REPORT

PU 45850/02 and PU 40318/01

The influence of the fuel on emissions
from diesel engines in large off-road machines

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Summary

The gradual increase of legal requirements and also growing requirements from customers have led to intensified efforts to lower engine emissions. The possibility to significantly reduce emissions is largely dependent on the fuel characteristics (for example sulphur content) and interest in cleaner fuels and alternatives to traditional diesel-fuel has therefore grown. Furthermore, there is a great interest in the development of alternatives to fossil fuels and in studying the emissions of unhealthy substances from these.

This project was carried out in order to study and compare the influence of traditional and alternative diesel fuels on emissions from diesel engines in large off-road machines.

Several types of diesel fuels were tested in three different, modern diesel-engines from large off-road machinery. The engines were not in any way tuned in order to optimise them for the different fuels. SMP Svensk Maskinprovning AB carried out the tests in their test laboratory in Umeå, Sweden. The Swedish National Testing and Research Institute (SP) performed the sampling and analyses of unregulated emissions, the measurement of particle-number and particle-size distributions, and also the analyses of these parameters.

The project was carried out in two parts. During Part 1 four fuels were tested: Eco-Par® (an example of a synthetic Fischer-Tropsch fuel), “EC1” (a Swedish Environmental diesel class-1), “Agrol Agro Light” (essentially an ”EC1”-fuel with an admixture of Rape Methyl Esther, RME), and “Etamix D 2” (essentially an ”EC1”-fuel with an admixture of ethanol). For these fuels, regulated emissions were measured.

During project Part 2, Eco-Par®, “EC1” and “Euro-Diesel” (a typical European so-called summer-diesel) were tested in the three engines. Apart from regulated emissions, several unregulated emissions and particle number and size distribution were also measured.

The values for the maximum power of the engines were significantly lower when “Etamix D2” was used than when the other fuels in project Part 1 were used and the specific fuel consumption was slightly higher with “Etamix D2”.

Other consistent differences between the tested fuels in project Part 1 could be found only for the emissions of Total Hydrocarbons (THC). These emissions were lowest with Eco-Par®, second lowest with “Agrol Agro Light”, second highest with ”EC1” and highest with “Etamix D2”.

In project Part 2 also, obvious differences were mainly observed regarding emissions of THC. The emissions of THC were higher for the fuel ”EC1” than for the two other fuels. Emissions of Particulate Matter (PM) were significantly higher with ”Euro-Diesel” than with the other fuels in one of the tested engines, but this pattern was not obvious for the other engine in which emissions of PM were measured for all three fuels.

It should be noted that the differences in the levels of the regulated emissions were generally small for the engines in question and it is therefore difficult to draw conclusions based on the small differences found.

The results from measurements of aldehydes and light, unsaturated hydrocarbons in project Part 2 showed that emission levels were low and that the results were more or less equivalent for the tested fuels. Propene emissions were slightly higher for Eco-Par® than for ”EC1”, which in its turn gave higher emission than ”Euro-Diesel”. Benzene emissions were slightly lower for Eco-Par® than for the other fuels.

The levels of particle-associated Polyaromatic Hydrocarbons (including di-aromatic PAH) did not show consistent differences between the fuels. A clear and consistent difference between the fuels could, however, be noted for the semi-volatile PAH (including di-aromatics) where Eco-Par® showed lower levels than ”EC1” and where the highest levels were found with ”Euro-Diesel”.

The results from the soot-analyses for metal-content showed that only a few detectable metal-substances were found. They most likely originated from single flakes that are part of the normal wear procedure of the engine.

Differences regarding particle number and size distribution from the different combinations of fuel and engines were small. For all cases, high concentrations of ultrafine particles were observed. Consequently the ultra-fine particles constituted a large part of the total number-concentration.

A tendency that could be observed for all three engines was that the use of Eco-Par® resulted in lower particle concentrations than for “EC1”, which in its turn showed lower number-concentrations than Euro-Diesel” in the interval 0.1 - 10 µm. The relationship was the opposite for ultrafine particles.

The higher particle-size number in the range 0.1 - 10 µm with “Euro-Diesel” could be an effect of its higher content of sulphur and heavy aromatic hydrocarbons. The high numbers of ultrafine particles for Eco-Par® and “EC1” may in its turn be an effect of ultrafine liquid-drops (condensate) that develop due to the cooling of the exhausts in the dilution tunnel where the samples are taken. A theoretical explanation of why higher numbers of ultrafine particles were found for Eco-Par® and “EC1” than for “Euro-Diesel”, could be that the more hydrogen and the more light fractions a fuel contains, the greater the risk of condensate liquid-drops affecting the result.

Introduction

Off-road machinery with diesel engines contributes significantly to air pollution. According to Statistics Sweden (SCB, 1999) these machines are responsible for approximately 25 % of the total amount of emissions to air in Sweden of nitrous oxides and nitrogen oxides. Emissions from diesel engines typically contain high levels of nitrogen oxides and particulate matter.

Since 1999, the EC-directive 97/68/EC, has been in force in the European Union. The directive stipulates the maximum emissions from engines in off-road machines with regard to total hydrocarbons (HC), carbon monoxide (CO) nitrogen oxides (NO_x) and particulate matter (PM). The requirements are being tightened up by gradual stages. The effect of the new legislation will therefore also be gradual, and in the near future the majority of the off-road machines will still be equipped with engines which were manufactured before the directive came into force. However, the gradual growth in the number of legal requirements and increasing requirements from customers have led to intensified efforts by engine manufactures to lower the engine emissions. The possibility to significantly reduce the emissions is largely dependent on the fuel characteristics (for example sulphur content) and the interest in cleaner fuels and alternatives to traditional diesel fuel has therefore grown.

In a broader and more long-term perspective, alternatives to fossil fuels must be found and developed since it is commonly accepted that oil-production will gradually decrease within a time perspective of 20 to 30 years. Furthermore, the requirements regarding these alternative fuels are high, since the cost for fuel must be reasonable, the emissions of unhealthy substances must be at an acceptable level, the raw material for the fuel should preferably be globally accessible, the fuel must be possible to use in the engines of the future etc. It is therefore of great interest to study and compare the influence of traditional and alternative diesel fuels on emissions from diesel engines in large off-road machines.

Since 1991, low-sulphur diesel fuel classified as environmentally friendly has been available on the Swedish market under the name “Environmental diesel class-1” (”EC1”). In the rest of Europe, however, the dominating diesel fuel is what in this report is called “Euro-Diesel”, which characteristically has a much higher sulphur content and aromatics content and corresponds to the former Swedish fuel “Environmental diesel class-3”. There are also several alternative diesel fuels on the market, some with an admixture of non-fossil substances such as ethanol and Rape Methyl Esther (RME), and at least one fully synthetic fuel, Eco-Par®[1], which is an example of a Fischer-Tropsch fuel, which can be produced using synthesis gas. All the above-mentioned fuels can be used without modification of the diesel-engine.

In this study the regulated and several non-regulated components in the exhaust emissions were measured and compared for Eco-Par®, ”EC1”, and ”Euro-Diesel” when used in three different 4- and 6- cylinder off-road diesel engines. In addition to this, regulated components were measured and compared for the fuels “Agrol Agro Light” (essentially an ”EC1”-fuel with an admixture of RME) from *Agro Oil AB*, and “Etamix D 2” (essentially an ”EC1”-fuel with an admixture of ethanol) from *Svensk Etanolkemi AB*, when used in the same three engines.

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[1] Eco-Par® is a registered trademark, owned by Oroboros AB.

Background

Factors such as engine design, type and status of motor oil, exhaust after-treatment, chemical and physical properties of the fuel, and operating conditions influence the composition of pollutants emitted from engines. The exhaust is a complex mixture of hundreds of different chemical constituents and during combustion a large number of different pollutants are either formed or emitted as unburned fuel.

For diesel engines, the focus is mainly set on emissions of particles and nitrogen oxides (NOx). From a health-risk point of view, however, many other combustion products are of interest. Examples of such products are Polyaromatic Hydrocarbons (PAH), aldehydes and ketones (carbonyls), and volatile hydrocarbons such as ethene, propene, 1,3-butadiene and benzene.

Exhaust components such as hydrocarbons, carbonyls, CO, and NO_X can during short-time exposure cause irritation, headache etc. Long-term exposure can result in more severe symptoms and diseases.

Benzene is classified as carcinogenic to humans by the *International Agency for Research on Cancer* and formaldehyde, 1,3-butadiene and some PAHs such as benzo[a]pyrene and benzo[a]anthracene are classified as probably carcinogenic to humans while acetaldehyde and many PAHs are classified as possibly carcinogenic to humans. For further information on toxicity, mutagenicity and carcinogenicity, see Annex 1.

When it comes to particle emissions, numerous epidemiological studies have shown correlations between negative health effects and increased concentrations of particulate matter in the ambient air. Particle concentrations are often reported as mass concentrations according to standard methods. However, in recent years an interest has grown in acquiring knowledge of the particle-size distribution, since it is thought that particle surface area, number of ultrafine particles (particles smaller than 100 nm), PAH and other particle-bound organic compounds, are probably more important than particle mass for the health effects of combustion particles.

It is likely that the particle concentrations are affected not only by, for example, the fuel and the engine design, but also by the engine oil and the possible use of catalytic converters, which is still uncommon on off-road machinery engines. The effects of these parameters, however, remain to be investigated.

Experimental procedures

Brake-test stand and controls

SMP Svensk Maskinprovning AB (The Swedish Machinery Testing Institute) carried out the engine tests at the testing laboratory in Umeå, Sweden.

The engines were mounted in a stationary brake-test stand. The engine axle was connected to a Schenck W400 electric eddy-current brake, via a power-transmission axle (see figure 1).

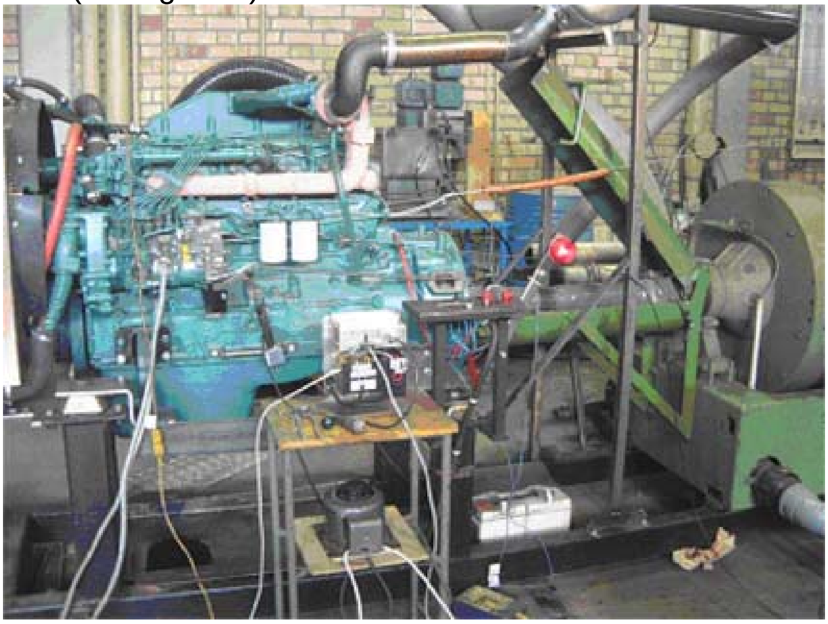

Figure 1. Engine Volvo TD63KDE connected to the eddy current brake SCHENCK W 400.

The brake was controlled with a Schenck electronic control-system which allows a specific number of revolutions to be set and controlled. The setting of the injection-pump was controlled by a servosystem, LinMot-E100.

For the logging of engine parameters, a National Instruments Lab-View system was used.

Testing standard

The measurements were carried out in accordance with ISO 8178-1996 ”Reciprocating internal combustion engines - Exhaust emission measurement” and the test cycle used was ”Test Cycle C1 - Off-road vehicles, diesel-powered off-road industrial equipment" which encompasses measurements in 8 of the 11 modes that are included in test cycle B “Universal”, in the same standard (see table 1).

Table 1. Test mode C1 and weighting factors used in the tests

Mode number (cycle B)	1	2	3	4	5	6	7	8	9	10	11
Mode number (cycle C1)	**1**	**2**	**3**		**4**	**5**	**6**	**7**			**8**
Speed	Rated speed					Intermediate speed					Low-idle speed
Torque, %	100	75	50		10	100	75	50			0
Weighting factor	0.15	0.15	0.15		0.10	0.1	0.1	0.1			0.15

Engines

Three different turbo-charged engines were used in the tests. One engine (TD63KDE) was equipped with a water-cooled intercooler. They were all type-approved according to stage I of 97/68/EC (regarding engine-emissions from non-road machinery). The engines were tested in their “original”-design, i.e. they were not in any way tuned in order to optimise them for the different fuels.

- SISU Diesel 420 DWRE, Valtra Tractor AB (used for example in farm tractors)
- Volvo TD40GJE, Volvo Construction Equipment (used for example in bucket loaders)
- Volvo TD63 KDE, Volvo Construction Equipment (used for example in bucket loaders)

See table 2 for further technical information.

Table 2. Various technical information regarding the engines used in the tests

Engine	**Volvo TD40GJE**	**Volvo TD63KDE**	**Valmet 420 DWRE**
No. of cylinders	4	6	4
Displacement (litres)	4.0	5.48	4.4
Maximum power (kW at rated speed)	75	93	84
Rated speed (rpm)	2200	2000*	2000
Fan	No	Yes	Yes

* In project Part 1, information to SMP indicated that the rated speed was 2000 rpm. Prior project Part 2, new information from the manufacturer stated that the rated speed was 2200 rpm.

General comments on test procedures

The project was divided into two parts. In Part 1, Swedish Environmental diesel class-1 (”EC1”), Eco-Par®, Agrol Agro Light and Etamix D2 were tested with the three engines. In Part 2, Eco-Par®, ”EC1” and a typical European so-called summer-diesel (”Euro-Diesel”) were tested in the same three engines (see “Introduction” and “Fuels” for further explanation). However, the fuel used in the different project-parts came from different batches and the external parameters and some engine settings differed slightly between the two project-parts and the results from the two respective project-parts should therefore be treated separately. That is, the results for the same combination of fuel and engine in one project-part cannot be compared with the results for the same combination in the other project-part. However, the results from the filter measurements of particulate matter can be compared, since they were carried out on a separate occasion.

Comments on project Part 1

In Part 1, only regulated emissions were measured and only one test was performed for each combination of fuel and engine. Whenever a change of fuel was made, the engine was run on the new fuel for approximately 1 hour (after emptying the fuel system) and the fuel filter was also changed in order to ascertain that all possible residues of the former fuel had been combusted.

Comments on project Part 2

In Part 2, the order of testing for the fuels was, for each separate engine, first Eco-Par®, then ”EC1” and finally ”Euro-Diesel”.

Whenever a change of fuel was made the same procedure was followed as in Part 1 so that all possible residues of the former fuel were combusted. Furthermore, the all-

synthetic engine oil (Shell Rimula Ultra 10W-40) and the oil-filter (as recommended by the respective engine-manufacturer) were also changed twice (the second change took place after the engine had run with the new oil for 10 minutes) whenever the fuel was changed.
In Part 2, all combinations of fuel and engine were tested twice and both regulated and unregulated emissions were measured during both cycles (except for PM which was measured once only). In addition, number- and size-distribution for particulate matter were measured in project Part 2.

General
The mass concentration of particulate matter was measured once for all combinations of the five different fuels used in project Parts 1 and 2, and the three engines, with the exception of one combination of fuel and engine.

Fuels

In all, five different fuels were used in the tests (see table 3). The three fuels used in project Part 2 were analysed by external laboratories (Saybolt Sweden AB and SLU, Swedish University of Agricultural Sciences, the Unit of Biomass Technology and Chemistry), with regard to 6 parameters. For the other two fuels used in project Part 1, the suppliers supplied the specifications.

Eco-Par® is a so-called Fischer-Tropsch fuel, “EC1” is a Swedish Environmental diesel class-1, “Euro-Diesel” is a typical European summer-diesel, “Agrol Agro Light” is essentially an ”EC1”-fuel with an admixture of Rape Methyl Esther (2 wt-%), RME and “Etamix D 2” is essentially an ”EC1”-fuel with an admixture of ethanol (7 wt-%), solubility agent (7 wt-%) and lubricating agent (1 wt-%).

Table 3. Specifications of the fuels used in the tests

Parameter	**Unit**	**Fuel**				
		Eco-Par®	**”EC1”**	**”Euro-Diesel”**	**Agrol Agro Light****	**Etamix D2****
Aromatics, total (SS 155116-97)	vol%	0.1*	4.7*	18.5*	4,5**	3,5**
Polyaromatics, total** (PAH)** (SS 155116-97)	vol%	<0.02*	<0.02*	0.06*	<0.02**	<0.02**
Cetane number (SS-EN-ISO 5165-98)		51.9*	57.2*	55.5*	51**	ca: 48**
Sulphur (ASTM D 5453-93)	mg/kg	1*	2*	336*	2-3**	2**
Hydrogen (ASTM D 5291-96)	wt%	15.2*	14.6*	14.0*	14.1**	14.1**
Density (EN ISO 12185:96)	kg/m^3	799**	815**	839**	818**	810**
Viscosity (EN ISO 3104:96/AC:99)	cSt	2.7-3.0**	2.0**	3.4**	2.1**	---
Gross/Net heat value (ASTM D 4868-90)	MJ/kg	-	-	-	46.1/43.1**	44.3/41.3**
Gross/Net heat value (SS ISO 1928)	MJ/kg	46.74/43.52***	46.42/43.32***	45.08/42.11***	-	-
Supplied by:		Oroboros AB	Preem Petroleum AB	Preem Petroleum AB	Agro Oil AB	Svensk Etanolkemi AB

* Analyses performed by Saybolt Sweden AB for the fuels used in project Part 2
** Information from supplier
*** Analyses performed by SLU (Swedish University of Agricultural Sciences, the Unit of Biomass Technology and Chemistry)
**** Total Aromatics include tri+-aromatics but not di-aromatic PAH

Regulated emissions and technical parameters

Instruments and software from Boo Instruments were used for measurements of regulated emissions. A list of the instruments used is presented in table 4. The measuring system includes computer-controlled data collection and calculation of mean values. Parameters such as fuel-consumption, torque, number of revolutions, exhaust temperature, water temperature in the engine and the pressure, humidity and temperature of the ambient air, were registered in parallel with the emissions.

Table 4. Instruments used for measurements of regulated emissions and carbon dioxide.

Parameter	Instrument	Manufacturer/type
Total Hydrocarbons (THC)	Flame Ionisation Detector (FID)	JUM Engineering, Model 109A
Nitrogen Oxides (NO_x)	Heated Chemiluminiscence Detector (HCLD)	ECO Physics, CLD 700 El ht
Carbon Monoxide (CO) and Carbon Dioxide (CO_2)	Non-dispersive infrared analyser (NDIR)	Maihak UNOR 610, MULTOR 610
Oxygen (O_2)	Para magnetism	M&C, O_2-analyser PMA30

The undiluted exhausts were pumped through a heated filter (190 ºC) and transferred by a heated tube (190 ºC) to the instruments.

Mass concentration of particles

The mass concentration of particles was measured in accordance with ISO 8178-1, 1996. The standard offers several alternatives for dilution- and sampling methods. In our tests, a “partial flow dilution system with flow control and total sampling” was chosen. A schematic picture of the testing arrangements is shown in figure 2.

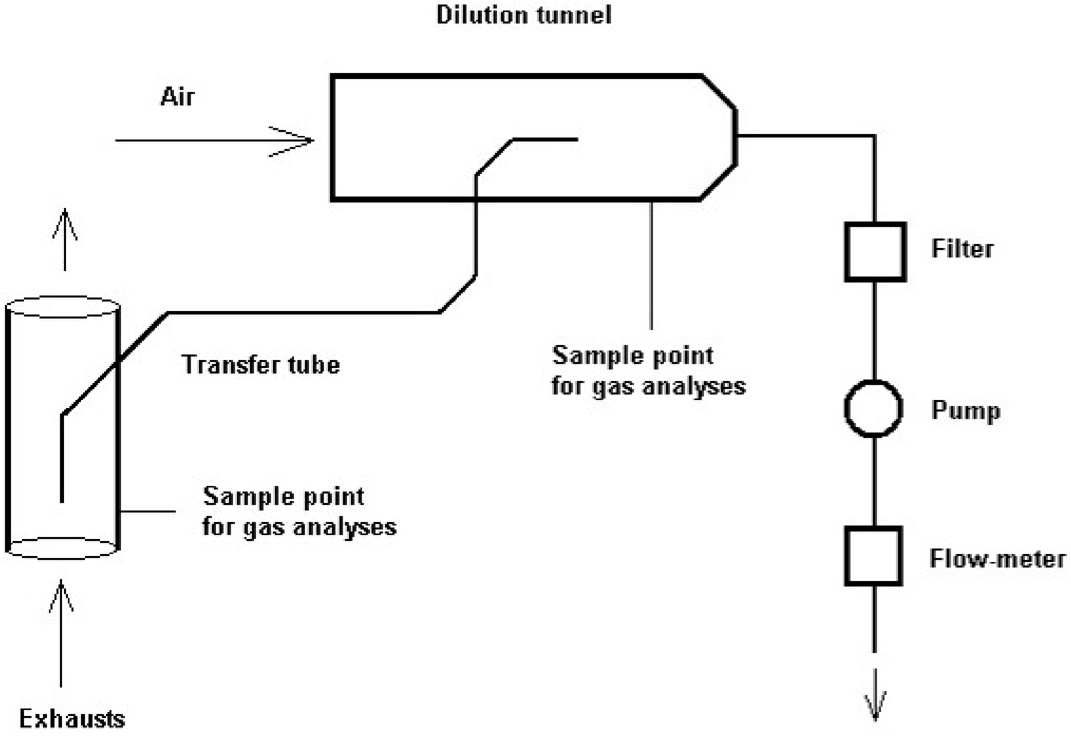

Figure 2. Schematic picture of the test set-up for measurements of mass concentration of particles.

The method used was a multiple-filter method in which one pair of filters is used for each of the individual modes of the test cycle. The filters used were Munktell, MG 400 with diameter 47 mm.

The mass concentration of particles was measured for all combinations of fuels and engines, except for the 420 DWRE when tested with “Euro-Diesel”.

Unregulated emissions

The following unregulated emissions were measured during Part 2 of the tests (tests with Eco-Par®, ”EC1” and ”Euro-Diesel”):

- Alkene emissions (ethene, propene, 1,3-butadiene) and benzene
- Aldehyde emissions (formaldehyde, acetaldehyde, benzaldehyde, propanal and acrolein)
- Ammonia
- 18 Polyaromatic Hydrocarbons, PAH, (particulate and semivolatile associated) of which 6 were di-aromatic and 12 were tri+-aromatic hydrocarbons)

In addition, soot-samples were taken for determination of the metal content (Cu, Mo, Ni, Pb, V, Zn, Fe, P, Mg, Ca, S).

The Swedish National Testing and Research Institute (SP) carried out all sampling of unregulated emissions as well as the analyses of metal content and all analyses of organic species. Analyses of ammonia were performed by IVL, Gothenburg, Sweden.

All measurements of the unregulated emissions and of particle number and size-distribution (see below) were made on diluted exhausts. The dilution set-up was identical to the one used in the measurements of the mass concentration of particles according to ISO 8178. The air used for dilution was filtered in an activated-carbon filter and a HEPA-filter. The dilution ratio was calculated as the ratio between the NOx concentrations in the undiluted exhausts and the diluted exhausts.

The flow in the dilution tunnel was monitored with a flow meter and the flow was kept constant during all measurements. The temperature of the gas in the dilution channel was approximately 45 °C.

The sampling was made according to the single-filter method that is specified in ISO 8178 for measurements of mass-concentration of particles. In this method, particles from all test-modes are collected on the same filter. Thereby, the results obtained are weighted in accordance with test cycle C1 of ISO 8178.

In the case of unregulated emissions, this is equivalent to pumping exhaust-gas from each mode through the same adsorbent. This requires that calculations be made prior to testing, in order to establish the “dose” of exhausts that should be delivered at each test mode. This includes paying regard to the exhaust flow, the weighting factor and the dilution ratio that are connected to each test mode. Therefore, preparatory tests have to be performed at each test mode (for each engine) in order to establish, for example, the exhaust flow and the dilution ratio.

All measurements were carried out on two separate test-runs with the exception of the filter measurements for metal-content, which were carried out once.

Figure 3 shows a schematic picture of the sampling set-up and figure 4 shows a photograph of the set-up.

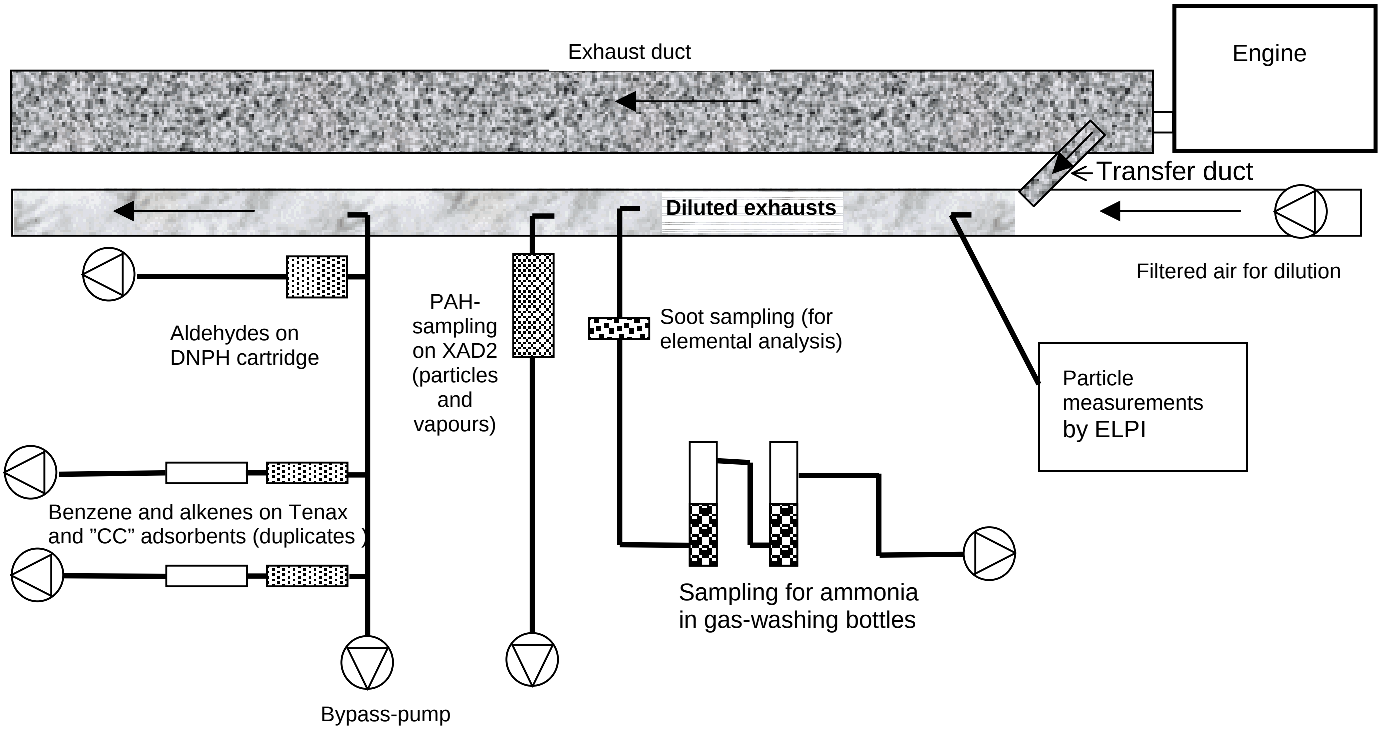

Figure 3. Schematic picture of the sampling set-up

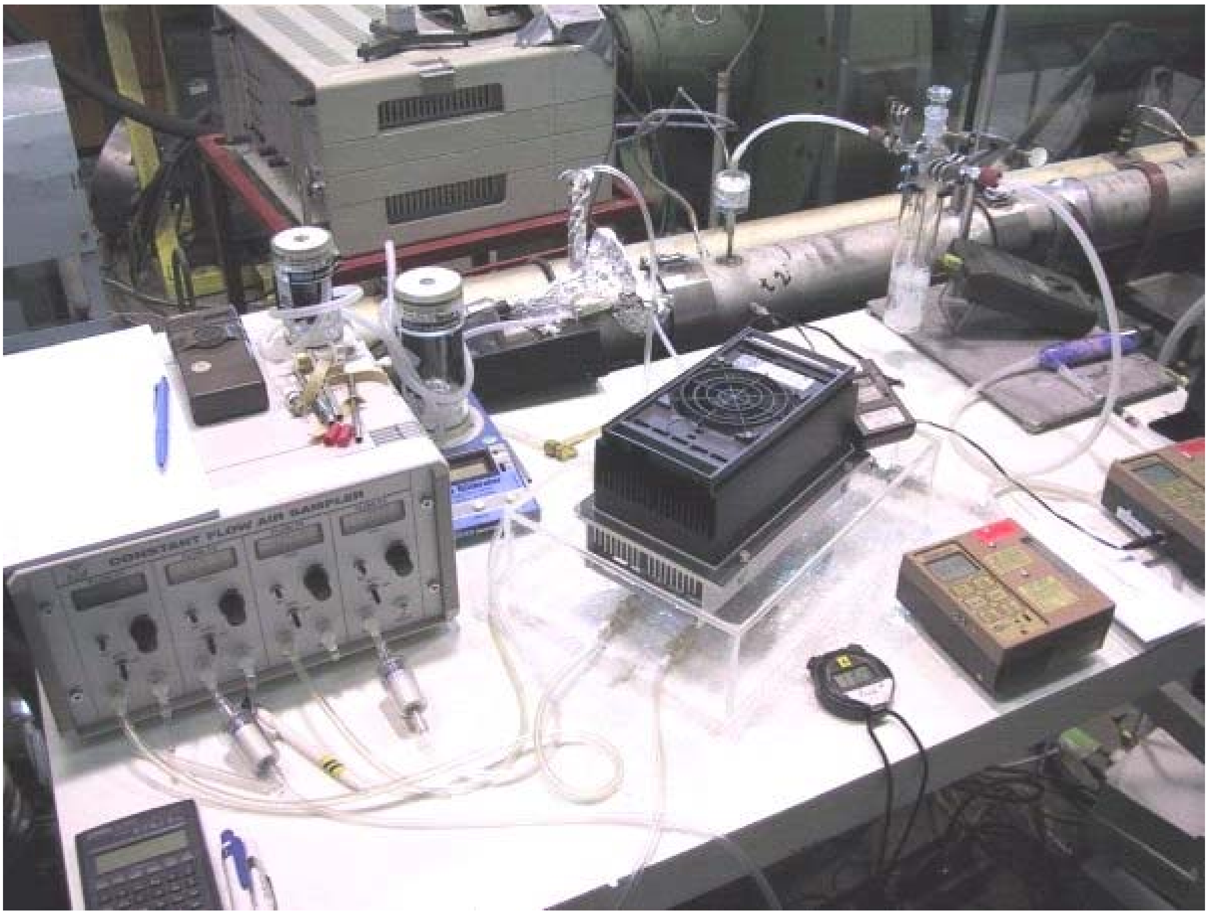

Figure 4. Photograph of the sampling set-up

Alkenes and benzene

For sampling of these hydrocarbons a combination of adsorbents were used. The porous polymer Tenax was used to adsorb 1,3-butadien and benzene and other slightly heavier compounds. On the downstream side of the Tenax-tube, a combination of the synthetic carbons Carbotrap and Carbosieve (CC) were used to adsorb ethene and propene and other low-molecular compounds that, to a great extent, pass through the first adsorbent. The Tenax-adsorbent has the advantage of being hydrophobic, i.e. not sensitive to moisture, which, on the other hand, the CC to some extent is. In order to protect the CC from the vapour in the diluted exhausts, a PTFE-tube, filled with approx. 5 cm of drying-agent consisting of magnesium-perclorate ("Anhydrone", Leco), was placed between the Tenax-tube and the CC-tube.

In order to increase the retention capacity of the adsorbents, they were cooled to 5–8 °C during sampling with the aid of a Peltier-cooler. The sampling flow was 20 and 50 ml/minute, respectively, on two parallel gas-sampling lines.

The analyses of the adsorbent-tubes was carried out through thermal desorption where the adsorbing substances are "heated off" into a cooling-trap (-30°C) for so-called cryo-focusing. The substances are subsequently "heated off" quickly and led into a gas chromatograph (GC) for separation and individual detection in a flame ionisation detector (FID), and a mass spectrometric detector (MS), respectively, (by split after the column). A short name for the technique described is TD-GC-FID/MS.

The Tenax-tubes and the CC-tubes were analysed separately with two different gas chromatographic columns. For the analyses of ethene, propene etc., a PLOT-column was used and for 1,3-butadien and benzene, a non-polar capillary column, BPX-5, was used. The temperature programming was also different for the two columns in order to achieve the best possible separation.

As standard and reference for ethene and propene, known concentrations of the compounds were created in Tedlar-bags, using pure gases (Air Liquide) and controlled dilution. The known atmosphere was tested on a CC-tube and yield- and response-calculations for the FID-detector were carried out.
In a similar way, known proportions of 1,3-butadien and benzene were sampled on Tenax-tubes from thermostated permeation-tubes which emit at a known level.

Aldehydes

Formaldehyde, acetaldehyde, benzaldehyde, propanal and acrolein were sampled by so-called chemosorption (chemical reaction) in a filter with a reagent covering (SepPak Exposure, Waters) where 2,4-dinitrophenylhydrazine (DNPH) reacts with existing aldehydes and ketones and forms hydrazons correspondingly.

The sampling flow was 100 ml/minute. In some of the tests, two series-connected filters were used in order to check that no "break-through" occurred (which would occur if the adsorption in the first filter were incomplete).

During analysis the formed compounds were eluted with acetonitrile and the solution was analysed by liquid chromatography (HPLC) with a UV-detector (SP is accredited for this method). Official standards and internal SP-standards were used for calibration.

Ammonia

Ammonia was sampled by bubbling particulate-matter filtered gas from the dilution-tunnel, through a gas-washing bottle containing approximately 50 ml of boric-acid solution (4 g/litre).

The sampling flow was 1000 ml/minute.

The trapped quantities of ammonia were determined using spectrophotometry.

Polyaromatic Hydrocarbons (PAH)

The PAH in the dilution tunnel were sampled in two steps. The sampling was carried out with a glassfibre-filter for soot, which was immediately followed by an XAD-2 adsorbent for gaseous PAH. Since the distribution between particulate-associated and gaseous PAH is very temperature-dependent, the sampler was placed as close as possible to the sampling-probe on the dilution tunnel.

The sampling flow was 1000 ml/minute and was kept constant during the sampling period thanks to the continuous pressure-fall compensator that is built-in in the equipment (if pressure-fall compensation is not used there is a risk of a continuous drop in the flow due to the build-up of soot on the filter).

Conversion of filter and XAD-2 adsorbent before analyses was carried out separately and included extraction with 2x3 ml toluene/methanol-compound (ratio1:1) in a ultrasonic-bath, followed by filtering of the extract. The extract was subsequently analysed with a GC/MS where so-called Selected Ion Monitoring (SIM-technique) was utilized for the highest possible selectivity and sensitivity.

A traceable standard from "Dr. Ehrenstorfer Reference Materials", "PAH Mix 14" for EPA metod 610 containing known quantities of eighteen different PAH-compounds (6 di-aromatic and 12 tri+-aromatic) was used. Out of those eighteen, sixteen are included in the EPA-method.

Metal content

Soot samples were taken on cellulose acetate filters (37 mm diameter) that are completely combustible and have a low background-metal value (the same type of filters as those used, for example, when sampling in welding fumes for occupational health measurements).

The sampling flow was 1000 ml/minute and was maintained throughout the sampling time by the aid of a pressure-fall compensated pump.

After microwave-digestion in nitric acid (including a drop of fluoric acid), the filters were analysed with optical emission spectrometry with inductively coupled plasma (ICP-OES) equipped with an ultrasonic atomizer.

Particle number and size distribution

During the tests with Eco-Par®, ”EC1” and ”Euro-Diesel” on the three engines, the particle concentrations (number of particles in, for example, a normal cubic centimetre gas) and size distributions, in the size range of 7nm to 7 µm, were continuously measured using an ELPI (Electrical Low-Pressure Impactor from Dekati Inc., Finland). A schematic picture of the instrument is shown in figure 5. The sampling probe was placed in the dilution tunnel as shown in figure 3, and the exhausts were transferred by a tube to an ejector-type diluter and thereafter to the ELPI-instrument. In order to avoid condensation, the exhausts were kept at the same temperature as in the dilution tunnel (approximately 45 ºC) during transfer to the ELPI-instrument and the air to the ejector-type diluter was heated and dried before the dilution.

The Swedish National Testing and Research Institute (SP) carried out the measurements and analyses of the particle-size and distribution measurements.

In the ELPI-instrument the exhaust first reaches the ELPI's Corona charger, and then enters a low-pressure impactor with several electrically-insulated collection stages. The electric current, carried by the charged particles into each impactor stage, is measured in real time by a sensitive multi-channel electrometer. The particle-sizes are measured as aerodynamic diameters.

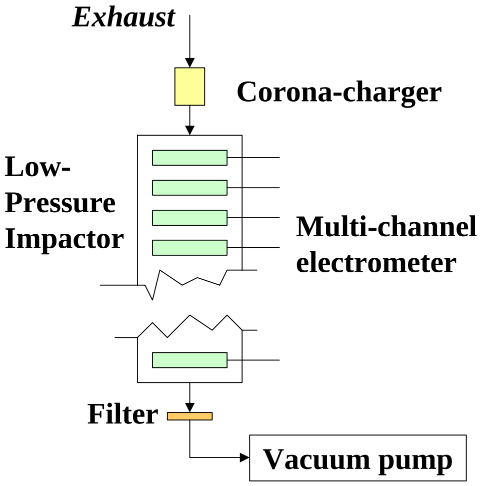

Figure 5. Schematic picture of the ELPI (Electrical Low-Pressure Impactor) with filter stage.

Comments on chemical analyses of certain compounds

Ethene

Ethene proved to be impossible to quantify in the analyses. The main reason was an incomplete retention in the cooling-trap during the analysis, where too high a temperature and the absence of Carbosieve resulted in the ethene, retained in the adsorbent, being lost before the analysis could be carried out.

It would have been preferable to use liquid nitrogen for cooling but this was not possible on the instruments used during the tests. However, the only slightly heavier compounds propene and butene could be detected with the cooling-trap used.

1,3-butadiene

Several pre-tests were carried out in good time before the actual tests. During the pre-tests no drying agent was used during sampling. Trapped moisture in the adsorbent caused the FID to be knocked out during the analyses.
Therefore, a drying agent was used in the main tests in order to try to eliminate this problem. Two samples were however taken without a drying agent.

After the analyses of all the samples it was concluded that the drying of the moist exhausts had caused the compound, which in itself is unstable, to partly disintegrate, which meant that it could not be quantatively caught in the CC-tube. This conclusion was drawn since the two CC-tubes without preceding drying-detergent showed higher contents of 1,3-butadiene than the corresponding dried samples.

Acrolein

Acrolein is very difficult to measure quantatively with the technique used since the formed derivate is not stable but causes several peaks in the chromatographic analysis. The internal relationship between these peaks is not stable either.

Thus, in aldehyde-standards, acrolein is no longer considered as possible to quantify with this technique. It can be strongly suspected that acrolein values presented in previous reports are under-estimated if based on this analysis method.

Results

Please note that the results for combinations of fuel-engine obtained in project Part 1 should not be compared with results for the same combination obtained in project Part 2 (with the exception of PM-results) as discussed earlier.

Regulated emissions

Results from project Part 1

Table 5. Results from project Part 1; regulated emissions etc. for the 4 tested fuels when used in engine Volvo TD40GJE.

		Fuel			
(Rated speed 2200 rpm)		**Eco-Par®**	**”EC1”**	**Agrol Agro Light**	**Etamix D2**
Maximum power	kW	75	74	74	69
Fuel consumption	kg/kWh	0.235	0.240	0.235	0.255
Exhaust flow	kg/kWh	8.25	8.85	8.30	9.09
Carbon Monoxide (CO)	g/kWh	0.62	0.69	0.65	0.85
Nitrogen Oxides (NOx)	g/kWh	6.47	6.41	6.44	6.37
Total Hydrocarbons (THC)	g/kWh	0.10	0.13	0.11	0.23
Particulate Matter (PM)	g/kWh	0.17	0.16	0.17	0.15

Table 6. Results from project Part 1; regulated emissions etc. for the 4 tested fuels when used in engine Volvo TD63KDE.

		Fuel			
*(Rated speed 2000 rpm)**		**Eco-Par®**	**”EC1”**	**Agrol Agro Light**	**Etamix D2**
Maximum power	kW	93	94	92	85
Fuel consumption	kg/kWh	0.226	0.231	0.239	0.250
Exhaust flow	kg/kWh	6.99	7.02	7.19	7.51
Carbon Monoxide (CO)	g/kWh	1.40	1.64	1.47	1.25
Nitrogen Oxides (NOx)	g/kWh	7.19	7.52	7.81	8.05
Total Hydrocarbons (THC)	g/kWh	0.11	0.14	0.13	0.18
Particulate Matter (PM)	g/kWh	0.15	0.21	0.21	0.28

* The rated speed for Volvo TD63KDE was 2000 rpm in Part 1 and 2200 rpm in Part 2, which explains the difference in e.g. fuel consumption for this engine between Part 1 and Part 2.

Table 7. Results from project Part 1; regulated emissions etc. for the 4 tested fuels when used in engine Valmet 420 DWRE.

		Fuel			
(Rated speed 2000 rpm)		**Eco-Par®**	**”EC1”**	**Agrol Agro Light**	**Etamix D2**
Maximum power	kW	85	82	83	77
Fuel consumption	kg/kWh	0.228	0.232	0.232	0.246
Exhaust flow	kg/kWh	7.78	7.82	7.96	8.23
Carbon Monoxide (CO)	g/kWh	1.14	0.89	1.11	0.87
Nitrogen Oxides (NOx)	g/kWh	9.85	9.93	10.18	10.76
Total Hydrocarbons (THC)	g/kWh	0.18	0.21	0.20	0.25
Particulate Matter (PM)	g/kWh	0.25	0.23	0.26	0.17

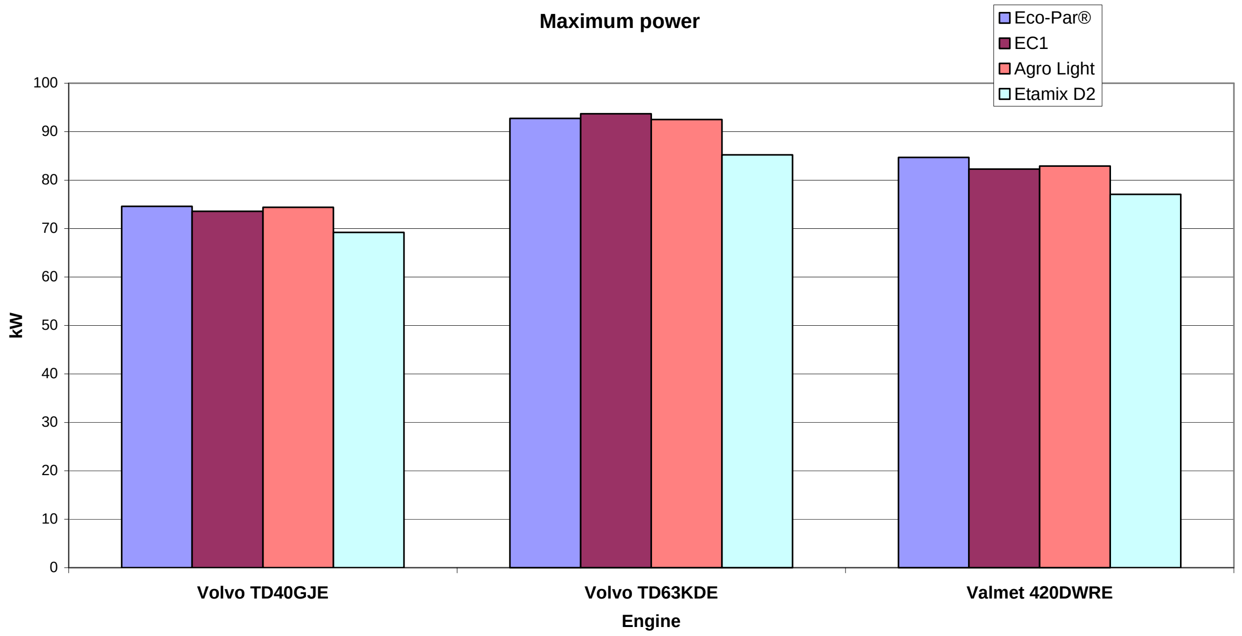

Figure 6. Maximum power for the four fuels tested in project Part 1.

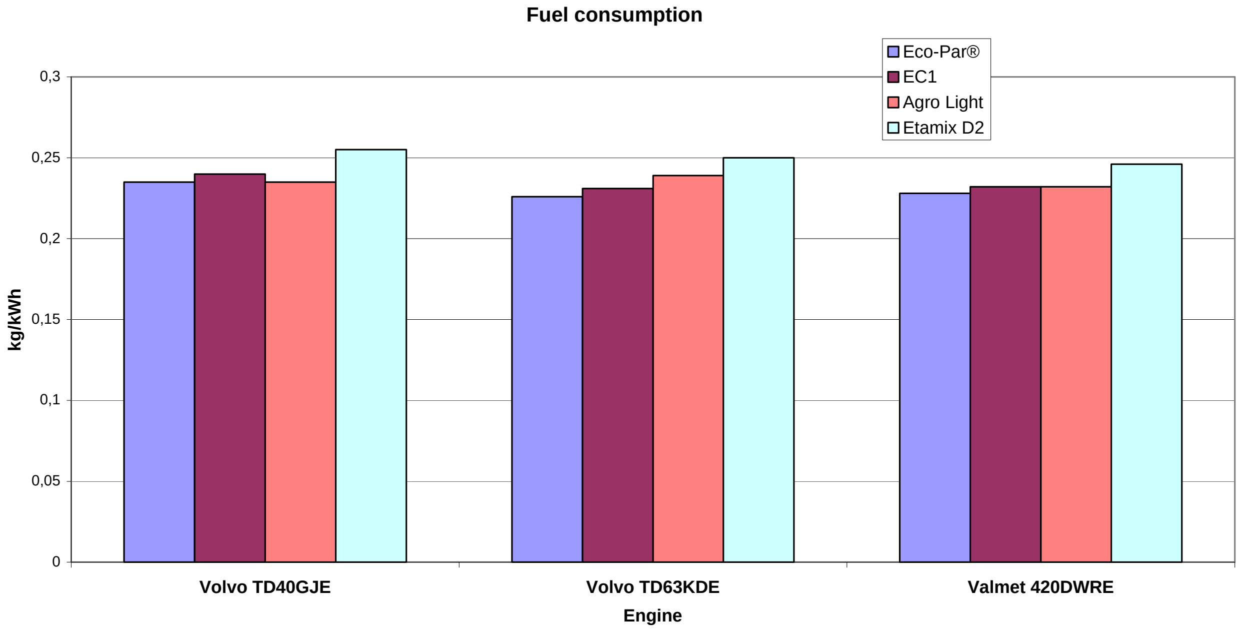

Figure 7. Specific fuel-consumption for the four fuels tested in project Part 1.

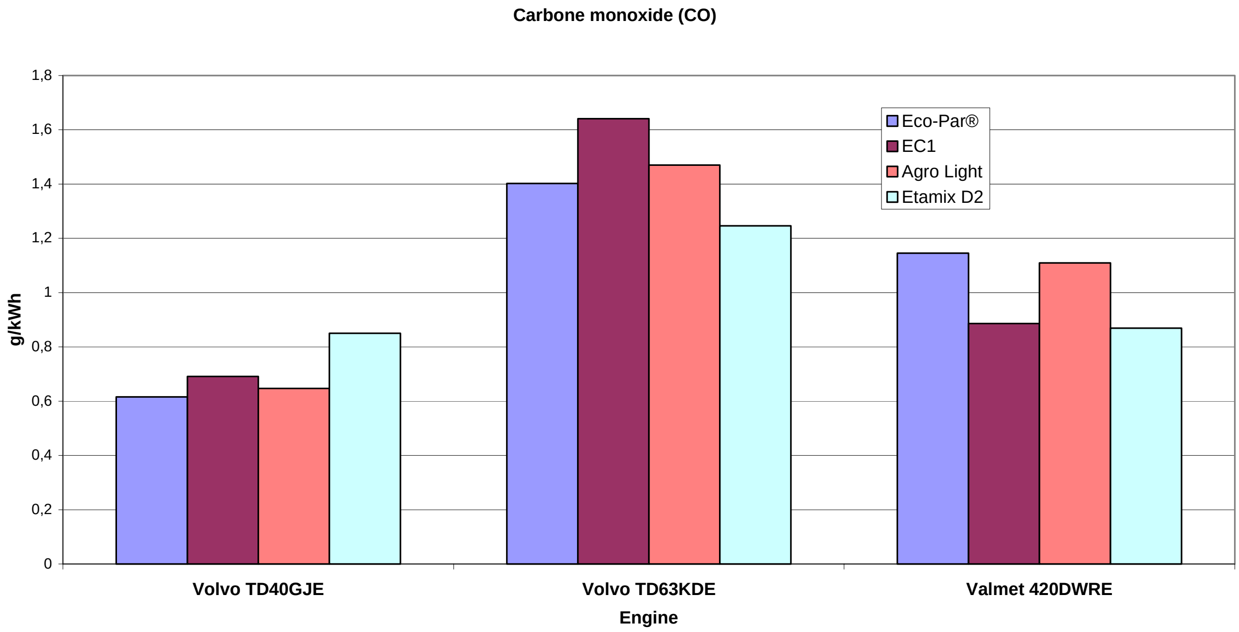

Figure 8. Specific emissions of Carbon Monoxide for the four fuels tested in project Part 1.

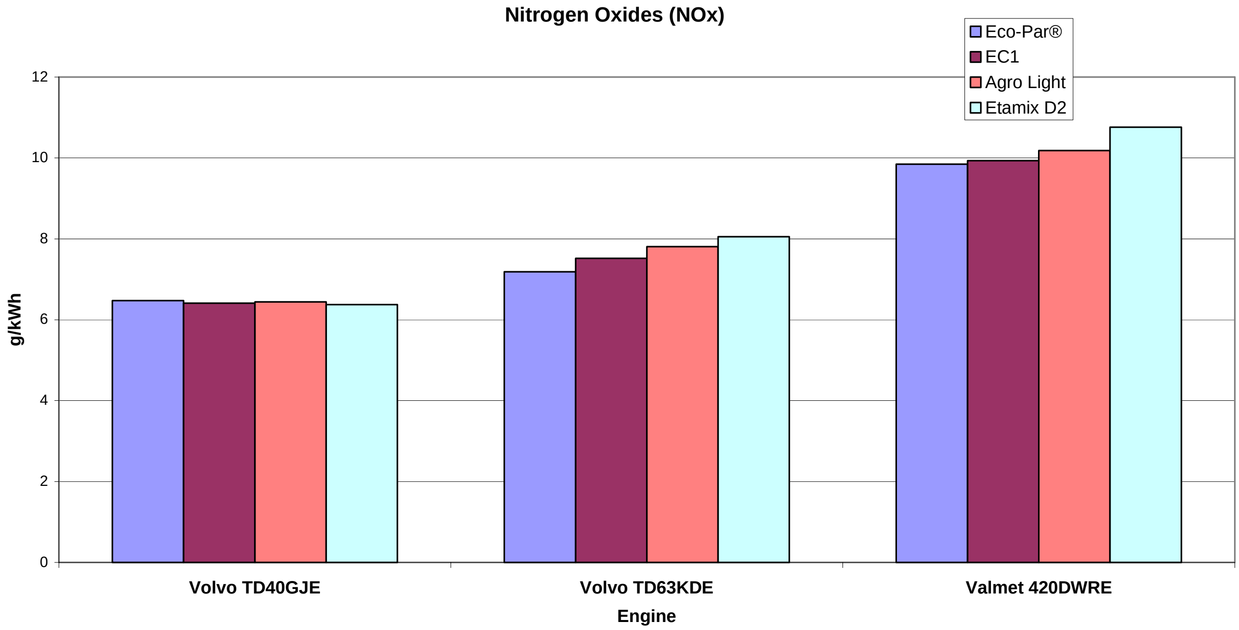

Figure 9. Specific emissions of Nitrogen oxides for the four fuels tested in project Part 1.

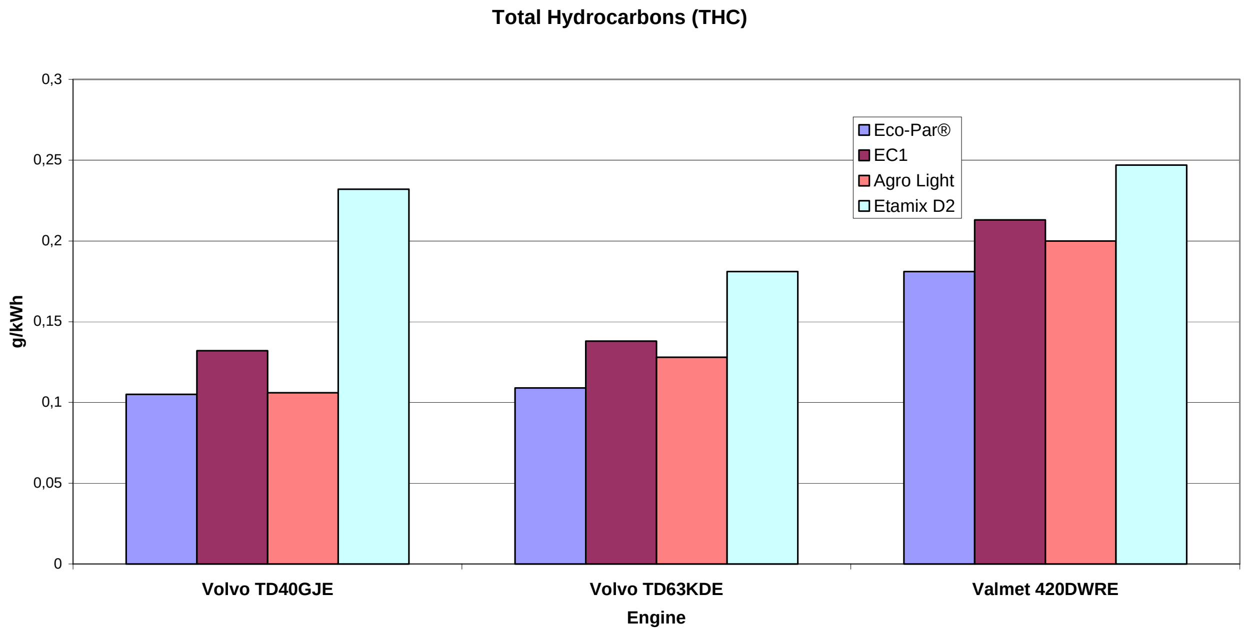

Figure 10. Specific emissions of Total Hydrocarbons for the four fuels tested in project Part 1.

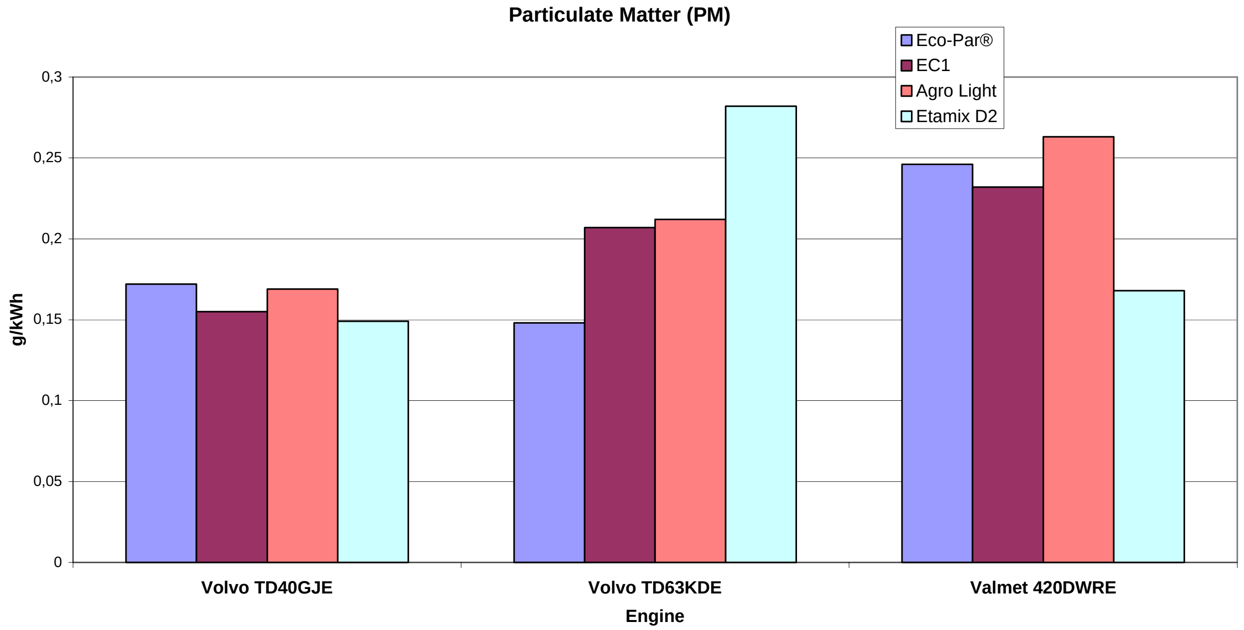

Figure 11. Specific emissions of Particulate Matter for the four fuels tested in project Part 1.

Results from project Part 2

In project Part 2, all tests of regulated emissions were repeated in separate test-runs and the results are therefore presented for test-run 1 and test-run 2.

Table 8. Results from project Part 2; regulated emissions etc. for the 3 tested fuels when used in engine Volvo TD40GJE.

		Fuel					
(Rated speed 2200 rpm)		**Eco-Par®**		**”EC1”**		**”Euro-Diesel”**	
		Test-run 1	**Test-run 2**	**Test-run 1**	**Test-run 2**	**Test-run 1**	**Test-run 2**
Maximum power	kW	72.9	73.2	73.8	72.6	76.9	76.1
Fuel consumption	kg/kWh	0.239	0.239	0.240	0.241	0.242	0.243
Exhaust flow	kg/kWh	8.49	8.51	8.52	8.58	8.35	8.45
Carbon Monoxide (CO)	g/kWh	0.58	0.59	0.63	0.61	0.62	0.61
Nitrogen Oxides (NOx)	g/kWh	6.89	6.74	6.96	7.16	7.34	7.33
Total Hydrocarbons (THC)	g/kWh	0.08	0.09	0.11	0.10	0.08	0.08
Particulate Matter (PM)	g/kWh	0.17		0.16		0.16	

Table 9. Results from project Part 2; regulated emissions etc. for the 3 tested fuels when used in engine Volvo TD63KDE.

		Fuel					
*(Rated speed 2200 rpm)**		**Eco-Par®**		**”EC1”**		**”Euro-Diesel”**	
		Test-run 1	**Test-run 2**	**Test-run 1**	**Test-run 2**	**Test-run 1**	**Test-run 2**
Maximum power	kW	81.6	81.2	81.4	80.3	86.4	86.6
Fuel consumption	kg/kWh	0.266	0.268	0.268	0.270	0.265	0.263
Exhaust flow	kg/kWh	8.41	8.53	8.34	8.62	8.18	7.99
Carbon Monoxide (CO)	g/kWh	0.98	0.95	0.95	0.95	0.99	0.91
Nitrogen Oxides (NOx)	g/kWh	6.56	6.87	6.73	6.75	7.05	7.08
Total Hydrocarbons (THC)	g/kWh	0.20	0.19	0.22	0.21	0.20	0.20
Particulate Matter (PM)	g/kWh	0.15		0.21		0.34	

* The rated speed for Volvo TD63KDE was 2000 rpm in Part 1 and 2200 rpm in Part 2, which explains the difference in e.g. fuel consumption for this engine between Part 1 and Part 2.

Table 10. Results from project Part 2; regulated emissions etc. for the 3 tested fuels when used in engine Valmet 420 DWRE.

		Fuel					
(Rated speed 2000 rpm)		**Eco-Par®**		**”EC1”**		**”Euro-Diesel”**	
		Test-run 1	**Test-run 2**	**Test-run 1**	**Test-run 2**	**Test-run 1**	**Test-run 2**
Maximum power	kW	85.2	84.5	85.2	83.6	85.9	85.0
Fuel consumption	kg/kWh	0.228	0.227	0.228	0.227	0.234	0.233
Exhaust flow	kg/kWh	7.65	7.61	7.67	7.57	7.52	7.44
Carbon Monoxide (CO)	g/kWh	1.04	1.08	1.01	1.01	1.22	1.22
Nitrogen Oxides (NOx)	g/kWh	10.36	10.36	10.42	10.45	10.39	10.25
Total Hydrocarbons (THC)	g/kWh	0.15	0.14	0.15	0.16	0.13	0.14
Particulate Matter (PM)	g/kWh	0.25		0.23		Not measured	

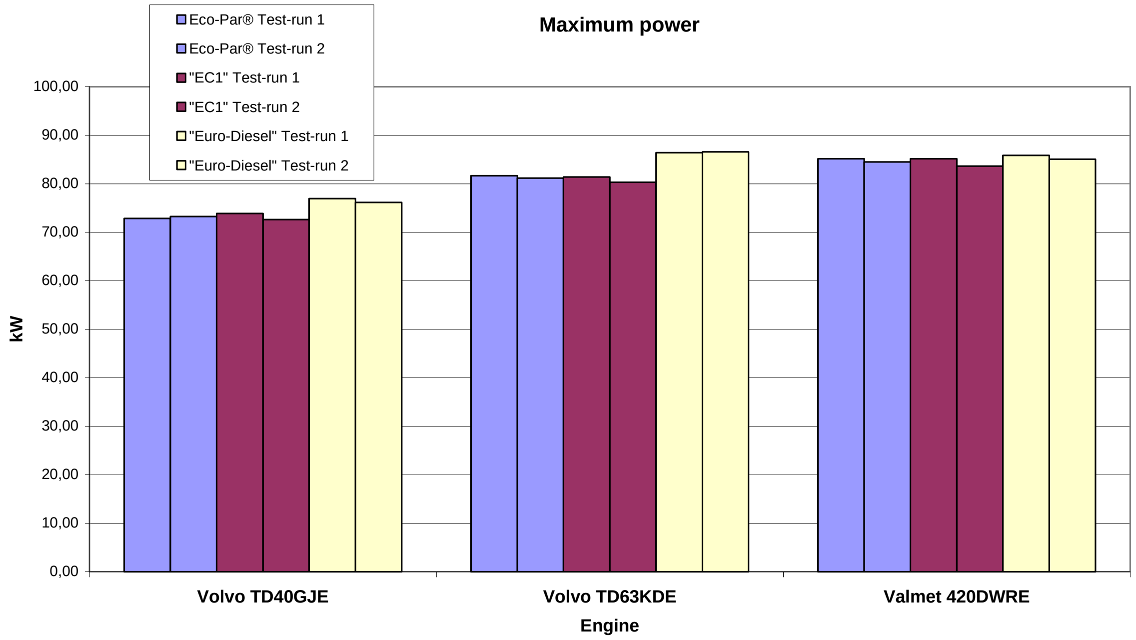

Figure 12. Maximum power for the three fuels tested in project Part 2.

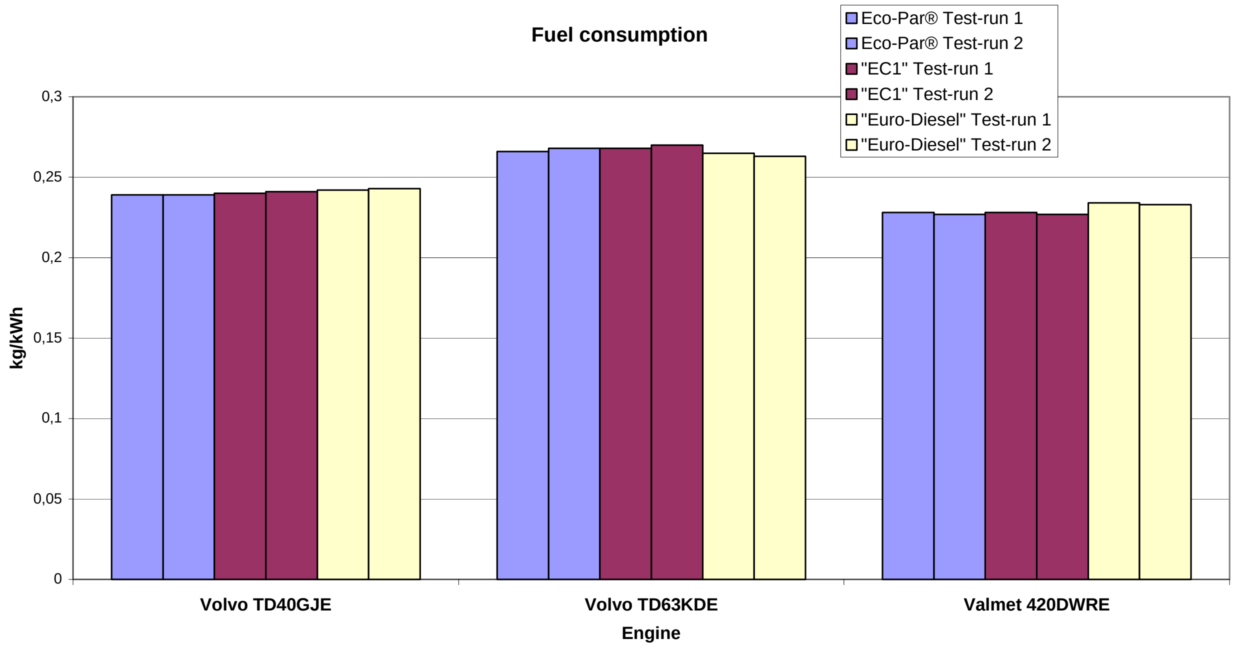

Figure 13. Specific fuel consumption for the three fuels tested in project Part 2.

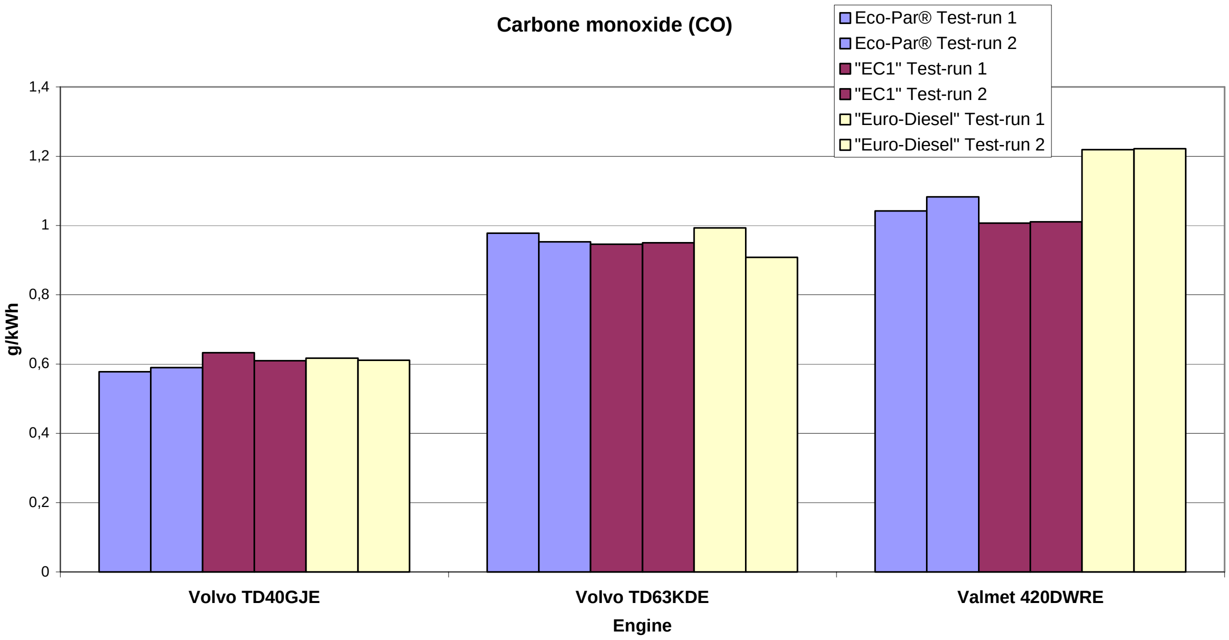

Figure 14. Specific emissions of Carbon Monoxide for the three fuels tested in project Part 2.

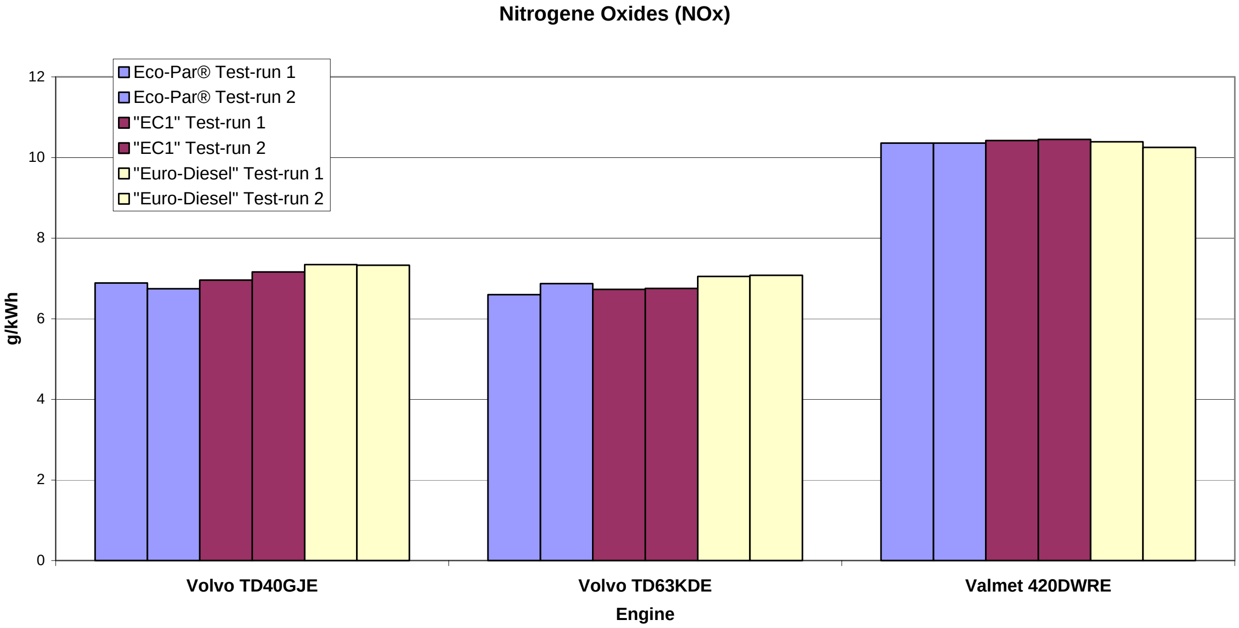

Figure 15. Specific emissions of Nitrogen Oxides for the three fuels tested in project Part 2.

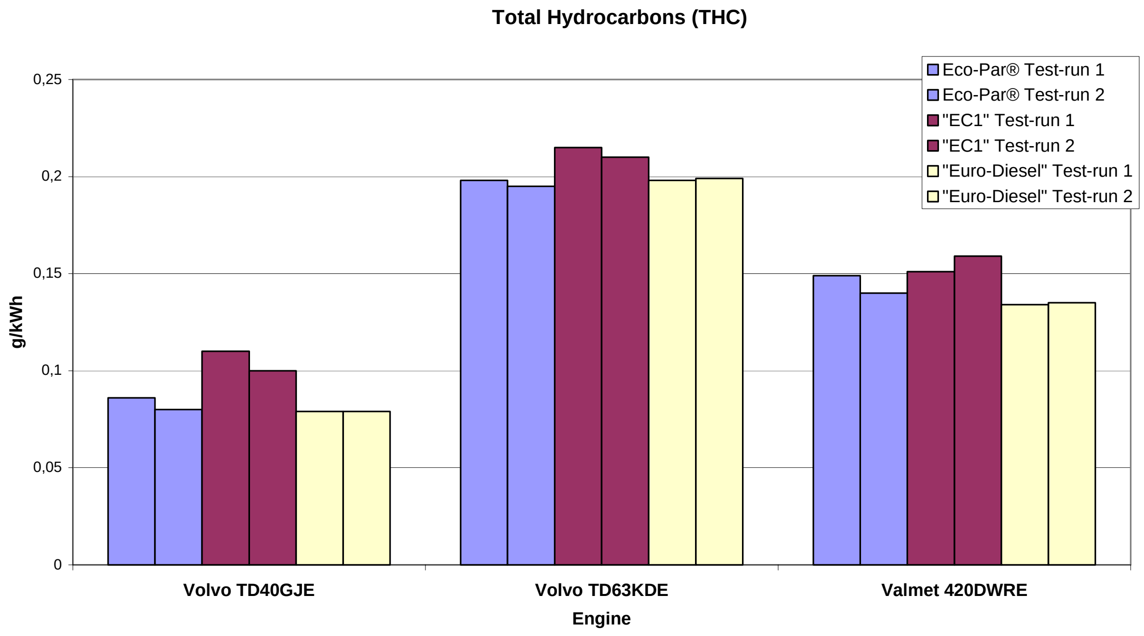

Figure 16. Specific emissions of Total Hydrocarbons for the three fuels tested in project Part 2.

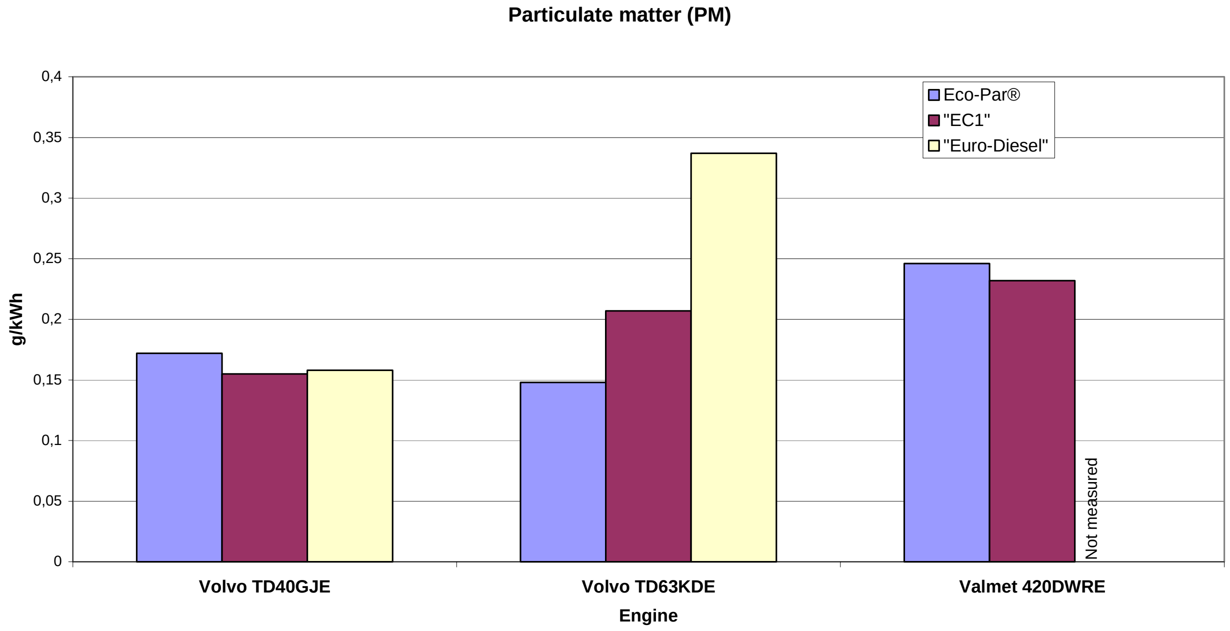

Figure 17. Specific emissions of Particulate Matter for the three fuels tested in project Part 2.

Unregulated emissions

General comments

As explained under heading “Comments on chemical analyses of certain compounds”, no trustworthy values for ethene, 1,3-butadiene and acrolein can be presented. Analyses of the two samples without a drying agent indicated that the content of 1,3-butadiene was in the vicinity of 10-15 % of that for propene.

In project-Part 2, all tests were repeated in separate test-runs except those for analyses of metal-content in soot. The results are, when available, therefore presented for test-run 1 and test-run 2.

Cells with values below the detection-limit are marked n.d. (non detectable).

Aldehydes, alkenes, benzene and ammonia

Table 11. Unregulated emissions for the 3 tested fuels when used in engine Volvo TD40GJE.

		Fuel					
Compound		**Eco-Par®**		**”EC1”**		**”Euro-Diesel”**	
		Test-run 1	Test-run 2	Test-run 1	Test-run 2	Test-run 1	Test-run 2
Formaldehyde	mg/kWh	25,0	25,5	30,4	24,7	24,7	25,0
Acetaldehyde	mg/kWh	6.6	6.9	7.4	6.7	6.8	7.1
Benzaldehyde	mg/kWh	3.4	n.d.*	n.d.*	3.9	2.0	1.4
Propanal	mg/kWh	n.d.**	n.d.**	n.d. **	n.d. **	n.d. **	n.d. **
Ammonia	mg/kWh	n.d. ***	n.d. ***	n.d. ***	n.d. ***	n.d. ***	n.d.***
Propene	mg/kWh	11.7	9.4	8.2	7.8	3.7	4.2
Benzene	mg/kWh	3.3	3.3	3.9	3.9	4.1	4.5

* Detection limit was approximately 1,3 mg/kWh
** Detection limit was approximately 1,3 mg/kWh
*** Detection limit was approximately 2,1 mg/kWh

Table 12. Unregulated emissions for the 3 tested fuels when used in engine Volvo TD63KDE.

		Fuel					
Compound		**Eco-Par®**		**”EC1”**		**”Euro-Diesel”**	
		Test-run 1	Test-run 2	Test-run 1	Test-run 2	Test-run 1	Test-run 2
Formaldehyde	mg/kWh	35.6	22.7	34.7	33.8	34.3	32.0
Acetaldehyde	mg/kWh	10.7	10.0	10.8	9.7	10.2	9.1
Benzaldehyde	mg/kWh	n.d*	2.2	2.7	3.8	3.8	2.5
Propanal	mg/kWh	n.d**	n.d**	n.d**	n.d**	n.d**	n.d**
Ammonia	mg/kWh	n.d***	n.d***	n.d***	n.d***	n.d***	n.d***
Propene	mg/kWh	18.3	15.7	11.9	13.3	11.4	Failed
Benzene	mg/kWh	3.2	3.1	4.4	4.2	4.1	4.0

* Detection limit was approximately 1,2 mg/kWh
** Detection limit was approximately 1,2 mg/kWh
*** Detection limit was approximately 2,0 mg/kWh

Table 13. Unregulated emissions for the 3 tested fuels when used in engine Valmet 420DWRE.

		Fuel					
Compound		**Eco-Par®**		**”EC1”**		**”Euro-Diesel”**	
		Test-run 1	Test-run 2	Test-run 1	Test-run 2	Test-run 1	Test-run 2
Formaldehyde	mg/kWh	36.7	37.5	31.0	31.3	29.3	28.0
Acetaldehyde	mg/kWh	10.1	9.5	8.8	8.6	8.0	7.1
Benzaldehyde	mg/kWh	2.8	n.d*	3.2	2.3	2.3	2.8
Propanal	mg/kWh	n.d**	n.d**	n.d**	n.d**	n.d**	n.d**
Ammonia	mg/kWh	n.d***	n.d***	n.d***	n.d***	n.d***	n.d***
Propene	mg/kWh	13.0	8.6	10.3	12.3	7.4	Failed
Benzene	mg/kWh	3.2	3.3	5.4	4.8	4.2	4.2

* Detection limit was approximately 1,1 mg/kWh
** Detection limit was approximately 1,1 mg/kWh
*** Detection limit was approximately 1,9 mg/kWh

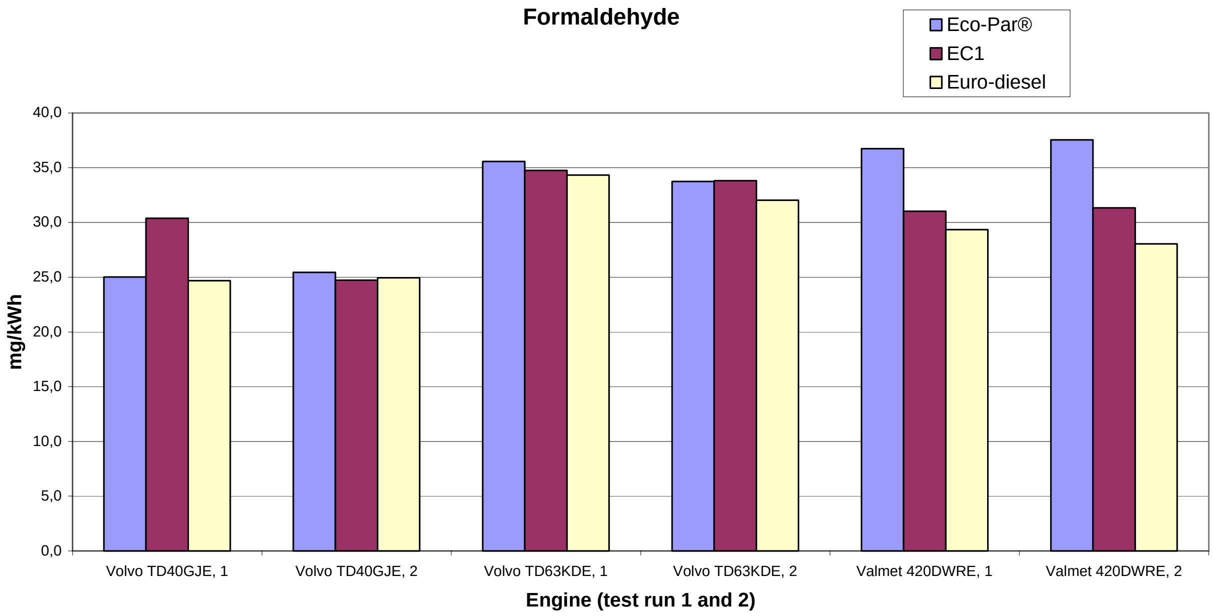

Figure 18. Specific emissions of Formaldehyde for the three fuels tested in project Part 2.

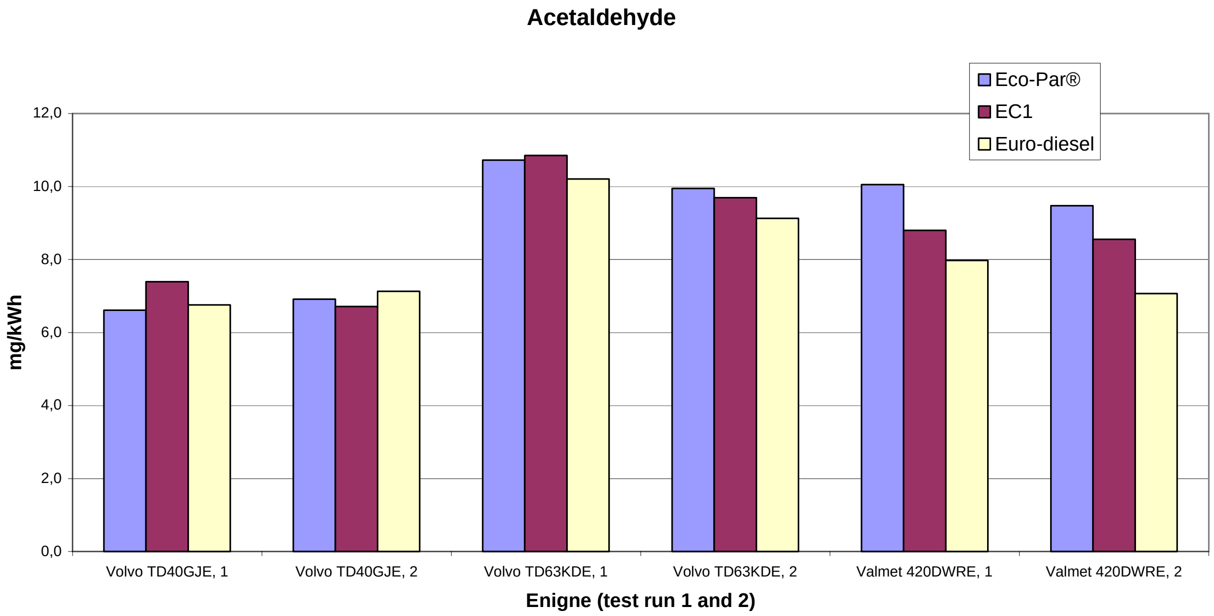

Figure 19. Specific emissions of Acetaldehyde for the three fuels tested in project Part 2.

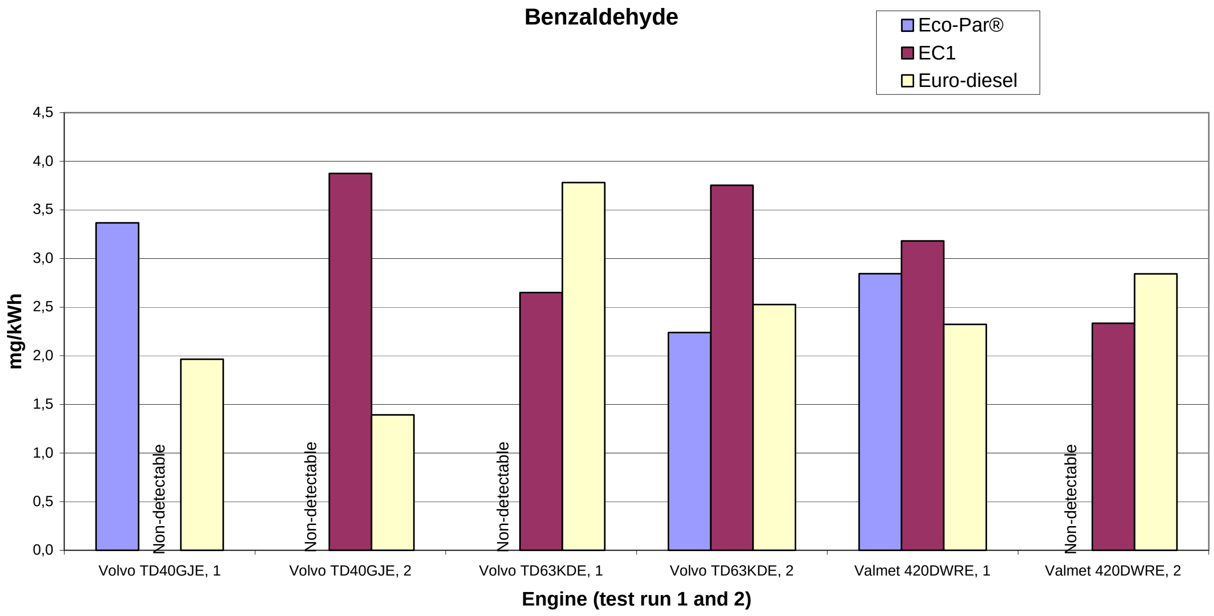

Figure 20. Specific emissions of Benzaldehyde for the three fuels tested in project Part 2.

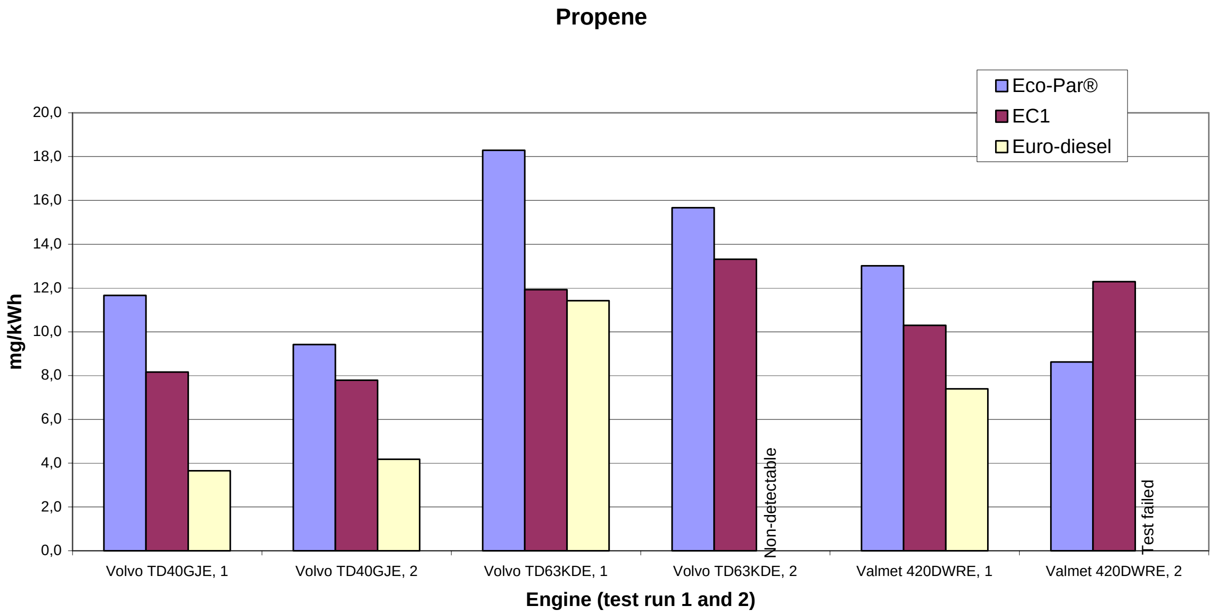

Figure 21. Specific emissions of Propene for the three fuels tested in project Part 2.

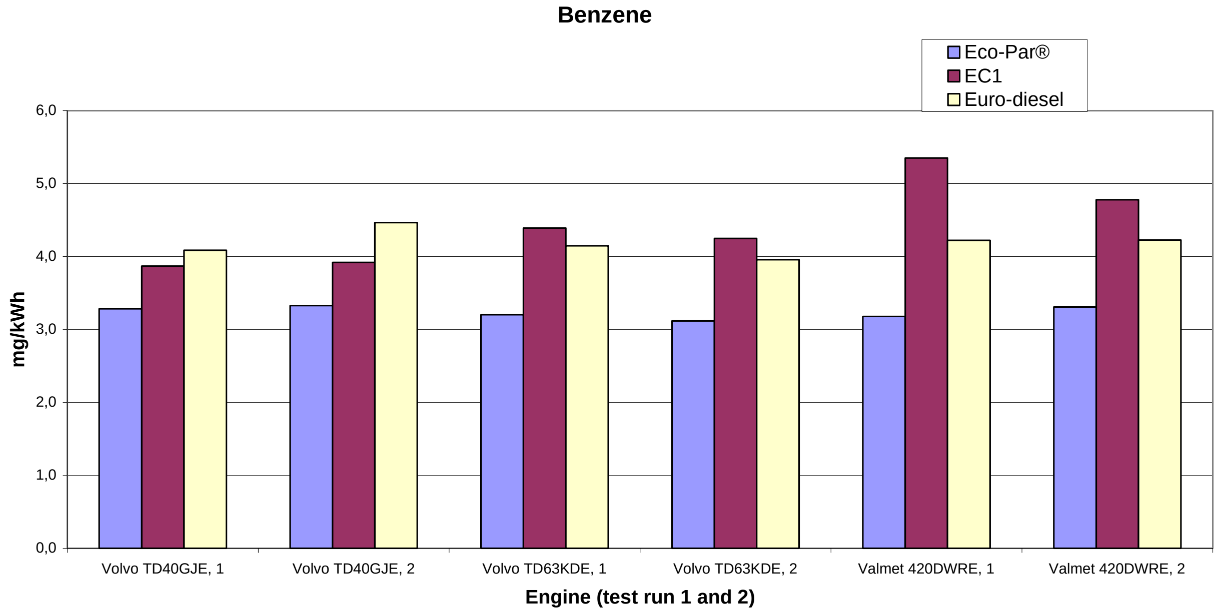

Figure 22. Specific emissions of Benzene for the three fuels tested in project Part 2.

Polyaromatic Hydrocarbons, PAH

Table 14. Emissions of Polyaromatic Hydrocarbons (di- and tri+), PAH, for the 3 tested fuels when used in engine Volvo TD40GJE. “1” and “2” indicate test-run 1 and test-run 2.

		Fuel											
Compound		**Eco-Par®**				**”EC1”**				**”Euro-Diesel”**			
	Detection limit (µg/kWh)	Particle associated (µg/kWh)		Semi-volatile (µg/kWh)		Particle associated (µg/kWh)		Semi-volatile (µg/kWh)		Particle associated (µg/kWh)		Semi-volatile (µg/kWh)	
		1	2	1	2	1	2	1	2	1	2	1	2
Naphthalene	6	n.d	8.6	133.0	152.2	7.0	n.d	201.0	271.2	14.0	11.8	414.6	488.4
1-Methylnaphthalene	11	n.d	n.d	29.4	17.2	n.d	n.d	89.4	121.2	14.7	11.0	205.2	259.2
2-Methylnaphthalene	11	n.d	n.d	23.3	32.6	n.d	n.d	55.3	93.2	17.7	10.5	191.7	235.3
Acenaphthylene	11	n.d	n.d	n.d	16.1	n.d	n.d	15.1	23.0	n.d	n.d	66.8	61.6
Acenaphthene	11	n.d	n.d	18.4	15.0	16.6	n.d	n.d	20.8	18.3	n.d	97.3	22.3
Fluorene	11	24.5	21.1	n.d	n.d	n.d	n.d	n.d	17.3	n.d	n.d	61.3	23.4
Phenanthrene	11	20.5	n.d	26.8	22.3	13.8	19.4	n.d	18.2	14.8	25.0	124.5	65.4
Anthracene	11	14.4	n.d	15.8	n.d	n.d	n.d	n.d	31.2	20.7	n.d	17.4	81.0
Fluoranthene	11	n.d	n.d	n.d	n.d	41.6	19.0	n.d	n.d	36.2	18.1	n.d	n.d
Pyrene	11	n.d	n.d	n.d	n.d	37.5	20.1	n.d	n.d	33.2	n.d	n.d	n.d
Benz(a)anthracene	40	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d
Chrysene	40	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d
Benzo(b)fluoranthene	40	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d
Benzo(k)fluoranthene	40	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d
Benzo(a)pyrene	40	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d
Indeno(1,2,3-cd)pyrene	120	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d
Benzo(ghi)perylene	120	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d
Dibenzo(a,h)anthracene	120	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d
Total di+ PAH (detected)		59.4	29.7	246.7	255.4	116	58.5	360.8	502.9	169	76.4	1178.8	1236.6
Total tri+ PAH (detected)		34.9	0	42.6	22.3	92.9	58.5	0	49.4	105	43.1	141.9	146.4
Average di+-PAH (detected)		45		251		88		432		123		1208	
Average tri+-PAH (detected)		17		32		76		25		74		288	

Table 15. Emissions of Polyaromatic Hydrocarbons (di- and tri+), PAH for the 3 tested fuels when used in engine Volvo TD63KDE. “1” and “2” indicate test-run 1 and test-run 2.

		Fuel											
Compound		**Eco-Par®**				**”EC1”**				**”Euro-Diesel”**			
	Detection limit (µg/kWh)	Particle associated (µg/kWh)		Semi-volatile (µg/kWh)		Particle associated (µg/kWh)		Semi-volatile (µg/kWh)		Particle associated (µg/kWh)		Semi-volatile (µg/kWh)	
		1	2	1	2	1	2	1	2	1	2	1	2
Naphthalene	6	7.0	n.d	146.8	163.5	41.5	7.3	468.1	191.0	12.7	14.9	386.4	444.3
1-Methylnaphthalene	12	n.d	n.d	33.3	19.9	25.2	n.d	251.1	124.1	12.9	n.d	296.3	366.5
2-Methylnaphthalene	12	n.d	n.d	28.6	16.6	16.4	n.d	203.2	86.2	20.8	n.d	249.2	396.2
Acenaphthylene	12	n.d	n.d	n.d	3.0	n.d	n.d	35.4	18.5	n.d	n.d	29.6	42.2
Acenaphthene	12	n.d	n.d	n.d	18.2	n.d	n.d	25.6	24.6	n.d	n.d	81.7	51.7
Fluorene	12	n.d	n.d	n.d	n.d	30.2	n.d	33.0	n.d	n.d	n.d	63.4	75.2
Phenanthrene	12	n.d	n.d	23.5	28.3	n.d	n.d	33.7	n.d	16.3	10.9	119.5	108.9
Anthracene	12	n.d	n.d	38.0	26.1	n.d	n.d	n.d	n.d	n.d	11.3	135.0	125.6
Fluoranthene	12	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d
Pyrene	12	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d
Benz(a)anthracene	40	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d
Chrysene	40	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d
Benzo(b)fluoranthene	40	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d
Benzo(k)fluoranthene	40	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d
Benzo(a)pyrene	40	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d
Indeno(1,2,3-cd)pyrene	120	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d
Benzo(ghi)perylene	120	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d
Dibenzo(a,h)anthracene	120	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d
Total di+-PAH (detected)		7.0	0	270.2	275.6	113	7.3	1050.1	444.4	62.7	37.0	1361.1	1610.6
Total tri+-PAH (detected)		0	0	61.5	54.4	0	0	33.7	0	16.3	22.2	254.5	234.5
Average di+-PAH (detected)		7		273		60		747		49.9		1485.9	
Average tri+-PAH (detected)		0		58		0		17		19		244	

Table 16. Emissions of Polyaromatic Hydrocarbons (di- and tri+), PAH for the 3 tested fuels when used in engine Valmet 420DWRE. “1” and “2” indicate test-run 1 and test-run 2.

		Fuel											
Compound		**Eco-Par®**				**”EC1”**				**”Euro-Diesel”**			
	Detection limit (µg/kWh)	Particle associated (µg/kWh)		Semi-volatile (µg/kWh)		Particle associated (µg/kWh)		Semi-volatile (µg/kWh)		Particle associated (µg/kWh)		Semi-volatile (µg/kWh)	
		1	2	1	2	1	2	1	2	1	2	1	2
Naphthalene	6	n.d	7.4	95	136.6	n.d	n.d	251.2	223.4	n.d	9.7	385.2	371.1
1-Methylnaphthalene	12	n.d	n.d	16.0	n.d	11.2	n.d	128.1	134.1	n.d	11.6	272.3	237.4
2-Methylnaphthalene	12	n.d	n.d	n.d	n.d	13.5	n.d	94.6	85.3	n.d	13.9	217.1	209.3
Acenaphthylene	12	n.d	n.d	n.d	n.d	n.d	n.d	24.6	12.4	n.d	n.d	31.9	22.1
Acenaphthene	12	n.d	n.d	n.d	n.d	n.d	n.d	23.2	18.7	n.d	n.d	49.1	40.5
Fluorene	12	n.d	n.d	n.d	n.d	n.d	n.d	22.9	11.9	n.d	20.9	54.8	45.2
Phenanthrene	12	17.3	n.d	n.d	n.d	n.d	n.d	11.5	13.7	28.3	28.7	34.0	67.3
Anthracene	12	17.9	15.1	11.2	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d
Fluoranthene	12	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d
Pyrene	12	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d
Benz(a)anthracene	40	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d
Chrysene	40	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d
Benzo(b)fluoranthene	40	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d
Benzo(k)fluoranthene	40	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d
Benzo(a)pyrene	40	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d
Indeno(1,2,3-cd)pyrene	120	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d
Benzo(ghi)perylene	120	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d
Dibenzo(a,h)anthracene	120	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d
Total di+-PAH (detected)		35.2	22.5	122.2	136.6	24.7	0	556.1	499.5	28.3	84.8	1044.4	992.9
Total tri+-PAH (detected)		35.2	15.1	11.2	0	0	0	11.5	13.7	28.3	28.7	34.0	67.3
Average di+-PAH (detected)		29		129		12		528		57		1019	
Average tri+-PAH (detected)		25		6		0		13		57		51	

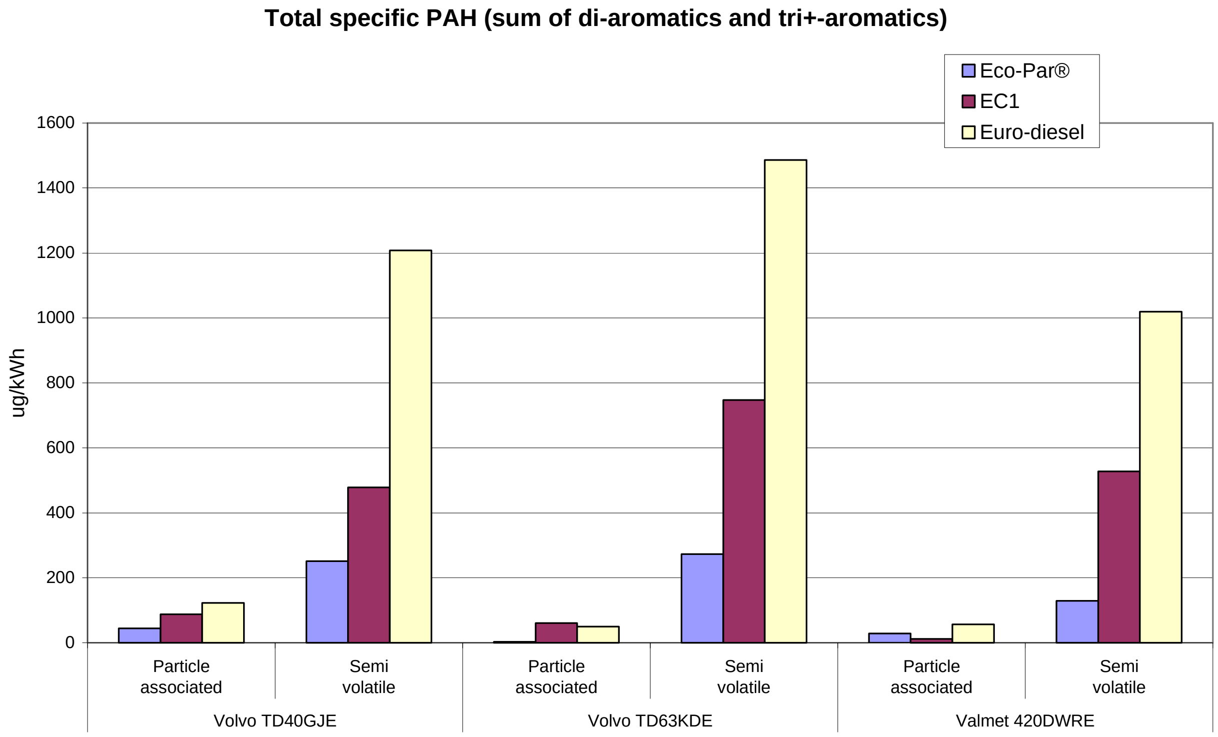

Figure 23. Total specific Polyaromatic Hydrocarbons (the sum of di- and tri+.-aromatics) Average values from test-run 1 and 2. Calculation based on values above detection-level only.

Metal content

Table 17. Specific metal content for the three tested fuels when used in the three engines

Substance			**Eco-Par®**			**”EC1”**			**”Euro-Diesel”**		
		Detection limit	Volvo TD40GJE	Volvo TD63KDE	Valmet 420DWRE	Volvo TD40GJE	Volvo TD63KDE	Valmet 420DWRE	Volvo TD40GJE	Volvo TD63KDE	Valmet 420DWRE
Cu	g/kWh	0,04	n.d	n.d	n.d	n.d	0.04	n.d	n.d	n.d	n.d
Mo	g/kWh	0,04	n.d	n.d	n.d	n.d	0.04	n.d	n.d	n.d	n.d
Ni	g/kWh	0,04	n.d	n.d	0.11	n.d	n.d	n.d	n.d	n.d	n.d
Pb	g/kWh	0,04	0.13	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d
V	g/kWh	0,8	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d
Zn	g/kWh	0,2	n.d	0.23	0.26	n.d	0.29	n.d	n.d	0.37	n.d
Fe	g/kWh	0,4	n.d	1.97	2.40	n.d	n.d	0.56	n.d	n.d	n.d
P	g/kWh	0,2	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d
Mg	g/kWh	0,2	n.d	n.d	0.37	n.d	n.d	n.d	n.d	n.d	n.d
Ca	g/kWh	0,8	n.d	n.d	1.70	n.d	n.d	n.d	n.d	n.d	n.d
S	g/kWh	12	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d

Particle number- and size-distribution

The number- and size-distributions for the different cases are shown in figures 24 - 27. Each combination of engine/fuel was measured in two separate test-runs, and each curve represents a mean of the two measurements.

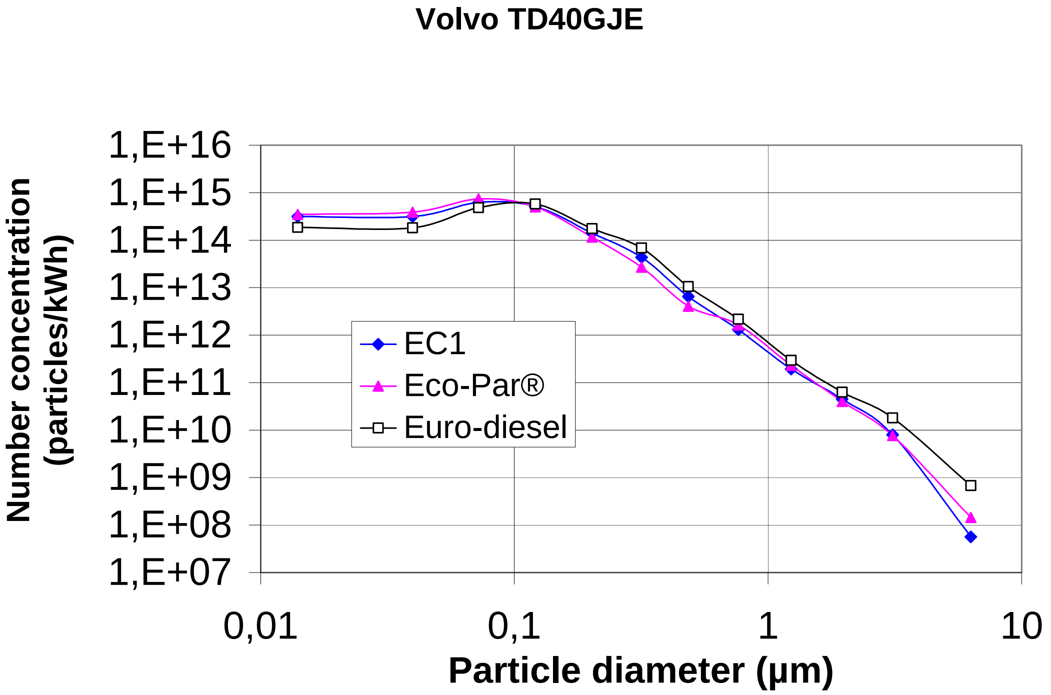

Figure 24. Particle-size distributions for the three fuels when used in Volvo TD40GJE.

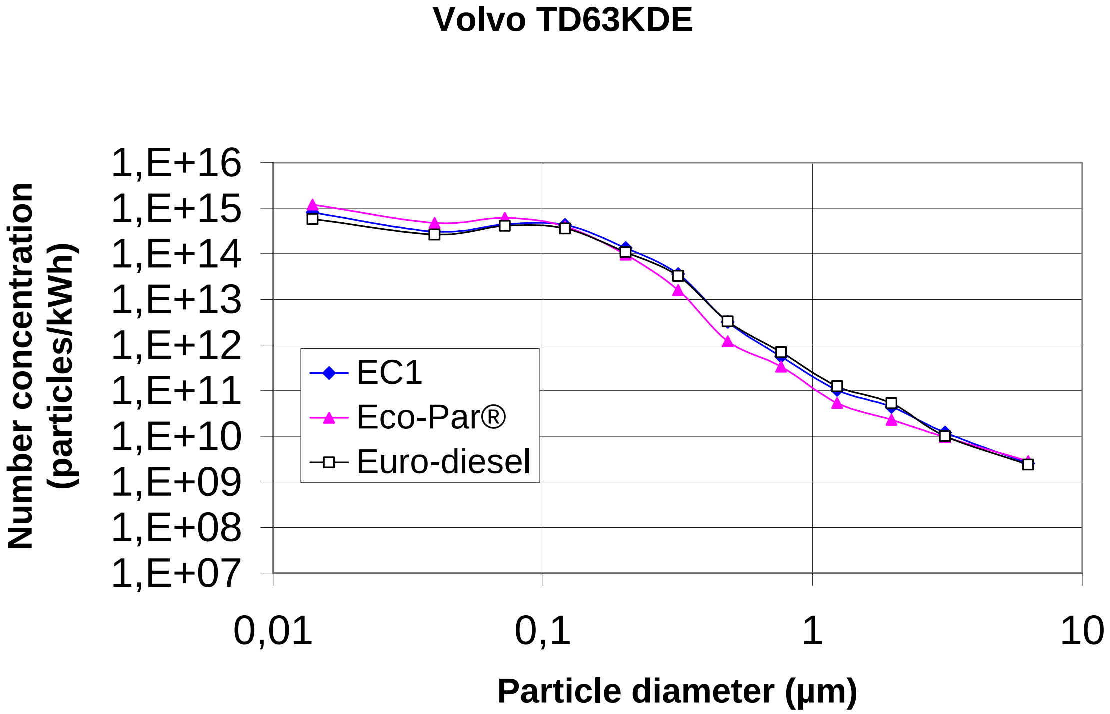

Figure 25. Particle-size distributions for the three fuels when used in Volvo TD63KDE.

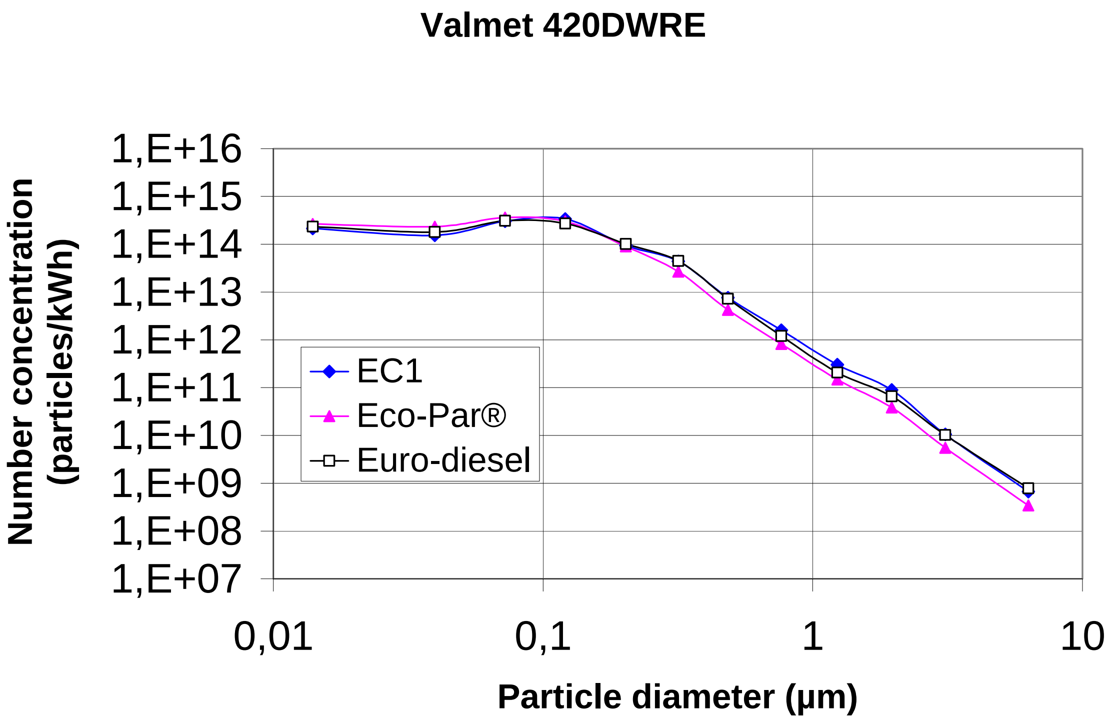

Figure 26. Particle-size distributions for the three fuels when used in Valmet 420DWRE.

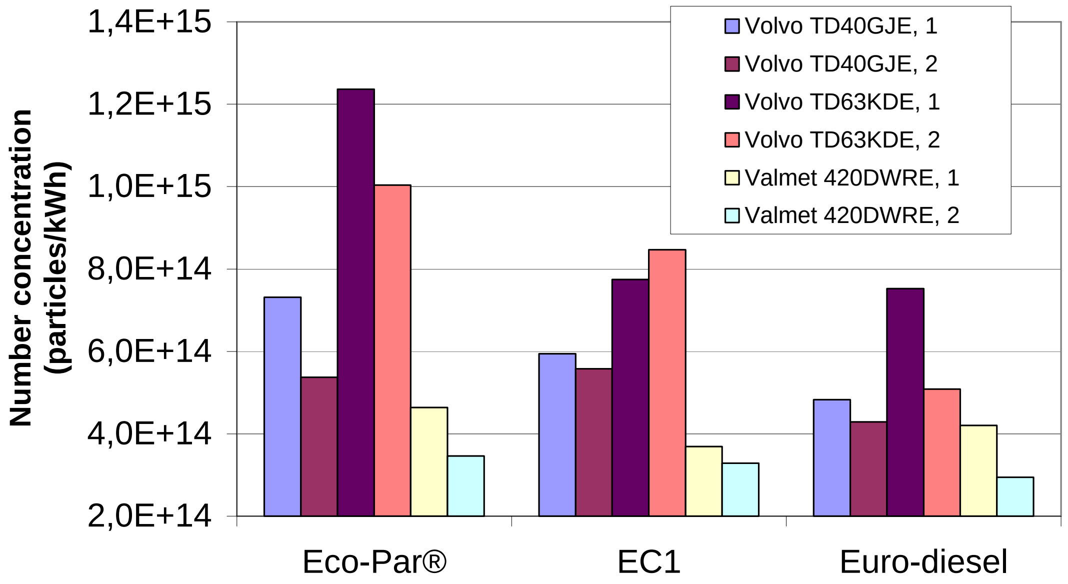

Figure 27. Number-concentrations (size range 7 nm – 7µm) in the exhaust for the different combinations.

Comments on the results

General

It should be noted that the engines were not in any way tuned in order to optimise them for the different fuels.

The values for the maximum power of the engines were significantly lower when the “Etamix D2” was used than when the other fuels in project Part 1 were used and the specific fuel consumption was slightly higher with “Etamix D2”.

Regulated emissions project Part 1

The differences between the tested fuels in project Part 1 regarding Carbon Monoxide (CO), Nitrogen Oxides (NOx) and Particulate Matter (PM) were either small or varied depending on the engine used. Therefore, no general conclusions can be drawn regarding differences for these emissions.

However, it is obvious from the results that the use of different fuels results in differences regarding emissions of Total Hydrocarbons (THC) in all three engines. The lowest THC-emissions were found with Eco-Par®, the second lowest with “Agrol Agro Light”, the second highest with ”EC1” and the highest with “Etamix D2”. It should, however, be noted that even though differences between the fuels can be found, the absolute levels of THC are low with the three tested “Euro-1” engines.

Regulated emissions project Part 2

Also in project Part 2 the differences between the different fuels were either small or varied depending on the engine used for several of the measured parameters. However, there was a tendency that the use of ”EC1”-fuel resulted in higher emissions of THC than the two other fuels. For one engine the emissions of PM were significantly higher with ”Euro-Diesel” than with the other fuels but this pattern was not obvious on the other engine in which emissions of PM were measured for all three fuels. Again it should be emphasized that the levels of THC-emissions were generally low with the engines in question and it is therefore difficult to draw conclusions based on the small differences found.

Unregulated emissions

Aldehydes, alkenes, benzene and ammonia

The results show low levels of emissions and small differences between the fuels. Tendencies that are consistent for all three engines can be observed for propene, where the emissions were higher for Eco-Par®, than for ”EC1”, which in its turn gave higher emissions than ”Euro-Diesel”. But for Benzene, a tendency can be observed that Eco-Par® gave lower emissions than the other fuels.

Polyaromatic Hydrocarbons, PAH

The levels of particle-associated Polyaromatic Hydrocarbons (including di-aromatic PAH) did not show consistent differences between the fuels. A clear and consistent difference between the fuels could, however, be noted for the semi-volatile PAH (including di-aromatics) where Eco-Par® showed lower levels than ”EC1” and where the highest levels were found with ”Euro-Diesel”.

Metal content

The results from the soot-analyses for metal-content showed that only a few detectable metal-substances were found. They most likely originated from single flakes that are part of the normal wear procedure of the engine.

Particle number and size distribution

It can be observed that the differences in particle emissions from the three engines and the fuels were small. For all cases, high concentrations of ultrafine particles were observed. Consequently the ultra-fine particles constituted a large part of the total number-concentration. The number-concentration in the exhaust was 10^{14} – 10^{15} particles per kWh (figure 27).

A tendency that can be observed for all three engines is that the use of Eco-Par® results in lower number-concentrations than for “EC1”, which in its turn showed lower number-concentrations than Euro-Diesel” in the interval 0.1 - 10 µm. The relationship was the opposite for ultrafine particles.

The higher particle-size number in the range 0.1 - 10 µm with “Euro-Diesel” could be an effect of its higher content of sulphur and heavy aromatic hydrocarbons. The high number of ultrafine particles may in its turn be an effect of ultrafine liquid-drops (condensate) that develop due to the cooling of the exhausts in the dilution tunnel where the samples are taken. A theoretical explanation of why higher numbers of ultrafine particles were found for Eco-Par® and “EC1” than for “Euro-Diesel” could be that the more hydrogen and the more light fractions a fuel contains, the greater is the risk of condensate liquid-drops affecting the results.

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Examples of SAE articles about Fischer-Tropsch fuels

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Paul Norton and Keith Vertin, NREL, Golden, Colorado, USA: *SAE 1999-01-1512, "Emissions from Buses with DDC 6V92 Engines Using Synthetic Diesel Fuel"*, SP-1458, **1999**, p. 81-91

Brigitte Martin, IFP France ; Päivi Akko, VTT Energy, Esbo, Finland ; Derek Beckman, TNO The Netherlands ; Nicola Del Giacomo, Instituto Motori, Italy ; Fulvio Giavazzi, EURON, Italy: SAE 972966, *"Influence of Future Fuel Formulations on Diesel Engine Emissions - A Joint European Study"*, Society of Automobile Engineers Incorporated (SAE), **1997**

Leena Rantanen, Seppo Mikkonen, Neste Oy, Finland ; Lars Nylund, Pirkko Kociba, Inst. of Occupational Health, Finland ; Maija Lappi and Nils-Olov Nylund, VTT Energy, Esbo, Finland: SAE 932686*, "Effect of Fuel on the Regulated, Unregulated and Mutagenic Emissions of DI Diesel Engines"*, Fuels and Lubricants Meeting and Exposition, Philadelphia, Pennsylvania, October 18-21, **1993**

Annex 1

Substance	Topical EU Risk Codes	Level Limit Value LLV [mg/m3]	CAS Nr.
1,3-butadiene	Canc1, Mut2, T	1,0	106-99-0
Acrolein	T+, N	0,2	107-02-8
Formaldehyde	Canc3, T, C	0,6	50-00-0
benzene	Canc1, T	1,5	71-43-2
Acetaldehyde	Canc3; Xi	45	75-07-0
Benzaldehyde	Xn	Not classified	100-52-7
Propene	None	900,0	115-07-1
di- and polyaromatic hydrocarbons			
Naphthalene	N, Xn	50	91-20-3
1-Methylnaphthalene	Not classified	Not classified	90-12-0
2-Methylnaphthalene	Not classified	Not classified	91-57-6
Acenaphthylene	Not classified	Not classified	208-96-8
Acenaphthene	Not classified	Not classified	83-32-9
Fluorene	Not classified	Not classified	86-73-7
Phenanthrene	Not classified	Not classified	85-01-8
Anthracene	Not classified	Not classified	120-12-7
Fluoranthene	Not classified	Not classified	206-44-0
Pyrene	Not classified	Not classified	129-00-0
Benz(a)anthracene	Canc2, T, N	Not classified	56-55-3
Chrysene	Canc2, Mut2, T, N	Not classified	218-01-9
Benzo(b)fluoranthene	Canc2, T, N	Not classified	205-99-2
Benzo(k)fluoranthene	Canc2, T, N	Not classified	207-08-9
benso(a)pyren	Canc2, Mut2, Repr2	0,002	50-32-8
Indeno(1,2,3-cd)pyrene	Not classified	Not classified	193-39-5
Benzo(ghi)perylene	Not classified	Not classified	191-24-2
Dibenzo(a,h)anthracene	Canc2, T, N	Not classified	53-70-3
Sources:			
The Swedish Occupational Health Board: AFS 2000:3 (homepage www.av.se)			
The Swedish National Chemicals Inspectorate: KIFS 2001:3 (homepage www.kemi.se)			
ChemID, homepage http://chem.sis.nlm.nih.gov/chemidplus/			
Explanation of EU Risk Codes			
Canc1 - Carcinogenic			
Canc2 - Probably Carcinogenic			
Canc3 - Possibly Carcinogenic			
Mut1 - Mutagenic			
Mut2 - Probably Mutagenic			
Mut3 - Possibly Mutagenic			
Repr1 - Toxic to reproduction			
Repr2 - Probably toxic to reproduction			
Repr3 - Possibly toxic to reproduction			
T+ Very toxic			
T Toxic			
Xi Irritating			
Xn Harmful			
N Harmful to the environment			
C Corrosive			
None - No risk code assigned to the chemical			
Not Classified - Usually because too little toxicological information is available			