NDIR CO2 tracer 0–20 %

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 cycle, which is internationally recognized method for simulating city bus driving conditions (Figure 1). The daily procedure, including warming up of vehicles, was followed at VTT. In addition, a "dummy" Braunschweig cycle without emission measurements was carried out before actual test cycles with measurements to fully stabilise vehicle and measurement system.

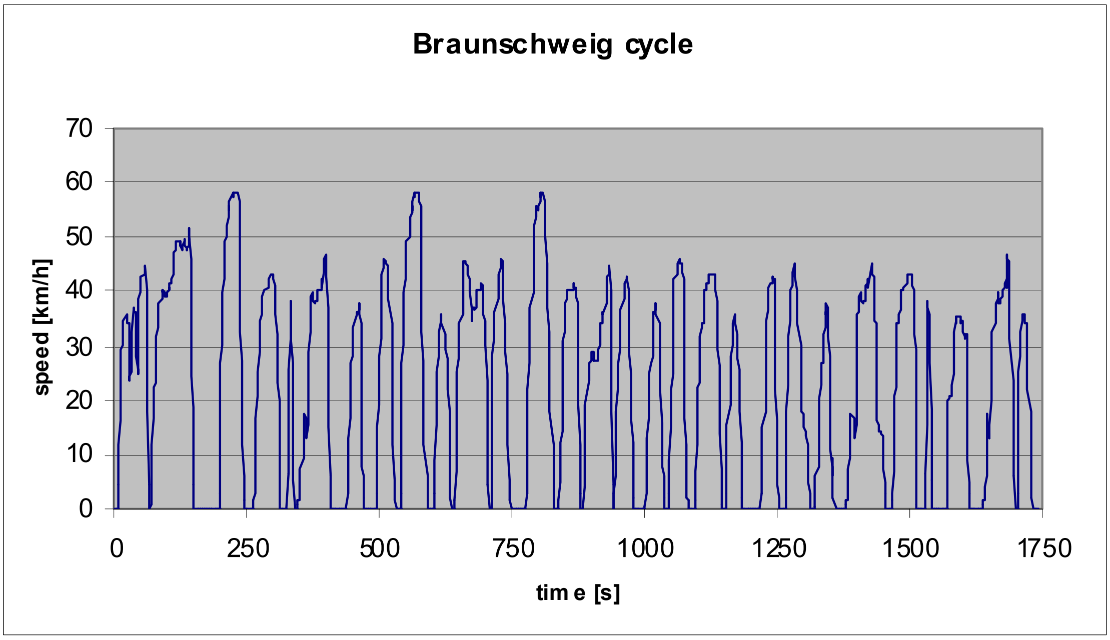

Figure 1. The Braunschweig driving cycle.

Test cycle with Cummins bus engine

Engine tests were carried with heavy-duty test cycle, ESC, described in the European legislation[4]. ESC test cycle comprises of 13 steady-state loads, and the final result is the average calculated with weighting factors (Figure 2).

The load modes of the ESC test cycle are calculated from certain parameters based on power curve. The maximum power output of an engine depends on properties of fuel used in the tests. When the fuels are compared with each other, it is reasonable to use the same power output, which is called the "constant torque" method.

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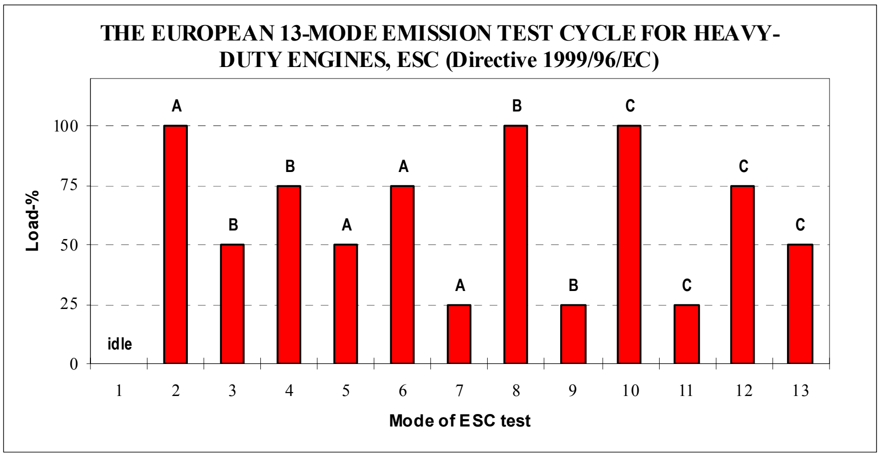
[4] Directive 88/77/EEC, amendment 1999/96/EC.



Mode	WF
1	0.15
2	0.08
3	0.10
4	0.10
5	0.05
6	0.05
7	0.05
8	0.09
9	0.10
10	0.08
11	0.05
12	0.05
13	0.05

Figure 2. Schematic Figure of 13-mode ESC test cycle.

Test cycle with Scania truck engine

Braunschweig test cycle was simulated in engine dynamometer for the measurements. For the simulation the engine torque and speed profile were recorded with Scania Euro 4 emission level bus on heavy-duty chassis dynamometer over the Braunscheig test cycle. The recorded values were transferred to engine dynamometer.

The power output of the Scania engine measured on engine dynamometer was higher when compared to Scania bus engine. Therefore the power profile of the recorded cycle was scaled so that the ratio between average power over the test cycle and maximum power of the engine was the same with measured bus and measured engine.

Test cycle with SisuDiesel non-road engine

SisuDiesel Stage 3B prototype engine was tested with Non Road Transient Cycle (NRTC) for mobile non-road engines, to be used for engine emission certification/type approval in the USA and in European Union. In addition, tests were carried out using ISO 8178, C1 test cycle, which consist of eight steady-state test modes and it is currently used for certification/type approval test for mobile non-road engines (Figure 3).

2.3.2 Aldehydes, individual hydrocarbons and FTIR

Aldehydes were collected from the CVS diluted exhaust gas by using dinitrophenylhydrazine (DNPH) cartridges. The diluted sample gas was taken from the same location as particle samples. The DNPH derivatives were extracted with acetonitrile/water mixture. Altogether 11 aldehydes were analysed with the HPLC-technology (HP 1050, UV detector, Nova-Pak C18 column). The main attention was given to formaldehyde and acetaldehyde.

Other aldehydes analysed were acrolein, propionaldehyde, crotonaldehyde, methacrolein, butyraldehyde, benzaldehyde, valeraldehyde, m-tolualdehyde and hexanal.

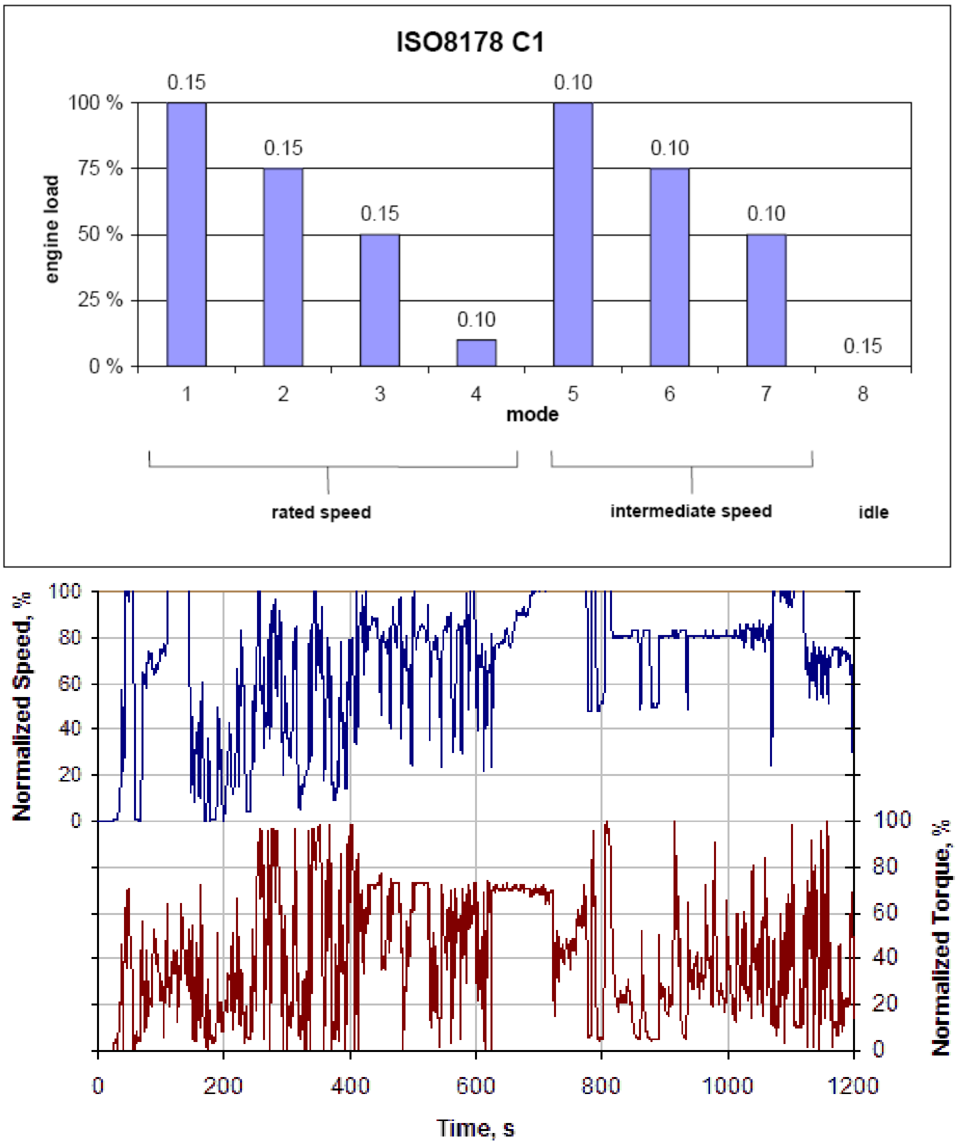


Figure 3. Test cycles used non-road Sisu Diesel engine, ISO 8178 CI and transient NRTC (www.dieselnet.com).

In the Cummins engine measurements aldehyde samples were collected from the AVL Mini Dilution Tunnel using same method as described above. In the tests with Bus C, probably high NO_2 emission from bus consumed all DNPH reagent from cartridges, and thus aldehydes could not be analysed. With Bus D, due to leakage of sampling the aldehyde results were rejected.

The diluted exhaust gas for individual hydrocarbon analysis was collected from the same Tedlar bags that were used for measurement of the regulated emissions. From those bags the diluted exhaust gas was drawn to smaller Tedlar bags, from which the diluted exhaust gas was fed to the gas chromatograph. The speciation of hydrocarbons from C1 to C8 from diluted exhaust gas was conducted by using HP 5890 Series II gas chromatograph (AL2O3, KCl/PLOT column). Hydrocarbons were identified by retention times and quantitative analysis was done by external standard method.

A number of compounds were measured on-line using Fourier Transformation InfraRed (FTIR) equipment Gasmet Cr-2000. Ahonen (2006) has reported the performance of the Gasmet FTIR equipment with exhaust gases from vehicles. More than 10 exhaust components were measured at two second time interval from raw exhaust gas. However, with diesel exhaust gas the concentrations of many compounds, e.g. hydrocarbons, are very low. Thus only a few compounds are presented in this report. NO_2 and ammonia results referred in this report are based on FTIR measurements. A summary of detection limits based on the reference spectrums from manufacturer are as shown in Table 6. The detection limits using one second measurement interval were converted to mass based emissions for buses and engines.

Table 6. Detection limits determined from reference spectrums from manufacturer. Reference spectrums are based on measurements at one and five seconds tme interval.

	Reference spectrum ppm	Detection limit for 1 second ppm	Detection limit for 5 seconds ppm	Detection limit (1s), transient (g/kWh)	Detection limit (1s), ESC test (g/kWh)
Carbon monoxide (CO)	103	7	3		
Nitric oxide (NO)	98.4	19	4		
Nitrogen dioxide (NO_2)	46.9	10	6	0.22	0.07
Nitrous oxide (N_2O)	100	4	1	0.08	0.01
Ammonia	25	2	1	0.02	0.00
Methane	100	2	1	0.02	0.00
Formaldehyde	50	20	9	0.28	0.07
Acetaldehyde	50	5	2	0.10	0.02

2.3.3 High-capacity collection system for particle matter and semivolatiles

Special analyses require a substantial particulate mass. Therefore, a high-capacity sampling system was used in parallel with the standard particle sampling system. The high capacity sampling system was developed at VTT originally for the measurements of low-emission engine/vehicles applications. This system is useful also for collection of sufficient mass of particles for special analyses like mutagenicity tests from conventional diesel vehicles (Kokko et al. 2000).

In the high-capacity system, up to 2000 lpm flow of diluted exhaust gas through one or two ∅ 142 mm filters can be used. In these tests, 300–1500 lpm flow was used to obtain appropriate particle masses. In some measurement campaigns two ∅ 142 mm filters were used in parallel to reduce face velocity and pressure drop on the filters.

Two type of filter materials were used in the measurements with high-capacity collection system: Pallflex T60A20 and Fluoropore 3.0 µm FSLW. A new balance was purchased at VTT due to tightening requirements for the standard particulate matter emission measurements. This balance is smaller than older balance and thus ∅ 142 mm filters need to be folded for weighing. It appeared that there is a risk with Pallflex T60A material to tear during emission test if it has been folded. Thus filter material was changed from Pallflex T60A to more durable Fluoropore filters.

The samples for semivolatile PAH compounds were collected in polyurethane foam (PUF) located after the PM filters in the particle collection system. A polyurethane foam (PUF) sampler was 50 mm in diameter and 50 mm in height. For the removal of impurities, PUF was prepared using an extensive solvent washing procedure. The parameters of collection of particles with different engines and vehicles are summarised in Table 7.

Table 7. Parameters of high-capacity collection system for particulate matter in different measurement campaigns.

	Tunnel flow	Diameter	Velocity	High-capacity collection system					
				sonde, id	flow	velocity	filters	velocity	Filter
	Nm^3/min	mm	m/s	mm	lpm	m/s	142 mm	cm/s	
Engine, bus (Cummins)	1 (~60 m^3/h)	isokinetic sampling		isokin.	206	isokinetic	1	29	T60A20
Engine, truck (Scania)	47	450	4.9	41	800	10.1	2	56	T60A20
Engine, non-road (SisuDiesel)	48	450	5.0	-	-	-	-	-	-
Bus A (SCR)	37	450	3.9	41	300	3.8	1	42	T60A20
Bus B (EGR)	47	450	4.9	41	300	3.8	1	42	T60A20
Bus C (EGR)	47	450	4.9	41	500	6.3	2	35	Fluoropore
Bus D (SCRT)	37	450	3.9	41	1000	12.6	1	139	T60A20
Bus CNG	37	450	3.9	41	1000	12.6	2	70	Fluoropore

Correlation of the particulate mass emission results (PM) using the two collection systems in the measurements was good in most cases (Figure 4). The results differed from each other on average of 4 % and at the most 13 %, with exception of EEV Bus D, which showed practically no correlation due to very low particulate emission level.

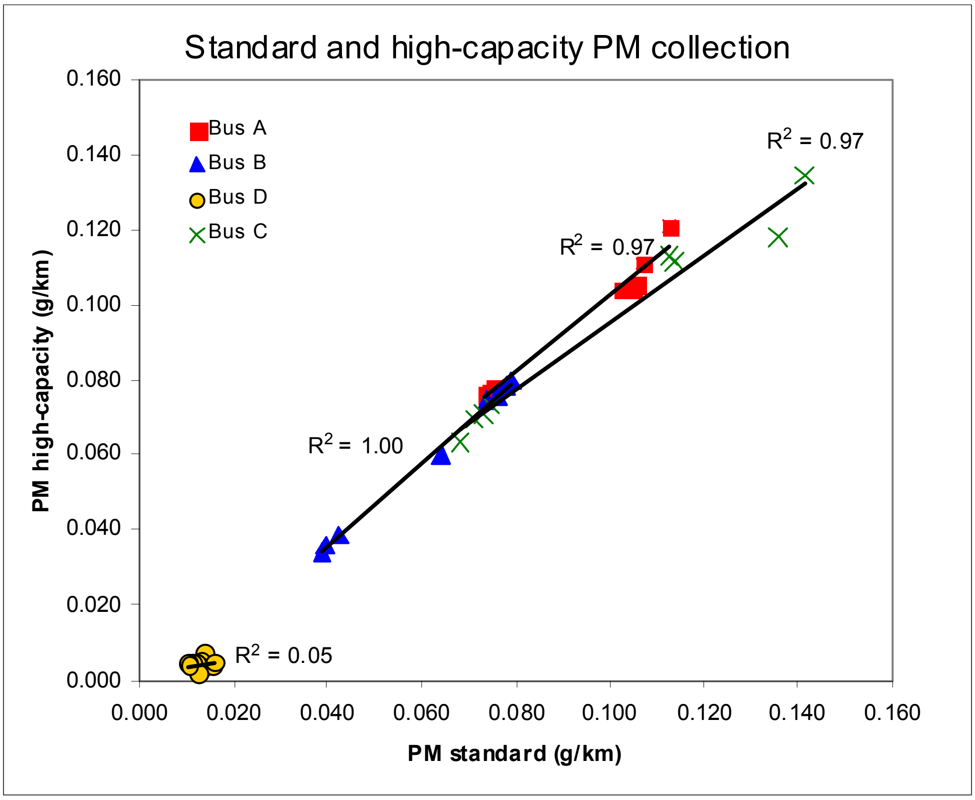


Figure 4. Correlation between standard and high-capacity collection system with buses.

2.3.4 PAH-analysis and Ames-tests

Several filter types were used for collection of particles in different measurement periods: Pallflex TX40HI20WW ∅ 70 mm, Pallflex T60A20 ∅ 142 mm and Fluoropore 3.0µm FSLW ∅ 142 (see previous Chapter). The Soxhlet extraction with dichloromethane was carried out from selected filters designed specially for each measurement campaign. One sample for PAH analysis and Ames test consisted of numerous filters. The samples for semivolatile PAHs collected in polyurethane filters were extracted with toluene.

A set of polyaromatic hydrocarbons (PAHs) were analyzed from the soluble organic fraction (SOF sample), which was obtained by Soxhlet extraction of particle samples with dichloromethane (Table 8). For mutagenicity analyses, the solvent was exchanged to dimethyl sulfoxide (DMSO).

PAH analyses were performed by using GC/SIM-MS after a liquid chromatographic purification of the extract. EPA 610 PAH mixture from Supelco and PAH-MIX 63 from Ehrensdorf is used to check the calibration standard. The calibration standard was made from pure solid substances of each PAH compound determined. Detection limits were 0.01 µg component/sample with an accuracy of measurement of about 30 %. The PAH analyses were carried out at Nablabs laboratories. The detection limits as µg/kWh or μg/km varies with application and test cycle. With the buses, the detection limit of individual PAH compound was below 0.4 μg/km using Braunschweig cycle.

There are several lists on priority PAHs. In this report, the sum of seven PAH compounds are reported based on the European and the US EPA definitions. The sum of seven PAHs includes the following compounds:

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

The sum of 14 PAH compounds includes also fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benzo(e)pyrene, benzo(g,h,i)perylene and dibenz(a.h)anthracene but excludes 7,12-dimethylbenz(a)anthracene (see Table 8).

Ames-test using *Salmonella typhimurium* bacteria strains was used to evaluate the mutagenicity of the extracted particulate samples. Strain TA98 was used without metabolic activation (–S9). Strain TA98 with metabolic activation (+S9) was used in the case that particulate mass was sufficient. With Scania engine also a strain TA98NR without metabolic activation was used. The results are calculated in krev/km or krev/kWh, which represents the mutagenic activity in emission basis.

Table 8. The analysed PAH-compounds.

NAF	naphthalene	2mANT	2-methylanthracene	**BaANT**	***benz[a]anthracene**
2mNAF	2-methylnaphthalene	1mFEN	1-methylphenanthrene	**KRY**/TRI	***chrysene/**triphenylene
1mNAF	1- methylnaphthalene	2fNAF	2-phenylnapthalene	**BbFLUT**	***benzo[b]fluoranthene**
BiF	biphenyl	FLUT	*fluoranthene	**BkFLUT**	***benzo[k]fluoranthene**
3mBiF	3-methylbiphenyl	PYR	*pyrene	BePYR	*benzo[e]pyrene
ANAF	acenaphthene	BaFLU	benzo[a]fluorene	**BaPYR**	***benzo[a]pyrene**
diBzFUR	dibenzofuran	BbFLU	benzo[b]fluorene	PERY	perylene
FLU	*fluorene	BbN21	benzo[b]naphtho[2,1-d]thiophene	**IPYR**	***Indeno[1,2,3-cd]pyrene**
diBzTIO	dibenzothiophene				
FEN	*phenanthrene	BbN12	benzo[b]naphtho[1,2-d]thiophene	dBahA	*dibenzo[a,h]anthracene
ANT	*anthracene			BghiPER	*benzo[g,h,i]perylene
				KOR	coronene
				7,12-dimethylbenz(a)anthracene	

PAH(14) is the sum of PAH-compounds marked with asterisk.
PAH(7) is the sum of bold PAH- compounds.

2.3.5 The particle number size distributions

Particle number size distributions were measured with the ELPI instrument (Electrical Low Pressure Impactor), manufactured by Dekati Ltd. The main parts of the ELPI are charger and low pressure impactor. Inside the charger the particles are charged and the aerodynamic size classification is done inside the impactor. The current values are measured from each stage of impactor and transformed to number of particles using complex calculations.

In these measurements a 10 lpm low pressure impactor was used with so called filter stage. With this set up the lowest cut point is about 8 nm. The sample was taken from raw exhaust gas and then diluted on two stages. The dilution air was filtered and dried with adsorber dryer. A porous tube diluter was used as primary diluter and an ejector type diluter as secondary diluter. The total dilution ratio (dr) was set to 40 (primary dr 12.5 and secondary dr 3). The dilution air and sample flows were controlled with mass flow controllers and the true dilution ration was measured via CO_2. The measured dilution ratio has been used for the calculations. Figure 5 presents a block diagram of the system.

The total number of particles was measured with CPC (Condensation Particle Counter) manufactured by TSI (model CPC 3022A). The sample was drawn from the same branch with ELPI and the sample flow was set to 1.5 lpm.

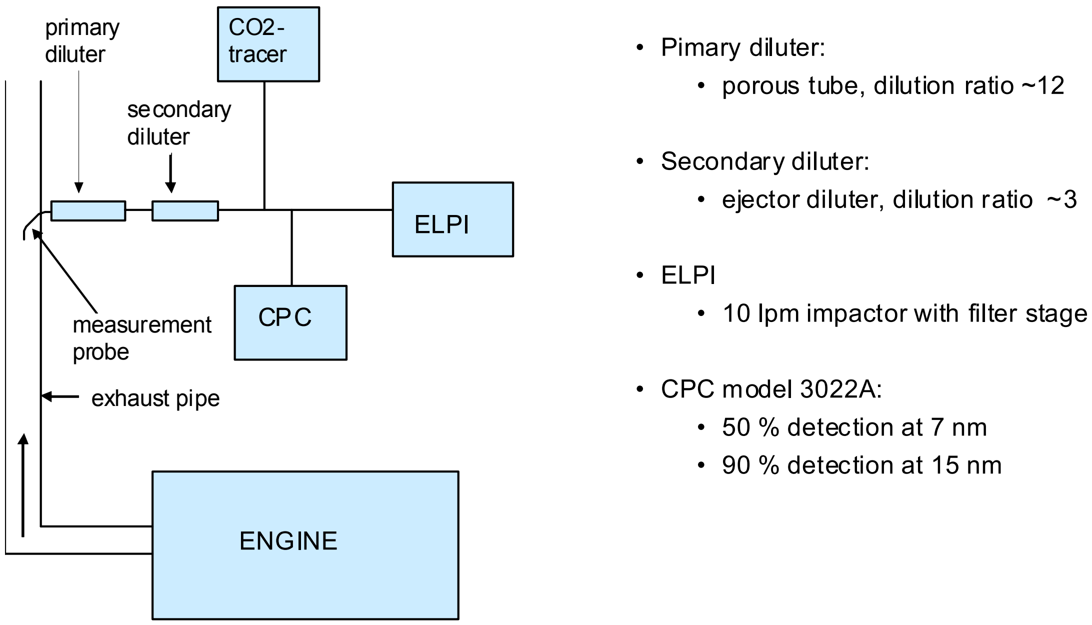


Figure 5. Schematic figure of VTT's particle number measurements.

3. Results with engines

Three engines were studied. One of those was SisuDiesel non-road engine, one was bus engine (Cummins Euro 4) and one was truck engine (Scania Euro 4). In total four measurement periods were carried out. Three of those concentrated on exhaust emissions, and one was a long-term test for oxidation catalyst with EN590 and RME fuels. Long-term test was carried out with Cummins engine. The results are presented separately for each measurement period. Numerical results are presented in the Appendices. The error bars in the Figures describe the standard deviation of the measurements unless otherwise noted.

3.1 Cummins bus engine, Euro 4 emission level

Measurements with Euro 4 emission level Cummins bus engine were carried out in June 2007. The fuels studied with Cummins engine were: EN590, GTL and RME. Cummins engine was originally equipped with the SCR system. However, in these tests SCR system was removed to study the DOC+POC system manufactured by Ecocat.

RME should have been used for determination of loads for the ESC test cycle, because RME was known to produce the lowest power output of the fuels tested. However, it was not possible to use RME due to delayed delivery of the fuel. Thus loads for the ESC test cycle were determined using EN590 fuel, and an estimation of 5 % was used to adjust loads for lower power output. However, the effect of RME on the maximum power output was underestimated: the power output with RME remained from 8 to 10 % lower than with EN590 and GTL fuels at 100 % load points (modes 2, 8 and 10). Power and torque in the other load modes of the ESC cycle were the same for each fuel (Table 9). After the test period the EN590 fuel was measured with the same power settings as RME. With EN590, there were no significant differences between emission results with different power settings.

The power and torque curves are presented in Figure 6. With RME, the power output decreased from 5 to 13 % compared to EN590. The power output with GTL and EN590 were basically the same.

3. Results with engines

Table 9. Loads of the ESC test cycle for EN590. GTL and RME fuels.

Mode	1	2	3	4	5	6	7	8	9	10	11	12	13
Speed	IDLE	A	B	B	A	A	A	B	B	C	C	C	C
Speed (1/min)	750	1437	1825	1825	1437	1437	1437	1825	1825	2212	2212	2212	2212
Power (%)	0	100	50	75	50	75	25	100	25	100	25	75	50
Power, (kW) EN590 and GTL	0.2	92	57	85	46	69	23	114	28	117	29	88	59
Power, RME (kW)	0.3	83	57	85	46	69	23	104	28	106	29	88	59
Torque, (Nm) EN590 and GTL	3	615	298	446	308	461	154	595	149	505	126	379	253
Torque, RME (Nm)	3	550	297	446	308	461	154	544	149	459	126	379	253
Weighing factor	0.15	0.08	0.1	0.1	0.05	0.05	0.05	0.09	0.1	0.08	0.05	0.05	0.05

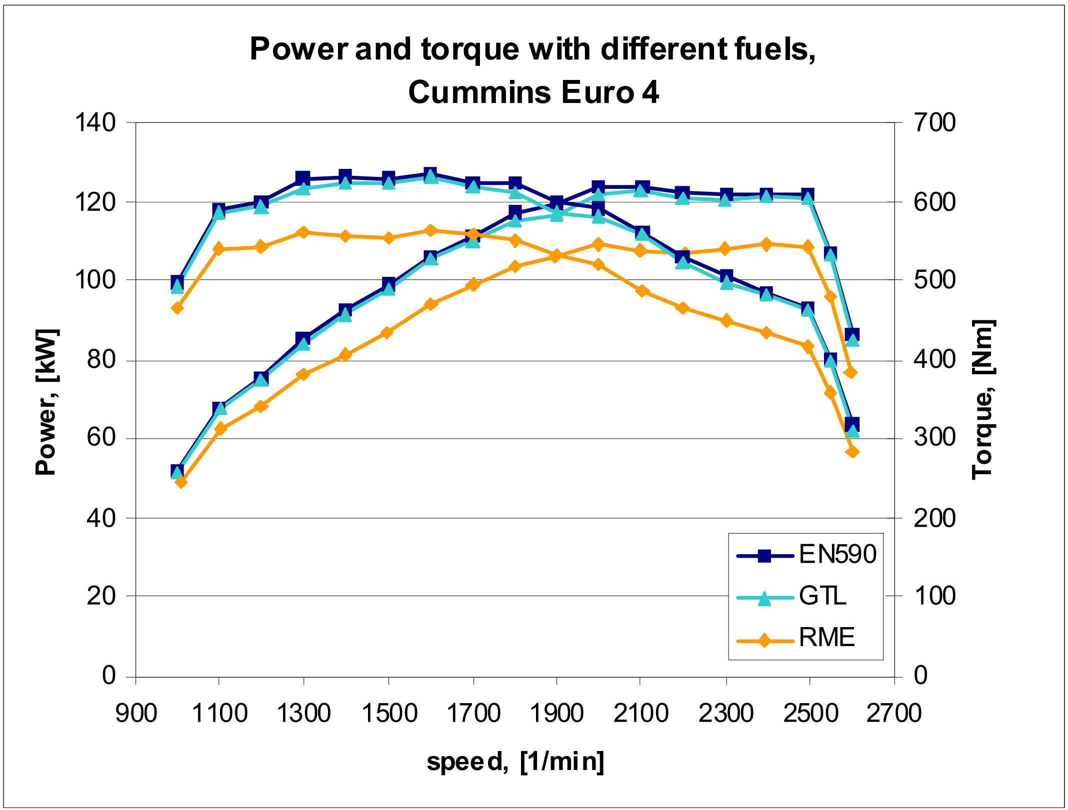


Figure 6. Power and torque curves with the EN590, GTL and RME fuels. Cummins engine.

3.1.1 Regulated emissions, CO_2 and fuel consumption

EN590 fuel was run before and after the testing period to study stability of the emission performance of the engine. The particulate matter emissions had shifted from 0.017 g/kWh to 0.019 g/kWh (13 %) and HC emissions from 0.07 g/kWh to 0.06 g/kWh (22 %). The relative change seems rather high, but changes in absolute terms are low.

Changes in other emissions stayed within 5 % over the test period (Table 10). The average emissions results presented in this report for EN590 fuel were calculated from the tests before and after the test period.

Table 10. Stability of Cummins engine during the test period. Results with the EN590 fuel before and after the measurement period.

	HC g/kWh	**CO** g/kWh	**NO_x** g/kWh	**NO** g/kWh	**PM** g/kWh	**CO_2** g/kWh	**FC** g/kWh
29.5.2007	0.07	0.64	10.0	5.9	0.017	642	208.0
2.7.2007	0.06	0.62	9.5	5.7	0.019	643	209.5
Change,%	-22	-4	-5	-4	13	0	1

When the HC, CO and PM emission results of Cummins engine are compared to the Euro IV emission limits, it can be seen that these emissions were within the limits for the ESC test. NO_x emission level was high, because SCR system was removed to allow tests with DOC+POC aftertreatment system (Table 11).

Table 11. Emission level of the Cummins engine without SCR-system with EN590.

	Measured value [g/kWh]	**EURO IV limit value [g/kWh]**
HC	0.07	0.46
CO	0.64	1.5
NO_x	9.84[a]	3.5
PM	0.017	0.02
CO_2	642	-
Fuel consumption	208	-

A NO_x emission cannot be compared to Euro 4 limit value, because the SCR system was removed to allow tests with DOC+POC aftertreatment system.

Regulated emissions, CO_2 and fuel consumption are shown in Figure 7, and relative differences between fuels in Figure 8. In the tests without catalyst, GTL decreased NO_x, PM, CO and HC emissions compared to EN590 fuel. The most significant reduction was observed for PM emission, which was 31 % lower with GTL than with EN590 fuel.

RME decreased other regulated emissions than the NO_x emissions when compared to EN590. NO_x emissions were 6 % higher with RME than with the EN590 fuel. RME had even greater effect on the PM and HC emissions than GTL. PM emissions decreased nearly 40 % and HC some 60 %.

The mass based fuel consumption and CO_2 emissions were lower with GTL than with EN590. This is due to differences in fuel properties: the hydrogen to carbon ratio, as well as heating value, is higher for GTL than for EN590. Density of GTL is lower than density of EN590, and thus volumetric fuel consumption with GTL was higher than with the EN590 fuel, namely 6 % higher. The CO_2 emission was the highest with RME. With RME, the mass based and volumetric fuel consumptions were 17 and 11 % higher compared to EN590. This is due to low heating value of RME.

Table 12 presents the fuel consumption on mass and volumetric basis with each fuel and also relative difference when GTL and RME are compared to EN590.

Table 12. Fuel consumption with different fuels in the tests without catalyst.

	Fuel consumption [g/kWh]	**Fuel consumption [dm^3/kWh]**	**Fuel density g/dm^3**	**Net heat of combustion MJ/kg**
EN590	208.4	0.248	840	43.2
GTL	204.1	0.263	777	43.8
RME	243.3	0.275	883	36*
Difference compared to EN590, [%]				
GTL	–2	6	–7	1
RME	17	11	5	–17

* typical value

The oxidizing aftertreatment system removed CO emissions completely with all fuels and the HC emissions decreased from 76 to 91 % (RME/EN590). With each fuel the PM emissions were roughly 30 % lower in the tests with catalyst when compared to the measurements without catalyst. However, the effect of fuel was still noticeable in the tests with catalyst. The PM emissions were some 30 % lower with GTL and RME than with EN590 in the tests with catalyst. The catalyst did not affect total NO_x emissions, but the share of NO_2 increased significantly. In the tests without catalyst, the share of NO_2 of NO_x emissions was between 7 and 14 % depending on the load mode of the test cycle. In the tests with catalyst the share of NO_2 increased from 47 to 78 %. Catalyst had no effect on fuel consumption or CO_2 emissions.

In Figure 8 the results measured with GTL and RME with catalyst are compared to results measured with EN590 without catalyst to find out the total potential of fuel and aftertreatment. When using catalyst and GTL or RME fuels, the PM emissions are 50 and 58 % lower than in the tests without catalyst using the EN590 fuel. At the same time, the HC emissions are reduced some 90 % and CO emissions are basically zero.

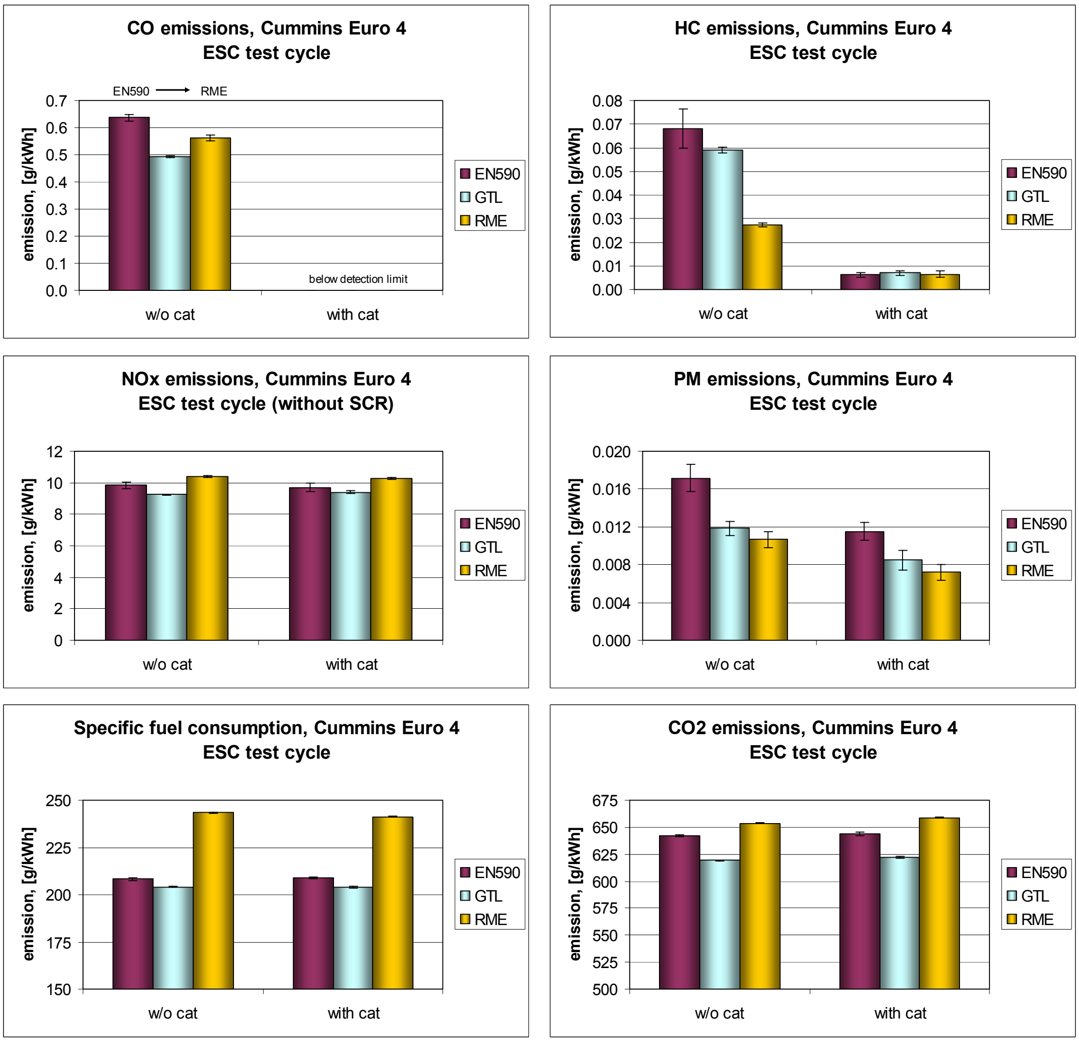


Figure 7. Regulated emissions, CO_2 emission and fuel consumption with Cummins engine using EN590, GTL and RME fuels. ESC test cycle.

3. Results with engines

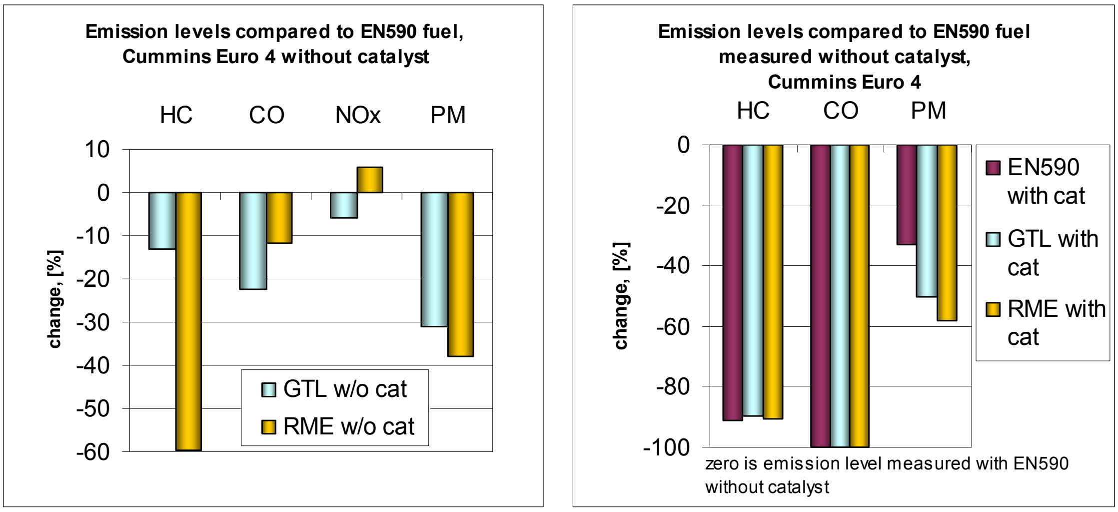
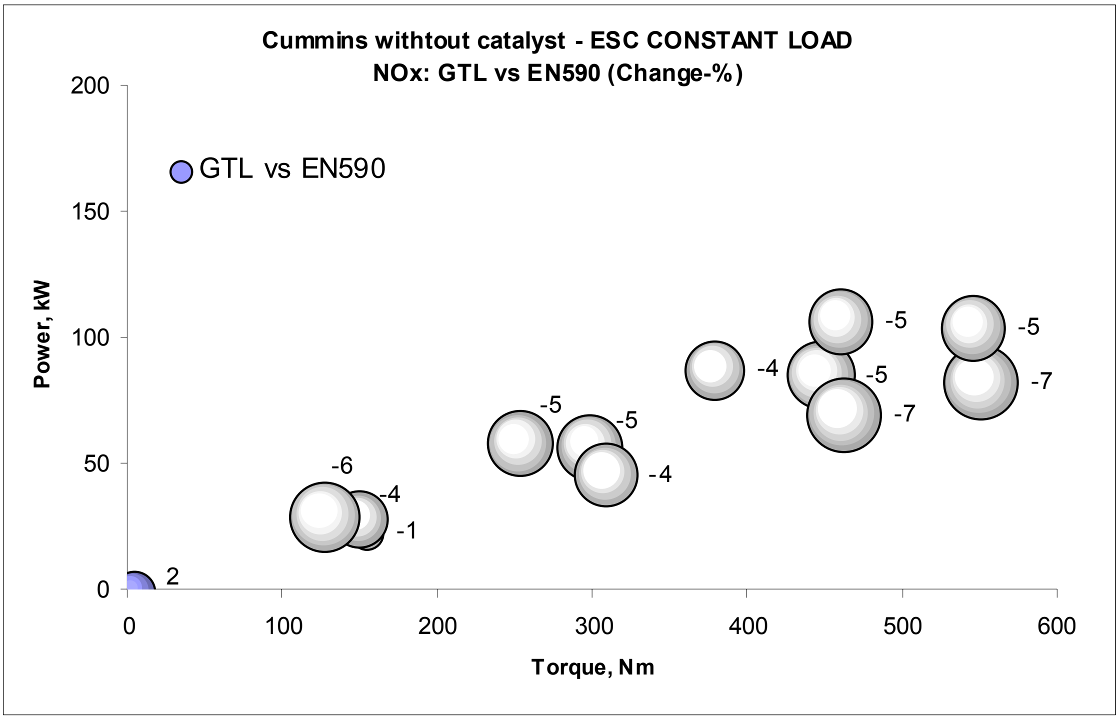


Figure 8. Changes in regulated emissions when GTL and RME are compared to the EN590 fuel. In the right-hand Figure the total benefit of oxidation catalyst and fuel can be seen. Cummins engine, ESC test cycle.

Figures 9 and 10 compare NOx emissions when GTL and RME are compared to EN590 in different load modes of the ESC test cycle. The effect of fuel on NOx emission is quite the same in different load modes in the tests with and without catalyst. The GTL reduces NOx emissions fairly equally on each lode mode. With RME the NOx emissions increase from 0 to 10 % on each load except on idle mode.



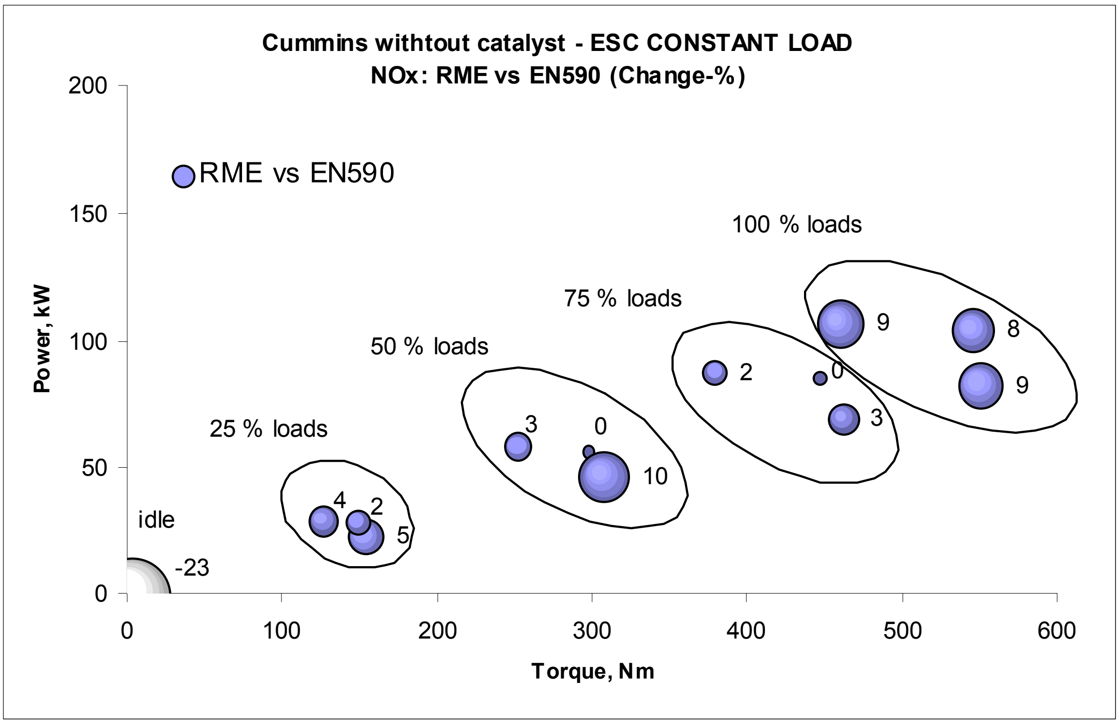
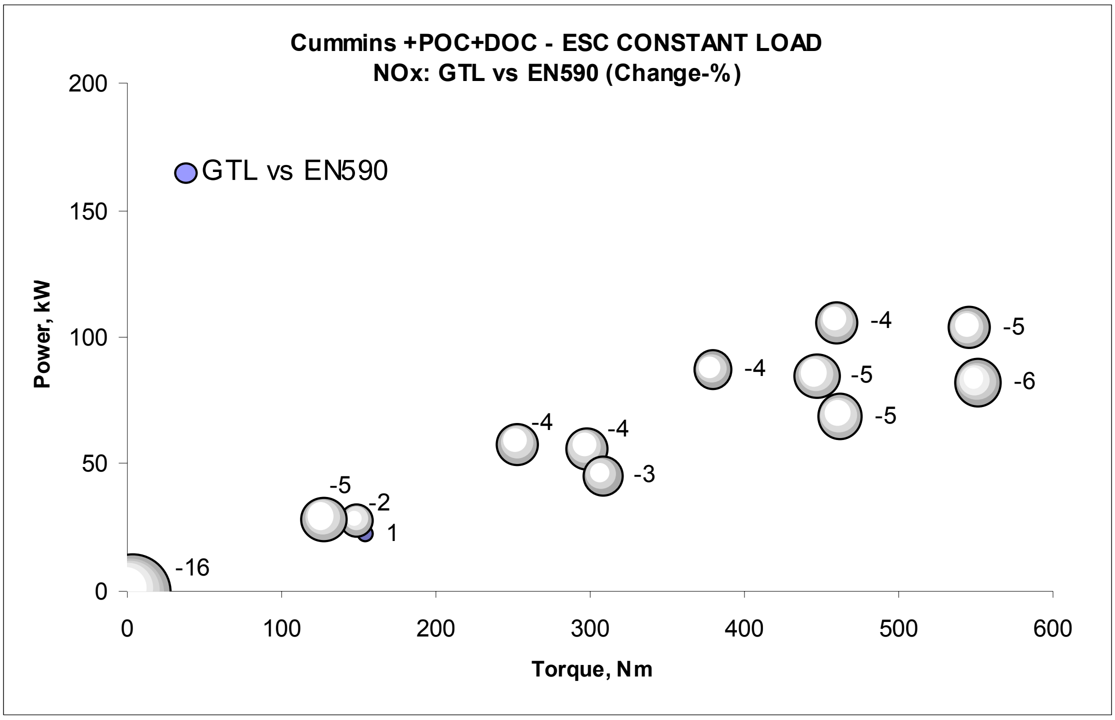


Figure 9. Changes in the NO_x emissions when GTL and RME are compared to the EN590 fuel on different modes of ESC test cycle. The number beside each “ball” indicates relative differences. Cummins engine without catalyst.

3. Results with engines



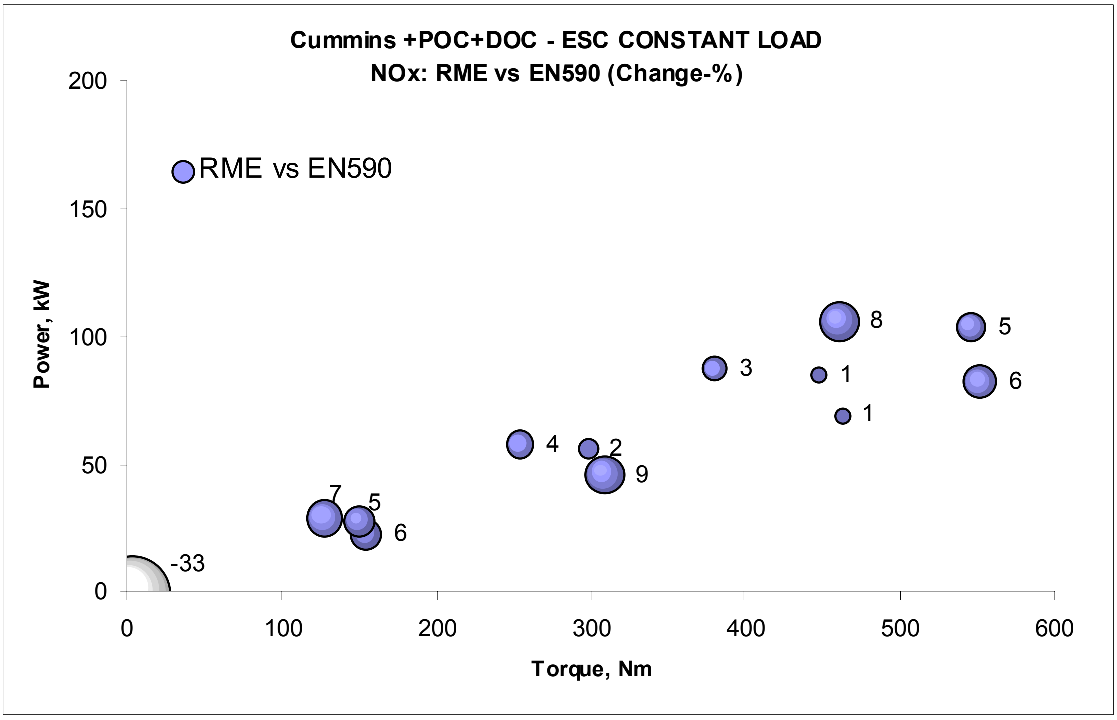


Figure 10. Changes in NO_X emissions when GTL and RME are compared to the EN590 fuel on different modes of ESC test cycle. The number beside each “ball” indicates relative differences. Cummins engine with catalyst.

Each fuel was also measured on four steady-state load conditions with and without catalyst. The gaseous emissions followed the same trend as presented on the previous Figures, and therefore only the PM emission results are presented in Table 13.

Table 13. Load modes and PM results of steady-state measurements.

ESC Mode	11	3	10	12
Speed (1/min)	2212	1825	2212	2212
Power (%)	25	50	100	75
PM results, (g/kWh)				
EN590 w/o cat	0.041	0.012	0.023	0.016
EN590 with cat	0.013	0.006	0.011	0.008
GTL w/o cat	0.025	0.009	0.013	0.010
GTL with cat	0.010	0.005	0.008	0.006
RME w/o cat	0.026	0.010	0.011	0.009
RME with cat	0.009	0.007	0.005	0.004

Figure 11 presents the PM emission changes with GTL and RME compared to EN590. Both fuels reduced PM emissions very efficiently and consistently on each load when measurements were made without catalyst. The highest reductions were on mode 10, which is the 100 % power at high engine speed. With both fuels the reductions were over 40 %. On mode 3 (intermediate engine speed, 50 % load) the reductions were lowest though still over 10 % (RME) and over 20 % (GTL).

In the tests with catalyst, the RME's effect on particulate matter emission was basically the same on modes 11, 10 and 12 than without catalyst. However, on mode 3 the PM emission was 5 % higher with RME compared to EN590. The GTL had smaller effect on PM emissions in the tests with catalyst than in the tests without catalyst when compared to EN590. The PM reductions were from 17 to 28 %.

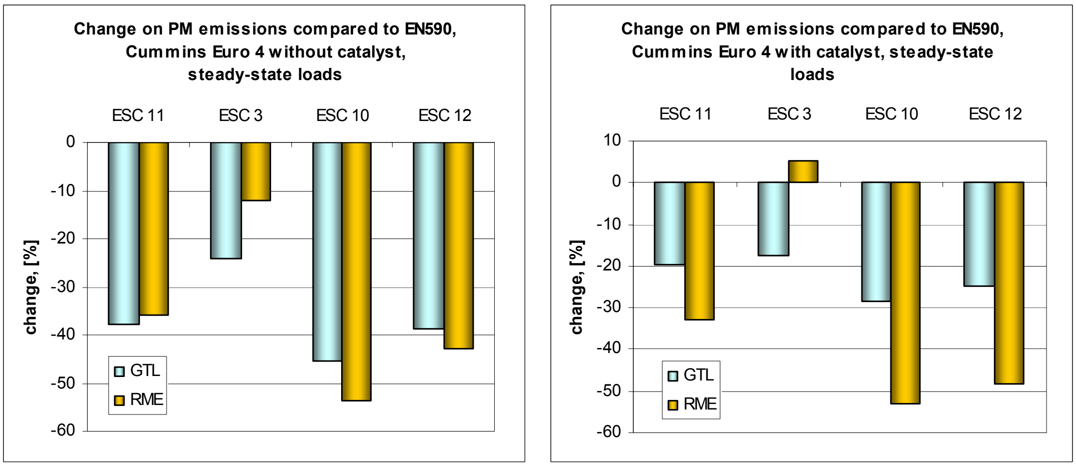


Figure 11. PM emissions with GTL and RME compared to EN590. Cummins engine with and without catalyst.

3.1.2 Aldehyde emissions

Aldehyde emission results from Cummins engine without aftertreatment are shown in Figure 12 and numerical results in Appendices. The aldehyde emission level of Cummins engine was very low. Formaldehyde and acetaldehyde were dominating compounds. Small portions of acrolein, propionaldehyde and valeraldehyde were also detected (0.2–0.5 mg/kWh).

EN590 fuel showed the highest aldehyde emissions and RME the lowest. With RME, the total aldehyde emissions were 25 % lower compared to EN590. With GTL the difference to EN590 fuel was 20 %, respectively. With each fuel the formaldehyde covered 64 to 68 % and acetaldehyde 20 to 22 % of the sum of aldehydes.

In the tests with catalyst the NO_2 concentrations were very high. Aldehyde samples are collected to DNHP cartridges, and reagent of the cartridge is not consumed only by aldehydes, but also by NO_2. In the tests with catalyst, NO_2 emissions were so high that the reagent of DNPH cartridges was completely consumed, and consequently, aldehyde analysis did not succeed. The NO_2 concentrations were so high that even though two cartridges were installed in series in the sampling line the reagent was consumed totally by NO_2.

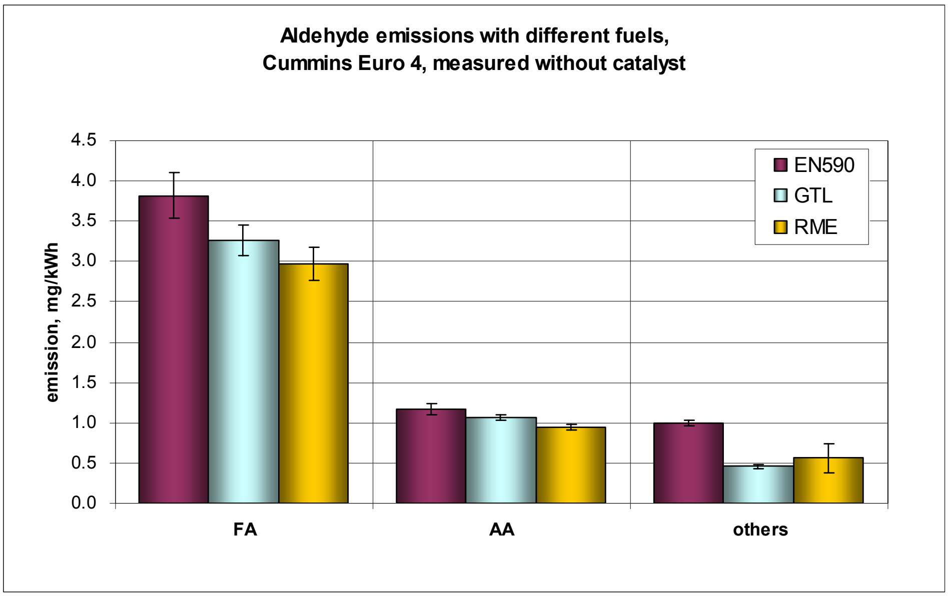


Figure 12. Aldehyde emissions using EN590, GTL and RME fuels. Cummins engine without catalyst.

3.1.3 PAH emissions associated with particulate matter and semivolatile fraction

The PAH emissions of Cummins engine were very low. The PAH emissions were the highest with the EN590 fuel and the lowest with RME. When the 7 priority PAHs (PAH7) are considered, the GTL fuel produces the lowest PAH emissions. The trend between fuels is the same in the tests with and without catalyst. However, the difference between EN590 and GTL is smaller in the tests with catalyst. The catalyst reduced total PAH emissions effectively. The effect of catalyst on PAH emissions were the highest with EN590 and the smallest with GTL. (Figures 13, 14 and 15.)

3. Results with engines

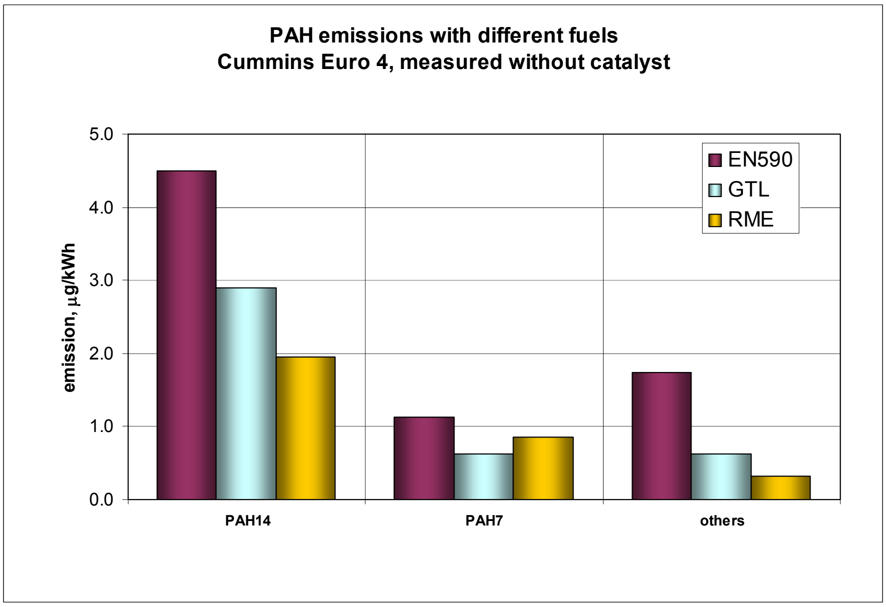


Figure 13. PAH emissions using EN590, GTL and RME fuels. Cummins engine without catalyst.

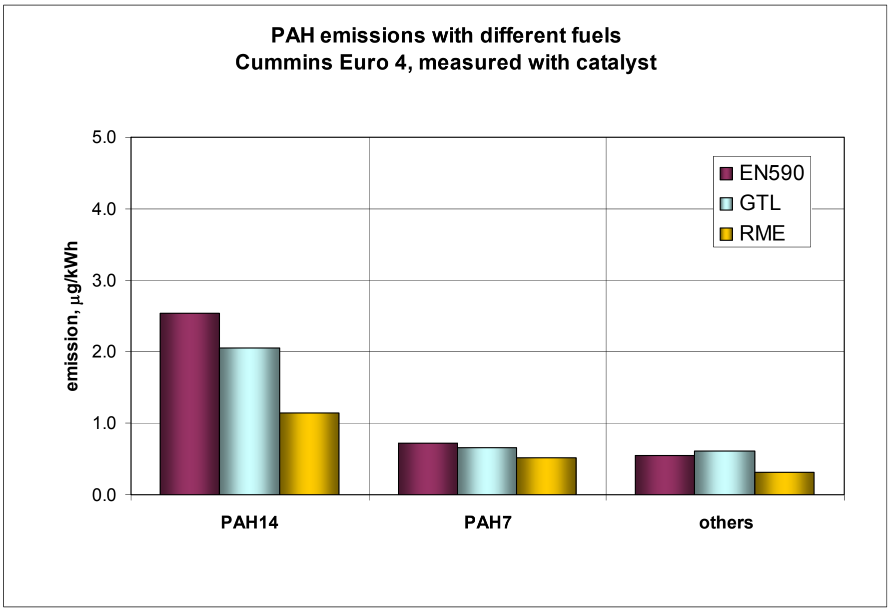


Figure 14. PAH emissions associated with particulate matter using EN590, GTL and RME fuels. Cummins engine with catalyst.

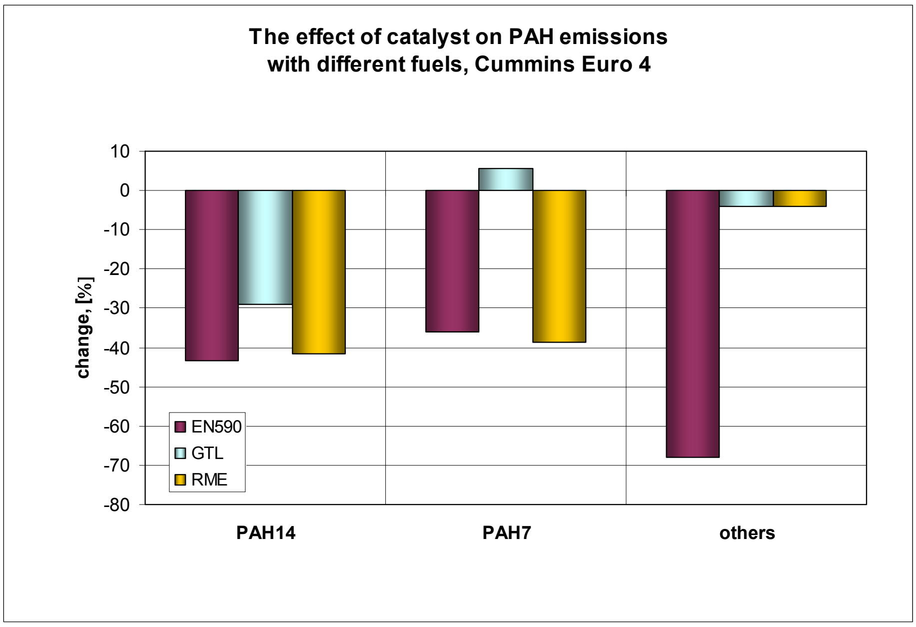


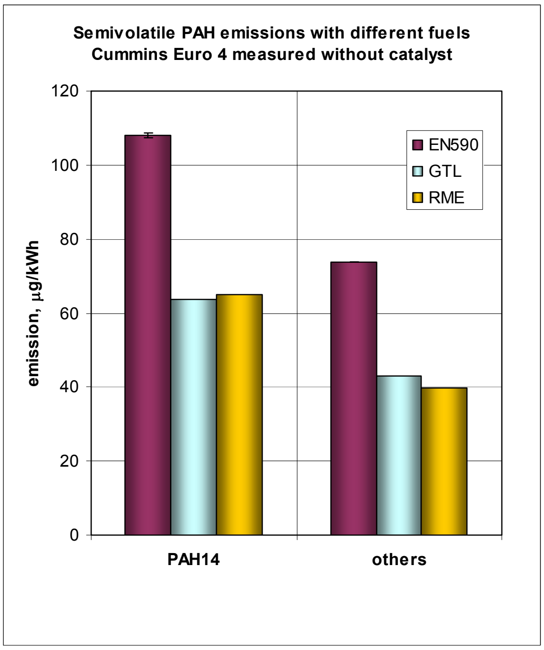
Figure 15. The effect of the catalyst on the PAH emissions associated with particulate matter. Cummins engine.

The amount of total semivolatile PAHs were much higher than the total PAHs analyzed from particulate matter samples. However, the amount of the seven priority PAHs were basically zero with EN590 and RME in the semivolatile fraction. With GTL, some heavy PAHs included in the list of 7 priority PAHs were detected, but the levels were insignificant. Therefore the sum of 7 priority PAHs is not presented in the Figures.

In the tests without catalyst, the sum of 14 PAHs from the semivolatile fraction, as well as the sum of other PAHs analysed, decreased some 40 to 46 % with GTL and RME when compared to EN590 (Figure 16). When measured with catalyst, the difference between GTL and EN590 was lower. However, GTL still showed 27 and 21 % (PAH14/others) lower PAH-emissions than the EN590 fuel.

In the tests without catalyst, the EN590 produced three times higher emission of phenanthrene (45 µg/kWh) and fluorene (16 µg/kWh) compared to GTL and RME. With catalyst those compounds had significantly lower emission levels with EN590. The catalyst dropped down semivolatile PAH emissions by 30 % with EN590 and RME fuels and 11 % with GTL (Figure 17).

3. Results with engines



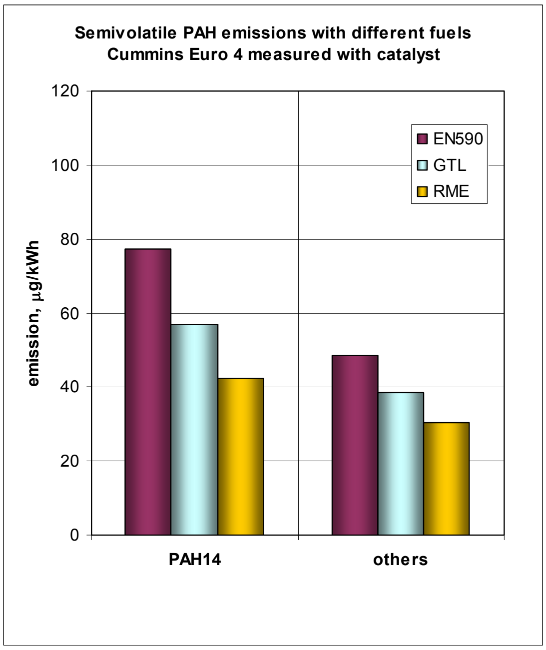


Figure 16. Semivolatile PAH emissions using EN590, GTL and RME fuels. Cummins engine without catalyst in the left-hand side and with catalyst in the right-hand side.

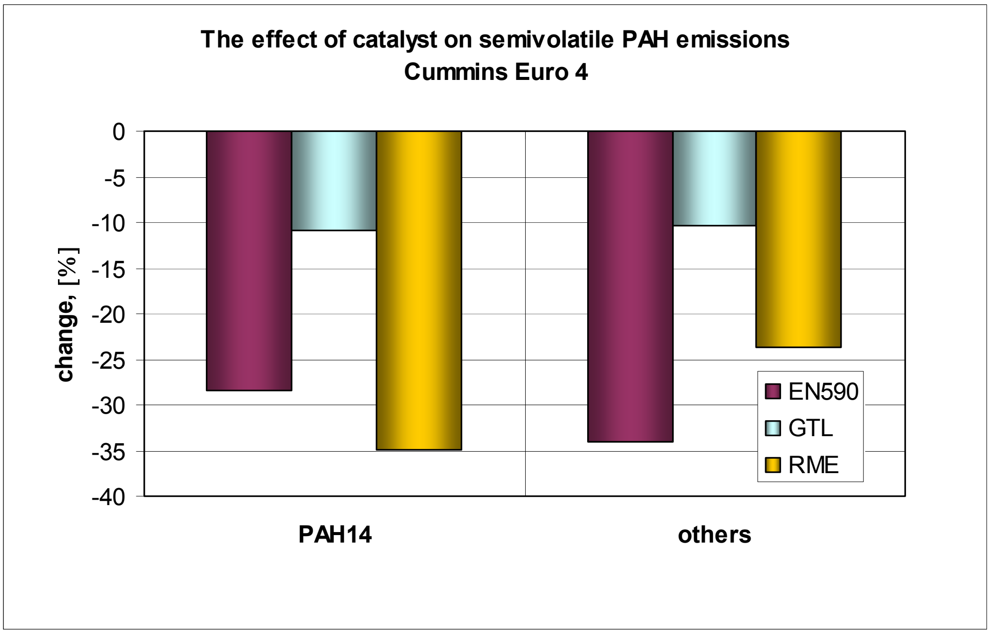


Figure 17. The effect of catalyst on semivolatile PAH emissions with Cummins engine.

3.1.4 Particle number emissions

Particle number size distributions were measured with ELPI and the total number of particles was determined with CPC. The shape of the size distribution varied between fuels. RME was the only fuel showing bimodal number size distribution having a clear nucleation mode and a small peak on soot mode at 80 nm. The particle size distributions with the GTL and EN590 fuels did not show nucleation mode. However, in the tests without catalyst for the GTL fuel, peak of the number size distribution was at lower size class, around 40 nm, than for EN590. The number of nanoparticles below 80 nm was higher with the GTL fuel than with the EN590 fuel (Figure 18).

In the size class above 100 nm, the EN590 fuel showed the highest number of particles and RME the lowest number, which is in accordance with the particulate mass results. Accumulation mode particles are the most determining as regard the particulate mass emissions.

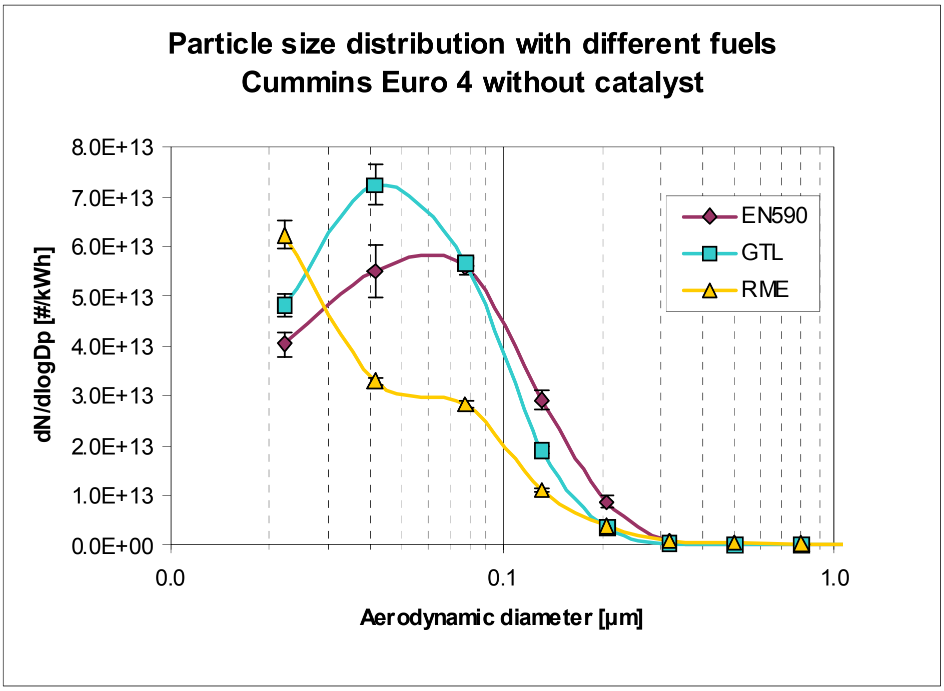


Figure 18. Particle size distributions with EN590. GTL and RME fuels. Cummins engine without catalyst.

With each fuel, the catalyst decreased significantly the number of particles on each size class, and with RME the nucleation mode particles were removed completely. Also with GTL the catalyst removed very efficiently particles below 80 nm size classes (Figure 19).

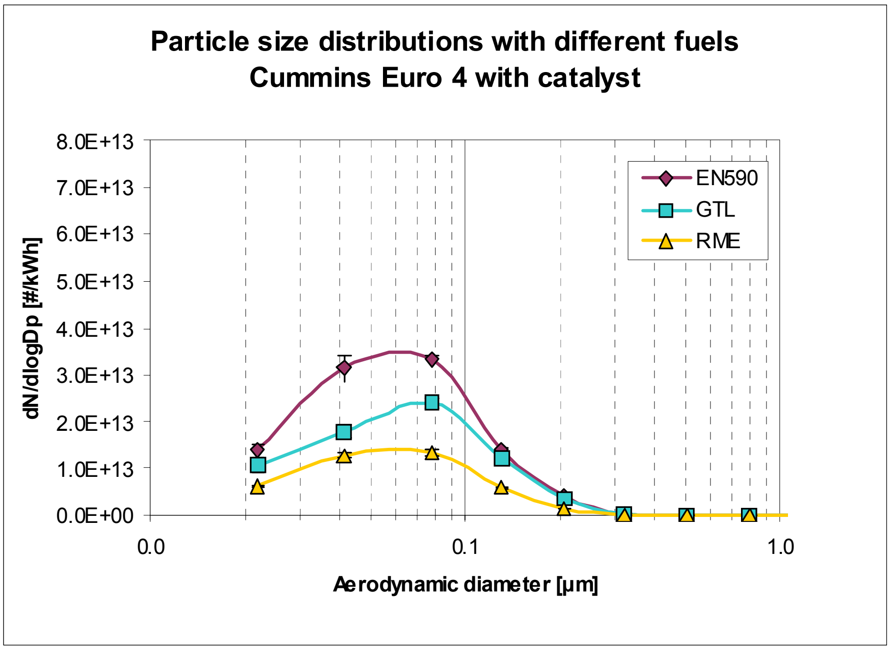


Figure 19. Particle size distributions with EN590. GTL and RME fuels. Cummins engine without catalyst.

When comparing the total number of particles measured with CPC the results show same trend as the total particle numbers measured with ELPI. In the tests without catalyst, GTL produces 9 % more particles compared to EN590 and 34 % more compared to RME. In the tests with catalyst, the number of particles decreased from 63 to 72 % when compared to the tests without catalyst depending on fuel. When catalyst was used, the EN590 showed the highest number of particles and RME the lowest number of particles (Figure 20).

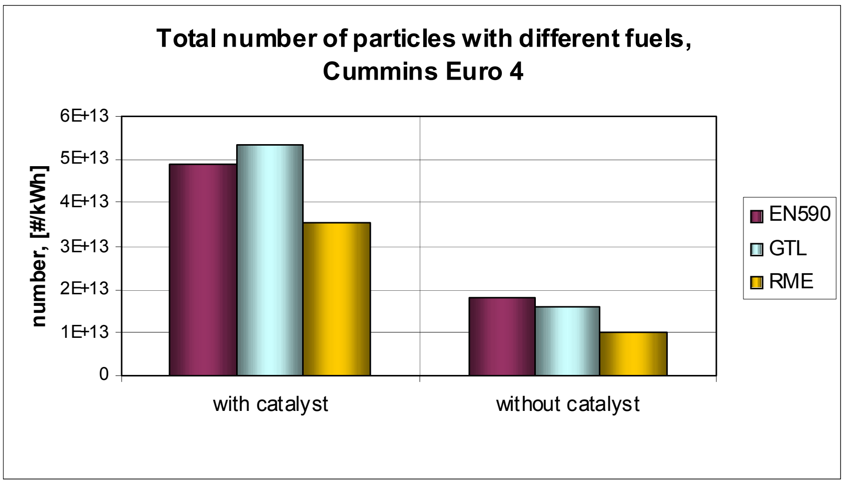


Figure 20. The total number of particles with EN590, GTL and RME fuels. Cummins engine with and without catalyst.

3.1.5 Cummins bus engine, long term test

Long term test was carried out with Euro IV emission level Cummins bus engine, which was equipped with Ecocat DOC catalyst. Long-term test was run with EN590 and 100 % RME fuels, 350 hours each. Identical DOC catalysts were used for both fuels. The regulated emissions were measured four times during the test period with both fuels: at the beginning, at 100 h, at 200 h and at the end. Each time two emission tests were performed.

Before the first emission test, both catalysts were run four hours at load 500 Nm / 1825 min^{-1} (exhaust temperature over 400 ºC). The emission levels of the engine without catalyst were measured at the beginning and at the end of the period to find out if the engine's emission levels had been changed (Table 14).

Table 14. Engine emission over the long term -test.

	HC [g/kWh]	CO [g/kWh]	NO_X [g/kWh]	CO_2 [g/kWh]	FC [g/kWh]	PM [g/kWh]
At the beginning of the 1st period	0.05	0.72	10.1	620	208	0.018
At the end of the 1st period	0.05	0.93	10.2	625	209	0.022
At the beginning of the 2nd period	0.05	0.86	10.2	631	210	0.023
At the end of the 2nd period	0.05	0.85	9.5	629	210	0.021

The emission test showed that the engine out HC and CO emissions increased over the entire test period roughly 10 and 20 %. The NO_x emission level dropped some 6 % during the test period with RME. PM emissions increased some 25 % during the test period though it needs to be mentioned that the absolute PM emission level was rather low and therefore the relative change in PM emission was rather high.

The engine lubricant was changed after the first 350 hours and new lubricant was aged for 40 hours using ESC test cycle. After ageing of the lubricant, the engine's emission level was checked again. The change of the lubricant did not affect the engine emissions. The complete measurement matrix is presented on Table 15.

The main engine and test cell parameters were recorded at 0.1 Hz interval over the test period. The recordings show that no significant changes occurred over the complete test period. The gaseous emissions were recorded on daily basis over one ESC test cycle.

Table 15. Emission tests matrix.

Test period hours	After-treatment	Fuel
0	-	EN590
+4	catalyst 1	EN590
+100	catalyst 1	EN590
+200	catalyst 1	EN590
+350	catalyst 1	EN590
+350	-	EN590
Lubricant change, 40 hours ageing		
0	-	EN590
0	-	RME
+4	catalyst 2	RME
+85	catalyst 2	RME
+200	catalyst 2	RME
+350	catalyst 2	RME
+350	-	RME
+350	-	EN590

The following results were obtained in the 350 hours long term-test:

- When using EN590 fuel, the catalyst reduced HC emission 82 % before the long-term test and 69 % after the test period. Reduction in CO was 91 % before and 92 % after the test. Reduction in PM was 36 % and 21 %, respectively.
- When using RME, reduction in HC emission was 66 % before the test and 26 % after the test period. Reduction on CO was 93 % and 48 % and on PM 41 % and 27 %, respectively.
- The average backpressure caused by catalyst increased with EN590 17 % whereas some 28 % with RME. The average backpressure over the ESC test cycle at the beginning of test periods was 14 mbar with both fuels.

The results clearly show that the catalyst's HC and CO conversion ratios decreased faster with RME than with EN590 fuel. The fuel did not affect the conversion ratio of particulate matter emission (Figures 21 and 22).

RME is different from diesel fuel in many respects. RME contains high-boiling compounds such as triglyserides and glycerine, and metals such as sodium, potassium and phosphorus. In this batch of RME, the highest concentrations were observed for potassium, silicon, tin, and sodium, altogether 4.6 mg/kg (different batch than in Table 1). Metal analysis was not carried out for EN590 batch used in the long-term test. Sum of potassium, silicon, tin, and sodium was below 1.2 mg/kg for another EN590 batch (Table 1). High-boiling compounds and metals may accumulate in the catalyst and decrease efficiency.

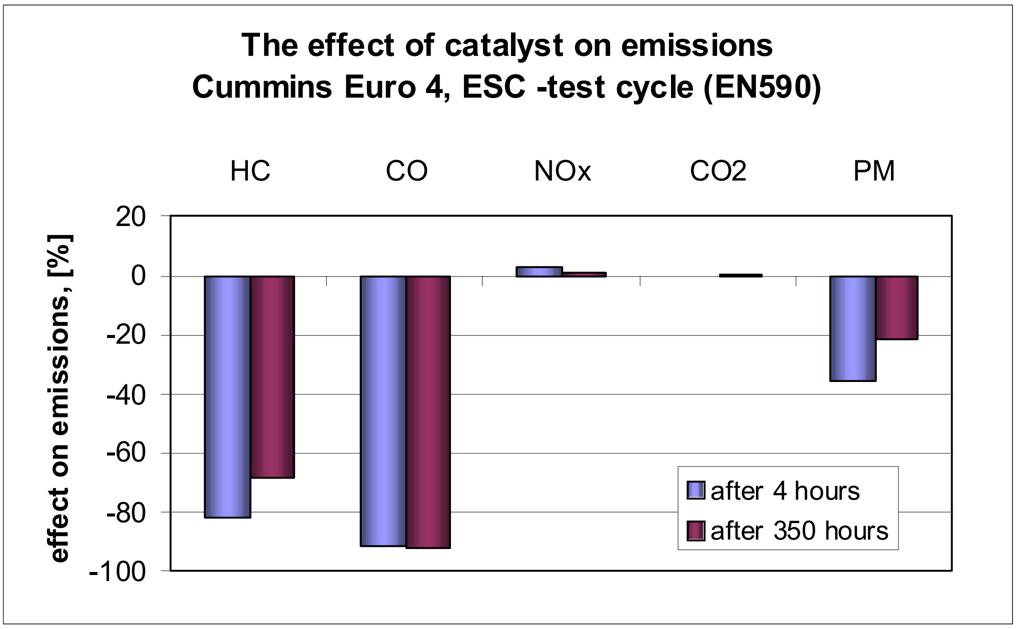


Figure 21. The effect of catalyst on emissions in the long-term test using EN590 fuel. Results achieved in the tests with catalyst are compared to results achieved in the tests without catalyst using the EN590 fuel. Cummins engine.

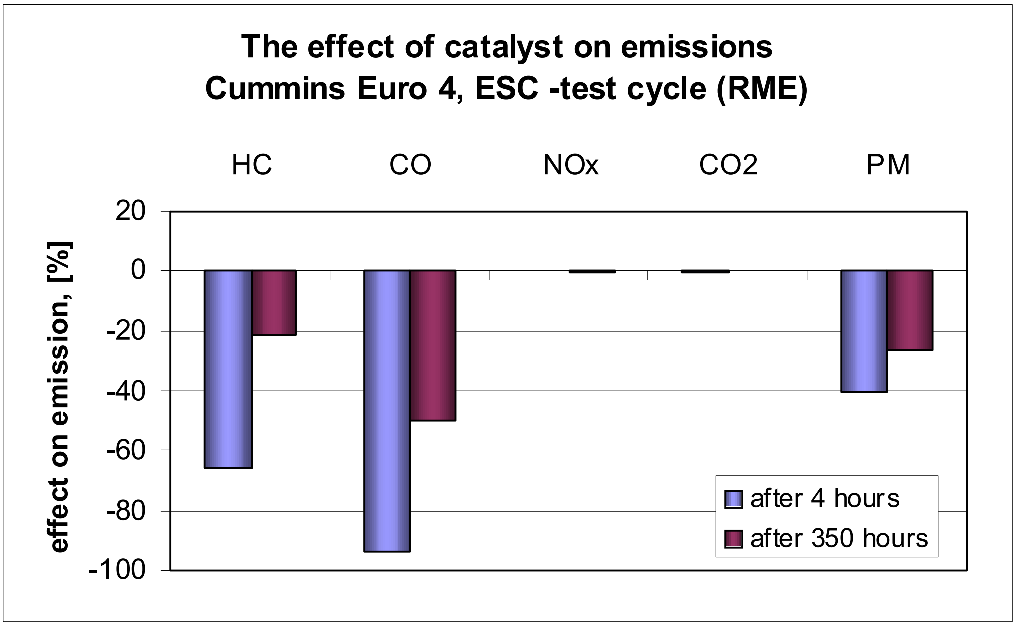


Figure 22. The effect of catalyst on the emissions in the long term using the RME fuel. Results achieved in the tests with catalyst are compared to results achieved in the tests without catalyst using RME fuel. Cummins engine.

3.2 Scania truck engine, Euro 4 emission level

3.2.1 Regulated emissions, CO_2 and fuel consumption

Scania engine was tested with six fuels without exhaust gas aftertreatment devices and with three fuels with catalyst. The emissions were measured over the Braunschweig test cycle, as well as on three steady-state loads with selected fuels. The Braunschweig test cycle is normally used for city bus measurements on chassis dynamometer.

The emission level of the engine was checked with the EN590 fuel at the beginning and at the end of the measurement period. Table 16 shows that the emission level was stable for CO, NO_x and PM emissions. The HC emission had increased by 30 % over the measurement period. The average results presented in this report for EN590 fuel include the tests before and after the test period.

Table 16. Emissions before and after the measurement period. Scania engine.

	CO g/kWh	HC g/kWh	NO_X g/kWh	CO_2 g/kWh	PM g/kWh	Fuel comsump. g/kWh
At the beginning	0.64	0.17	5.99	697	0.031	228
At the end	0.66	0.23	5.88	688	0.032	228
Change,%	3	30	–2	–1	1	0

Figures 23 and 24 present the emission results. In the tests without aftertreatment, the NExBTL and GTL decreased CO emissions close to 25 % and HC emissions by 11 % (GTL) and 35 % (NExBTL) compared to EN590 fuel. The RME had no effect on the CO emissions, but it significantly decreased the HC emissions (60 %). The 30 % NExBTL and RME blends decreased the HC emissions by 20 %. NExBTL blend decreased also CO emissions by 12 %.

The NO_x emissions increased some 5 % with GTL and NExBTL. With RME the NO_x emission raised over 10 %. For RME it is typical that NO_x emissions are higher than with conventional diesel fuel. In the opposite, for GTL and NExBTL this was unexpected as these fuels generally show decrease in NO_x emission when compared to conventional diesel fuel. With 30% blends, the NO_x emissions did not change significantly. Unexpected NO_x results are discussed in Chapter 3.2.2.

The PM emission reduced significantly with GTL and NExBTL fuels. With NExBTL, the PM emissions decreased by 44 % and with GTL by 51 %. With 30 % NExBTL blend the decrease in PM was 17 %. With RME, PM emission increased nearly 40 %, which is rather unusual. With 30 % RME blend, PM emission increased by 7 %. Discussion on unexpected PM results with RME is in Chapter 3.2.2.

The CO_2 emissions decreased with GTL and NExBTL some 5 %, and mass-based fuel consumption decreased slightly over 2 % when compared to EN590. With RME, the CO_2 emissions increased 4% and the mass-based fuel consumption increased even 17 %. The volumetric fuel consumptions increased with each fuel compared to EN590. With NExBTL and GTL the increment was some 5 % and with RME 11 %.

The engine with DOC+POC aftertreatment system was measured with three fuels (EN590, NExBTL, RME). The HC emissions dropped to zero and CO emission reductions were slightly over 90 % with DOC+POC system for each fuel. The PM emission reductions with the catalyst were significant: with EN590 from 57 % to 77 % (NExBTL/RME). The aftertreatment system did not affect CO_2, NO_x or fuel consumption results.

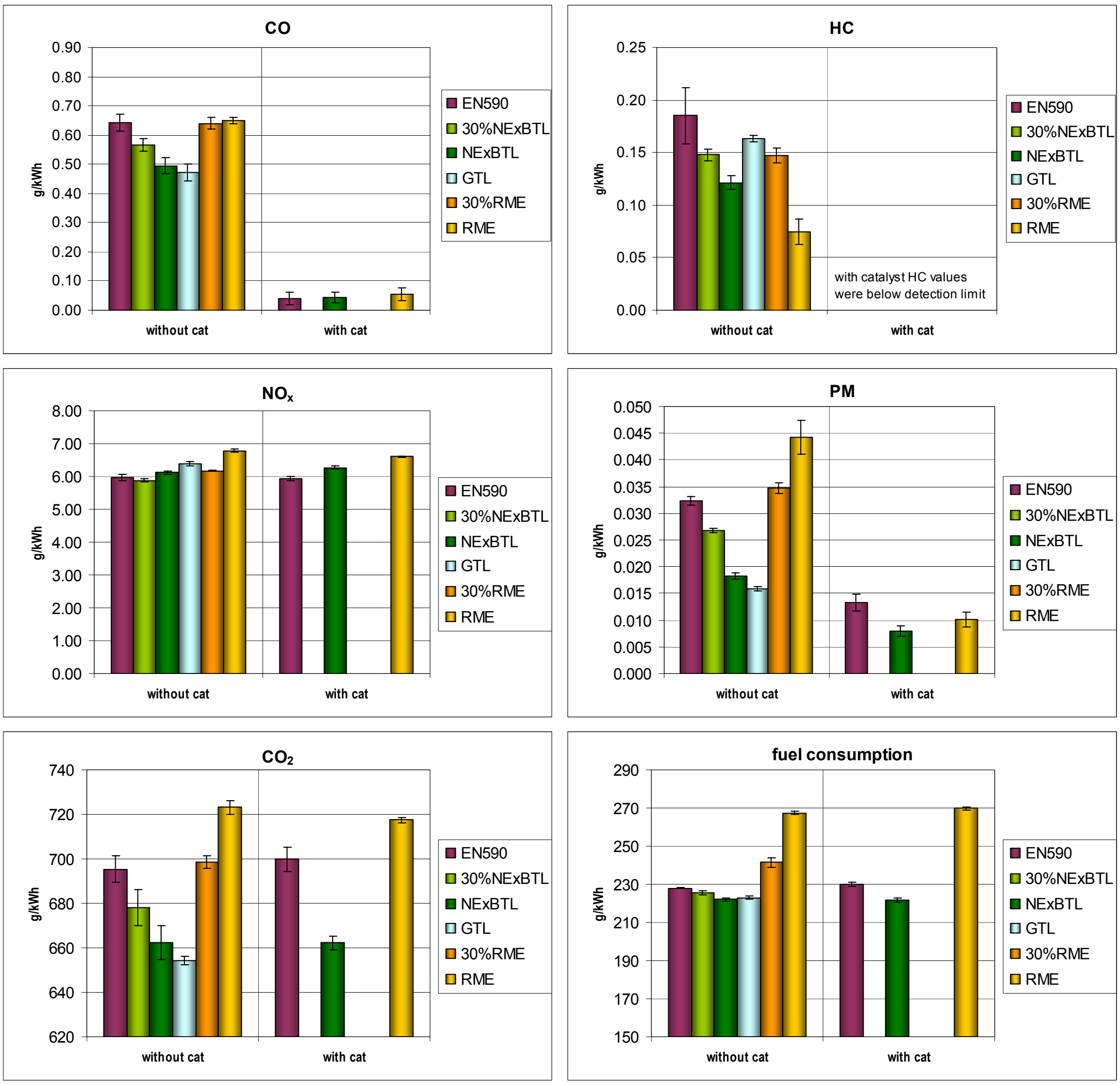


Figure 23. Regulated emissions, CO_2 and fuel consumption with Scania engine with and without catalyst. Braunschweig test cycle.

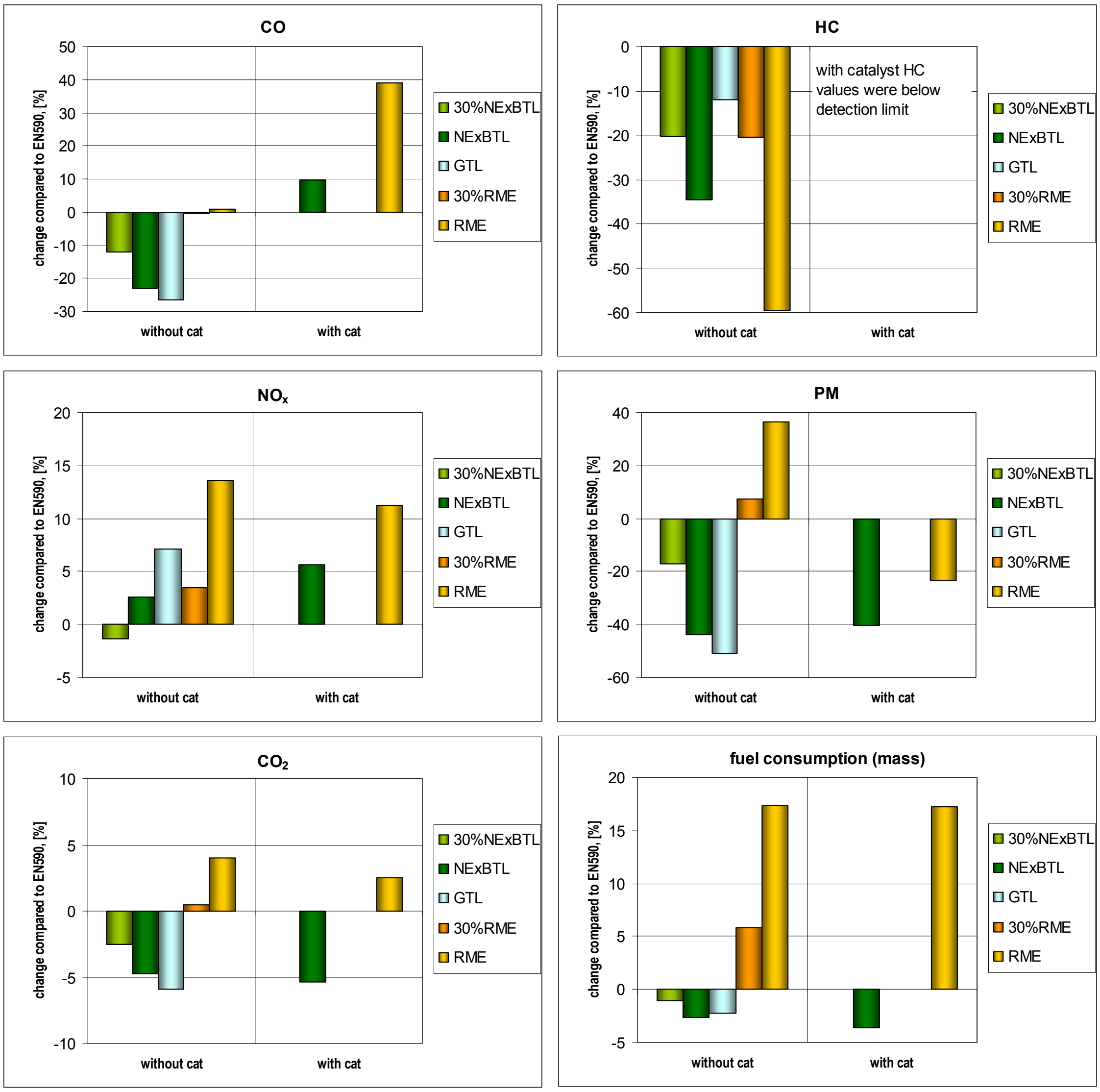


Figure 24. Regulated emissions, CO_2 and fuel consumption with Scania engine with and without catalyst. Braunschweig test cycle.

With Scania engine, three different steady-state loads were measured. Loads were selected from ESC test cycle to cover low, medium and high load conditions. Table 17 presents the load points and Table 18 the emission values with EN590. Particle number emissions are presented in chapter 3.2.6.

Table 17. Loads selected for the steady-state tests with the Scania engine.

ESC-mode	Speed rpm	Torque Nm	Power kW	Exh. gas temp. before catalyst °C
Mode 11	1950	290	59	~ 250
Mode 3	1600	863	145	~ 300
Mode 10	1950	1373[1)]	280*	~ 380 [2)]

[1)] With RME the torque and power values were 14% lower.
[2)] With RME ~ 350 °C.

Table 18. Emission results in the steady-state tests with the Scania engine using EN590 fuel (without catalyst).

ESC-mode	CO g/kWh	HC g/kWh	NO_X g/kWh	CO_2 g/kWh
Mode 11	1.00	0.42	2.9	853
Mode 3	0.19	0.14	3.5	585
Mode 10	0.31	0.12	3.7	593

In Figure 25 the results with NExBTL and RME are compared to the results with EN590. With NExBTL, the CO and HC emissions decreased consistently on each mode. It seems that the effect of high cetane number of NExBTL is emphasized on lower loads when observing HC and CO results. The effect of NExBTL on the NO_x emissions on mode 3 was negligible, and on the other two modes NExBTL increased NO_x emissions by 3 and 4 %. The CO_2 emissions decreased roughly 5 %.

For the HC emissions, RME showed the same trend as NExBTL, though the reduction in HC emission was slightly lower. The CO emissions on mode 3 were 66 % higher when RME was compared to EN590. On mode 3 RME had over 10 % lower NO_x emissions than EN590. On the other modes the NO_x emissions were 10 and 6 % higher with RME compared to EN590. The CO_2 emissions were from 4 to 8 % higher with RME.

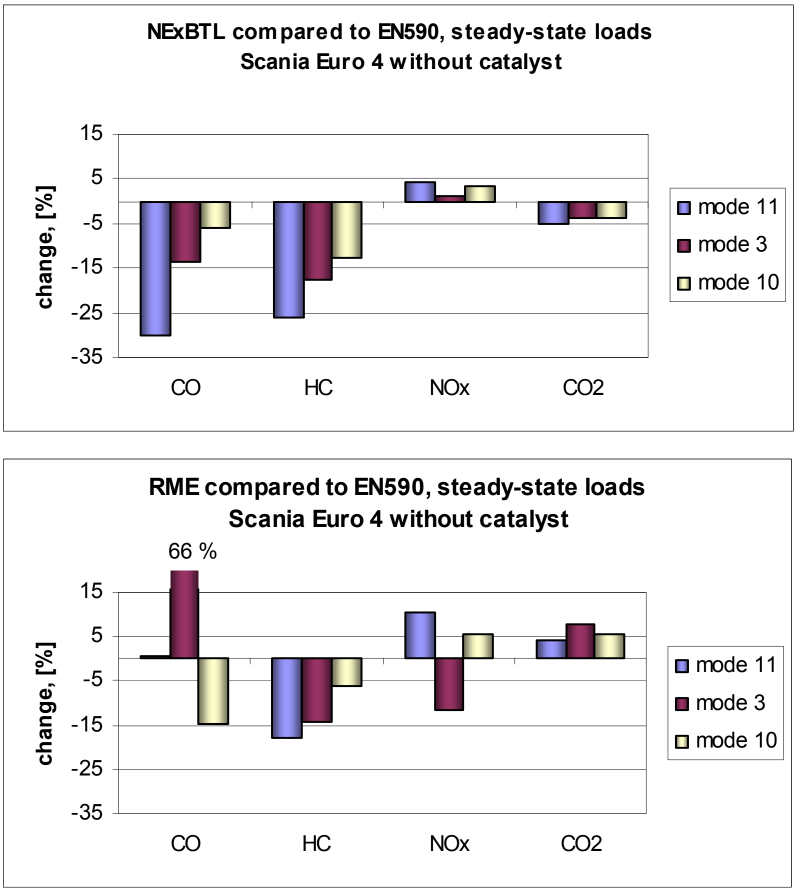


Figure 25. Changes in emissions when NExBTL and RME are compared to the EN590 fuel. Scania engine without catalyst.

In the tests with catalyst the HC emissions decreased by 88–97 % compared to tests without catalyst depending on fuel and load mode. The CO emission was basically zero in the tests with catalyst. The catalyst changed the NO/NO_2-ratio of total NO_X emissions significantly on modes 3 and 10. On mode 11 there was only slight change in NO_2 emissions due to lower exhaust gas temperature. (Ambs & McClure 1993.)

Figure 26 presents the trend of increasing NO_2 emissions due to the catalyst when using the EN590 fuel. With NExBTL and RME the trend was similar, though with RME the increment of NO_2 was lower at 100 % load than with other fuels. This is probably caused by lower exhaust gas temperature with RME. Numeric results are presented in Table 19.

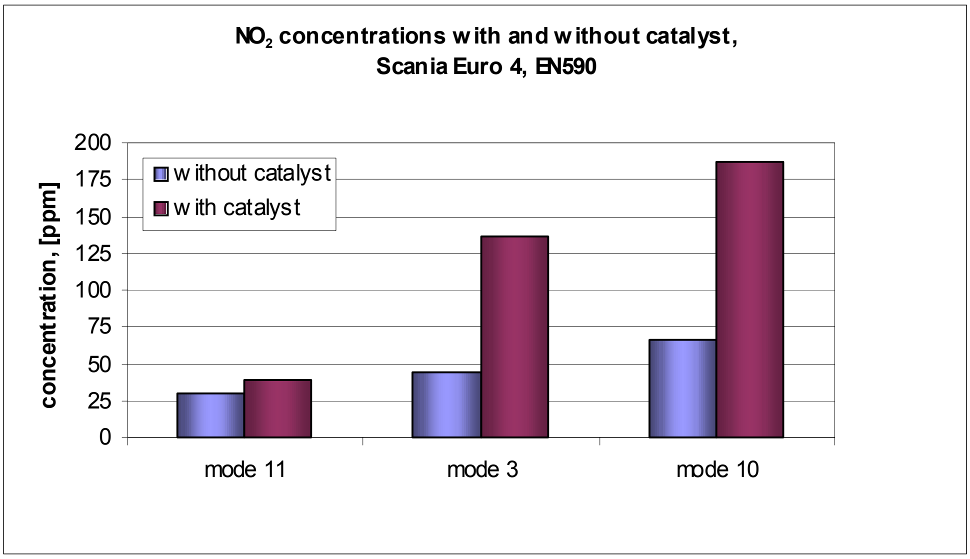


Figure 26. NO_2 concentrations in the exhaust gases from Scania engine with and without catalyst.

Table 19. The share of NO_2 of total NO_X emissions. Scania engine.

		without catalyst			with catalyst		
		NOx	NO2	share of NO_2	NOx	NO2	share of NO_2
Mode	Fuel	ppm	ppm	%	ppm	ppm	%
mode 11	EN590	148	30	20	163	39	24
mode 3	EN590	349	45	13	373	137	37
mode 10	EN590	439	67	15	468	187	40
mode 11	NextBtl	161	32	20	171	36	21
mode 3	NextBtl	360	50	14	392	124	32
mode 10	NextBtl	458	73	16	492	199	41
mode 11	RME	165	26	16	167	29	17
mode 3	RME	300	39	13	306	95	31
mode 10	RME	428	60	14	424	143	34

3.2.2 Discussion on NO_X and PM emissions

With Scania engine, two unexpected phenomena were seen: higher NO_x emission with the paraffinic fuels and higher PM emission with the RME fuel when compared to the EN590 fuel.

Several explanations for abnormally high NO_X emissions with paraffinic fuels were explored: the role of density/EGR, the effect of engine parameters on NO_X/PM trade-off curve, low load test cycle and the effect of fuel density and viscosity on fuel injection system. For light-duty cars, higher NO_X emission with GTL than with conventional diesel fuel has been reported by Clark et al. (2006). In this case, they thought that the reason was lower EGR rate with low-density fuel. One explanation might be related to the

NO_X/PM trade-off curve, which has been studied by Aatola et al. (2008). If engine parameters change unintentionally with new fuel, e.g. due low density, this may lead to conditions which favour low particles / high NO_X emissions. Unexpected results might be related also to the low average load of Braunschweig cycle. However, this theory is not supported because NO_X emissions with NExBTL were higher than with the EN590 fuel also at high loads in the steady-state tests.

When considering the high PM emissions with RME, one possible explanation might be related to RME's high density and flat distillation curve at high boiling range. It is well-known that RME tends to increase the amount of unburned hydrocarbons condensed on particles, which may lead to high PM emissions especially at low temperatures and at low loads. The rather low average load might bring up excessive formation of SOF in particulate matter (Figure 27). The EGR decreases combustion temperatures and this combined to the SOF formation may lead to the high PM emissions with RME. On the other hand, if low density fuel decreases EGR rate, high density fuel might increase EGR rate.

Overall, an important issue concerning unexpected results with this Scania engine is the fact this engine is not similar to buses and bus engines tested. Cylinder volume of Scania truck engine was 12 liters, whereas buses in the tests were 9 liters models. The 12 liters Scania truck engine may be adjusted differently than 9 liters bus engines. In addition, there probably are also other differences between bus and truck engines even if they represent same generation.

3.2.3 Composition of particulate matter (SOF, SO_4 and NO_3)

The soluble organic faction of particulate mass was analysed from particulate mass collected on 70 and 142 mm filters. The rate of SOF varied from 22 to 74 % with different fuels when no catalyst was used. With the RME and RME blend the share of SOF was 74 and 54 % while for the other fuels the share of SOF was less than 40 % (Figure 27).

With DOC+POC aftertreatment the share of SOF dropped significantly especially with RME (Figure 28). RME contains heavy hydrocarbons, which do not burn completely during combustion and tend to condense on particles. Since the oxidation catalyst efficiently removes unburned hydrocarbons, the SOF content of particulate matter obtained with RME fuel drops dramatically with catalyst. With the other fuels the effect of catalyst is not that high, since the particulate mass contains less organic fraction, which catalyst could oxidise.

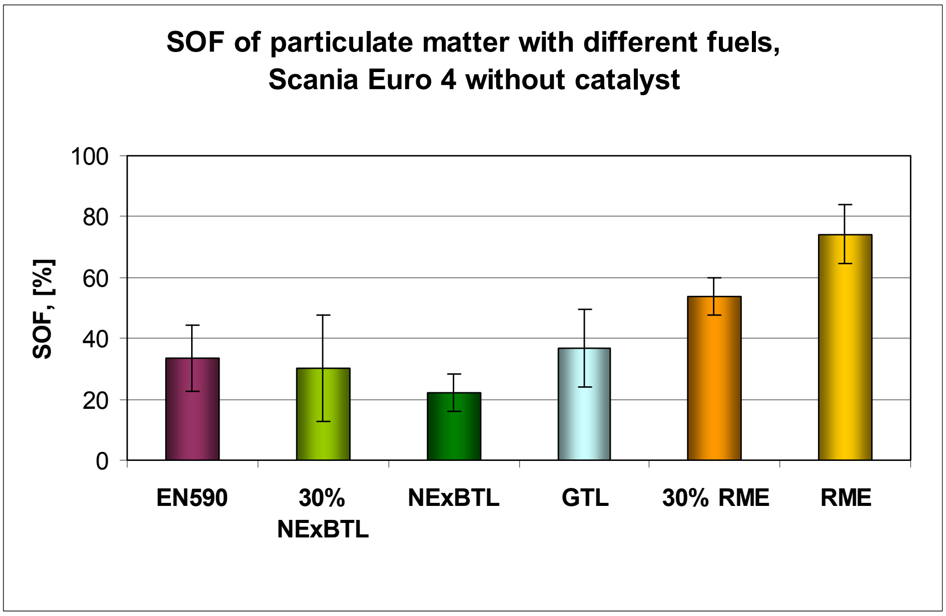


Figure 27. Soluble organic fraction of particulate matter with different fuels. Scania engine without catalyst.

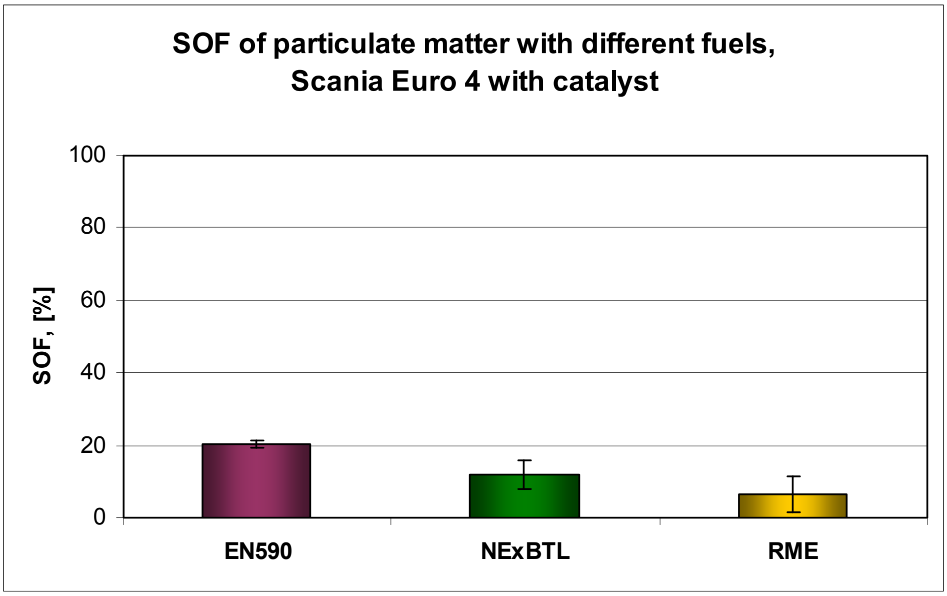


Figure 28. Soluble organic fraction of particulate matter with different fuels. Scania engine with catalyst.

Figure 29 shows that sulphates (SO_4) and nitrates (NO_3) are minor fractions of the particulate matter. Especially the analysed SO_4 emissions were very low, since the sulphur content of fuels was less than 10 mg/kg. The SO_4 emissions measured with and without catalyst were between 0.1–0.4 mg/kWh and 0.7 mg/kWh with NExBTL in the tests with catalyst. "Others" portion in Figure 29 includes soot, water and other material that do not belong to SOF or anions.

In the tests with catalyst, NExBTL showed the highest NO_3 emissions (4.5 mg/kWh) which was expected due to high NO_2 concentrations. Therefore it was unexpected that the NO_3 emission with EN590 measured with catalyst was rather low (1.4 mg/kWh). Without catalyst, the NO_3 emissions varied between fuels from 0.8 to 1.8 mg/kWh. RME measured with catalyst did not produce enough particulate mass to perform SO_4 or NO_3 analysis.

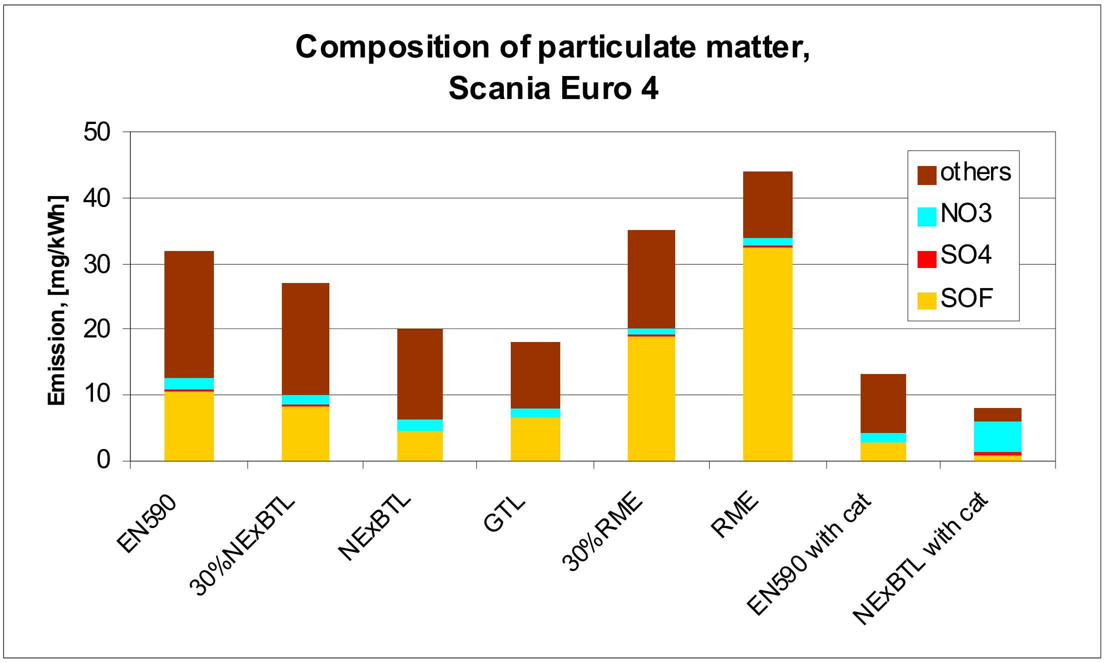


Figure 29. Composition of particulate matter. Scania engine with and without catalyst.

3.2.4 Aldehyde emissions

With diesel fuels the form- and acetaldehyde emissions are normally the main aldehyde compounds in the exhaust gas. With this engine these two compounds represented 80% of total amount of analysed aldehyde emissions. The formaldehyde concentration was some 3 times higher than acetaldehyde concentration. 30 % NExBTL, NExBTL and GTL decreased the formaldehyde emissions by 9 to 18 % compared to EN590, while the RME fuels increased formaldehyde emission levels by 9 to 13 %. The parafinic fuels also decreased acetaldehyde emissions (Figures 30 and 31). In the tests with catalyst the high NO_2 levels hindered the determination of aldehyde emissions. Numerical results are shown in Appendices.

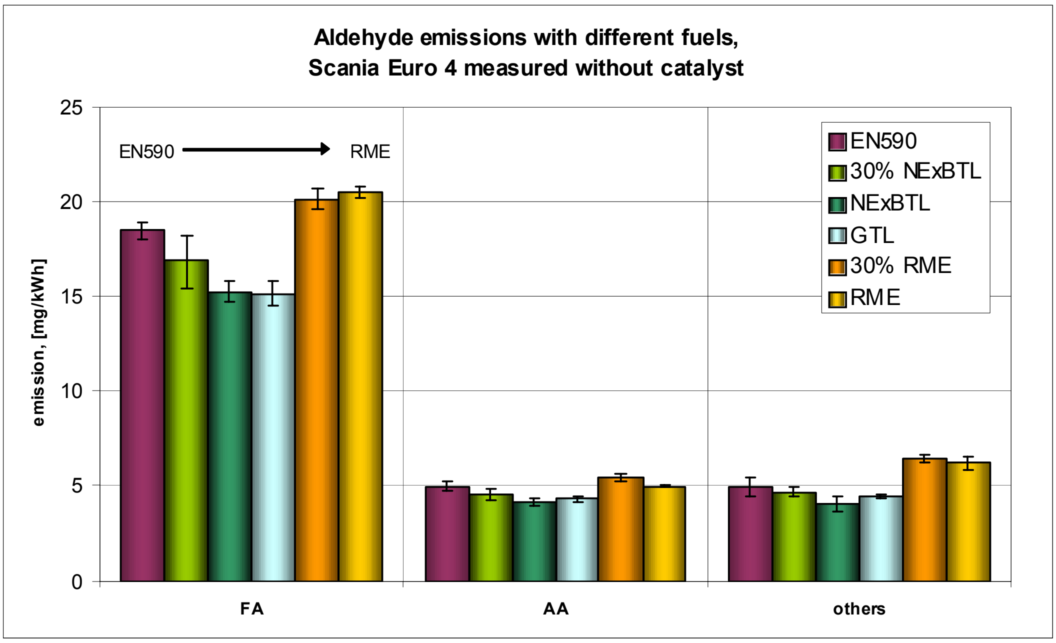


Figure 30. The aldehyce emissions measured with different fuels. Scania engine without catalyst.

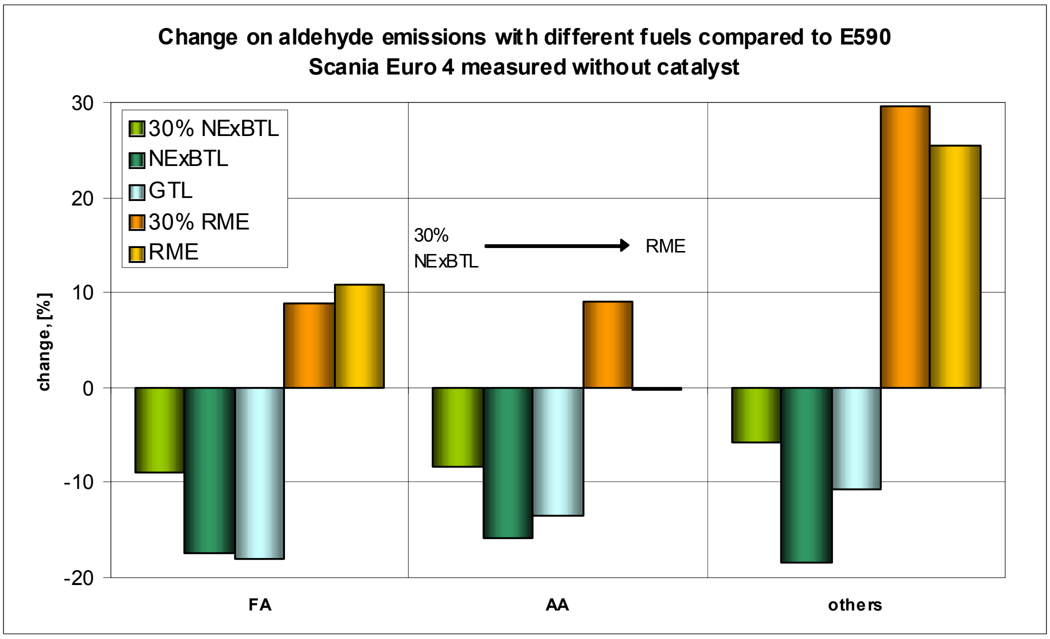


Figure 31. Changes in aldehyde emissions compared to EN90. Scania engine without catalyst.

3.2.5 PAH and Ames emissions

The analysis of PAH emissions and Ames tests were carried out with each fuel and aftertreatment combination. However, low particulate mass emission of Scania engine limited the number of replicate tests. In the tests without catalyst, with EN590, 30 % NExBTL and RME there was enough particulate mass to perform two parallel analyses. Figures 32 and 34 present the absolute emission results and Figures 33 and 35 the relative changes. Numerical results are shown in Appendices.

With GTL, NExBTL and 30 % NExBTL the PAH emissions were lower than with EN590. The PAH emissions were the lowest with GTL. With RME the sum of 7 priority PAHs and non-priority PAH compounds (outside PAH14 and PAH7 lists) increased when compared to EN590. The non-priority compounds which were clearly higher with RME than with EN590 were 2-methylanthracene and 1-methylphenanthrene.

Catalyst reduced significantly the PAH emissions from Scania engine. In the tests with catalyst, EN590 showed the highest and NExBTL the lowest PAH emissions.

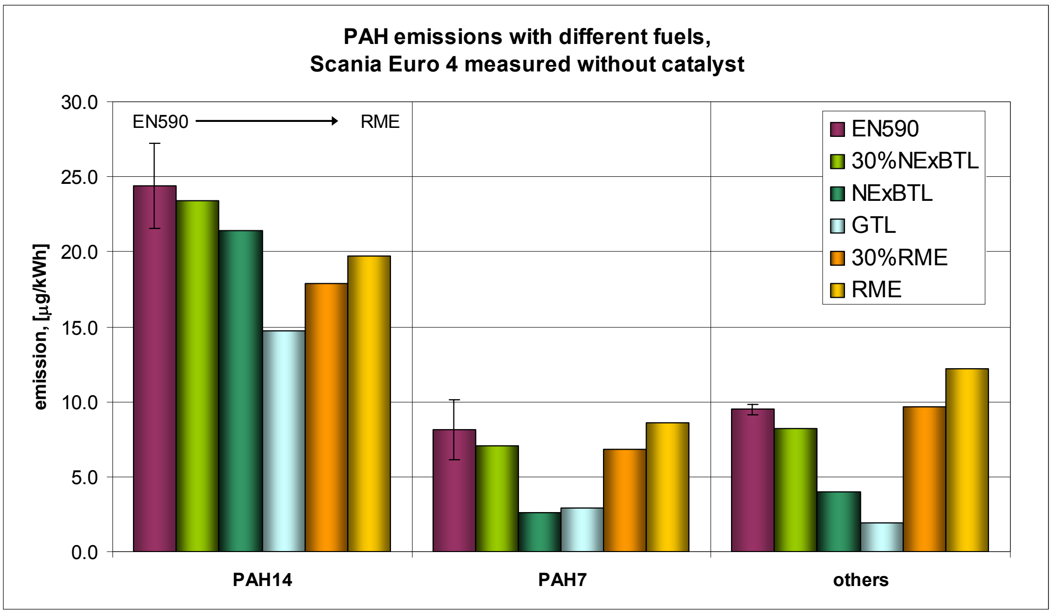


Figure 32. Sum of 7 and 14 priority PAH emissions and sum of other PAHs analysed. Scania engine without catalyst.

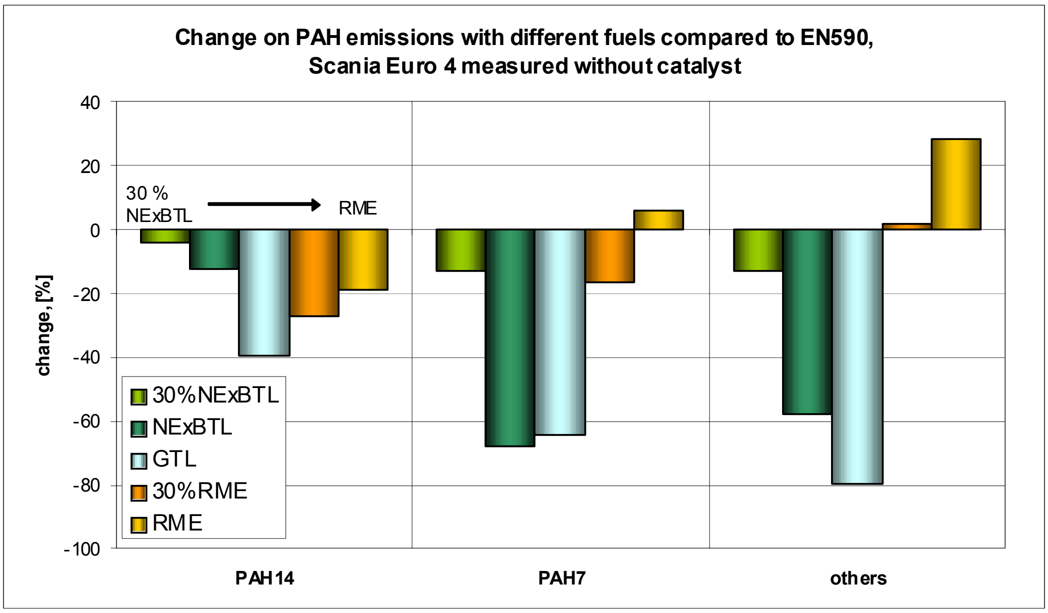


Figure 33. Changes in PAH emissions when NExBTL, GTL and RME containing fuels are compared to EN590. Scania engine without catalyst.

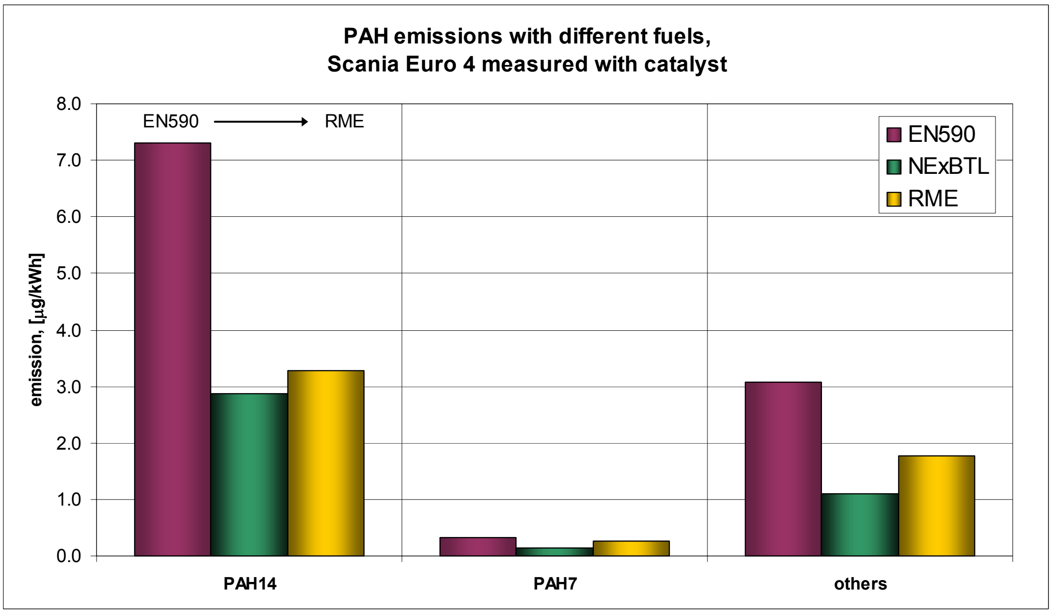


Figure 34. SUM of 7and 14 priority PAH emissions and sum of other PAHs analysed. Scania engine with catalyst.

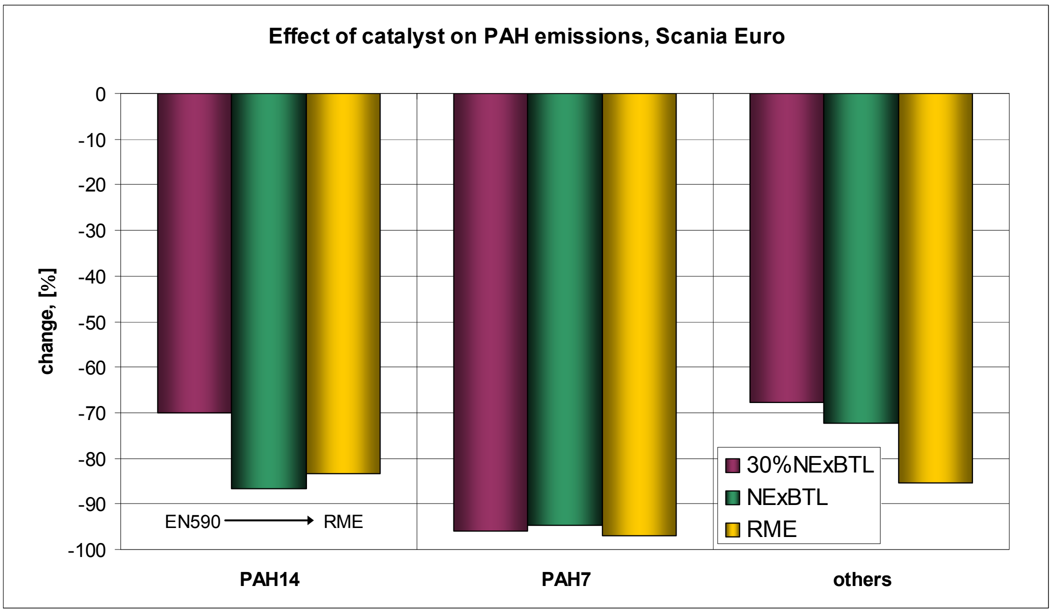


Figure 35. Changes in PAH emissions when the results obtained with catalyst are compared to the results obtained with EN590 measured without catalyst. Scania engine.

The mutagenicity was tested using Ames test. Tests were performed with three different bacterial strains. Strain TA98 without metabolic activation (–S9) indicates direct mutagenicity and with metabolic activation (+S9) indirect mutagenicity. Strain TA98NR –S9 indicates direct mutagenic activity to nitrous PAH compounds.

Each tested sample was mutagenic to all bacterial strains. EN590 fuel showed roughly the same direct and indirect mutagenic activity. NExBTL and GTL had almost identical responses to all strains. With both fuels the responses were clearly lower compared to EN590. RME's responses were somewhat higher when compared to NExBTL and GTL. Each fuel had response to TA98NR strain which indicates that there are nitrous-PAH compounds present in the extract of the particulate matter (Figure 36). Figure 37 presents the relative changes when fuels are compared to EN590.

In the tests with catalyst the EN590 fuel showed minor mutagenicity with strain TA98 –S9 and TA98NR –S9. With NExBTL and RME fuels no mutagenic activity was seen with strain TA98 –S9.

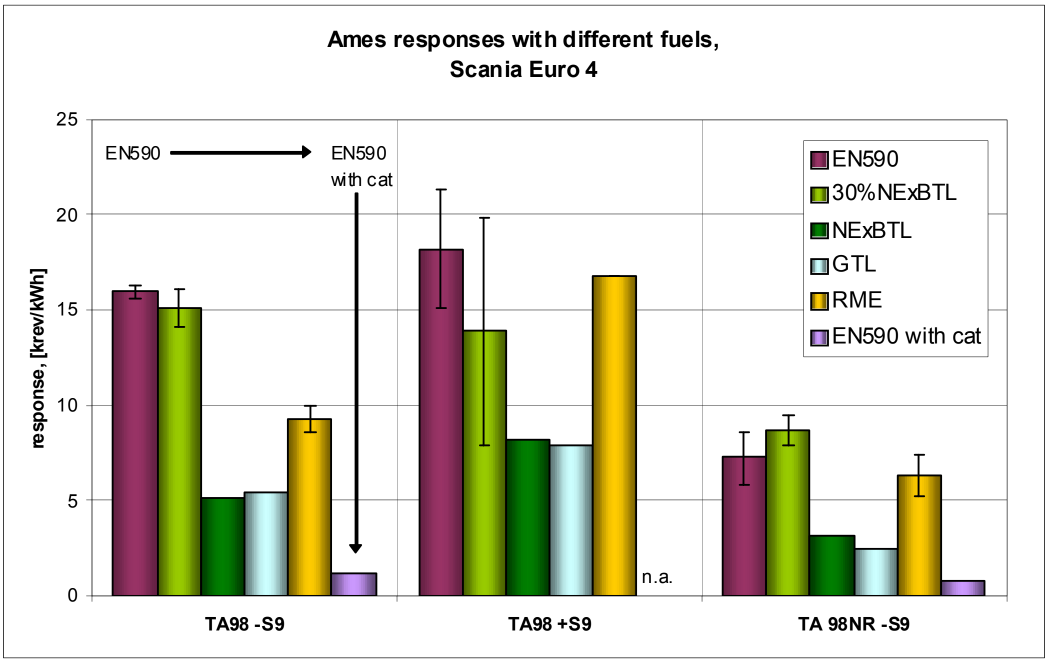


Figure 36. Results of the Ames tests. Scania engine with and without catalyst.

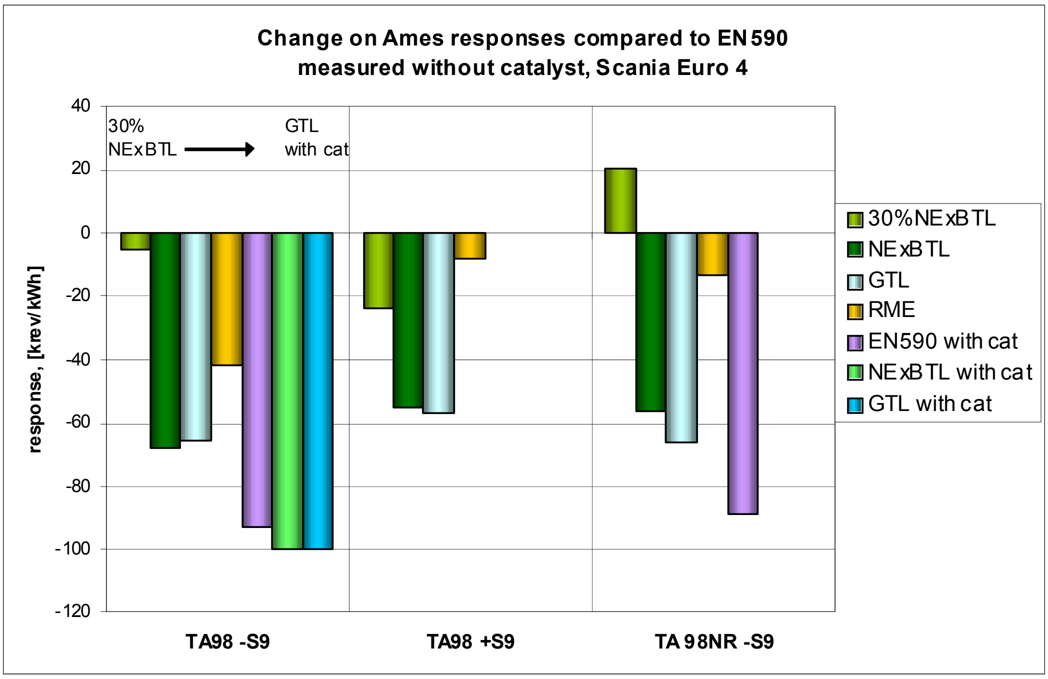


Figure 37. Changes in Ames responses compared to EN590 measured without catalyst. Scania engine.

3.2.6 Particle number emissions

The particle size distributions were measured with ELPI and the total number of particles with CPC. Figure 38 presents the size distributions with EN590 fuel measured with and without catalyst. There is a fundamental difference between the results at the beginning and at the end of the measurement period measured with ELPI, whereas the parallel CPC results show no difference between the beginning and the end of the measurement period (Figure 39). Since the total number and size distributions were measured from the same branch of sampling line there is a reason to believe that the dilution system has stayed stable. Thus it is concluded that there has been some sort of change on ELPI device. One possible reason is a contamination of RME as the last measurements with EN590 were carried out after the measurements with RME. ELPI's impactor was not cleaned after the RME measurements.

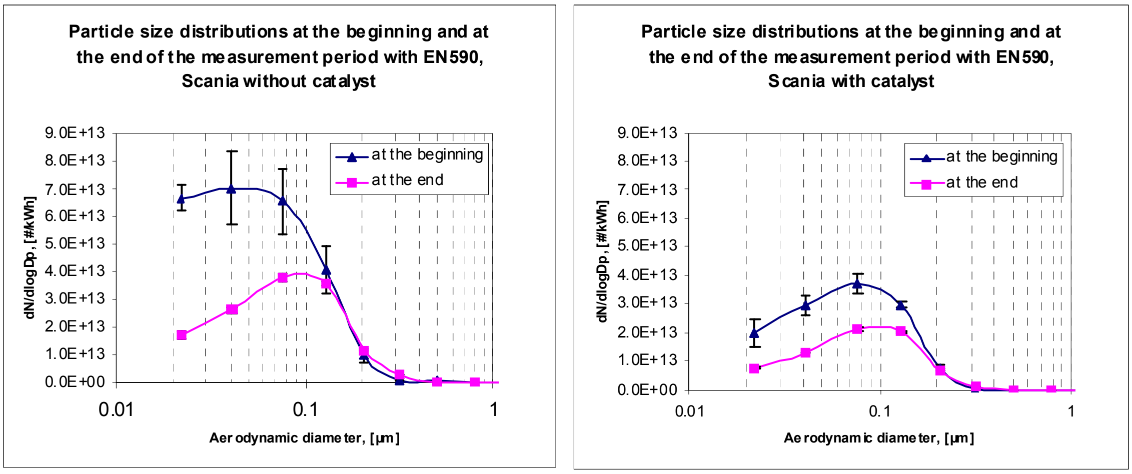


Figure 38. Particle size distribution at the beginning and at the end of the measurement period using EN590 fuel. Scania engine with and without catalyst.

The particle size distributions using different fuels in the tests without catalyst are presented in Figure 40. The size distribution of EN590 is the average of the measured distributions at the beginning of the measurement period. EN590 and NExBTL fuels showed the highest number of particles in size class from 30 to 70 nm. The accumulation mode was the smallest with RME. RME and GTL had a bimodal distribution curve showing tendency for nucleation.

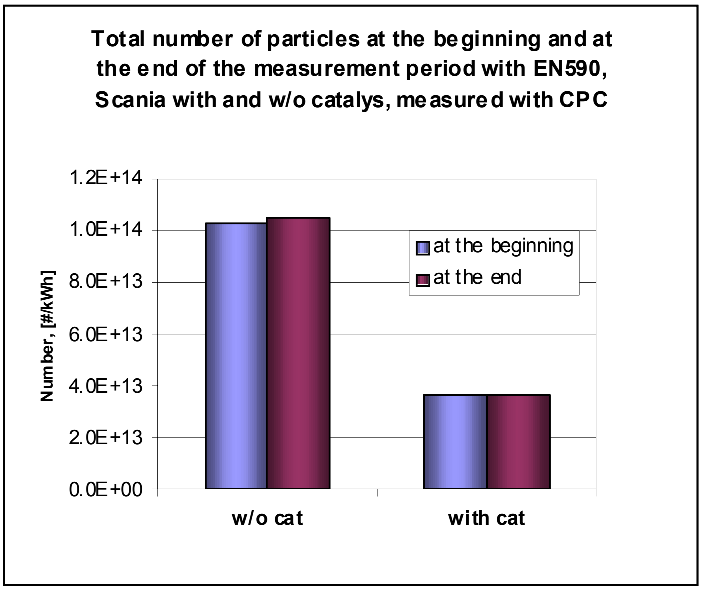


Figure 39. Total number particles measured with CHP at the beginning and at the end of the measurement period with EN590. Scania engine with and without catalyst.

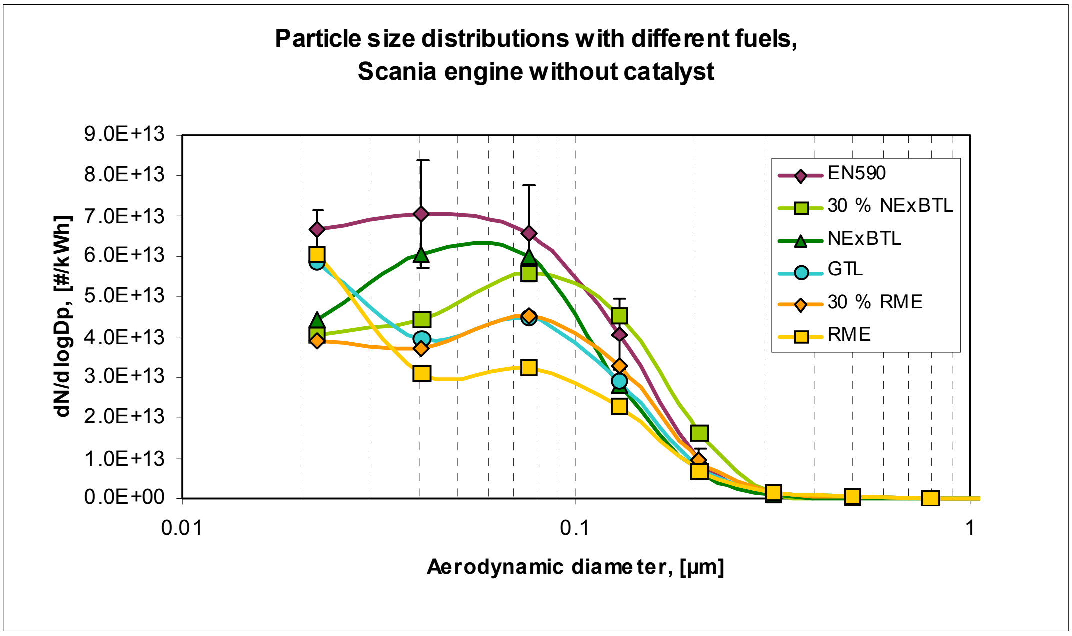


Figure 40. Particle size distributions with different fuels. Scania engine without catalyst.

Figure 41 shows the particle size distributions measured in the tests with catalyst. With each fuel the number of the smallest particles (d < 40 nm) decreased over 50 % compared to results measured without catalyst. On other size classes there were also significant reductions.

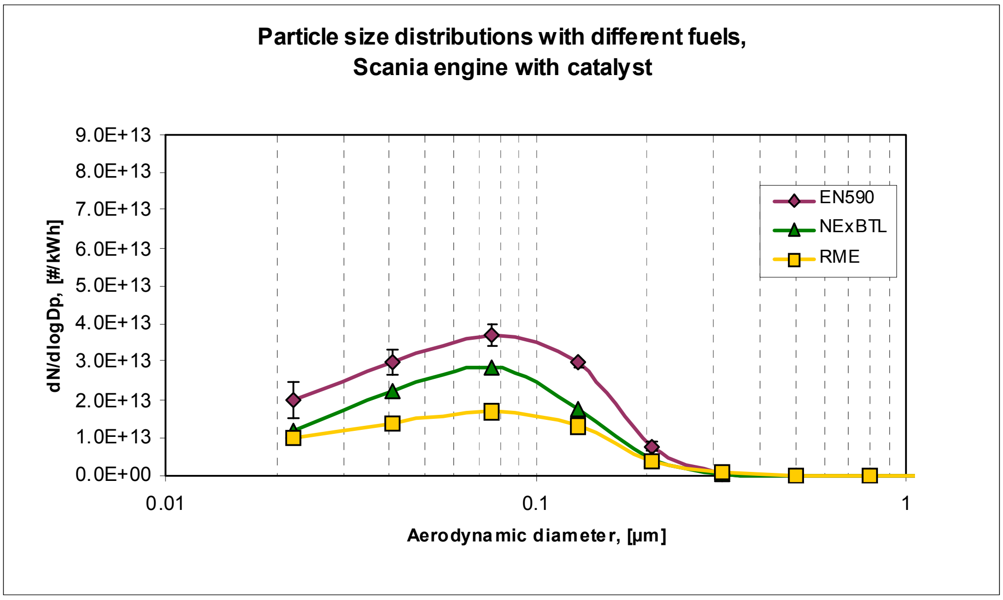


Figure 41. Particle size distributions with EN590, NExBTL and RME. Scania engine with catalyst.

The total number of particles is presented in Figure 42. The number of particles with different fuels correlates rather well with PM results. The number of particles with NExBTL and GTL were 20 and 14% lower compared to EN590, and with RME the number of particles increased by 14 %. The differences between EN590, 30 % NExBTL and 30 % RME were relatively low. Catalyst decreased the number of particles by 64 to 77 % depending on fuel.

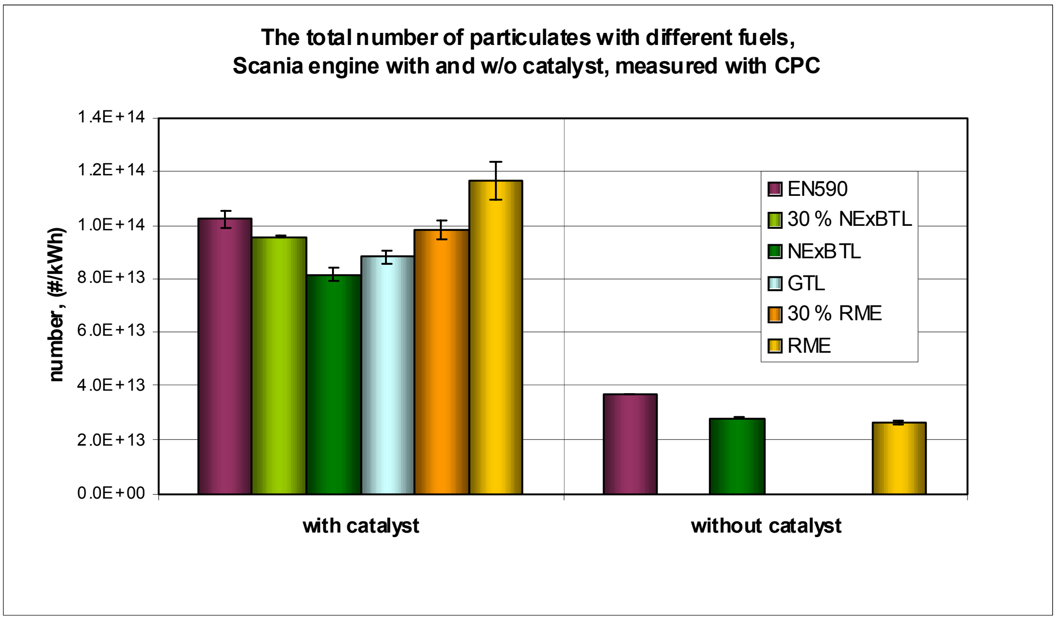


Figure 42. The total number of particles with different fuels. Scania engine with and without catalyst.

Figure 44 presents the particle size distributions on selected steady-state loads. RME was the only fuel having a clear nucleation mode, which was seen in the tests without catalyst. NExBTL showed higher number of particles than EN590 in the size class below 70 nm. The number of particles larger than 100 nm was the highest with the EN590 fuel.

Catalyst decreased efficiently the number of particles. Nucleation mode, which was seen for RME in the tests without catalyst, disappeared when engine was equipped with catalyst. The number of particles below 130 nm was the lowest with RME. In the tests with catalyst, the EN590 and NExBTL fuels had almost identical particle size distributions.

In the tests without the catalyst, the total number of particles was the highest on each load with RME. When engine was equipped with catalyst, the results change so that the RME had the lowest number of particles. With RME the catalyst decreased number of particles by 89 to 96 % depending on load, with EN590 by 62 to 76 % and with NExBTL by 64 to 69 %, respectively (Figure 43).

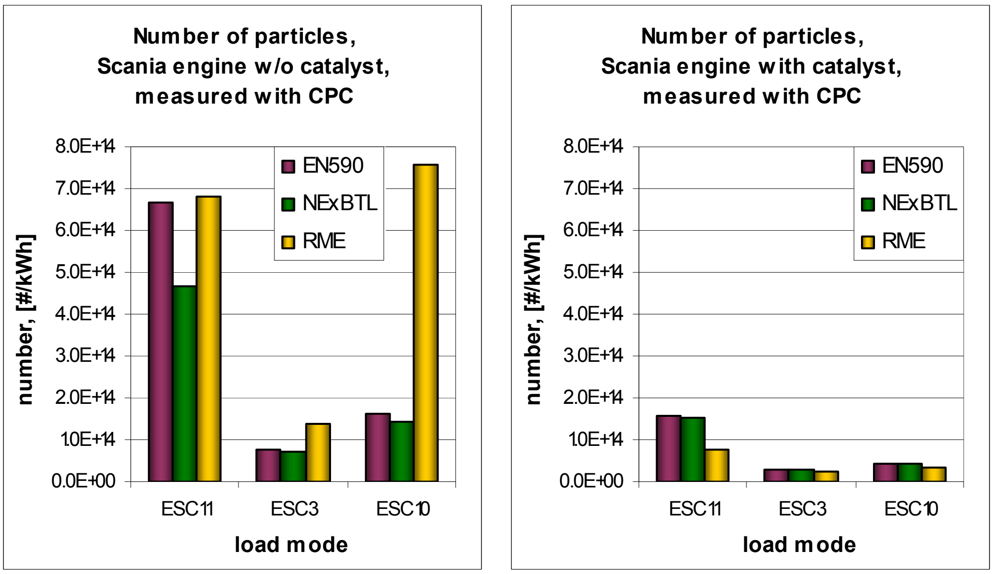


Figure 43. Number of particles with EN590, NExBTL and RME on selected loads. Scania engine with and without catalyst.

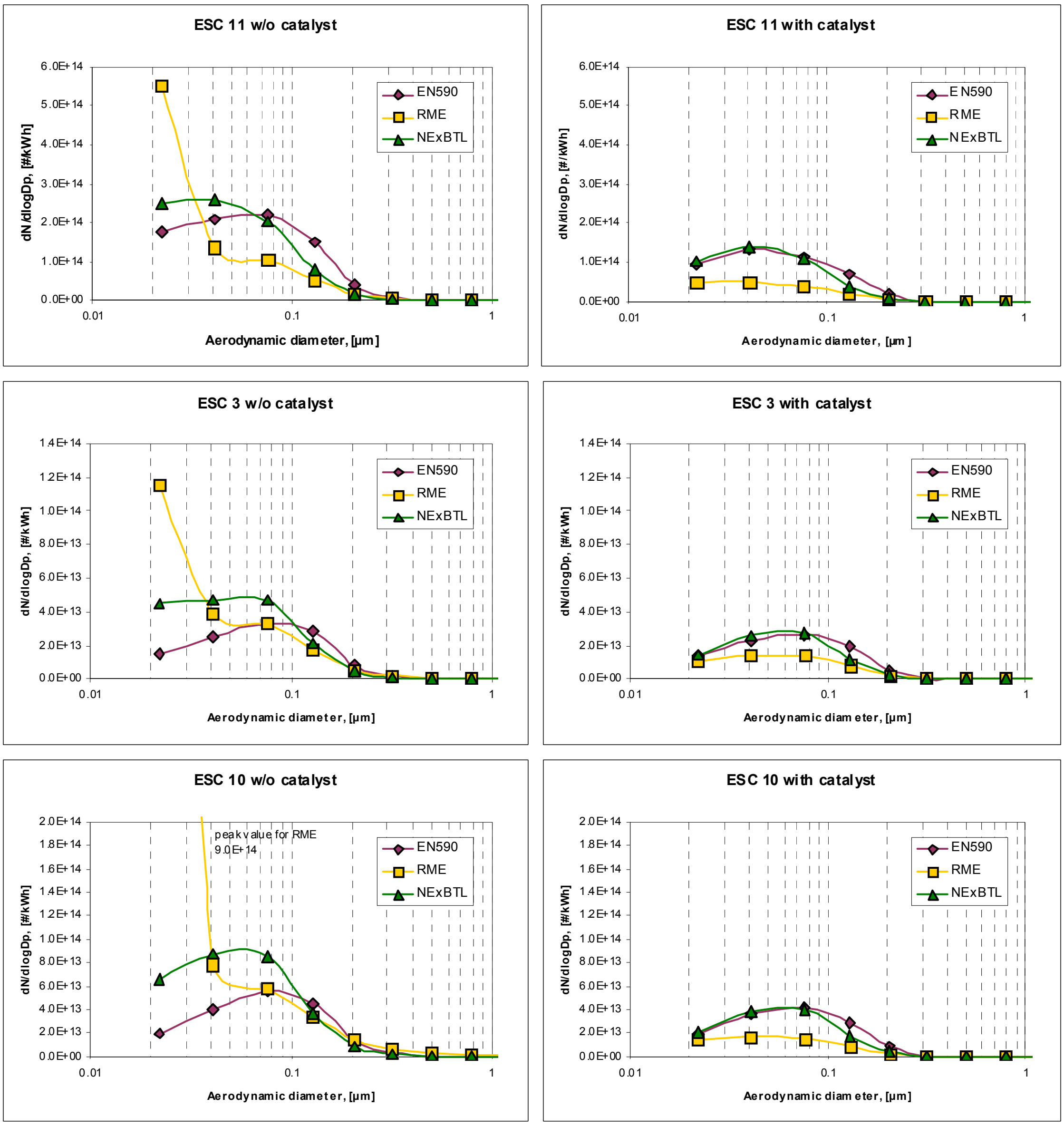


Figure 44. Particle size distributions with EN590. NExBTL and RME on selected loads. Scania engine with and without catalyst.

3.3 SisuDiesel non-road engine, stage 3b emission level (prototype)

The measurements with the SisuDiesel non-road engine were performed using EN590 and NExBTL fuels. Engine had a SCR aftertreatment system. Measurements were performed using ISO8178-C1 steady state test cycle and NRTC transient test cycle.

3.3.1 Regulated emissions, CO_2 fuel consumption and ammonia

Table 20 presents the European Stage 3b limit values for non-road diesel engines and the emissions from SisuDiesel engine using EN590 fuel. Stage 3b comes into force on January 2011 (power range 130–560 kW).

Table 20. Regulated emissions, CO_2 and fuel consumption with SisuDiesel engine using ISO8178 and NRTC test cycles. Results are compared to upcoming limit values.

	ISO8178-C1 measured, g/kWh	NRTC measured, g/kWh	Limit value for stage 3b, g/kWh *
HC	0.05	0.04	0.19
CO	0.3	1.0	3.5
NO_x	2.4	3.3	2.0
PM	0.017	0.034	0.025
CO_2	689	733	
Fuel consumption	220	-	-

* For verification purposes gaseous emissions are measured with ISO8178-C1 cycle and PM with NRTC. It is allowed to use NRTC also for gaseous emissions.

With NExBTL the PM and NO_x emission were significantly lower on both test cycles compared to EN590 (Figures 45 and 46). NO_x emissions decreased from 12 to 15 %, and urea consumption was not affected by tested fuels. With NExBTL the urea consumption was only 1 % higher compared to EN590. The HC emissions decreased on both test cycles with NExBTL compared to EN590. The NExBTL fuel produced slightly less CO_2 emissions than EN590 on both test cycles. The mass based fuel consumption was 2.5 % lower with NExBTL than with EN590 over the ISO8178 C1 cycle. Figure 47 presents the relative changes when NExBTL is compared to EN590. It was noted that a clear ammonia slip was detected in the transient NRTC tests (0.15 g/kWh).

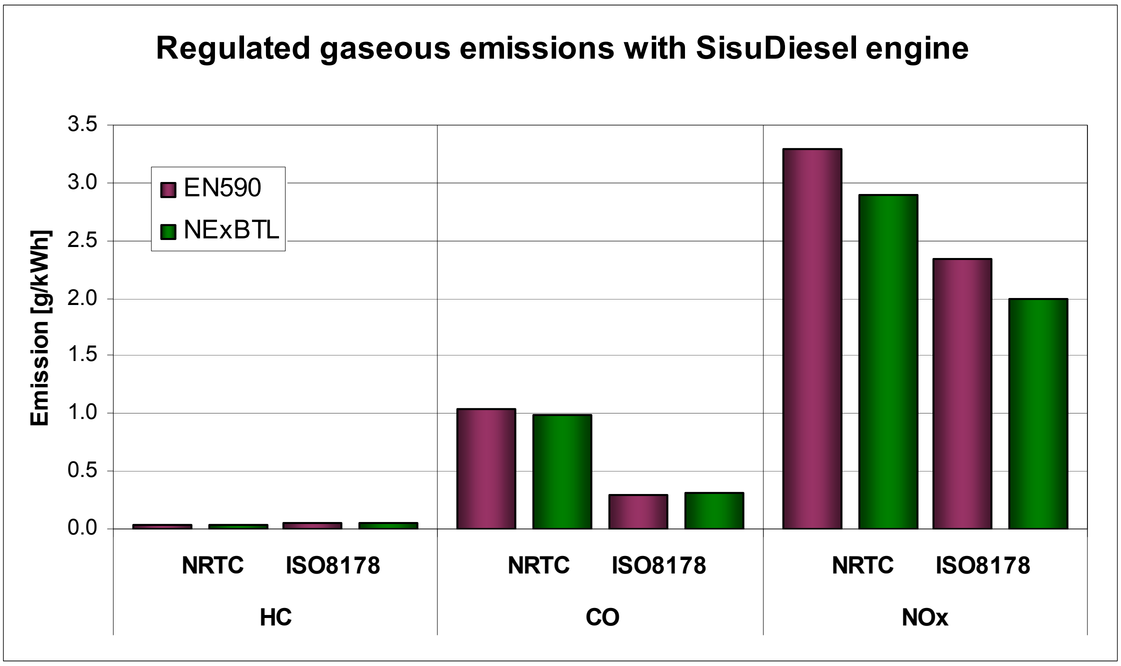


Figure 45. Regulated gaseous emissions with the EN590 and NExBTL fuels. SisuDiesel engine, NRTC and ISO 8178 test cycles.

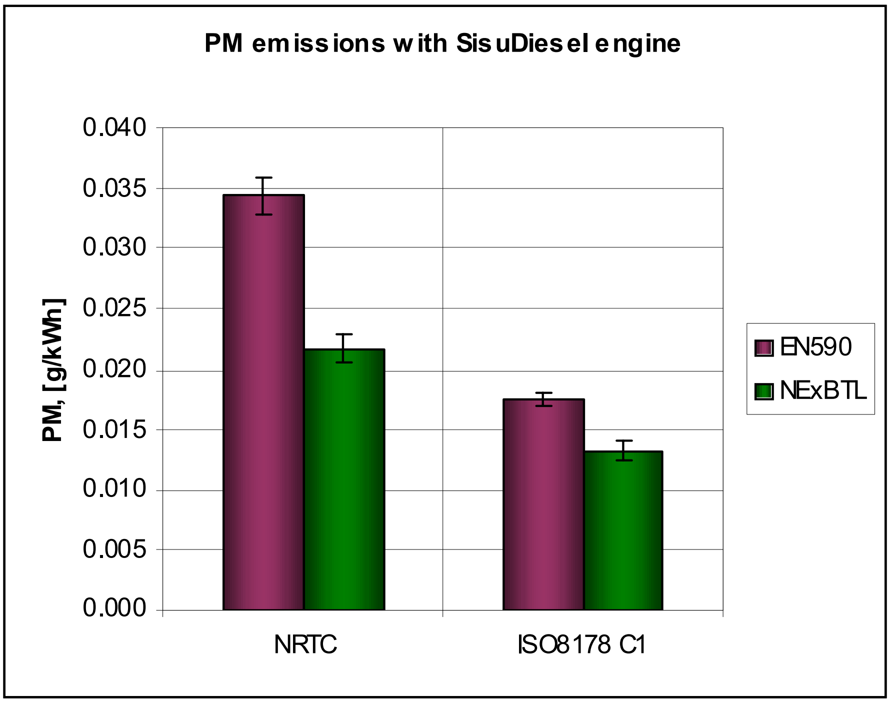


Figure 46. PM emissions with the EN590 and NExBTL fuels. SisuDiesel engine, NRTC and ISO 8178 test cycles.

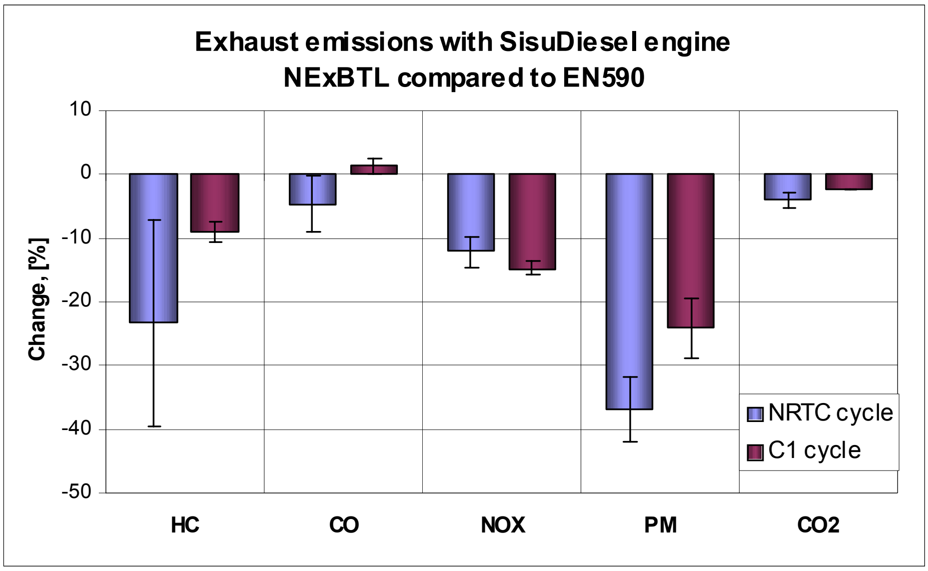


Figure 47. Changes in regulated emission with the NExBTL fuel is compared to EN590 fuel. SisuDiesel engine, NRTC and ISO 8178 test cycles.

3.3.2 Aldehyde emissions

The aldehyde emissions were measured with the NRTC test cycle and the emission levels were generally rather low. With NExBTL, the aldehyde emissions slightly increased compared to EN590, though the changes are practically within measurement accuracy (Figure 48).

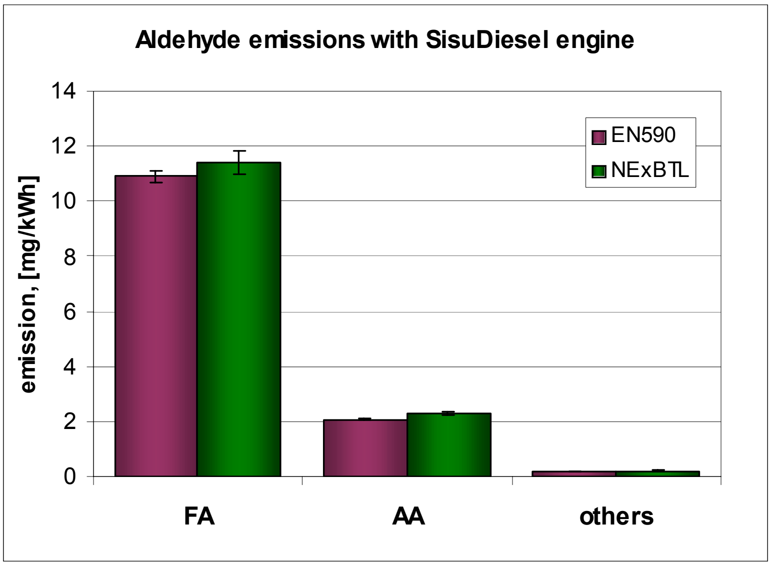


Figure 48. Aldehyde amissions with the EN590 and NExBTL fuels. SisuDiesel engine, NRTC test cycle.

3.3.3 PAH emissions

With SisuDiesel engine the PAH14 and PAH7 emissions as well as the total PAH emissions were at very low level. The dominating PAH compound with both fuels was 2-methylanthracene, which explains the high level of non-priority PAH compounds. The 2-methylanthracene covered 81 to 91 % of non-priority PAH compounds and 69 to 77 % of all PAH compounds depending on test cycle and fuel. With NExBTL the PAH emissions were lower than with EN590 (Figure 49).

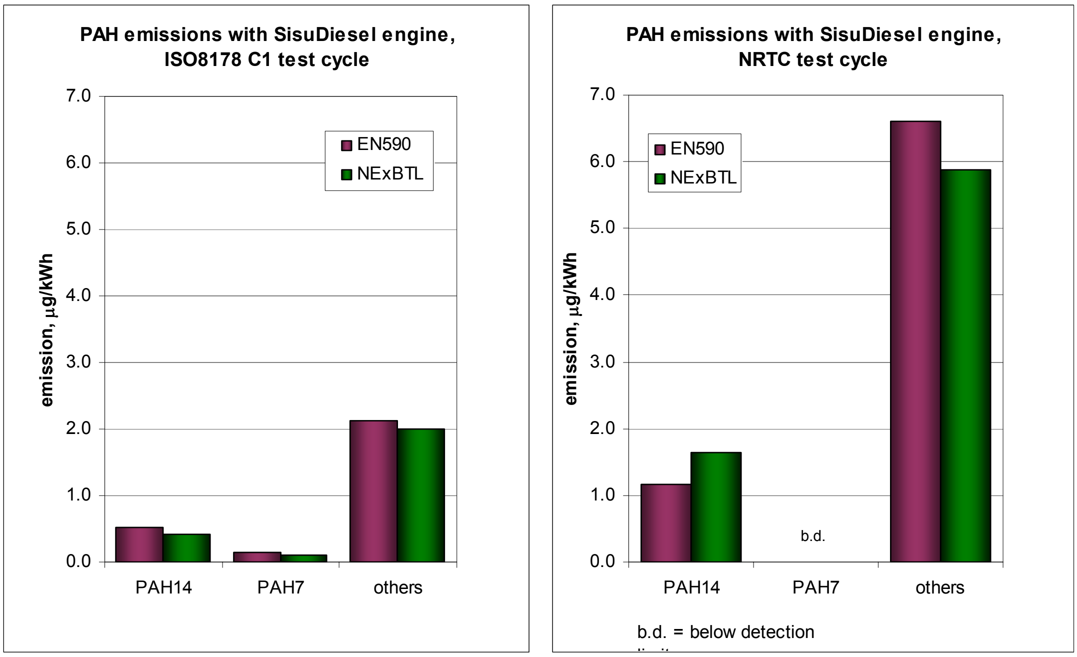


Figure 49. PAH emissions with the EN590 and NExBTL tuels. SisuDiesel engine. NRTC and ISO8178 Cl test cycles.

3.3.4 Particle number emissions

The particle size distributions were very similar on both test cycles (Figures 50 and 51). There was a clear soot mode and no nucleation tendency was detected. The number of particles on the smallest size class (d < 50 nm) was slightly higher with NExBTL than with the EN590 fuel. On particle size range between 50 and 200 nm, NExBTL produced lower number of particles than EN590. This in good agreement with the PM results, since the smallest particles do not play significant role on PM emissions.

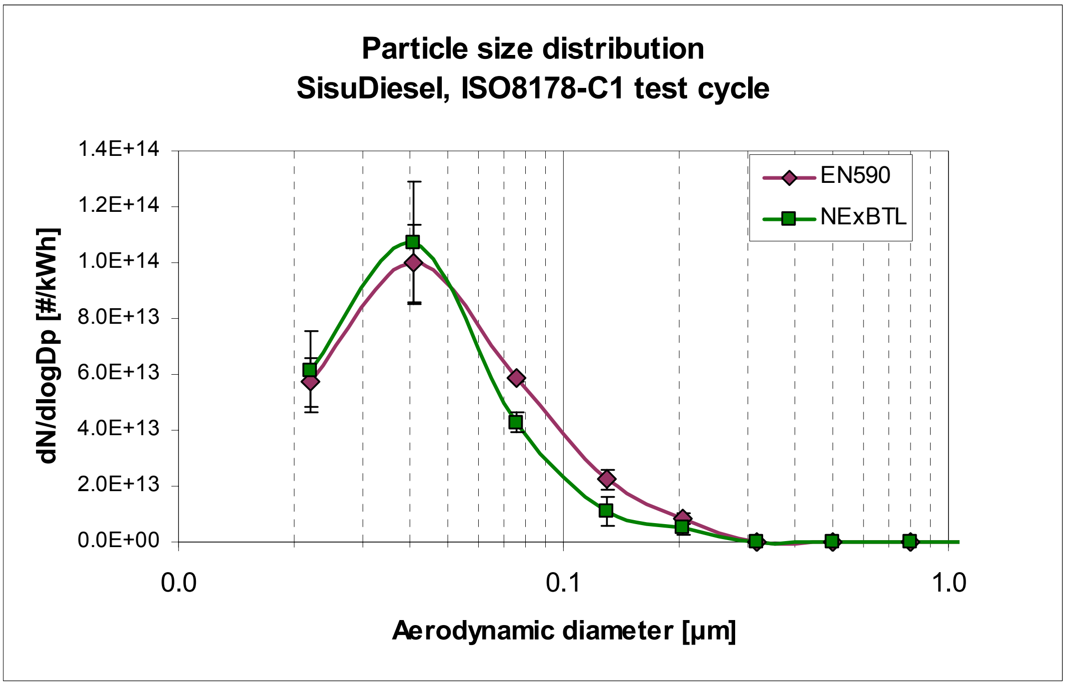


Figure 50. Particle number size distributions with the EN590 and NExBTL fuels. SisuDiesel engine, ISO 8178-C1 test cycle.

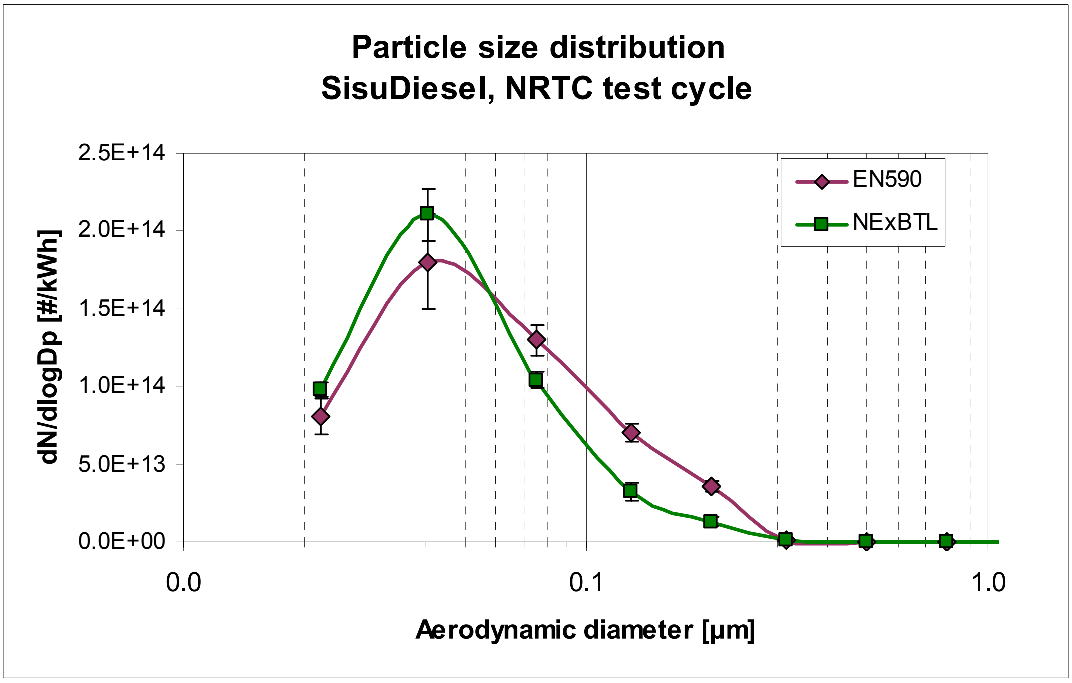


Figure 51. Particle number size distributions with EN590 and NExBTL fuels. SisuDiesel engine, NRTC test cycle.

4. Results with buses

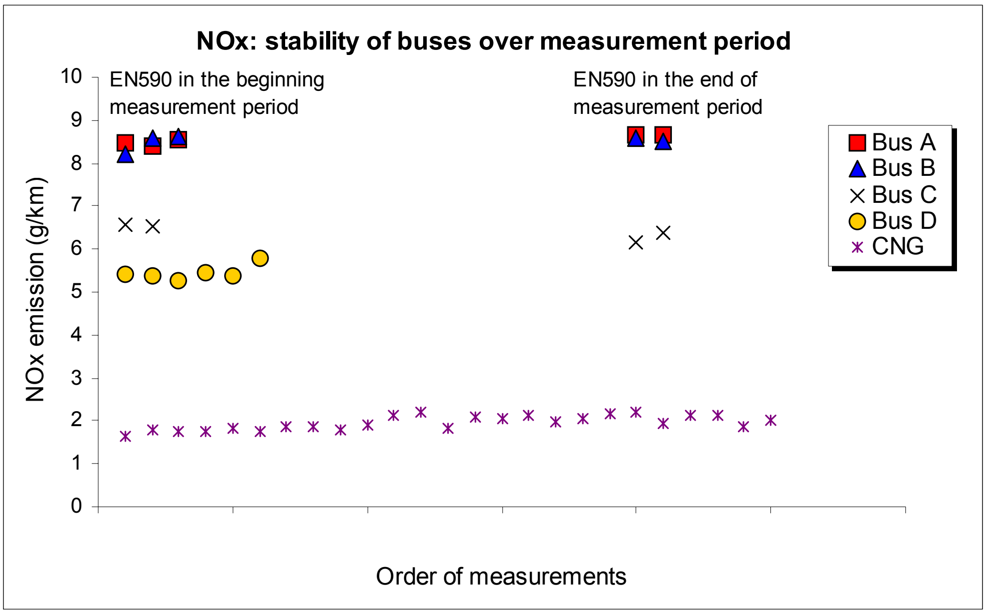
Five buses were studied on chassis dynamometer. Two buses represented Euro 4 emission level and three buses EEV emission level technologies. One bus was a stoichiometric CNG bus. The error bars in the Figures describe the standard deviation of the measurements unless otherwise noted.

4.1 Stability of buses over the test period and validity of results

The results from the individual tests over the measurement period are shown in Figure 52. European grade diesel fuel was tested in the beginning and in the end of measurement period to study stability of buses.

The emission level of buses stayed at the same level over the measurement period in the most cases. However, for Bus C, PM emission level decreased to some extent. When calculating the average results for each bus and fuel combination, all results were taken into account, if no clear technical reason for rejection was found. With Bus A, when using NExBTL fuel, one of the NO_X emission results was at lower level than the other results, which was concluded to be due to high urea injection rate and this result was rejected. With CNG bus, two measurements of particulate matter were rejected, because they were contaminated by particles from engine measurements (same CVS system for engine and vehicle measurements).

4. Results with buses



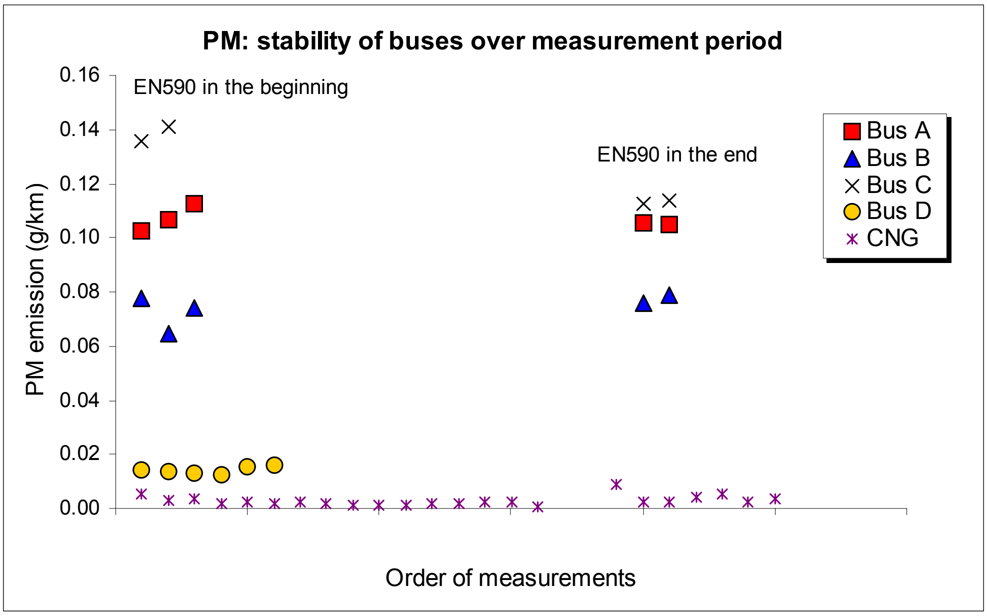


Figure 52. NO_x and PM emissions from individual tests in the order of testing. EN590 fuel was tested in the beginning and end of the testing period to screen stability of buses.

4.2 Regulated emissions, CO_2 and fuel consumption

4.2.1 Overall view on emission level

The buses A and B represent Euro 4 emission level and buses C and D represent EEV emission level. Bus E is a CNG bus. The numerical results of regulated emissions with these vehicles are shown in Appendices.

There is no legislative limit for the exhaust emissions from heavy-duty vehicles tested on chassis dynamometer. However, the limit values set for engine tests can be converted approximately to representative limit values for vehicle tests. The conversion factor of 1.8 can be used for two-axle city buses over the Braunschweig cycle (about 1.8 kWh of work per km) (Nylund et al. 2007). In this Chapter, the converted limit values are based on the transient ETC engine dynamometer test (Figures 53 and 54).

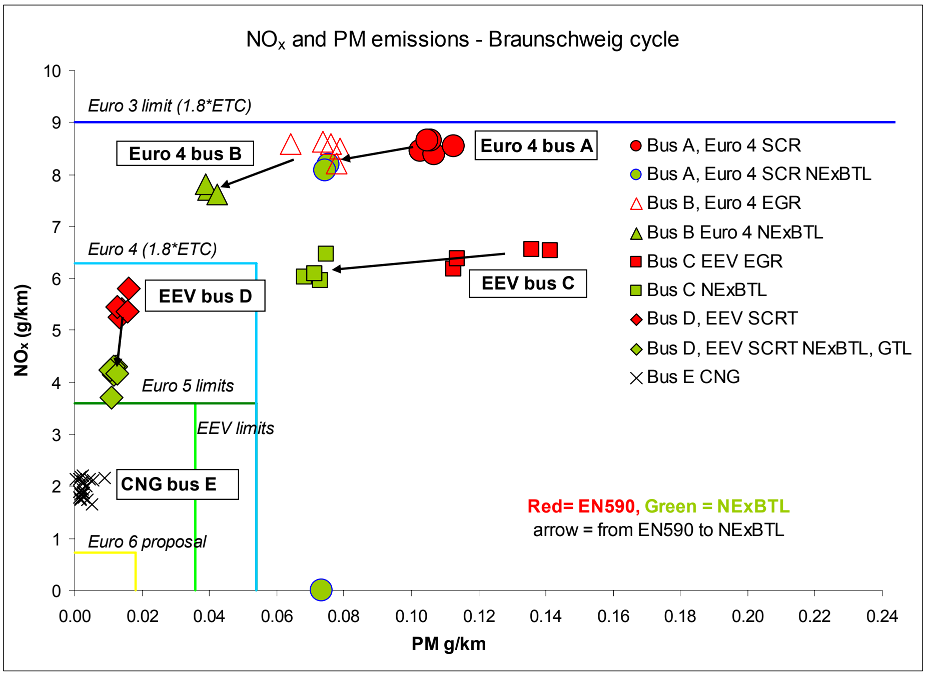


Figure 53. The NOx and PM emissions with the EN590, NExBTL and GTL fuels. Euro 4 and EEV emission level buses with Braunschweig test cycle. Limit values are converted from ETC test (1.8 x ETC).

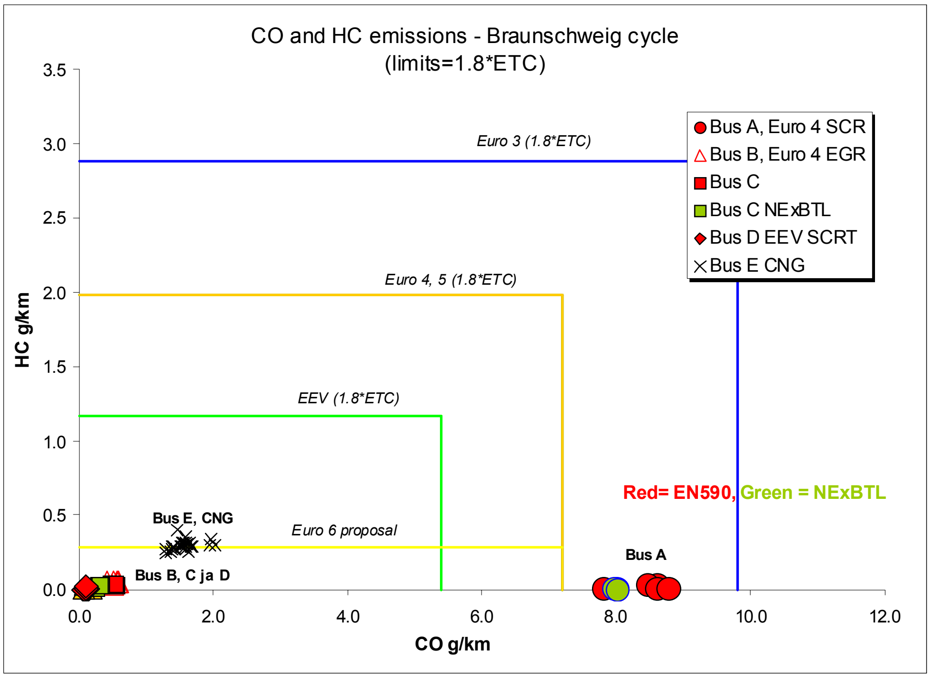


Figure 54. The NO_x and PM emissions with the EN590, NExBTL and GTL fuels. Euro 4 and EEV emission level buses with Braunschweig test cycle. Limit values are converted from ETC test (1.8 x ETC).

Euro 4 buses

The variation in emissions between individual buses and bus branches were high. Buses A and B exceeded significantly the “converted” Euro 4 limit for NO_X emissions. PM emissions with Bus A equipped with the SCR system and Bus B equipped with the EGR system were also higher than the Euro 4 limit when using EN590 fuel. However, Bus B fulfilled the converted PM limit value when using NExBTL as fuel.

The CO and HC emissions are typically low with diesel vehicles, but now CO emissions from Bus A equipped with the SCR system were exceptionally high: around 8–9 g/km, which is close to converted Euro 3 emission limit. CO emission may increase with the certain SCR catalysts, which oxidizes hydrocarbons effectively to CO_2, but partly also to CO (Gekas et al. 2002). It seems evident that the post-oxidation catalyst is needed with this kind of SCR technology. CO emissions from Bus B were low, as well as HC emissions from both buses.

EEV buses

Bus C representing EEV technology exceeded substantially the converted EEV limit values for particulate matter and NO_X emission. These emissions were more than double compared to the required emission level and did not fulfil even the converted Euro 4 limits. CO and HC emissions from Bus C were well below the EEV limit values.

Bus D representing EEV technology fulfilled the converted EEV limit value for PM emission, but not for the NO_X emission. NExBTL and GTL fuels reduced both NO_X and PM emissions when compared to EN590 fuel. Thus Bus D was close to the converted EEV limit of NO_X when using NExBTL as fuel. CO and HC emissions from Bus D were well below the EEV limit value. CNG bus E fulfilled the converted EEV limit values for regulated emissions.

4.2.2 The effect of fuel

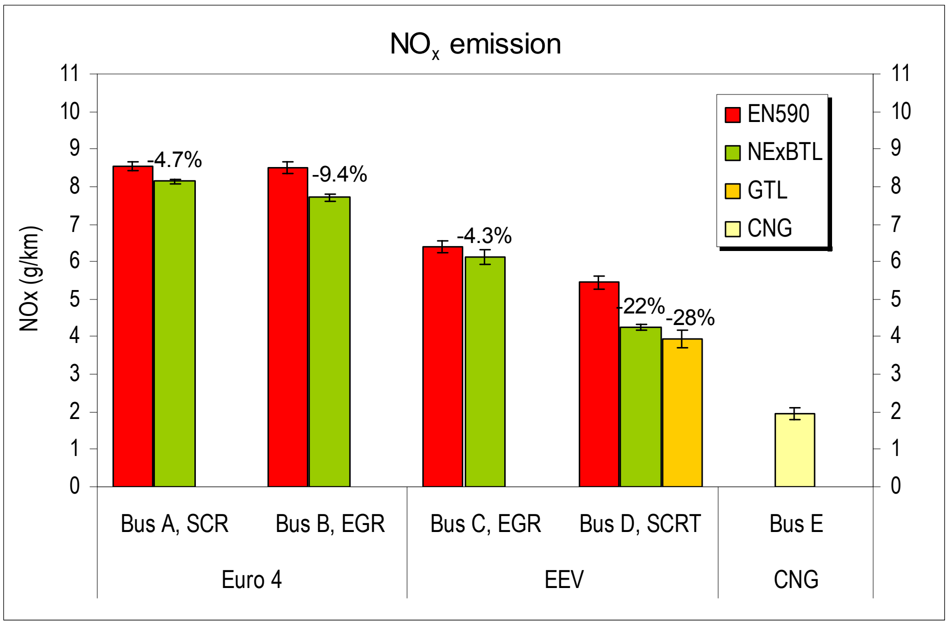
The effect of renewable diesel, NExBTL, on regulated emissions is shown in Figures 55 and 57. The NExBTL fuel reduced NO_X-emissions with all four diesel buses: the reduction was around 5 % for Bus A equipped with SCR technology, 9 % for Bus B equipped with EGR, 4 % for Bus C equipped with EGR and 22 % for Bus D equipped with SCRT technology. GTL fuel showed a reduction of 28 % with Bus D when compared to EN590 fuel, which is at the same level as the reduction achieved with NExBTL. CNG bus showed the lowest NO_X emission level.

FTIR equipment is capable to monitor nitrogen dioxide emissions (Appendices). NO_2 emissions were at slightly higher level with the EGR equipped Bus B than with the SCR equipped Bus A. Both EEV buses, C and D, showed very high NO_2 emission level, which represented 50–70 % of the total NO_X emissions. CNG bus did not show any significant NO_2 emission (Figure 56).

Urea consumption of Bus D was 12–16 % higher for NExBTL and GTL than for EN590. It is noted that such difference in urea injection between EN590 and NExBTL fuel was not seen with Bus A equipped with the SCR system.

The effect of the NExBTL fuel on the PM emission was even higher than on the NO_X emission. With bus A, the particulate matter emission was 30 % lower with the NExBTL fuel when compared to EN590 fuel. The PM emission from Bus B equipped with the EGR system was 46 % lower with NExBTL than with the EN590 fuel. EGR equipped bus C showed 43 % lower PM emission, respectively. SCRT equipped bus D did not emit much particle mass when compared to the diesel buses without particle trap. However, even in this case benefit of NExBTL and GTL fuels was seen. PM emission was reduced 19 % with NExBTL and 17 % with the GTL fuel when compared to the EN590 fuel. CNG bus showed the lowest PM emission level.

4. Results with buses



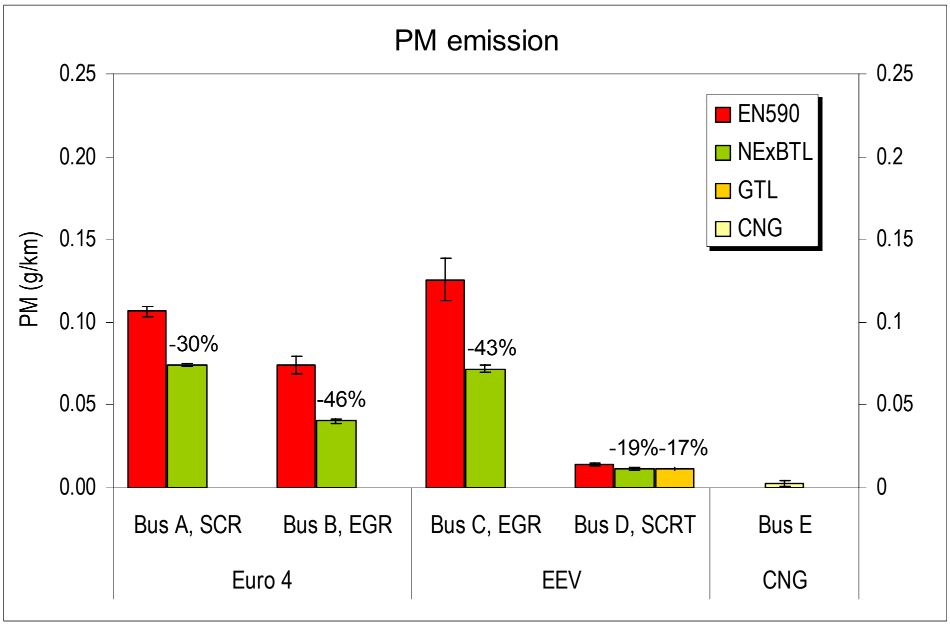


Figure 55. NO, NO_x and PM emissions with different buses and fuels. Percentage shows the difference in emissions when NExBTL and GTL are compared to the EN590 fuel. Braunschweig test cycle.

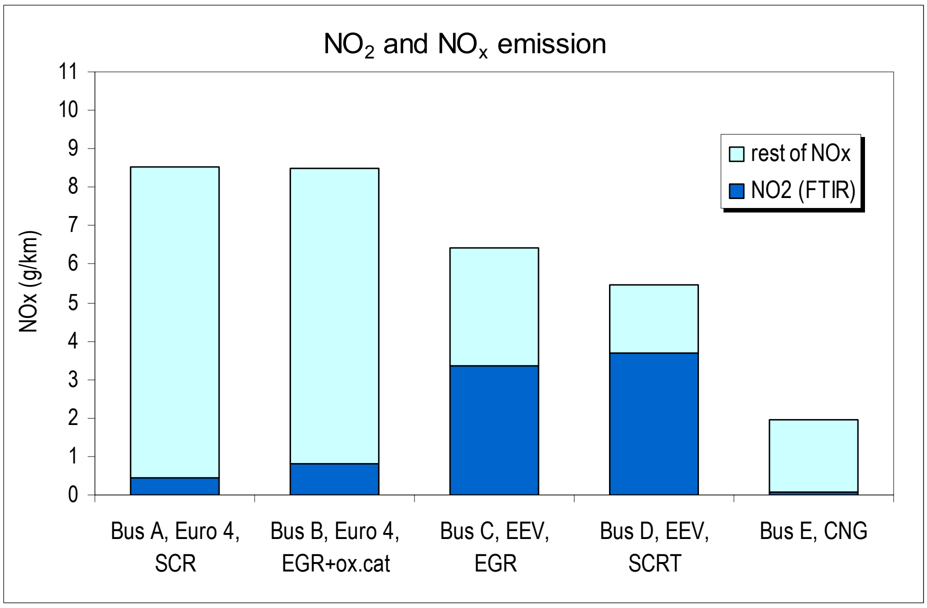


Figure 56. NO_2 emissions measured with FTIR and total NO_x emissions with different buses (EN590 fuel for diesel buses). Braunschweig test cycle.

As already mentioned, Bus A equipped with the SCR technology resulted in exceptionally high CO emissions. This emission component was reduced by 5 % when NExBTL was compared to EN590 fuel. Benefit of NExBTL was seen also in HC emissions, even though this was not significant change in absolute terms due to low HC emission level of bus A. For other diesel buses, CO and HC emission levels were generally low, but still NExBTL or GTL fuel showed lower emissions when compared to the EN590 fuel. The CNG bus showed significantly higher CO emission than buses B, C and D. However, CO emission from CNG bus was only a fraction when compared CO emission from bus A. HC emission with CNG bus was many-fold when compared to diesel buses. This is mainly due to unburned fuel, which is methane in the case of CNG vehicle. It is typical that CNG applications emit more methane than diesel applications.

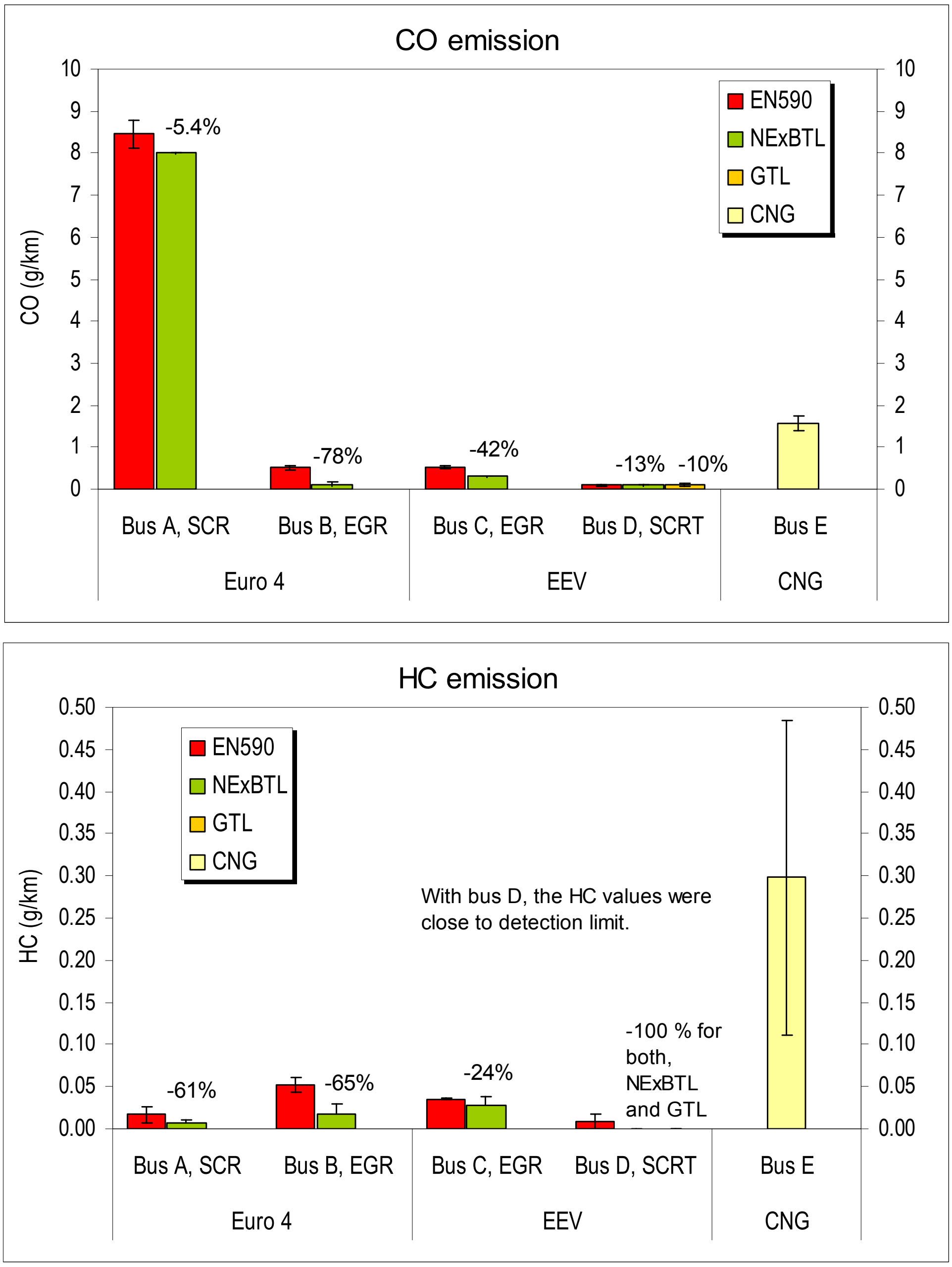


Figure 57. CO and HC emissions with different buses and fuels. Percentage shows the difference in emissions when NExBTL and GTL are compared to the EN590 fuel. Braunschweig test cycle.

Combustion process is a complicated phenomenon. However, differences in fuel consumption between the test fuels can be estimated with simplified assumptions. Based on the better heating value of NExBTL than that of EN590, the mass based fuel consumption would be some 1.9 % lower with NExBTL than with the EN590 fuel for Bus A and Bus B (Table 21). The volumetric fuel consumption would be some 5 % higher for NExBTL than for EN590, when the differences in densities of the test fuels are taken into account.

In real life, the fuel consumptions with all buses tested were well in line with the estimations. However, fuel consumption cannot be directly derived from heating values and densities of fuels. For instance, cetane number may affect engine performance, as well. In addition, it is possible to optimise engines for paraffinic fuels to avoid adverse effect of lighter fuel on fuel consumption (Aatola et al. 2008).

With Bus A and B, tailpipe CO_2 emissions were about 2.5 % lower when using NExBTL than when using the EN590 fuel. With buses C and D the tailpipe CO_2 emissions were 4–5 % lower, respectively. EEV buses C and D seemed to benefit more on the higher hydrogen to carbon ratio of NExBTL and GTL fuels when compared to buses A and B. Consequently, volumetric fuel consumption raised only by 4 % when NExBTL and GTL fuels were compared to EN590 fuel (Figure 58).

The reduction of CO_2 emission is based on the higher hydrogen to carbon ratio of NExBTL than that of the EN590 fuel. The life-cycle CO_2 emissions are low for the bio-based NExBTL fuel when compared to the fossil EN590 fuel, but the life-cycle emissions are not taken into account in this report.

Table 21. Heating values and densities of the test fuels.

	Density kg/m^3	Heating value MJ/kg	Heating value MJ/l
EN 590	835	43.2	36.1
NExBTL	779	44.0	34.3
Difference (%) Neat NExBTL vs EN590		*1.9*	*-5.0*

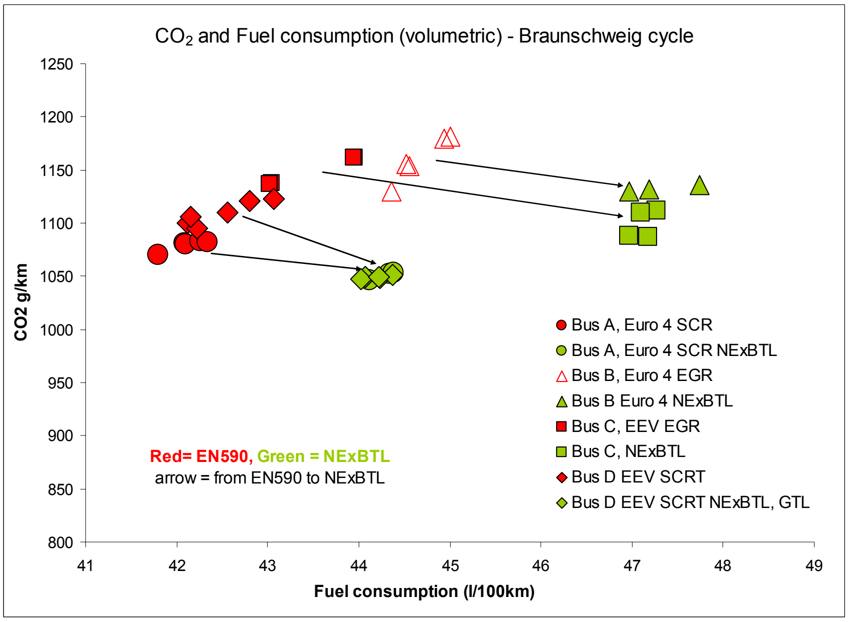


Figure 58. The CO_2 emission and volumetric fuel consumption with the EN590, NExBTL and GTL fuels Braunschweig test cycle.

4.3 Gaseous unregulated emissions

4.3.1 Aldehydes

The individual carbonyl compounds were analysed with HPLC from the samples obtained with Bus B, C, D and E. In addition, formaldehyde and acetaldehyde were screened with the FTIR equipment. The numerical results are shown in Appendices.

Bus B equipped with the EGR system showed significantly higher aldehyde emissions than the SCR equipped bus A (Figure 60). CNG bus showed low level of aldehyde emissions, practically at the same level as with Bus A. Aldehydes from bus C and D could not be analysed due to strong NO_2 formation by catalyst. NO_2 formation does not disturb formaldehyde measurement with FTIR equipment, and thus FTIR results were screened to study aldehyde emissions. Formaldehyde concentrations in the exhaust gas were well below the detection limit of FTIR instrument for all buses: concentrations were below 3 ppm, whereas the detection limit is 20 ppm. Detection limit for acetaldehyde is as low as 5 ppm. Buses B and A resulted in the highest acetaldehyde concentrations. Acetaldehyde concentrations for buses C, D and E were very low (Figure 59).

With buses A, B and E, formaldehyde represented the major part of aldehyde emissions. For Bus A, also acetaldehyde and propionaldehyde, and with Bus B acetaldehyde and valeraldehyde existed in the exhaust gas. For CNG bus E, formaldehyde dominated and additionally only a small amount of acetaldehyde and propionaldehyde was found.

The effect of fuel on aldehyde emissions was below 5 % with buses A and B, which is not significant difference when the uncertainty of the measurement method is taken into account. With bus B valeraldehyde was found only with the EN590 fuel.

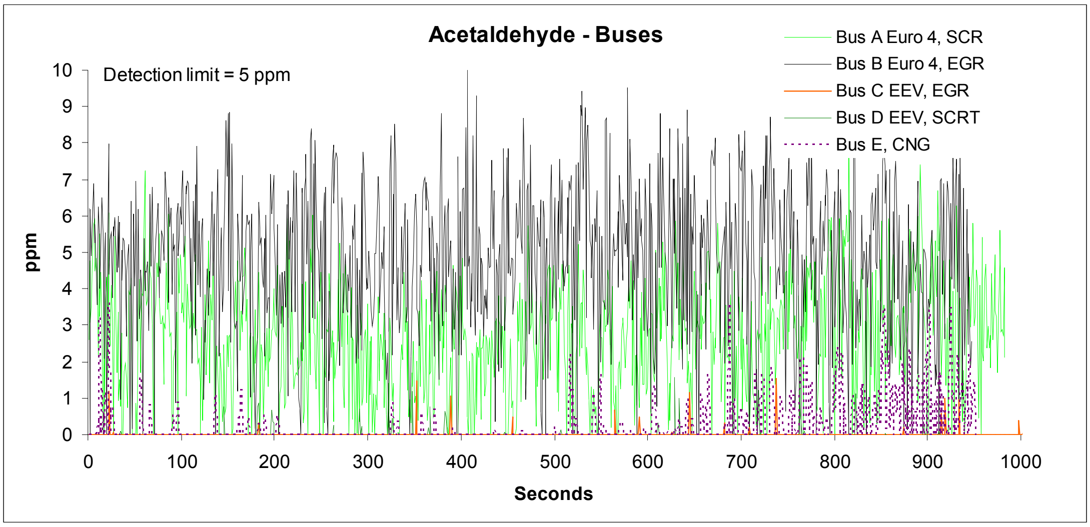


Figure 59. The acetaldehyde concentration over the Braunschweig test cycle. Measured with FTIR.

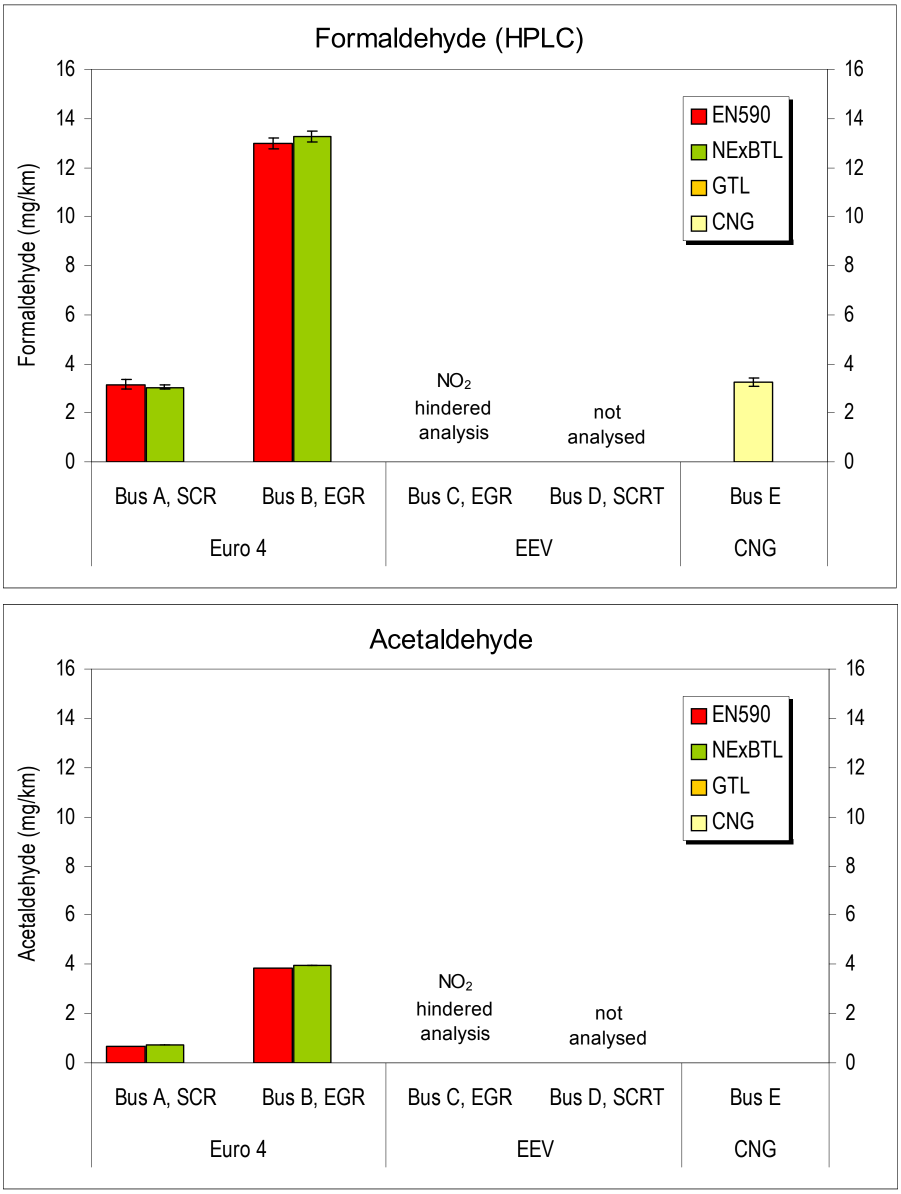


Figure 60. The formaldehyde and acetaldehyde emissions with the EN590 and NExBTL fuels. Buses with Braunschweig test cycle.

4.3.2 Individual hydrocarbons

The individual hydrocarbons were analysed with gas chromatograph from the samples obtained with buses B, C, D and E. The numerical results are shown in Appendices. Major part of the GC and FTIR results were below detection limit.

CNG bus showed the highest methane emission, which originates from unburned fuel (CNG is mainly methane). Methane emissions were at low level with EN590 and NExBTL fuels. In the FTIR analysis methane emissions were observed for all fuels, NExBTL, GTL and the EN590 fuel. For buses B and C, NExBTL seemed to give a slight benefit regarding benzene emissions (Figure 61).

Ozone forming potential was not calculated due to the limited number of the individual aldehydes and hydrocarbons analysed in this study. However, there was no indication of increased ozone forming potential with NExBTL or GTL when compared to EN590 fuel, preferably vice versa. Individual aldehyde and hydrocarbon emissions were at the same or lower with the NExBTL than with the EN590 fuel.

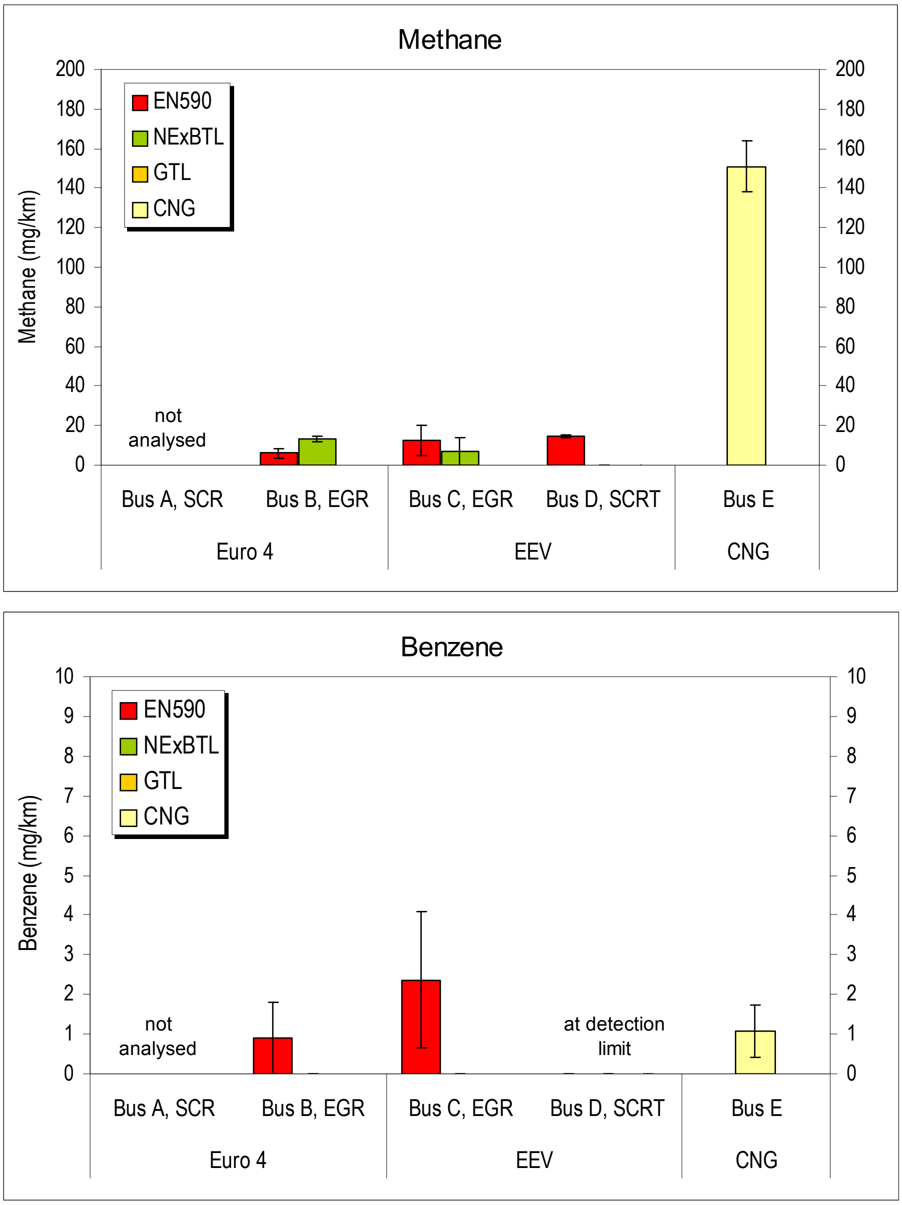


Figure 61. The methane and benzene emissions with the EN590 and NExBTL fuels. Buses with Braunschweig test cycle.

The individual gaseous unregulated compounds measured with Gasmet FTIR equipment were at very low level, most of them at the detection limit. Ammonia, nitrous oxide and sulphur dioxide concentrations over the Braunschweig cycle are shown in Figures 62 and 63. Ammonia emission level was below 3 ppm with all diesel buses. CNG bus resulted ammonia peaks and mass emission was 0.29 g/km. It is known that a three-way catalyst forms ammonia randomly. Nitrous oxide level was at the detection limit with buses A, B, C and E. Bus D equipped with the SCRT technology showed higher emissions of nitrous oxide than the other buses. Despite of low emission level of nitrous oxide, it is noted that NExBTL and GTL fuels showed systematically slightly lower emission level than the EN590 fuel with buses A, B, C and D. Sulphur dioxide emissions were generally below 3 ppm, even though some peaks up to 7 ppm were observed. No bus or fuel related differences were seen.

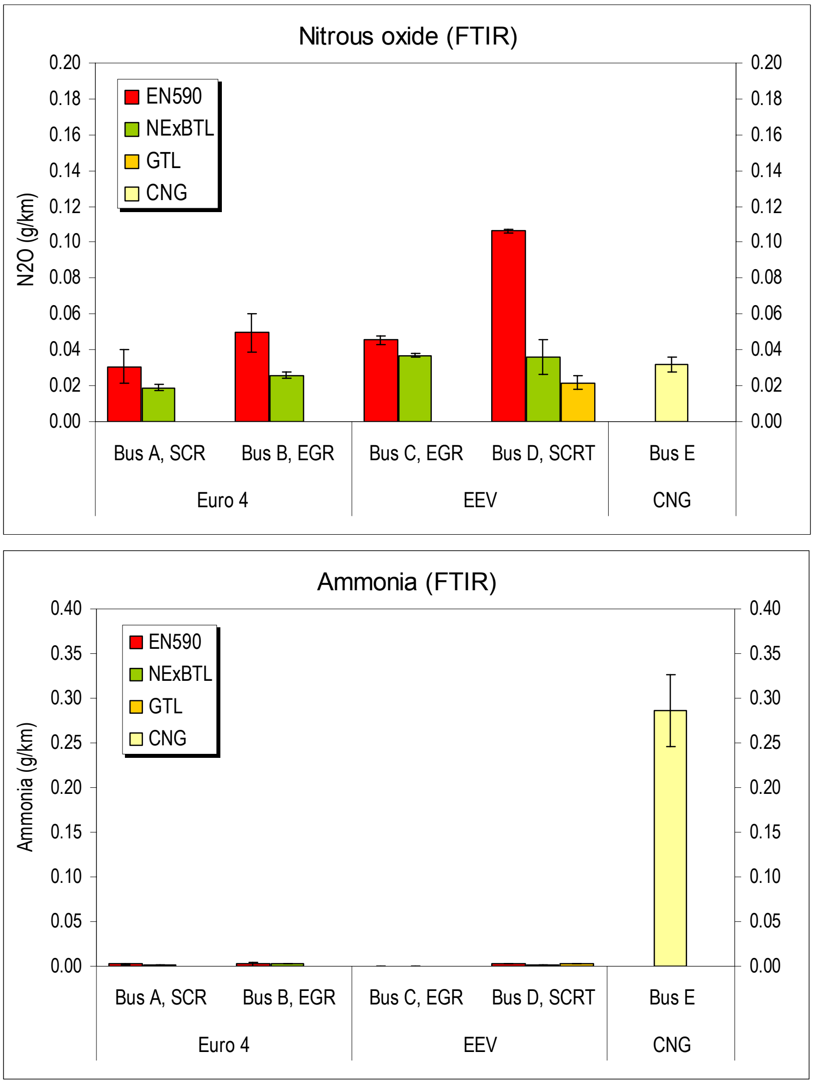
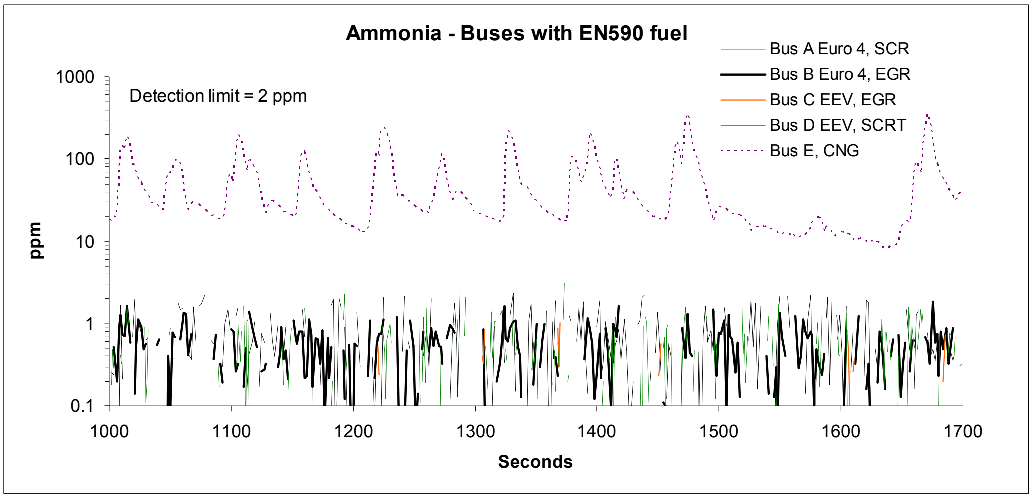
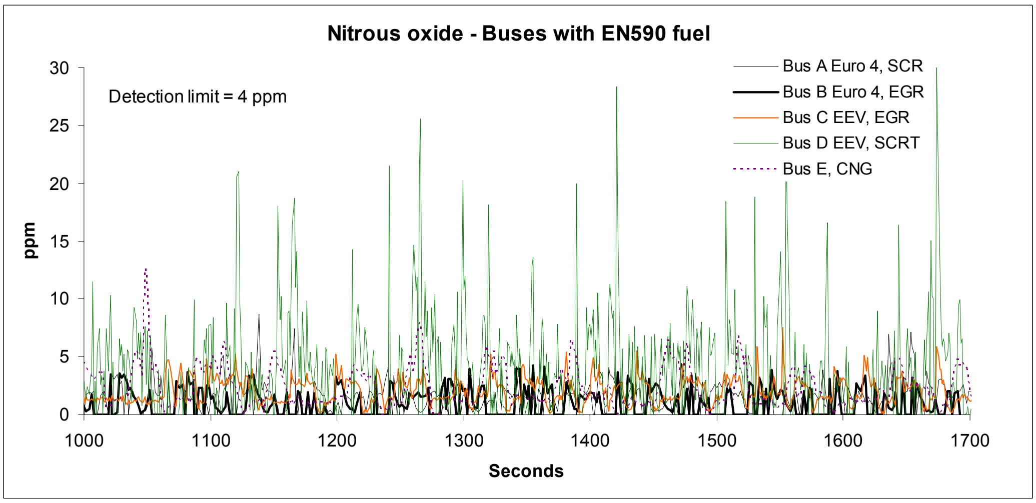


Figure 62. Nitrous oxide and ammonia emissions measured with FTIR equipment. Braunschweig test cycle.





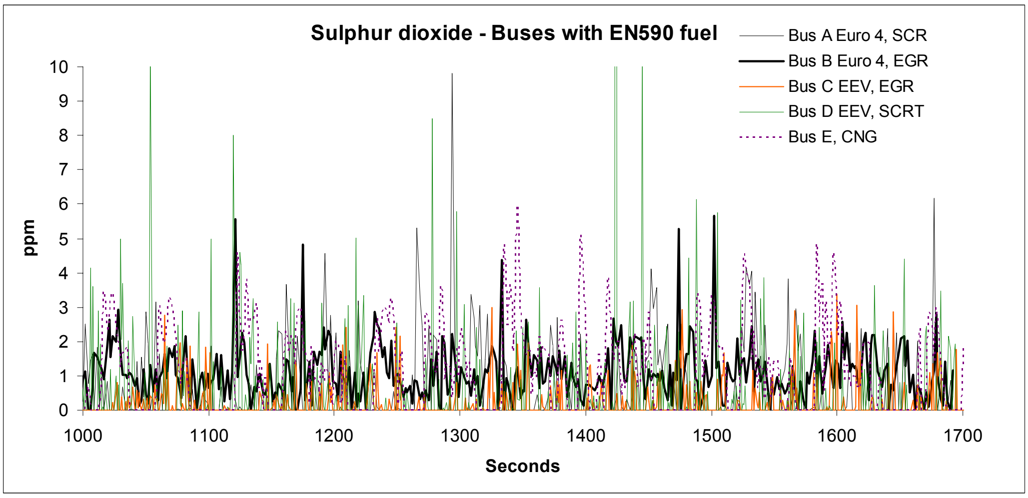


Figure 63. Ammonia, nitrous oxide and sulphur dioxide emissions with buses over the Braunschweig test cycle. Measured with FTIR. Note logarithmic y-axis for ammonia.

4.3.3 Composition of particulate matter (SOF, SO_4 and NO_3)

The results of the compositional analysis of particulate matter are shown in Appendices and in Figures 64–66. The soluble organic fraction (SOF) of particulate matter was low with buses A, B and C, around 5–13 % of the particulate mass emission. Share of SOF with bus D seemed to be higher than SOF with other diesel busses. PM emission level of bus D was low, which increases uncertainty of the measurement. PM emission level from CNG bus E was too low for compositional analysis of particles.

The effect of fuel on the share of SOF could not be seen for buses B, C and D. With bus A, the particles seemed to contain higher share of SOF with NExBTL when compared to EN590. However, the differences between fuels were very low.

The sulphur content of the EN590 fuel was very low, around 5 ppm. The NExBTL and GTL fuels did not contain any sulphur. Slightly lower sulphate emission was observed for the NExBTL fuel than for the EN590 fuel with buses A, B and C (Figure 65). Bus D and the CNG bus resulted in the lowest level of sulphate emission.

Nitrate emissions were below 1 mg/km with buses A and B, and 0.1 mg/km for the CNG bus. High nitrate emission, 5–6 mg/km, was detected from particulate matter from buses C and D, which also showed strong NO_2 formation.

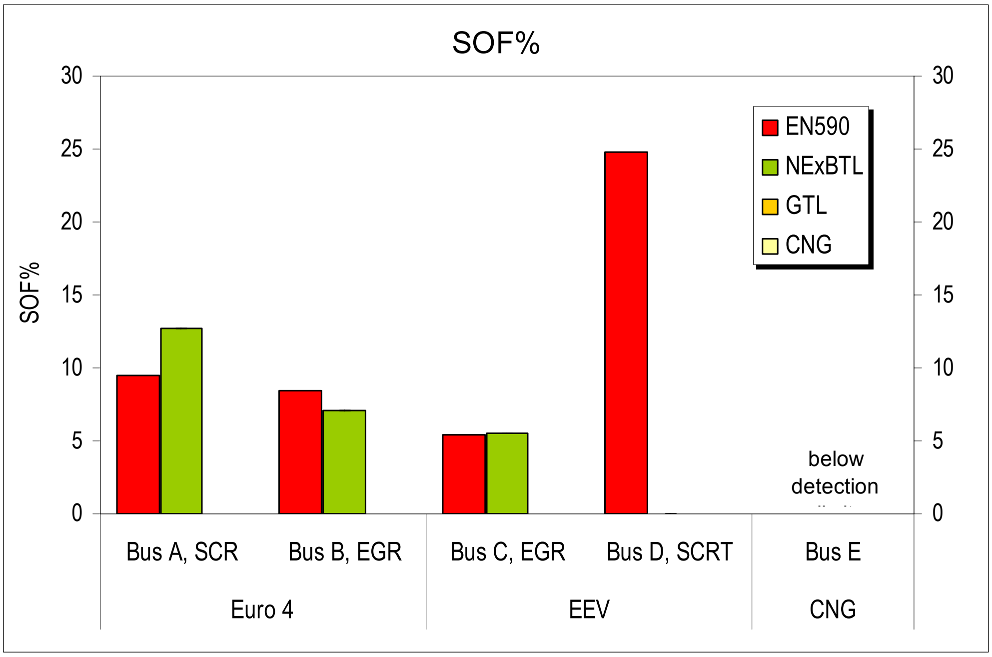
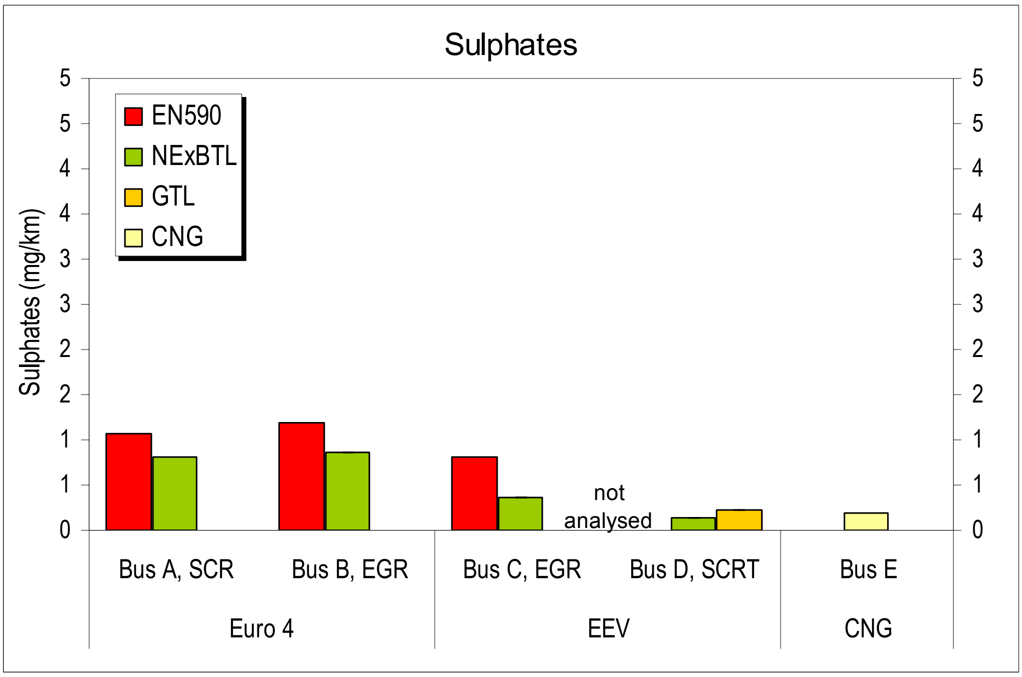


Figure 64. Soluble organic fraction of particulate matter. Braunschweig test cycle.



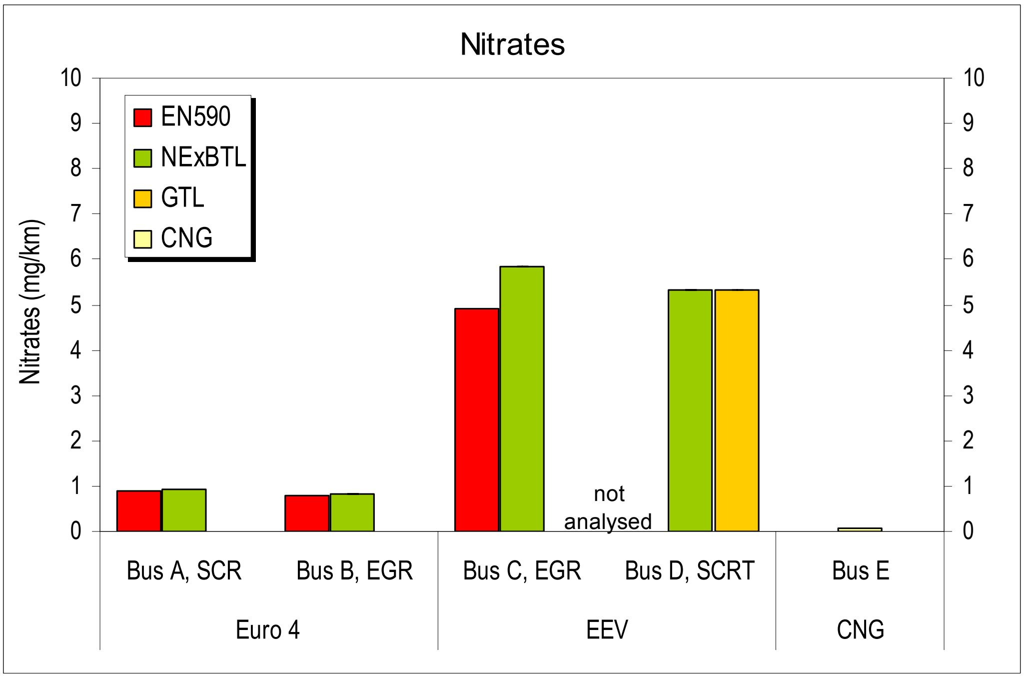


Figure 65. Sulphate and nitrate emissions with buses over Braunschweig test cycle.

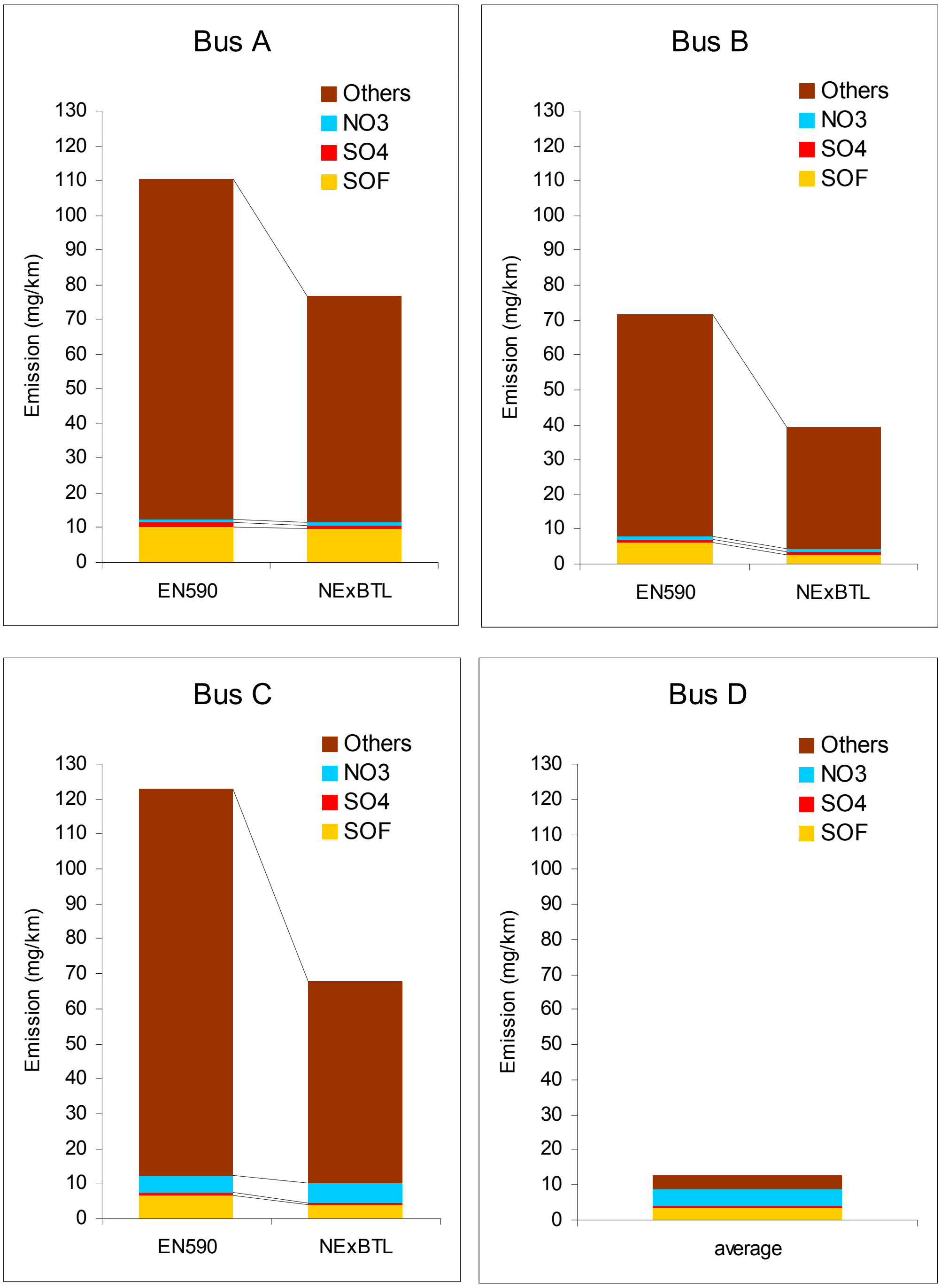


Figure 66. The composition of particulate matter with buses A, B, C and D. PM emission from CNG bus E was too low for compositional analysis. Braunschweig test cycle.

4.4 PAH analyses and Ames tests

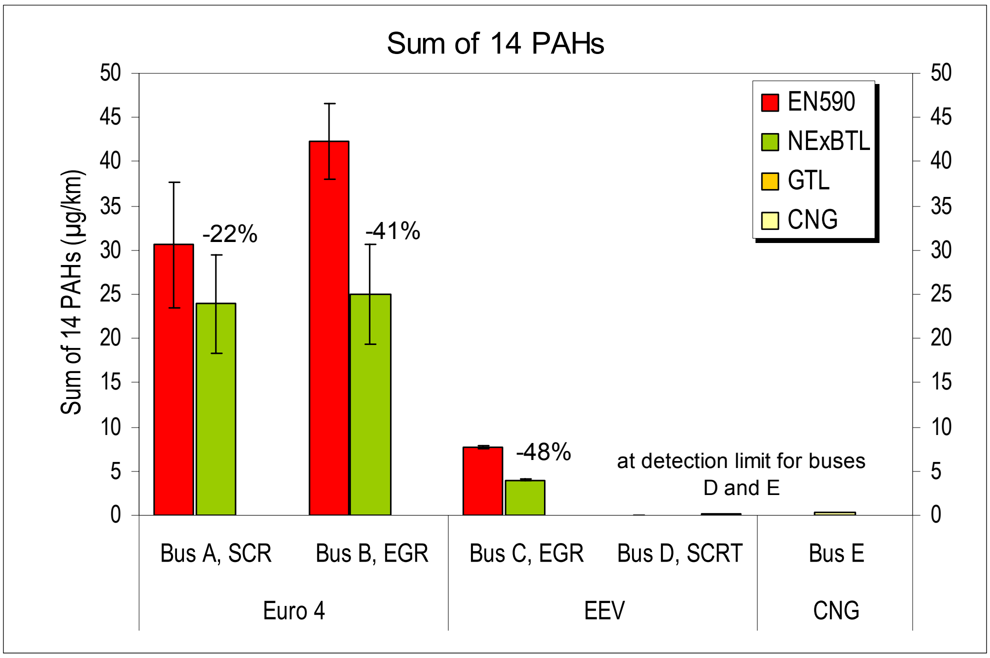
The aromatic contents of the EN590 fuel batches used in this study were relatively low, namely 18 and 22 wt-%. In addition, EN590 contained very low level of polyaromatics, below 2 wt-%.

Sum of 14 priority PAHs varied from 0 to 40 µg/km with different buses. Sum of 7 priority PAHs varied from 0 to 4 µg/km and benzo(a)pyrene from 0 to 0.7 µg/km, respectively. Ames test with strain TA98-S9 showed mutagenic activity from 0 to 22 krev/km. The PAH emission results are at the same level as in another study (Aakko et al. 2006): BaP <0.03 µg/km with aftertreatment devices; up to 0.5 µg/km without catalysts; sum of 7 PAHs <1 µg/km. Ames test results in the study at hand were at lower level than in the earlier study, which showed mutagenic activity from 16 to 100 krev/km for buses (Aakko et al. 2006).

Figure 67 shows that the general trend in PAH emissions as µg/km was beneficial for the NExBTL and GTL fuels when compared to the EN590 fuel with buses A, B and C. The difference between fuels was observed concerning the sum of 14 PAHs. Sum of 7 PAHs was low for all buses tested, and the differences between fuels were not significant when the deviation of the measurements is taken into account. Buses D and E resulted in very low PAH emission level.

When the PAH emissions were evaluated as µg/g, it was noted that there were substantial differences between vehicles. PAH14 emissions were around 300 µg/g with bus A, 600 µg/g with bus B, 60 µg/g with bus C, 10 µg/g with bus D and 95 µg/g with CNG bus E. NExBTL and GTL showed lower concentration of 7 PAHs than the EN590 fuel as µg/g (Figure 68). There were no significant differences between EN590, NExBTL and GTL considering the sum of PAH14 as µg/g,

Figure 69 shows the emissions of individual PAH compounds. It is noted that the emission level of the PAHs heavier than pyrene is extremely low. Bus A resulted in high emission of the lightest PAHs. Buses D and E showed very low PAH emissions (scale 0–1 µg/km).



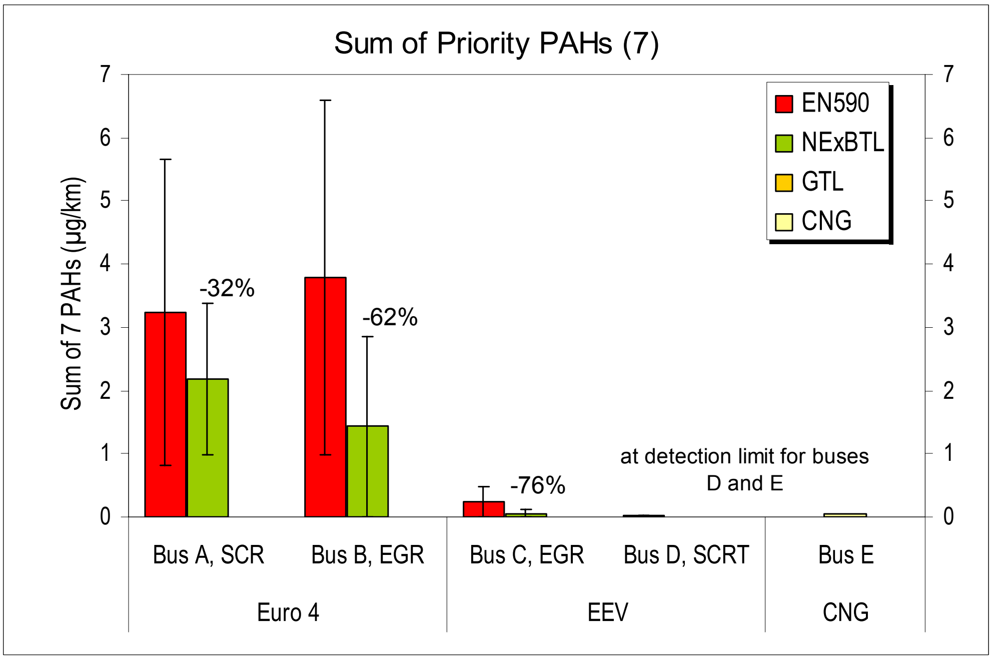


Figure 67. The sum of 14 and 7 PAH compounds as µg/km. Braunschweig test cycle.

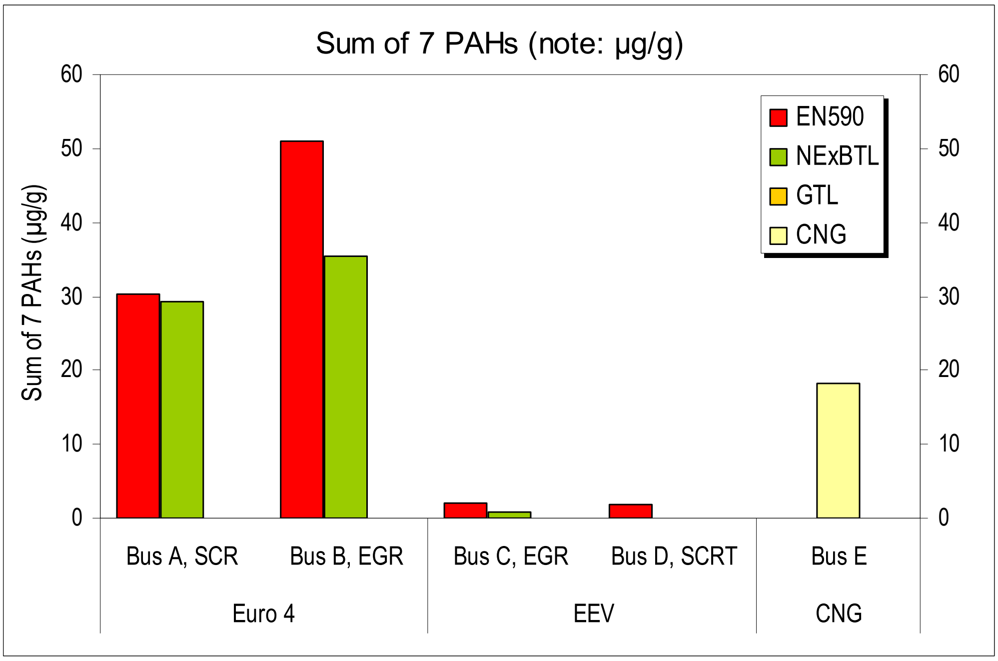


Figure 68. The sum of 7 PAH compounds as µg/g. Braunschweig test cycle.

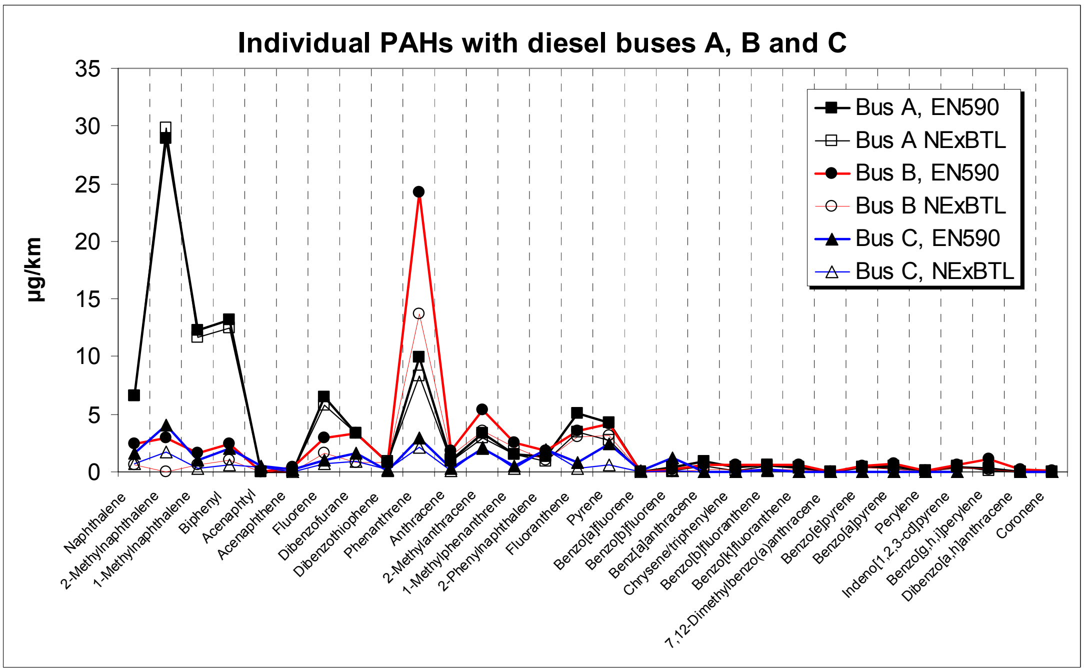


Figure 69. Individual PAHs with diesel buses A, B and C. SCRT equipped bus D and CNG bus showed extremely low PAH emissions. Braunschweig test cycle.

The Ames test results with strain TA98-S9 did not show any mutagenic activity for the particulate SOF from Bus A. Slight mutagenicity was observed for buses B, C and D. Mutagenic activity as krev/g varied for bus B from 70 to 300 krev/g. Buses C and D showed mutagenicity of 38 and 90 krev/mg with the EN590 fuel, but no mutagenicity with the NExBTL fuel. CNG bus E showed mutagenic activity of 71 krev/mg (Figure 70).

NExBTL seems to give benefit on mutagenic activity of particulate SOF when compared to EN590 fuel with buses C and D. However, mutagenic activity was low also with the EN590 fuel.

One sample with bus B showed high mutagenic activity for the NExBTL fuel, whereas the parallel sample did not. The other sample with Bus B using the NExBTL fuel did not show similar activity as parallel sample, and thus the high result is thought to be due to contamination.

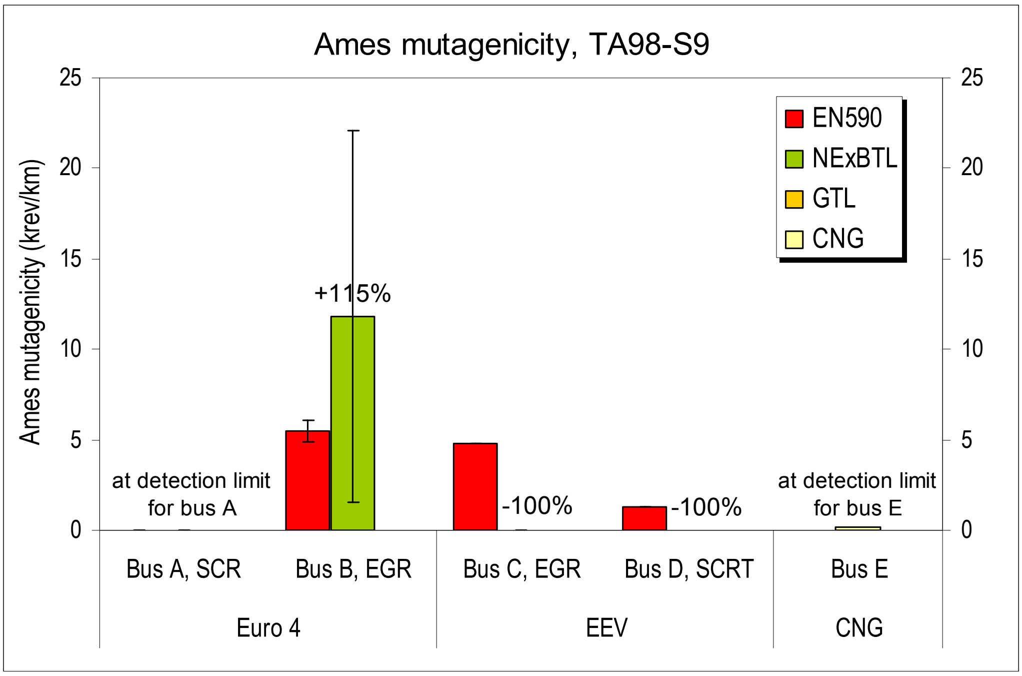
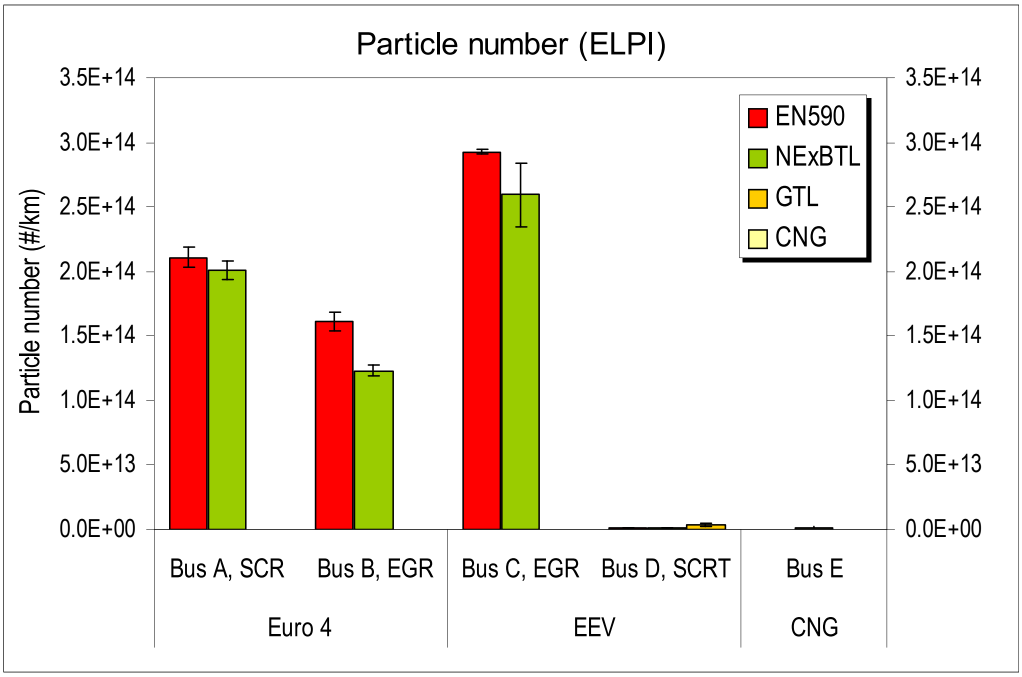


Figure 70. Mutagenic activity with Ames test strain TA98-S9. Buses with Braunschweig cycle.

4.5 Particle number emissions

The error bars in Figures are based on the standard deviation calculated from the replicate tests with the EN590 fuel. The particle number results are presented in Appendices and Figure 71.

With bus A the number of particles emitted per kilometre was about at the same level with NExBTL and EN590. With NExBTL the momentary particle number peaks were higher than with EN590. Buses B and C produced smaller total number of particles with NExBTL compared to EN590. Bus D equipped with particle trap and CNG bus showed very low particle number emission level when compared to diesel buses A, B and C.



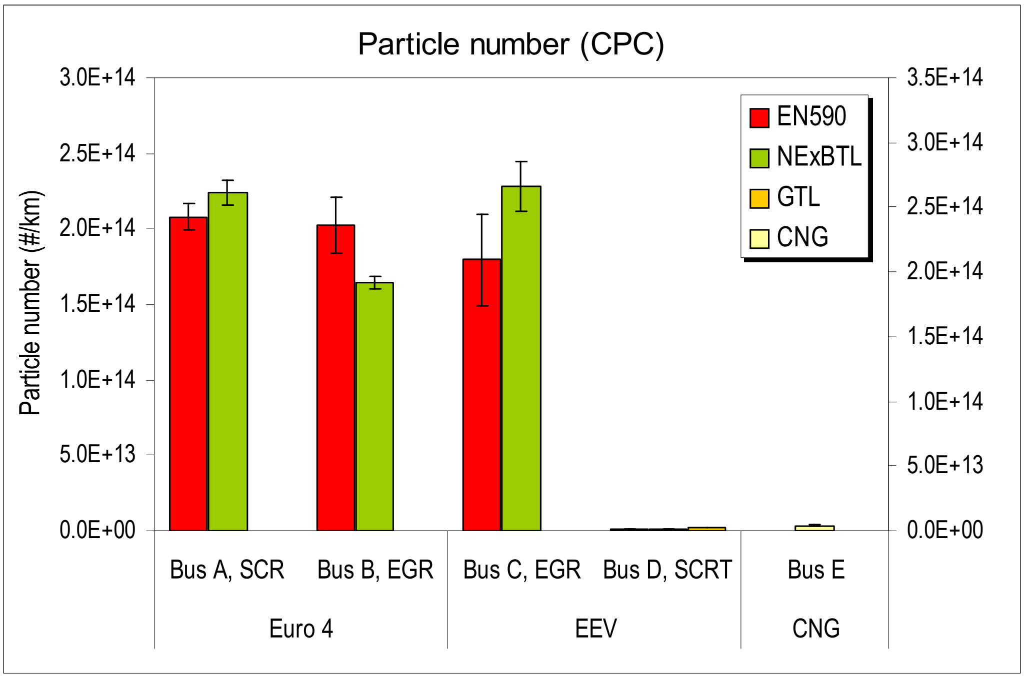


Figure 71. Total particle number measured with ELPI and CPC. Buses with Braunschweig test cycle.

Figure 72 shows the particle number size distributions. Average values are based on several parallel measurements with each fuel. The EN590 produces slightly higher number of particles on 0.1 µm size class than the NExBTL fuel. The shape of the distribution is similar with both fuels for diesel buses. NExBTL reduces number of particles in the size class larger than 80 nm, but the number of smaller particles is not necessarily reduced.

As mentioned, particle trap equipped bus D and CNG bus resulted in extremely low number of particles, at different order of magnitude than with the other buses. Due to low number of particles with these buses, the differences in particle size distributions between fuels are deemed to be insignificant.

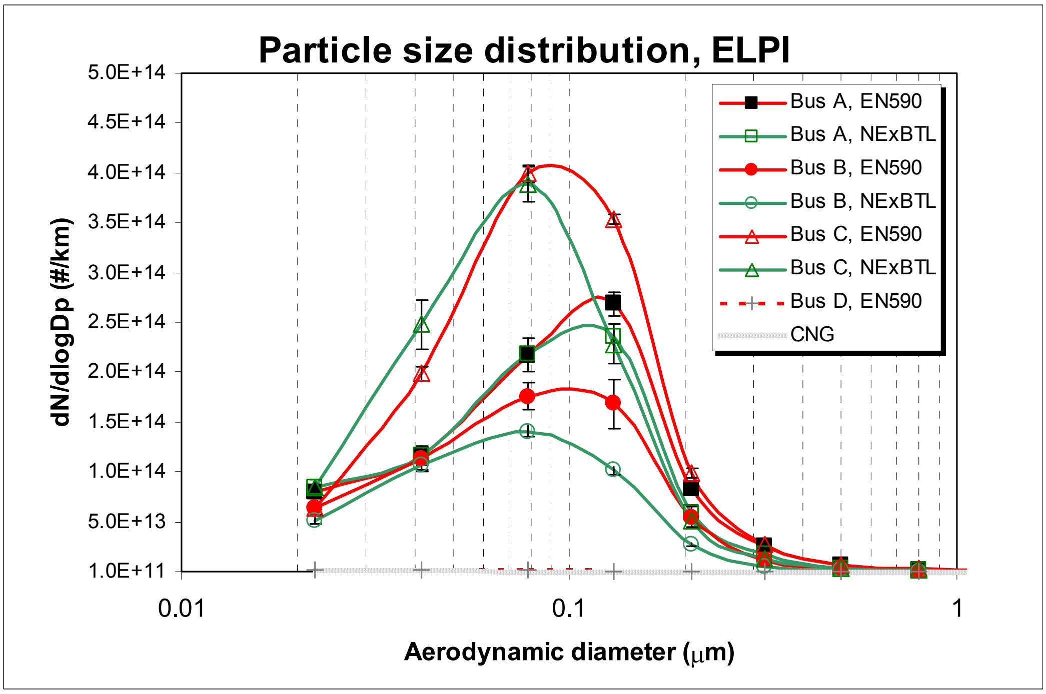


Figure 72. The particle size distribution measured with ELPI. Buses with Braunschweig test cycle.

5. Summary

Three heavy-duty engines and four diesel buses were measured using various fuels. Test fuels covered European diesel fuel (EN590), rapeseed methyl ester (RME), paraffinic fuels NExBTL and GTL. NExBTL and RME were studied as neat, and restrictedly as a 30 % blend with EN590 diesel fuel. All fuels were not tested with all engines and vehicles.

Two of the engines represented Euro 4 emission level: Cummins bus engine and Scania truck engine. One engine, SisuDiesel, was for non-road applications. Two buses represented Euro 4 emission level and three buses EEV emission level technologies. One bus was a stoichiometric CNG bus. Diesel oxidation catalyst (DOC), particle oxidation catalyst (POC), EGR, SCR and SCRT emission control technologies were represented in the engines and vehicles. Cummins engine was originally equipped with SCR system, which was removed to study behaviour of DOC+POC system with different fuels.

Measurements covered regulated emissions and a number of unregulated emissions e.g. aldehydes, composition of particulate matter, PAH emissions, Ames mutagenicity and particle size distributions. In addition to emission tests, a long-term test with Cummins engine was performed to study behaviour of DOC catalyst with RME and EN590 fuels.

The effect of fuel on the regulated emissions

Generally, the NExBTL and GTL reduced all regulated emissions: PM, NO_X, CO and HC (Figure 73). For RME, the NO_X emissions were higher than for EN590, which is an expected result. The NO_X emissions were about 3–28 % lower with the NExBTL and GTL fuels compared to EN590 fuel with exception of Scania truck engine. The 12 liters Scania truck engine may be adjusted differently than 9 liters bus engines.

The PM reductions compared to EN590 generally varied between –17 and –51 %. With Scania truck engine equipped with catalyst, RME decreased PM emissions by 23 %, but in the tests without catalyst increased by 38 %, which was an unexpected result. PM with RME tends to be “wet” including high share of soluble organic fraction (SOF) due to high boiling compounds of RME. In this case, adjustment of Scania engine may favour formation of wet particles, and low load cycle might strengthen this phenomenon.

The tailpipe CO_2 emissions decreased from 2 to 6 % with paraffinic NExBTL and GTL fuels, and also mass-based fuel consumption reduced due to better hydrogen to carbon ratio and higher heating values of paraffinic fuels compared to EN590. As the densities of paraffinic fuels are significantly lower compared to conventional diesel, the volumetric fuel consumption was 3–6 % higher, respectively. With RME, the mass-based and volumetric fuel consumption, as well as CO_2 emissions, were higher compared to EN590. Even though RME's density is high the volumetric fuel consumption increased roughly 10% when compared to EN590 fuel due to low heating value of RME.

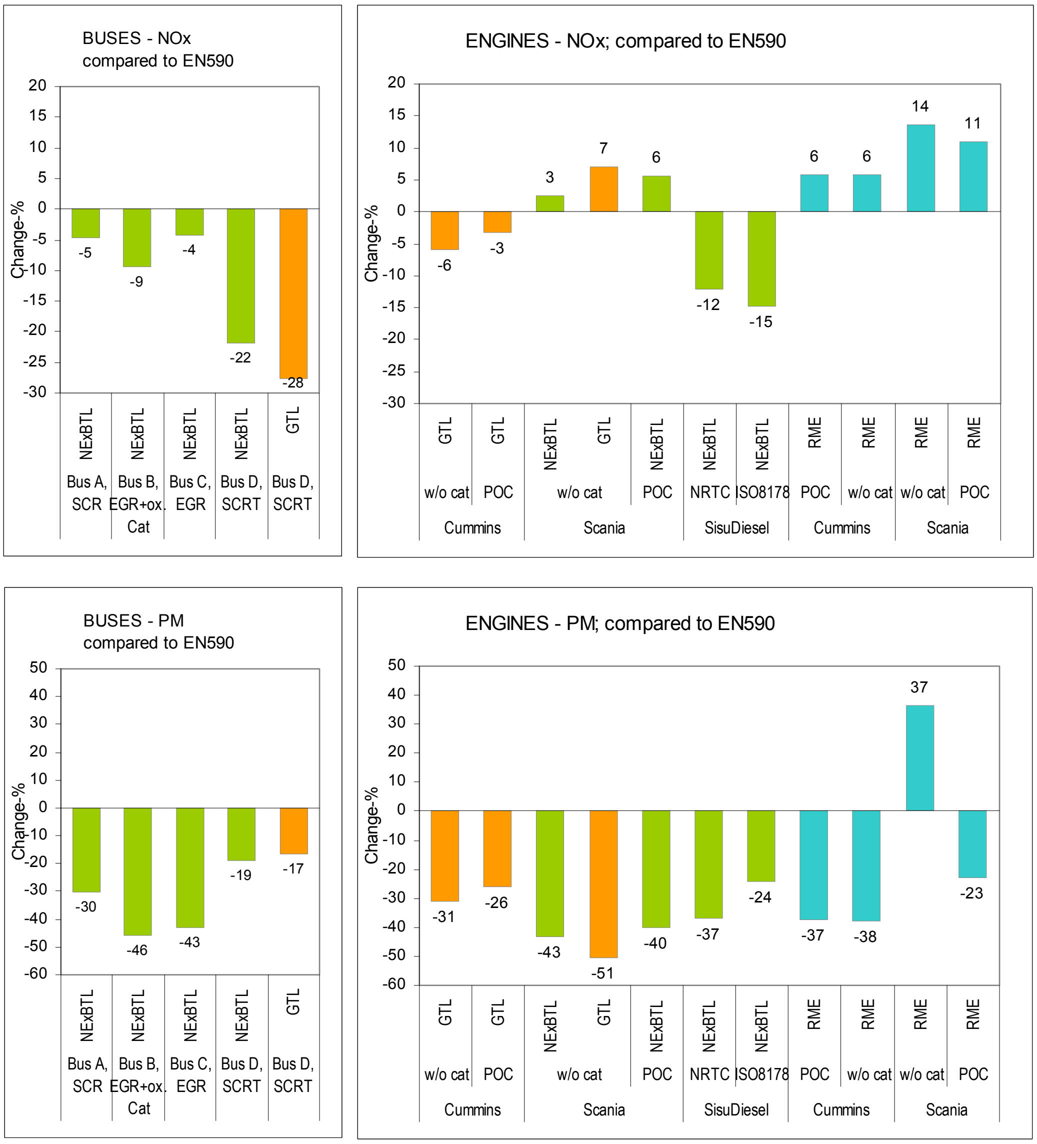


Figure 73. The difference in NO_x and PM emissions when NExBTL, GTL and RME are compared to the EN590 fuel.

The effect of fuel on the unregulated emissions

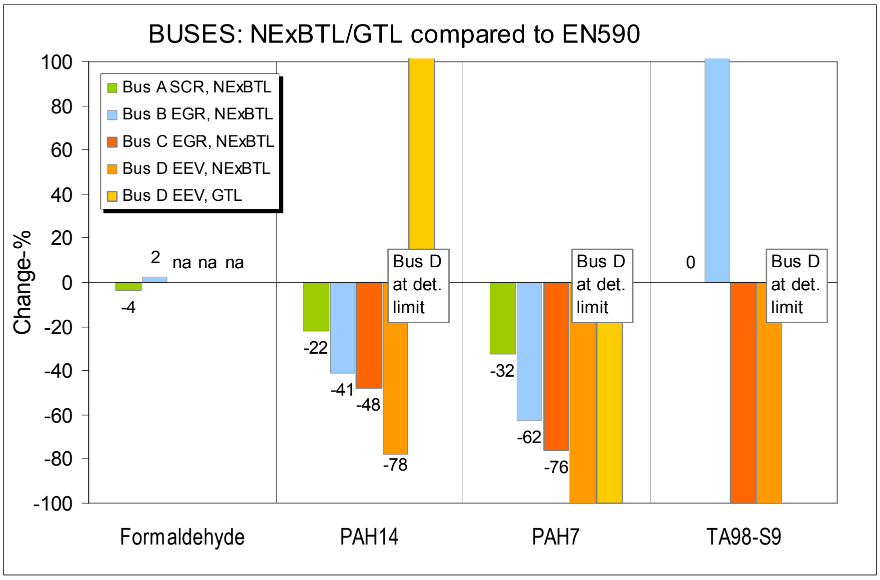
With engines, in most cases the paraffinic fuels decreased formaldehyde emissions, whereas with buses no significant differences in aldehyde emissions between fuels were observed. With engines equipped with catalyst and buses C and D, strong NO_2 formation hindered aldehyde analysis. In the tests without catalyst, GTL showed a 15 % reduction in formaldehyde emission with Cummins engine. With Scania engine without catalyst, aldehyde emissions were relatively high. NExBTL and GTL decreased the formaldehyde emission by 17 to 18 % compared to EN590 with Scania engine. With RME the formaldehyde emission decreased by 22 % with Cummins engine and increased by 11 % with Scania engine when compared to EN590 (Figure 74).

The particulate matter emission from buses contained low share of soluble organic fraction, namely 5–13 %. Scania engine showed surprisingly high share of SOF in the particulate matter, from 22 to 37 % with other fuels and 74 % with RME in the tests without catalyst. Sulphur content of fuels was below 10 mg/kg, and consequently, particle associated sulphate emissions very low. The highest nitrate emissions were observed in the tests with catalysts, which generated high NO_2 emissions.

With buses, the general trend in the emissions of PAHs associated in the particulate matter was slightly beneficial for the NExBTL fuel when compared to the EN590 fuel. With Cummins engine, the priority PAHs associated with particulate matter and semi-volatile fraction were the highest with the EN590 fuel and the lowest with GTL and RME. With Scania engine, the PAH emissions were generally rather high. Clear benefit in PAH emissions was gained when GTL and NExBTL when compared to EN590, whereas an opposite phenomenon was seen with RME. With SisuDiesel engine, for NExBTL the PAH emissions were lower than for EN590.

The Ames test with strain TA98-S9 showed only slight mutagenic activity for the extract of particulate matter from buses. NExBTL seemed to give some benefit on mutagenic activity with diesel buses C and D. With Scania engine, NExBTL, GTL and RME showed lower response on Ames mutagenicity than EN590.

With diesel buses, the number of particles emitted per kilometre was about at the same level with NExBTL and EN590, or in some cases slightly lower with NExBTL. Bus D equipped with particle trap and CNG bus showed very low particle number emission level when compared to other buses. Generally, with buses and engines, the paraffinic fuels, NExBTL and GTL, efficiently reduce number of particles in the size class larger than 80 nm, but the number of smaller particles is not necessarily reduced when compared to EN590. Nucleation tendency was seen with RME in the tests with Cummins and Scania engines. At the accumulation "soot" mode, the RME showed the lowest number of particles, which is in accordance with the particulate mass results with Cummins engine.



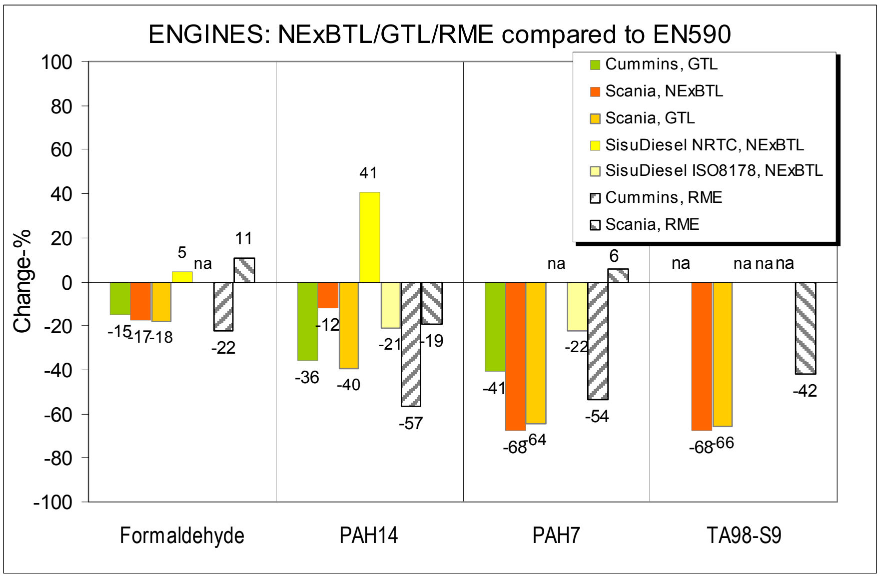


Figure 74. The difference in selected unregulated emissions when paraffinic fuels and RME are compared to EN590.

Performance of POC and DOC catalysts

POC and DOC catalysts were studied with Cummins and Scania engines. The HC and CO emissions were reduced by over 90 % with oxidizing catalyst, close to zero level. The NO_X emissions were not significantly affected by catalyst and the changes in NO_X were mainly fuel related. NO_X typically contains mainly NO and to lesser extent NO_2. In these tests, oxidation catalyst generated NO_2 so that the ratio of NO_2 to NO increased substantially. For both engines, high NO_2 concentrations in the tests with catalyst hindered aldehyde analyses as the reagent of the DNPH cartridge is consumed by NO_2.

Both fuel and catalyst reduced PM emission efficiently. The most substantial benefit with PM is gained by using DOC+POC catalyst with paraffinic fuels or with RME, a reduction of 75 % can be obtained with paraffinic fuel together with DOC+POC. Soluble organic fraction of particulate matter was reduced significantly with DOC+POC. The catalyst significantly dropped down the priority PAH emissions and Ames mutagenicity of extract of particulate matter. For both engines, with each fuel, the catalyst decreased significantly the number of particles on each size class. In addition, the nucleation mode particles were removed completely.

Figure 75 presents the combined effect of fuel and catalyst on particulate matter and selected unregulated emissions with engines when the base level of emissions is EN590 without catalyst. It can be seen that DOC+POC catalyst clearly decreased PM emissions, particle associated PAH emissions and the mutagenicity of particle matter. These changes are mainly due to decreased particulate mass emissions.

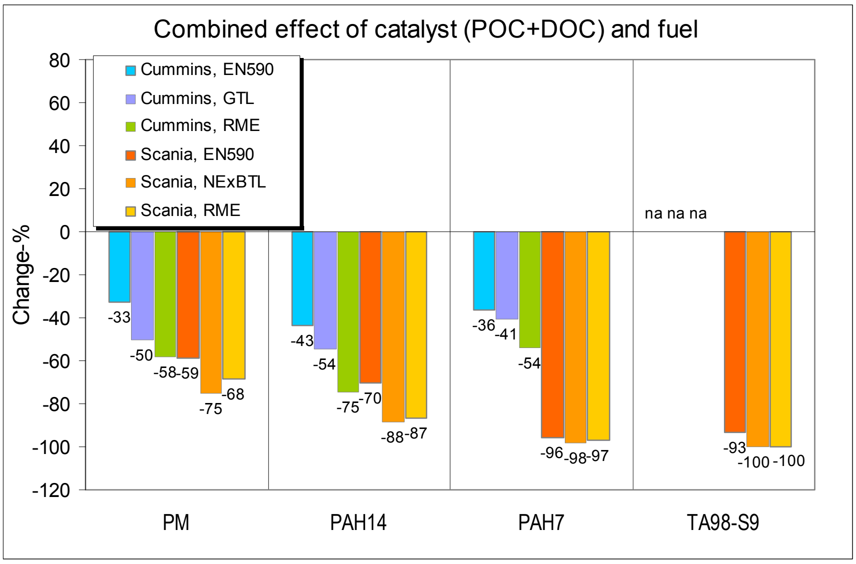


Figure 75. The combined effect of fuel and catalyst on selected unregulated emission. Comparison made to EN590 fuel measured without catalyst.

Long term test was carried out with Cummins bus engine equipped with Ecocat DOC catalyst. EN590 and 100 % RME fuels were run 350 hours each. The emission test showed that the engine out HC and CO emissions increased roughly 10 and 20 % over the entire test period, and PM emissions increased some 25 %. However, the absolute PM emission level was low and therefore the relative change is not very significant.

The results showed that the catalyst's HC and CO conversion ratios decreased faster with RME than with the EN590 fuel. The fuel did not have an effect on the conversion ratio of PM emission.

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Appendix A

Average results of engines. Regulated emissions, CO2 and fuel consumption.

		number of measurements	CO g/kWh	HC g/kWh	NOx g/kWh	PM g/kWh	CO_2 g/kWh	Fuel consumption FC kg/kWh	FC l/kWh
Cummins engine, ESC test cycle									
without catalyst	EN590	8	0.64	0.07	9.8	0.017	642.0	208.4	248.1
	GTL	6	0.49	0.06	9.3	0.012	619.2	204.1	262.7
	RME	6	0.56	0.03	10.4	0.011	653.5	243.3	275.4
with POC+DOC	EN590	8	0.000	0.006	9.7	0.012	643.7	208.9	248.6
	GTL	6	0.0007	0.007	9.4	0.009	622.0	204.0	262.5
	RME	6	0.000	0.006	10.3	0.007	658.8	241.2	272.9
Scania engine, simulated Braunschweig cycle.									
without catalyst	EN590	10	0.64	0.19	6.0	0.032	695.4	228.0	271.5
	NExBTL30%	8	0.57	0.15	5.9	0.027	677.9	225.5	274.4
	NExBTL	9	0.50	0.12	6.1	0.018	662.3	222.0	285.0
	GTL	3	0.47	0.16	6.4	0.016	654.3	222.9	286.9
	RME30%	4	0.64	0.15	6.2	0.035	698.6	241.4	283.0
	RME	5	0.65	0.07	6.8	0.044	723.1	267.5	302.7
with POC+DOC	EN590	14	0.04	0.00	5.9	0.013	700.0	230.1	273.9
	NExBTL	13	0.04	0.00	6.3	0.008	662.2	221.8	284.7
	RME	4	0.06	0.00	6.6	0.010	717.5	269.8	305.4
SisuDiesel engine									
NRTC cycle	EN590	4	1.04	0.04	3.3	0.034	733.0	na	na
	NExBTL	4	0.99	0.03	2.9	0.022	702.8	na	na
SO 8178 C1 cycle	EN590	3	0.30	0.05	2.3	0.017	689.2	220.3	262.2
	NExBTL	3	0.30	0.05	2.0	0.013	672.1	214.8	275.7

Appendix B

Average results of engines. Composition of particulate matter.

		SOF%	SOF mg/kWh	SO4 mg/kWh	NO3 mg/kWh	Others mg/kWh
Cummins engine, ESC test cycle						
without catalyst	EN590	na	na	na	na	na
	GTL	na	na	na	na	na
	RME	na	na	na	na	na
with POC+DOC	EN590	na	na	na	na	na
	GTL	na	na	na	na	na
	RME	na	na	na	na	na
Scania engine, simulated Braunschweig cycle.						
without catalyst	EN590	34	11	0.4	1.3	19.6
	NExBTL30%	30	8	0.3	1.8	16.8
	NExBTL	22	4	0.2	1.7	13.7
	GTL	37	7	0.1	1.1	10.1
	RME30%	54	19	0.3	0.8	15.0
	RME	74	33	0.3	1.0	10.1
with POC+DOC	EN590	20	3	0.2	1.4	8.8
	NExBTL	12	1	0.7	4.5	1.9
	RME	na	na	na	na	na
SisuDiesel engine						
NRTC cycle	EN590	na	na	na	na	na
	NExBTL	na	na	na	na	na
SO 8178 C1 cycle	EN590	na	na	na	na	na
	NExBTL	na	na	na	na	na

Appendix C

Average results of engines. Aldehyde emissions.

		Formaldehyde mg/kWh	Acetaldehyde mg/kWh
Cummins engine, ESC test cycle			
without catalyst	EN590	3.8	1.2
	GTL	3.3	1.1
	RME	3.0	0.9
with POC+DOC	EN590	*)	*)
	GTL	*)	*)
	RME	*)	*)
Scania engine, simulated Braunschweig cycle.			
without catalyst	EN590	18.5	5.0
	NExBTL30%	16.8	4.6
	NExBTL	15.3	4.2
	GTL	15.1	4.3
	RME30%	20.1	5.4
	RME	20.5	5.0
with POC+DOC	EN590	*)	*)
	NExBTL	*)	*)
	RME	*)	*)
SisuDiesel engine			
NRTC cycle	EN590	10.9	2.1
	NExBTL	11.4	2.3
ISO 8178 C1 cycle	EN590	na	na
	NExBTL	na	na

*) Strong formation of NO2 by catalyst prohibited analysis of aldehydes with DNPH cartridges.

Appendix D

Average results of engines. PAH and Ames emissions.

		FLU µg/kWh	FEN µg/kWh	ANT µg/kWh	FLUT µg/kWh	PYR µg/kWh	**BaANT** µg/kWh	**KRY/TRI** µg/kWh	**BbFLUT** µg/kWh	**BkFLUT** µg/kWh	**7.12-dBaA** µg/kWh	BePYR µg/kWh	**BaPYR** µg/kWh	**IPYR** µg/kWh	BghiPER µg/kWh	dBahA µg/kWh	PAH14 µg/kWh	PAH7 µg/kWh	Ames TA98-S9 krev/kWh	Ames TA98+S9 krev/kWh	Ames TA98NR krev/kWh
Cummins engine, ESC test cycle																					
without catalyst	EN590	0.09	0.26	0.09	0.69	2.08	0.26	0.61	0.00	0.09	0.00	0.09	0.09	0.09	0.09	0.00	4.5	1.1	na	na	na
	GTL	0.00	0.19	0.06	0.44	1.45	0.13	0.50	0.00	0.00	0.00	0.06	0.00	0.00	0.06	0.00	2.9	0.7	na	na	na
	RME	0.00	0.13	0.00	0.20	0.65	0.20	0.52	0.00	0.07	0.00	0.07	0.00	0.07	0.07	0.00	2.0	0.5	na	na	na
with POC+DOC	EN590	0.00	0.11	0.00	0.39	1.27	0.17	0.55	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.00	2.5	0.7	na	na	na
	GTL	0.00	0.12	0.00	0.30	0.85	0.12	0.42	0.00	0.06	0.00	0.06	0.00	0.06	0.06	0.00	2.1	0.7	na	na	na
	RME	0.00	0.10	0.00	0.10	0.42	0.10	0.42	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.1	0.5	na	na	na
Scania engine, simulated Braunschweig cycle.																					
without catalyst	EN590	0.00	0.73	0.16	2.76	8.69	1.51	1.89	1.16	0.45	0.00	2.04	1.36	1.78	1.31	0.55	24.4	8.1	16.0	18.2	7.2
	NExBTL30%	0.00	0.76	0.18	2.99	8.16	1.31	1.66	1.15	0.40	0.00	1.94	1.35	1.21	1.79	0.47	23.4	7.1	15.1	13.9	8.7
	NExBTL	0.05	1.20	0.21	5.31	10.09	0.44	0.73	0.39	0.11	0.00	0.85	0.50	0.46	0.88	0.21	21.4	2.6	5.2	8.2	3.1
	GTL	0.00	0.75	0.12	3.39	5.42	0.49	0.66	0.47	0.15	0.00	0.95	0.56	0.56	0.98	0.25	14.8	2.9	5.5	7.8	2.4
	RME30%	0.00	0.71	0.00	1.83	4.57	1.12	1.32	1.12	0.51	0.00	1.72	1.42	1.32	1.83	0.41	17.9	6.8	na	na	na
	RME	0.00	0.49	0.06	1.60	2.85	1.16	1.54	1.56	0.60	0.00	2.46	1.75	2.01	2.93	0.73	19.7	8.6	9.2	16.7	6.3
with POC+DOC	EN590	0.00	0.32	0.05	1.49	4.86	0.08	0.12	0.03	0.00	0.00	0.03	0.03	0.07	0.15	0.08	7.3	0.3	1.1	na	0.8
	NExBTL	0.04	0.53	0.04	0.66	1.31	0.05	0.07	0.00	0.00	0.00	0.04	0.02	0.00	0.08	0.01	2.9	0.1	0	na	na
	RME	0.00	0.19	0.00	0.97	1.79	0.10	0.12	0.00	0.00	0.00	0.00	0.00	0.03	0.07	0.00	3.3	0.3	0	na	na
SisuDiesel engine																					
NRTC cycle	EN590	0.11	0.77	0.00	0.28	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.16	0.00	na	na	na
	NExBTL	0.06	0.86	0.07	0.40	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.64	0.00	na	na	na
ISO 8178 C1 cycle	EN590	0.00	0.05	0.03	0.14	0.16	0.04	0.04	0.03	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.53	0.14	na	na	na
	NExBTL	0.01	0.02	0.03	0.12	0.13	0.03	0.03	0.04	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.42	0.11	na	na	na

Appendix E

Average results with buses. Regulated emissions, CO_2, fuel and urea consumption. Braunschweig cycle.

		CO	HC	NOx	PM	CO_2	Fuel consumption kg/100 km		Fuel consumption l/100 km		Urea consumption
		g/km	g/km	g/km	g/km	g/km	theor.	weighed	theor.	weighed	kg/100 km
Bus A, Euro 4, SCR	EN590	8.46	0.02	8.5	0.106	1079	34.5	35.2	41.3	42.1	1.6
	NExBTL	8.01	0.01	8.1	0.074	1051	33.6	34.5	43.1	44.3	1.6
Bus B, Euro 4, EGR	EN590	0.52	0.05	8.5	0.074	1160	36.7	37.3	43.9	44.7	
	NExBTL	0.11	0.02	7.7	0.040	1132	35.8	36.8	45.9	47.3	
Bus C, EEV, EGR	EN590	0.51	0.04	6.4	0.126	1149	36.3	37.8	43.5	45.3	
	NExBTL	0.30	0.03	6.1	0.072	1099	34.7	36.7	44.6	47.1	
Bus D, EEV, SCRT	EN590	0.10	0.01	5.4	0.014	1109	35.0	35.5	41.9	42.5	2.0
	NExBTL	0.09	0.00	4.3	0.012	1049	33.1	34.4	42.5	44.1	2.2
	GTL	0.09	0.00	3.9	0.012	1050	33.2	34.5	42.6	44.3	2.3
Bus E, CNG	CNG	1.57	0.30	2.0	0.003	1158	42.3				

Appendix F

Results from individual tests with buses. Regulated emissions, CO_2 and fuel consumption.

		Regulated emission					Fuel consumption			
		CO	HC	NOx	PM*	CO2	theoretical	weighed	theoretical	weighed
		g/km	g/km	g/km	g/km	g/km	kg/100 km	kg/100 km	l/100 km	l/100 km
Bus A, Euro 4, equipped with SCR.										
26R379	EN590	7.82	0.01	8.45	0.103	1070	34.2	34.9	40.9	41.8
26R381	EN590	8.61	0.03	8.40	0.107	1082	34.6	35.1	41.4	42.1
26R382	EN590	8.48	0.03	8.54	0.113	1080	34.5	35.2	41.4	42.1
26R386	EN590	8.61	0.01	8.65	0.106	1083	34.6	35.3	41.5	42.3
26R387	EN590	8.79	0.01	8.65	0.105	1082	34.6	35.4	41.4	42.3
26R383	NExBTL	8.02	0.01	8.18	0.075	1053	33.6	34.5	43.2	44.3
26R384	NExBTL	7.98	0.01	8.09	0.075	1053	33.6	34.6	43.2	44.4
26R385	NExBTL	8.02	0.00	(7.6)	0.074	1047	33.4	34.4	42.9	44.1
Bus B, Euro 4 equipped with EGR.										
26R499	EN590	0.51	0.06	8.21	0.078	1155.8	36.5	37.2	43.7	44.5
26R500	EN590	0.42	0.06	8.58	0.064	1129.4	35.7	37.0	42.7	44.4
26R501	EN590	0.57	0.06	8.63	0.074	1153.4	36.4	37.2	43.6	44.6
26R505	EN590	0.50	0.03	8.59	0.076	1181.7	37.3	37.6	44.7	45.0
26R506	EN590	0.58	0.06	8.50	0.079	1179.9	37.3	37.5	44.6	44.9
26R502	NExBTL	0.19	0.01	7.70	0.040	1135.7	35.9	37.2	46.0	47.7
26R503	NExBTL	0.07	0.01	7.81	0.039	1130.2	35.7	36.6	45.8	47.0
26R504	NExBTL	0.08	0.03	7.61	0.042	1131.4	35.7	36.8	45.9	47.2
Bus C EEV, equipped with EGR+catalyst.										
28R455	EN590	0.49	0.04	6.55	0.136	1161.6	36.7	38.2	44.0	45.8
28R456	EN590	0.48	0.04	6.52	0.141	1161.4	36.7	38.3	43.9	45.8
28R461	EN590	0.55	0.03	6.17	0.113	1137.5	35.9	37.5	43.0	44.9
28R462	EN590	0.53	0.04	6.39	0.114	1137.0	35.9	37.3	43.0	44.6
28R457	NExBTL	0.30	0.03	5.95	0.073	1111.7	35.1	36.8	45.1	47.3
28R458	NExBTL	0.33	0.03	6.02	0.068	1110.1	35.1	36.7	45.0	47.1
28R459	NExBTL	0.25	0.01	6.09	0.071	1086.7	34.3	36.7	44.1	47.2
28R460	NExBTL	0.32	0.03	6.47	0.075	1087.7	34.4	36.6	44.1	47.0
Bus D EEV, equipped with SCRT.										
27R396	DIKC	0.13	0.01	5.42	0.014	1122.8	35.5	36.0	42.5	43.1
27R397	DIKC	0.11	0.01	5.38	0.014	1120.6	35.4	35.7	42.4	42.8
27R398	DIKC	0.10	0.00	5.26	0.013	1099.7	34.7	35.2	41.6	42.1
27R399	DIKC	0.07	0.00	5.45	0.013	1094.9	34.6	35.3	41.4	42.2
27R401	DIKC	0.11	0.01	5.37	0.016	1109.6	35.0	35.5	42.0	42.6
27R402	DIKC	0.11	0.03	5.80	0.016	1105.9	34.9	35.2	41.8	42.2
27R404	NExBTL	0.08	0.00	4.16	0.012	1048.4	33.1	34.5	42.5	44.2
27R405	NExBTL	0.08	0.00	4.31	0.012	1049.8	33.1	34.3	42.5	44.1
27R406	NExBTL	0.11	0.00	4.31	0.012	1049.4	33.1	34.3	42.5	44.1
27R407	NExBTL	0.09	0.00	4.23	0.011	1047.2	33.1	34.3	42.4	44.0
27R409	GTL	0.06	0.00	4.17	0.013	1051.0	33.2	34.6	42.6	44.4
27R410	GTL	0.13	0.00	3.72	0.011	1049.1	33.1	34.4	42.5	44.2
Bus E CNG										
28R471	CNG	1.58	0.29	1.65	0.005	1162.8	42.5			
28R472	CNG	1.58	0.32	1.79	0.003	1161.9	42.4			
28R473	CNG	1.54	0.29	1.74	0.004	1139.9	41.6			
28R474	CNG	1.67	0.29	1.74	0.002	1160.3	42.4			
28R475	CNG	1.58	0.27	1.84	0.002	1140.9	41.7			
28R476	CNG	1.53	0.32	1.76	0.002	1161.0	42.4			
28R477	CNG	1.42	0.27	1.87	0.003	1153.2	42.1			
28R478	CNG	1.37	0.27	1.85	0.002	1155.5	42.2			
28R479	CNG	1.51	0.29	1.79	0.001	1130.6	41.3			
28R480	CNG	1.60	0.31	1.90	0.001	1150.9	42.0			
28R481	CNG	1.36	0.25	2.14	0.001	1151.4	42.0			
28R482	CNG	1.63	0.25	2.18	0.002	1163.1	42.5			
28R483	CNG	1.29	0.24	1.83	0.002	1152.0	42.1			
28R484	CNG	1.45	0.41	2.10	0.003	1171.3	42.8			
28R485	CNG	1.41	0.29	2.06	0.002	1133.9	41.4			
28R486	CNG	1.39	0.29	2.13	0.000	1151.7	42.1			
28R487	CNG	1.69	0.29	1.97	0.039	1156.3	42.2	***)		
28R488	CNG	1.65	0.31	2.06	0.069	1177.0	43.0	***)		
28R489	CNG	1.58	0.36	2.17	0.009	1157.4	42.3			
28R490	CNG	1.55	0.32	2.20	0.002	1160.3	42.4			
28R491	CNG	1.51	0.29	1.94	0.002	1161.1	42.4			
28R492	CNG	1.29	0.27	2.14	0.004	1181.2	43.1			
28R493	CNG	1.94	0.30	2.12	0.006	1177.9	43.0			
28R494	CNG	2.03	0.30	1.88	0.003	1173.1	42.9			
28R495	CNG	1.96	0.34	2.01	0.004	1174.2	42.9			

*) PM with standard collection system. In addition, high-capacity collection system was used.

**) Collections for special analysis

***) PM results rejected. High contamination with known origin.

Appendix G

Average results of carbonyl compounds with buses. Braunschweig test cycle.

		Carbonyl compounds				Hydrocarbons with Gas Cromatography				
		Formaldeh	Acetaldehy	Others	Sum (11)	CH4	C2H4	3H6	C6H6	:6H5CH:
		mg/km	mg/km	mg/km	mg/km	mg/km	mg/km	mg/km	mg/km	mg/km
Bus A, Euro 4, SCR	EN590	3.2	0.7	0.4	4.2	na	na	na	na	na
	NExBTL	3.0	0.7	0.5	4.2	na	na	na	na	na
Bus B, Euro 4, EGR+	EN590	13.0	3.9	1.5	18.3	6.0	7.9	0.5	0.9	0.0
	NExBTL	13.3	3.9	0.8	18.0	13.3	3.9	1.6	0.0	0.8
Bus C, EEV, EGR	EN590	strong NO2 formation consumed reagent				12.7	0.0	0.0	2.4	4.4
	NExBTL					7.1	0.0	0.0	0.0	0.1
Bus D, EEV, SCRT	EN590	leak in measurement system				14.7	0.0	0.0	0.0	0.0
	NExBTL					0.0	0.0	0.0	0.0	0.0
	GTL					0.0	0.0	0.0	0.0	0.0
Bus E, CNG	CNG	3.2	0	0	3.2	151.0	0.0	0.0	1.1	2.3

Average results of composition of particulate matter with buses. Braunschweig test cycle.

			Composition of PM			
		SOF, %	SOF	SO4	NO3	Others
			mg/km	mg/km	mg/km	mg/km
Bus A, Eur	EN590	9.5	10.3	1.1	0.9	98.3
	NExBTL	12.7	9.7	0.8	0.9	65.3
Bus B, Eur	EN590	8.4	6.0	1.2	0.8	63.5
	NExBTL	7.1	2.7	0.9	0.8	35.0
Bus C, EE\	EN590	5.4	6.5	0.8	4.9	110.7
	NExBTL	5.5	3.9	0.4	5.8	57.6
Bus D, EE\	EN590	24.8	3.6			
	NExBTL	not valid		0.1	5.3	
	GTL	not valid		0.2	4.6	
Bus E, CN(	CNG	below dl		0.2	0.1	

Appendix H

Average results of 14 PAHs and Ames tests with buses. Braunschweig test cycle.

		FLU	FEN	ANT	FLUT	PYR	BaANT	KRY/TRI	BbFLUT	BkFLUT	7.12-dBa	BePYR	BaPYR	IPYR	BghiPER	dBahA	PAH14	PAH7	Ames TA98-S9	Ames TA98+S9	Ames TA98NR
		µg/km	µg/km	µg/km	µg/km	µg/km	µg/km	µg/km	µg/km	µg/km	µg/km	µg/km	µg/km	µg/km	µg/km	µg/km	µg/km	µg/km	krev/km	krev/km	krev/km
Bus A, E	EN590	6.5	9.9	1.0	5.0	4.3	0.9	0.4	0.6	0.4	0.0	0.4	0.5	0.4	0.3	0.0	30.6	3.2	0		
	NExBTL	5.8	8.3	0.9	3.5	2.7	0.5	0.1	0.5	0.3	0.0	0.4	0.3	0.5	0.1	0.0	23.9	2.2	0		
Bus B, E	EN590	2.9	24.2	1.8	3.5	4.2	0.6	0.6	0.6	0.6	0.0	0.5	0.7	0.6	1.1	0.2	42.3	3.8	5.5		
	NExBTL	1.6	13.7	1.4	3.0	3.1	0.2	0.2	0.2	0.2	0.0	0.4	0.2	0.4	0.2	0.0	25.0	1.4	11.8		
Bus C, E	EN590	1.0	2.9	0.3	0.8	2.4	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.7	0.2	4.8	0.0	0.0
	NExBTL	0.7	2.1	0.1	0.3	0.6	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.0	0.1	0.0	0.0	0.0
Bus D, E	EN590	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	1.3		
	NExBTL	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
	GTL	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0			
Bus E, C	CNG	0.0	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.1	0.2	0.2	

Average results of particle number distributions with buses. Braunschweig test cycle.

		Stage1	Stagel2	Stage3	Stage4	Stage5	Stage6	Stagel7	Stage8	Stage9	Stage10	Stage11	Stage12
		0.022	0.0414	0.078	0.1308	0.2061	0.318	0.5032	0.8006	1.2728	2.0003	3.1432	6.3906
		N/logDp (#/km	N/logDp (#/km	N/logDp (#/km	N/logDp (#/km	N/logDp (#/km	N/logDp (#/km	N/logDp (#/km	N/logDp (#/km	N/logDp (#/km	N/logDp (#/km	N/logDp (#/km	N/logDp (#/km
Bus A, Eur	EN590	8.0E+13	1.2E+14	2.2E+14	2.7E+14	8.3E+13	2.6E+13	5.8E+12	1.5E+12	5.5E+11	2.9E+11	1.7E+11	6.4E+10
	NExBTL	8.4E+13	1.2E+14	2.2E+14	2.4E+14	5.9E+13	1.8E+13	4.0E+12	1.3E+12	4.8E+11	2.6E+11	1.6E+11	6.0E+10
Bus B, Eur	EN590	6.3E+13	1.1E+14	1.8E+14	1.7E+14	5.5E+13	1.1E+13	2.6E+12	7.3E+11	3.0E+11	1.7E+11	1.0E+11	3.8E+10
	NExBTL	5.1E+13	1.1E+14	1.4E+14	1.0E+14	2.7E+13	5.6E+12	1.3E+12	3.7E+11	1.6E+11	9.3E+10	5.5E+10	2.1E+10
Bus C, EE\	EN590	6.4E+13	2.0E+14	4.0E+14	3.5E+14	9.9E+13	2.7E+13	6.3E+12	2.7E+12	1.2E+12	8.0E+11	4.4E+11	1.8E+11
	NExBTL	8.4E+13	2.5E+14	3.9E+14	2.3E+14	5.1E+13	1.3E+13	3.9E+12	2.0E+12	8.9E+11	5.9E+11	3.2E+11	1.3E+11
Bus D, EE\	EN590	1.3E+12	1.4E+12	1.1E+12	3.9E+11	1.3E+11	4.2E+10	1.9E+10	8.3E+09	2.7E+09	1.4E+09	5.7E+08	4.1E+08
	NExBTL	9.6E+11	1.1E+12	8.5E+11	2.9E+11	1.2E+11	4.7E+10	2.4E+10	9.5E+09	3.0E+09	1.5E+09	5.6E+08	3.5E+08
	GTL	2.9E+12	3.6E+12	2.7E+12	6.9E+11	1.5E+11	4.4E+10	2.3E+10	1.1E+10	3.2E+09	1.7E+09	1.0E+09	4.3E+08
Bus E, CN(	CNG	1.96E+12	1.2E+12	5.8E+11	1.3E+11	3.1E+10	1.6E+10	9.9E+09	6.2E+09	2.7E+09	1.0E+09	2.7E+08	1.4E+08

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