FUEL EFFECTS ON EMISSIONS FROM NON-ROAD ENGINES

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VTT PROCESSES

ABSTRACT

The objective of this project was to study how fuel quality affects the exhaust emissions from different kinds of non-road engines. The project was divided into two parts: emissions from small gasoline engines and emissions from diesel engines.

The measured small engines were a 2-stroke chainsaw engine, and a 4-stroke OHV engine, which could be used in different applications. Measurements were done with three different fuels, with and without catalyst. Also a comparison between biodegradable vs. conventional lubrication oil was done with the 2-stroke engine. Measurements were done according to ISO8178 standard. The results clearly demonstrate that using a good quality fuel (e.g. low sulphur, low aromatics) and a catalyst gives the best outcome in overall emission levels from these small engines.

In the second part two different diesel engines were tested with five different fuels. Two of the fuels were biodiesel blends. The engines were chosen to represent old and new engine technology. The old engine (MY 1985) was produced before EU emission regulations were in place, and the new engine fulfilled the current EU Stage 2 emission limits. These measurements were also done according to the ISO8178 standard. With the new engine comparison with and without oxidation catalyst was done using two fuels. The results in general are similar compared to the results from the small gasoline engines: fuel quality has an effect on the emissions and when combining a good quality fuel (e.g. low sulphur, low aromatics) and an oxidation catalyst the emission levels are significantly reduced.

Also some unregulated emission measurements were done but those results are not included to this report.

PREFACE

The project “Fuel Effects on Emissions from Non-Road Engines” is part of an IEA-AMF program work. The project came into force as Annex XXV of the IEA-AMF program in 2001. The purpose of the project was to produce a document on the effects of fuel quality and exhaust gas aftertreatment on emissions from non-road machinery. The project was carried out during 2001-2003 by VTT. The project has been founded by international IEA and Finnish partners. The international participants of this project have been:

Agence de l´Environnement et de la Maîtrise de l´Energie (ADEME), Institut Français du Pétrole (IFP), France

Swedish Energy Agency (STEM), Sweden,

United States Department of Energy (DOE), USA

The Finnish companies, which have took part to this project are Fortum Oil and Gas Oy, Kemira Metalkat Oy and Sisu Diesel Oy.

Part of the measurements of this project has been carried out in close co-operation with Agrifood Research Finland, Agricultural Engineering Research (MTT, Vakola).

The report at hand is the partial technical report of the project, intended for the public use. This report does not include the unregulated emission results.

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LIST OF ABBREVIATIONS

BIO5	5 % mixture of RME and reformulated high quality automotive diesel
BIO30	30 % mixture of RME and reformulated high quality automotive diesel
Biolube	biodegradable lubrication oil for small two-stroke gasoline engines
CO	carbon monoxide in exhaust gases
EUD2005	reformulated high quality automotive diesel (S< 50 mg/kg)
EUD2000	automotive diesel fulfilling the EU year 2000 specifications (S< 350 mg/kg)
EUG2000	gasoline fulfilling the EU year 2000 specifications (S< 150 mg/kg)
HC	total hydrocarbons in exhaust gases
ISO8178	exhaust emission test procedure for engines according to standard ISO8178
LAMBDA	relative air-fuel ratio
LFO	light fuel oil (S ≅ 2000 mg/kg)
MON	motor octane number
MTT	Agrifood Research Finland, Agricultural Engineering Research
NO_x	oxides of nitrogen in exhaust gases
PM	particle matter emission
RME	rape seed oil methyl ester
RON	research octane number
SEG	special alkylate gasoline for small engines (S< 20 mg/kg)
SEGO	special alkylate gasoline for small engines with oxygenate (S< 20 mg/kg)
STDEV	Standard deviation calculated with the “STDEV” function of Excel program
WF	weighing factors

1 INTRODUCTION

The emission regulations for non-road engines are less stringent than for on-road applications. In addition, it is allowed to use heating type fuel oils in diesel equipment in some countries. The quality requirements for heating oils are much less stringent than for automotive diesel fuels. Within the European Union, some countries will allow the use of heating oil containing 2000 mg/kg sulphur in non-road machinery until the year 2008, whereas the sulphur content of automotive fuels will be limited to a maximum of 50 mg/kg sulphur in 2005.

In Finland, for example, non-road mobile machinery consume some 30 % of the amount of middle distillates used for engine applications. The specific emissions of mobile non-road machinery are higher than those of on-road engines. Thus the relative share of emissions from non-road mobile machines is even higher than their share of energy use. This ratio is growing, as the on-road vehicles are cleaning up faster than the non-road engines.

The operation of non-road mobile machinery often includes very variable duty cycles, including extended periods of low-load operation or even idling. To avoid excessive smoke formation, the fuel used should have good ignition properties (high cetane number). Some machines are used indoors, e.g. forklifts in warehouses, terminal tractors pulling containers out of ships and mining equipment in mines. For these machines it would be very important, also from an occupational safety point of view, to have fuels with high quality, i.e. low sulphur, low aromatics and high cetane.

The engines used in hand-held equipment like chain saws and trimmers and also in equipment like lawn movers are quite simple, and therefore the specific emissions are extremely high compared for example with modern catalyst equipped gasoline cars. The emissions from small gasoline engines can be reduced by improving fuel quality and also by applying simple exhaust aftertreatment systems. People using these engines are normally subjected to the exhaust fumes. Therefore there is also in this case a clear concern for occupational safety.

The main objective of this project was to produce a document on the effects of fuel quality and exhaust gas aftertreatment on emissions from non-road machinery, both diesel and gasoline powered engines. On the international level, new emission regulations and fuel specifications for non-road machinery are under discussion. It is in the interest of the international community to stimulate a positive development in the reduction of emissions also from non-road machinery.

In this project measurements were done with small gasoline engines and with diesel engines designed for non-road machinery. Engines were tested with different fuels and with and without catalyst. The main fuel variables were sulphur and aromatics contents. With the diesel engines, also one fuel containing two different amounts of bio component (RME) was evaluated. Tests were carried out at VTT's and MTT's (Agrifood Research Finland, Agricultural Engineering Research) facilities in Vihti, Finland.

2 SMALL GASOLINE ENGINES

2.1 TEST PROCEDURES AND MEASUREMENT EQUIPMENT

The small gasoline engine measurements were carried out in MTT's facilities. A two-stroke chain saw engine and a four-stroke OHV engine were measured. Measurements were done according to the ISO 8178 standard. The ISO 8178 cycle G3 (Figure 1) was used for the two-stroke engine and cycle G2 (Figure 2) was used for the four-stroke engine. For the measurements with the two-stroke engine, the mode length was set at four minutes. The weighting factors were 0.9 for 100 % mode and 0.1 for idle mode. An exception to this was made in measurements with biodegradable lubrication oil, as the length of the first mode was shortened to 3 minutes 30 seconds due to overheating problems. In four-stroke engine measurements the length of each mode was 3 minutes. The weighting factors of four-stroke measurement cycle are presented in Figure 2.

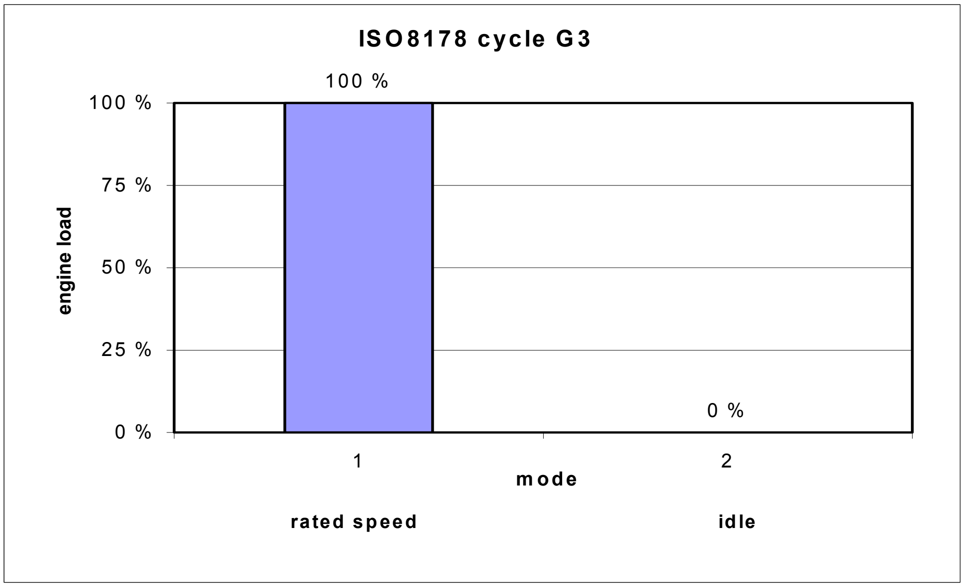
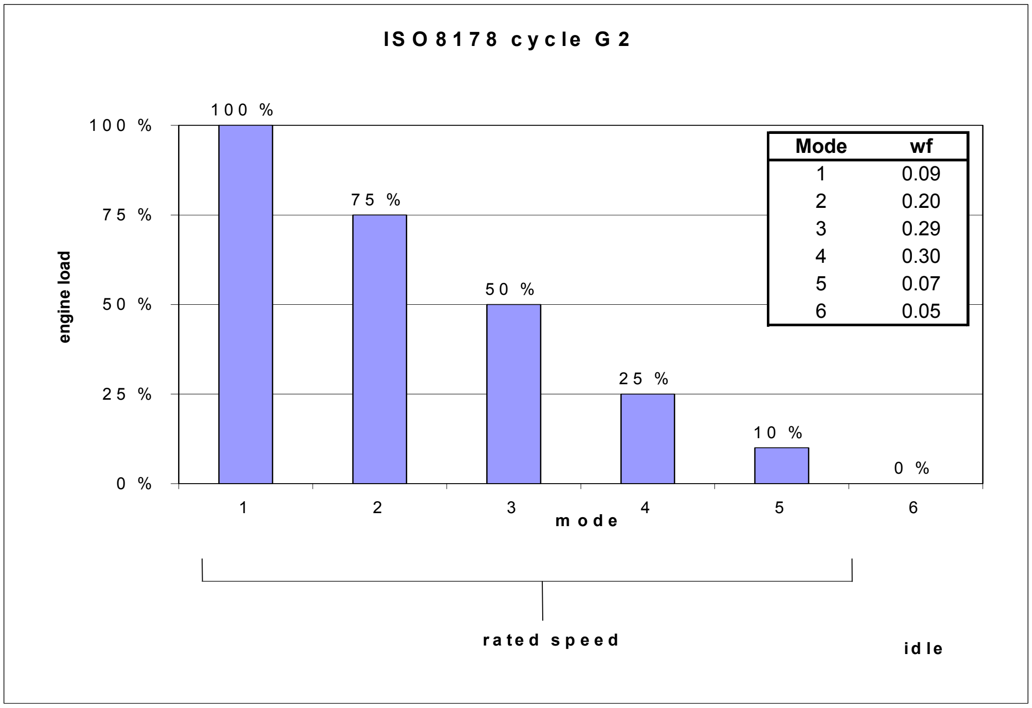


Figure 1. Measurement cycle for the two-stroke chain saw engine.



Mode	wf
1	0.09
2	0.20
3	0.29
4	0.30
5	0.07
6	0.05

Figure 2. Measurement cycle for the four-stroke engine.

The measuring equipment consists of gas analysers, a full-flow dilution tunnel and a particle matter sampling system. For the two-stroke engine an eddy-current dynamometer (Vibro-Meter 2 WB-65, 12 kW) was used, and for the four-stroke engine a hydraulic dynamometer (Stuska Model 90, 40 kW) was used. The total system conforms to standard ISO 8178. Gaseous emissions were measured from raw exhaust gas. Total hydrocarbons (HC) were measured on wet basis with a heated flame ionisation detector (HFID). Other gases were measured on dry basis. Carbon monoxide (CO) and carbon dioxide (CO_2) were measured with a NDIR absorption analyser, oxides of nitrogen (NO_x) with a CLD and oxygen (O_2) with PMD detector. The particle mass samples were collected from the dilution tunnel. Particle mass was collected on one 142 mm Pallflex T60A20 filter over the test cycle. Sample collection times were adjusted to take into account the weighting factors for each load mode. The fuel was fed into carburettor from a separate tank placed on an automatic scale. The scale was connected to a computer, and the fuel consumption was monitored. Figure 3 shows the measurement arrangement for the small engine measurements.

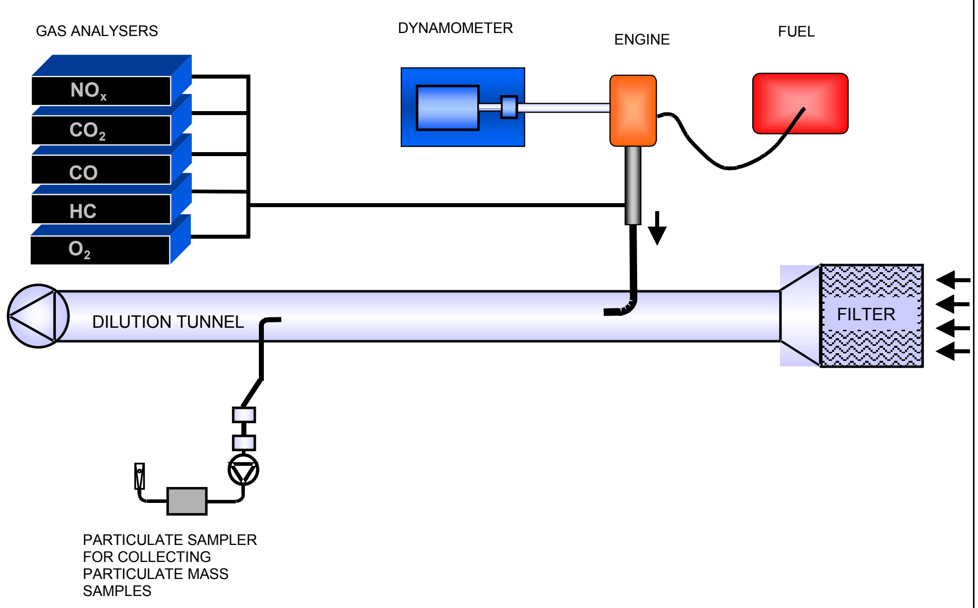


Figure 3. The measurement system for small gasoline engines.

2.2 FUELS

Three different fuels were selected for the test runs with the small gasoline engines. Gasoline fulfilling EU year 2000 specifications was selected as the baseline fuel. The other fuels evaluated were especially designed for small engines. Both were alkylate gasolines with low sulphur content and low aromatics. One contained an oxygenated component (ETBE), one was a pure hydrocarbon fuel. The selected baseline fuel has a high-octane number (RON98/MON87) because a high performance chain saw does not work properly if the MON value of the gasoline is too low. SEG has naturally a high MON value, so the RON value of that fuel is lower compared to EUG2000. The fuel specifications are presented in Table 1. All fuels were supplied by Fortum Oil & Gas Oy.

In the two-stroke engine the oxygenated gasoline was also tested in combination with a biodegradable lubrication oil.

The following acronyms for the test fuels are used in this report:

- EUG2000, gasoline fulfilling the EU year 2000 specifications
- SEG, special alkylate gasoline for small engines, commercially available
- SEGO, special alkylate gasoline for small engines with oxygenate

Table 1. Fuel specifications for the small gasoline engines.

Gasoline		
EUG2000	RON/MON	98/87
	Sulphur content	109 mg/kg
	Aromatics	44 vol-%[1)]
	Vapour pressure	74 kPa [2)]
	Oxygen content	0.0 wt-%
SEG	RON/MON	95/92
	Sulphur content	< 1.0 mg/kg
	Aromatics	0 vol-%
	Vapour pressure	56 kPa
SEGO	RON/MON	99/94
	Sulphur content	< 1.0 mg/kg
	Aromatics	0 vol-%
	Vapour pressure	54 kPa
	Oxygen content	2.0 wt-%
	Oxygenate content	12.9 wt-%

1) Slightly over the EU2000 requirement of < 42 vol-%

2) Slightly over the EU summer grade requirement of < 70 kPa (for EU Member States with arctic or severe winter conditions)

2.3 TWO-STROKE ENGINE

The engine used in measurements was from a commercially available chain saw. The engine fits into the size class of 50-60 cm^3. The engine was adjusted as recommended by the engine manufacturer. The adjustments were made with EUG2000 fuel. The adjustments of the engine were kept constant over the measurement period.

The changes in back pressure with and without catalyst were eliminated by using uncoated catalytic plate with the original silencer, so the flow resistant with noncatalytic silencer and catalytic silencer was the same.

2.3.1 Measurement matrix

The small two-stroke gasoline engine was measured with three different fuels. Each of these fuels was measured with and without a platetype catalytic converter. The precious metals in catalyst were Pt, Pd and Rh and the precious metal loading was 0,36 mg/cm^2.

Each fuel/engine/catalyst combination was measured at least three times to ensure reliability of the measurements. The SEGO fuel was run both with conventional and biodegradable lubrication oil.

With each fuel the regulated emissions and some unregulated emissions were measured. Table 2 presents the measurement matrix.

Table 2. Measurement matrix for the small 2-stroke engine.

Fuel	**Regulated**	**Aftertreatment**
EUG2000	CO, HC, NO$_x$, PM	no
SEG	CO, HC, NO$_x$, PM	no
SEGO	CO, HC, NO$_x$, PM	no
EUG2000	CO, HC, NO$_x$, PM	catalyst
SEG	CO, HC, NO$_x$, PM	catalyst
SEGO	CO, HC, NO$_x$, PM	catalyst
SEGO+biolube	CO, HC, NO$_x$, PM	catalyst
SEGO+biolube	CO, HC, NO$_x$, PM	no

2.3.2 Regulated emission results

Fuel quality had a clear effect on the NO$_x$ emission levels. Without catalyst the NO$_x$ emissions were at maximum with EUG2000 whereas SEGO + biolube gave the lowest NO$_x$ emissions. The trend was similar both with and without catalyst. NO$_x$ emission levels were lower with catalyst than without catalyst. The conversion rate of the catalyst was between 25 and 35 %. The results are presented in Figure 4.

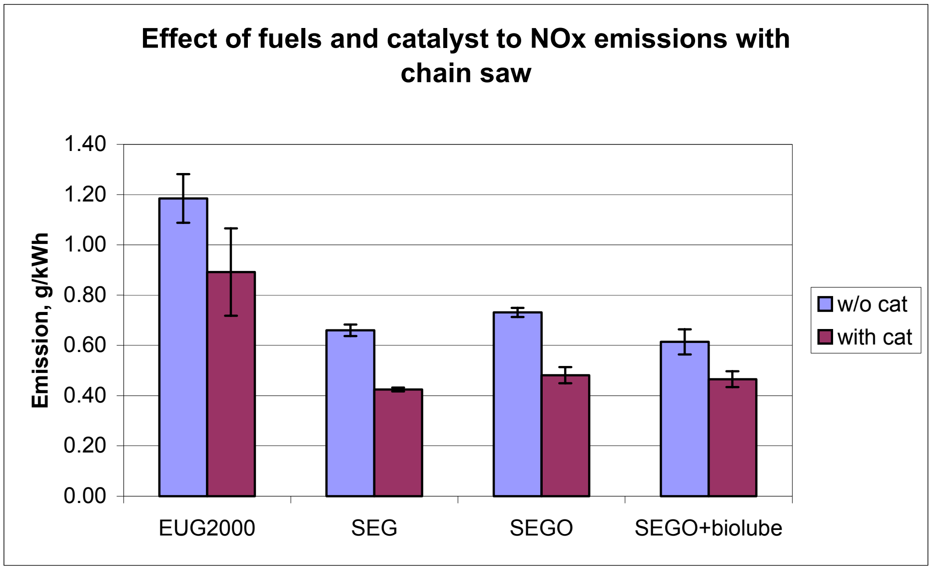


Figure 4. NO_x emissions from the chain saw engine.

In general, CO and HC emissions from two-stoke engines are very high, partly because the air/fuel mixture is below stoichiometric ratio and partly due to scavenging losses. The CO emission did not vary much from fuel to fuel (Figure 5). With catalyst the difference between the worst (SEG) and the best (EUG2000) fuel was 16 % and without catalyst 14 % (SEGO+biolube vs. SEGO).

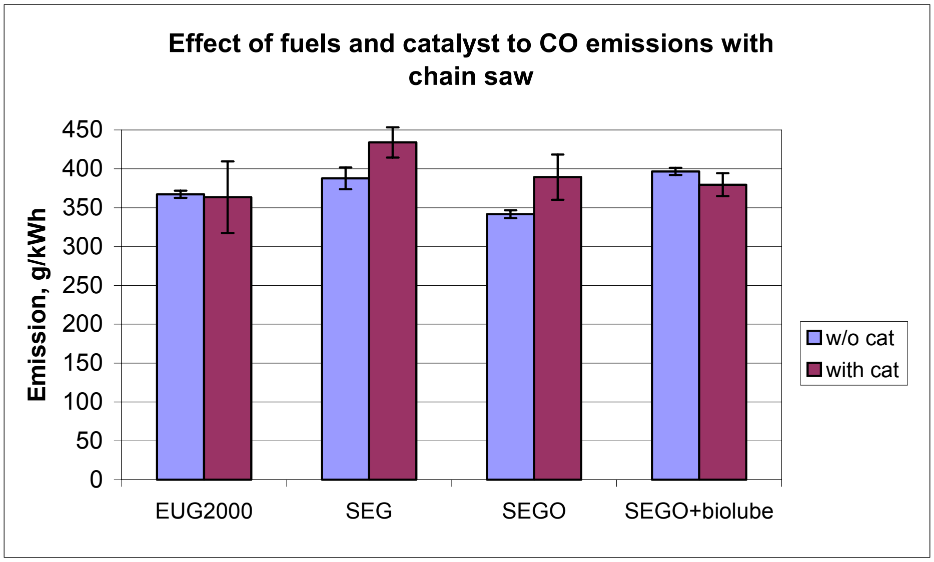


Figure 5. CO emissions from the chain saw engine.

The HC emission results show that a better quality fuel gives slightly lower HC emissions. The best conversion ratio of the catalyst was only 13 % (EUG2000), so the catalyst had a limited effect on HC emission levels (Figure 6). The poor conversion ratios of the catalyst might be explained by variations of lambda values. For some reason, the lambda value was lower (mixture richer) in the measurements with catalyst than without catalyst and this could affect the level of gaseous emissions. Especially with the SEG fuel the lambda value ratio was very low. See Figure 7. Figure 7 also shows the lean-out effect of the ETBE addition.

It is difficult to say how much the changes in lambda affected the CO and HC results. Small engines typically use “rich” air/fuel mixture, and therefore a small change in lambda value could cause significant changes in CO and HC levels. The theoretical air demand values of the test fuels were different. This caused changes in lambda values from fuel to fuel, because the settings of the carburettor were kept constant over the measurement period. In real life the end-user adjusts the chain saw so, that it works properly. However, in our study it was decided to keep the settings constant with different fuels.

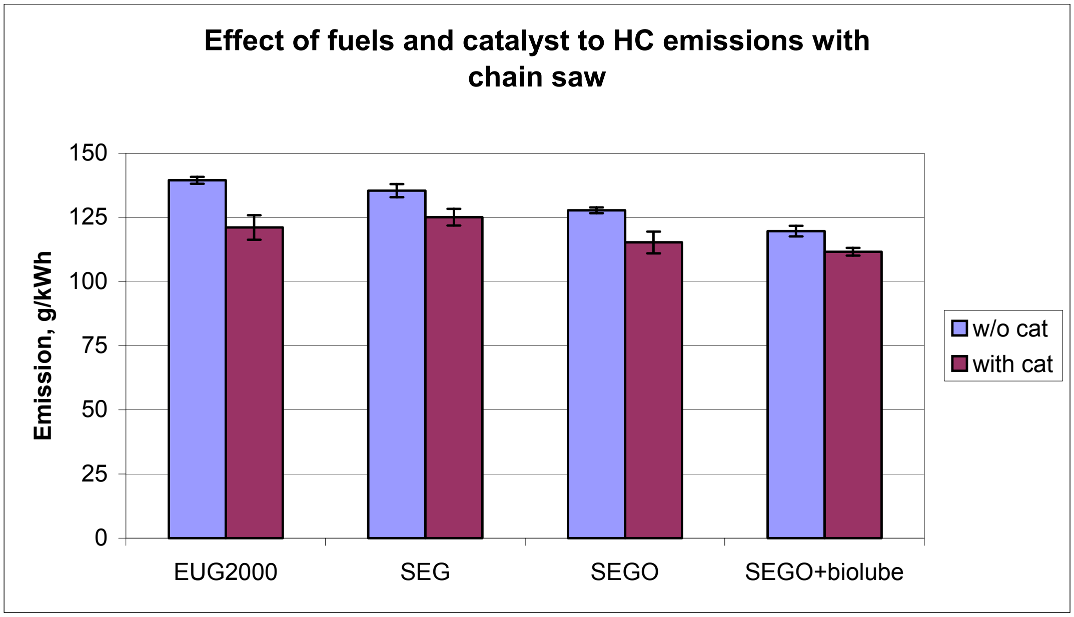


Figure 6. HC emissions from the chain saw engine.

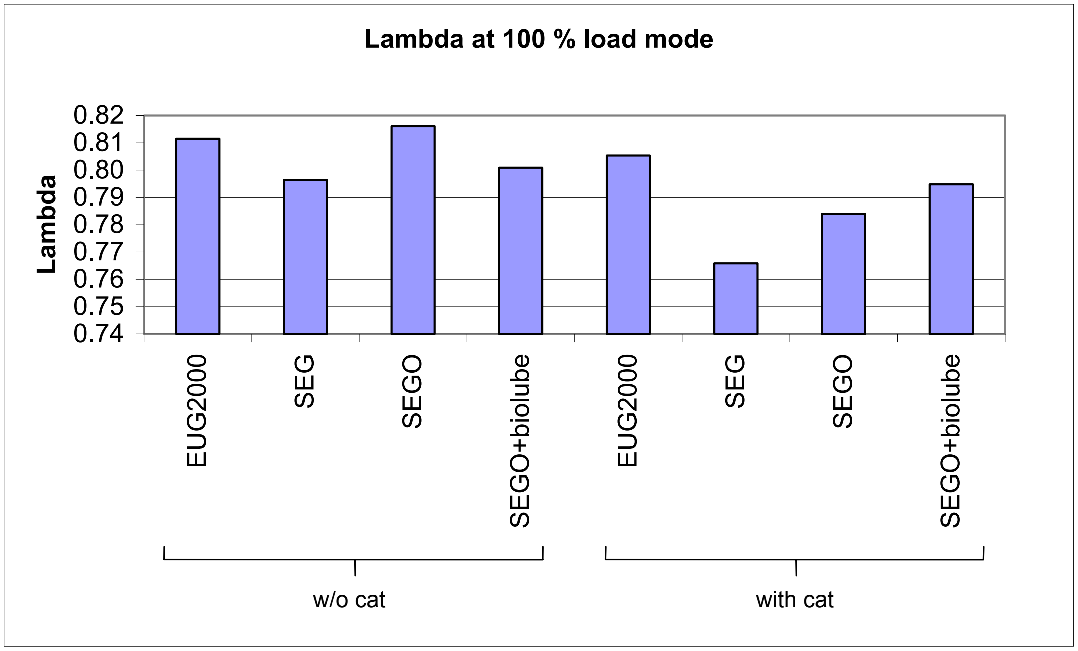


Figure 7. Variation in lambda values in measurements with the chain saw engine.

The particle mass emission was lowest with the SEGO fuel with catalyst, and highest with the EUG2000 fuel without catalyst (Figure 8), quite as anticipated. The EUG2000 fuel had the highest sulphur content, and this partly explains the results. It is also easy to notice that oxygenate added to the alkylate gasoline burned part of the particles, resulting in lower particle mass emissions. There was an indication that biodegradable lubrication oil in combination with catalyst produced a bit more particle mass than conventional lubrication oil.

With catalyst the emission levels were lower because the catalyst burned particles during the conversion of the gaseous components. However, the effect varied from fuel to fuel. The catalyst was especially efficient in combination with the oxygenated fuel. The result measured with the EUG2000 fuel in combination with catalyst does not follow the general trend that the catalyst reduces the particle mass emissions. The standard deviation of these three measurements was very high. The engine was running quite unstable during these three measurements, and this seemed to affect the particle mass emission. For this reason the result is not reliable.

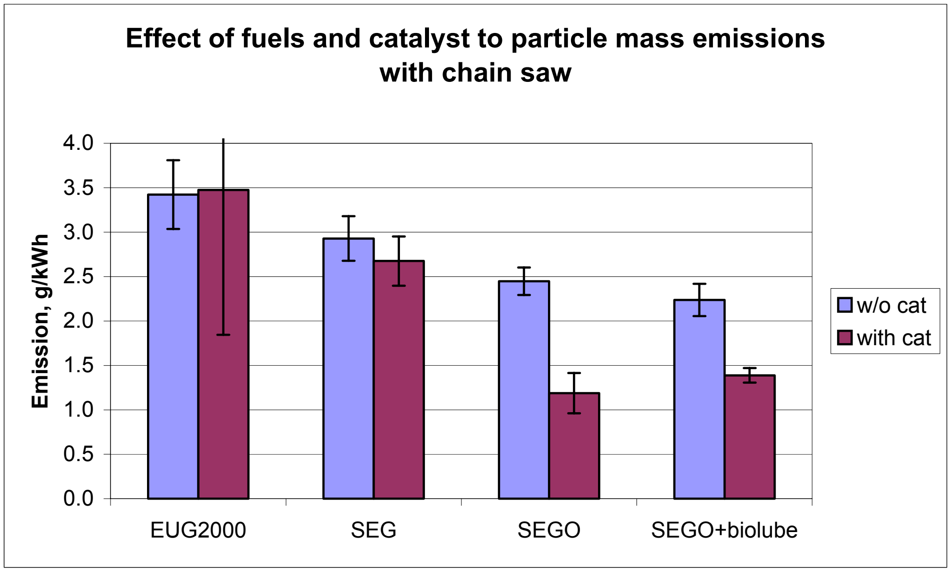


Figure 8. Particle mass emissions with different fuels with and without catalyst.

2.4 FOUR-STROKE ENGINE

The four-stroke engine selected for the measurements was a 190 cm^3 Briggs & Stratton OHV –type engine. This engine can be used in generator or lawn mover applications. The power output of the engine is 3.8 kW. The engine was tested with and without catalyst. The catalyst for this engine had an additional ejector-type air supply system. The precious metals in catalyst were Pt and Rh and the precious metal load was 40 g/ft^3. The cell density of the catalyst was 300 cpsi.

2.4.1 Measurement matrix

The small four-stroke gasoline engine was measured with three different fuels. Each fuel was measured with and without catalyst. Each fuel/engine/catalyst combination was measured at least three times to ensure reliability of measurements.

With each fuel the regulated emissions and some unregulated emissions were measured. Table 3 presents the measurement matrix.

Table 3. Measurement matrix for the 4-stroke engine.

Fuel	Regulated	Aftertreatment
EUG2000	CO, HC, NOx, PM	no
SEG	CO, HC, NOx, PM	no
SEGO	CO, HC, NOx, PM	no
SEG	CO, HC, NOx, PM	catalyst
SEGO	CO, HC, NOx, PM	catalyst
EUG2000	CO, HC, NOx, PM	catalyst

2.4.2 Regulated emission results

The lowest HC emission levels were obtained with SEGO. The difference between EUG2000 and SEGO without catalyst was 25 %. The catalyst turned out to be quite effective on the 4-stroke engine, and the conversion ratio of the catalyst varied from 75 % to 85 %depending on the fuel. Figure 9 presents the HC emission results measured with and without catalyst.

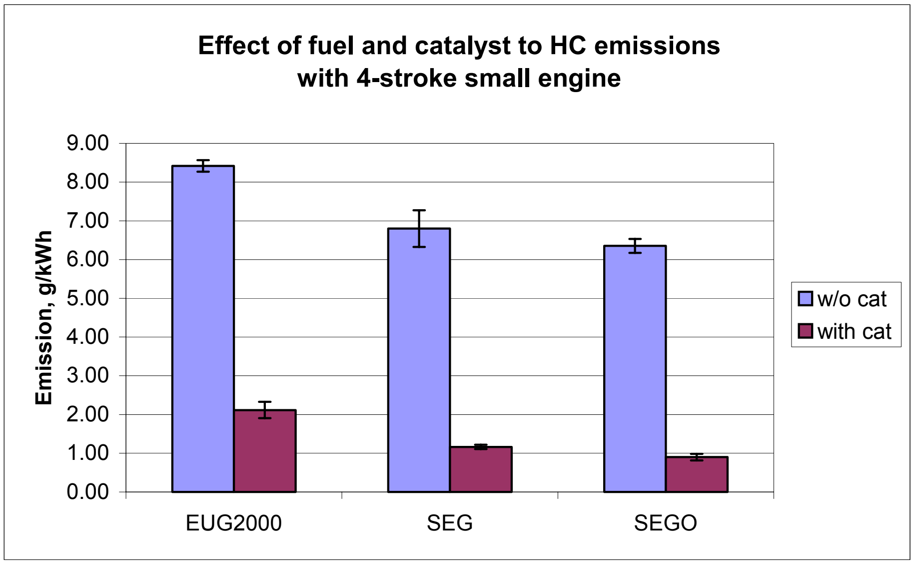


Figure 9. HC emissions from the four-stroke engine.

Figure 10 presents NO_x emissions from the four-stroke engine. The NO_x emissions were highest with EUG2000 and lowest with SEG. The difference between these fuels was 30 %. The catalyst was very effective, and the conversion ratio with every fuel was over 90 %.

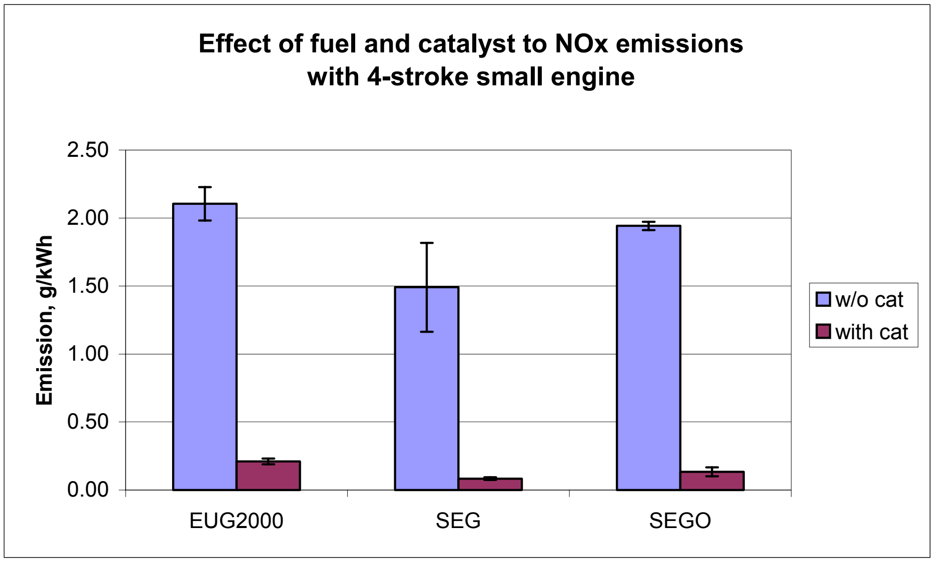


Figure 10. NO$_x$ emissions from the four-stroke engine.

Regarding fuel effects, the CO results are very similar to the HC results. The emission level with SEGO is around 15 % lower than with EUG2000. The catalyst was not working so efficiently for CO as for the other gaseous components, and the conversion ratio was between 45 % and 60 %. Figure 11 shows the CO results with different fuels measured with and without catalyst.

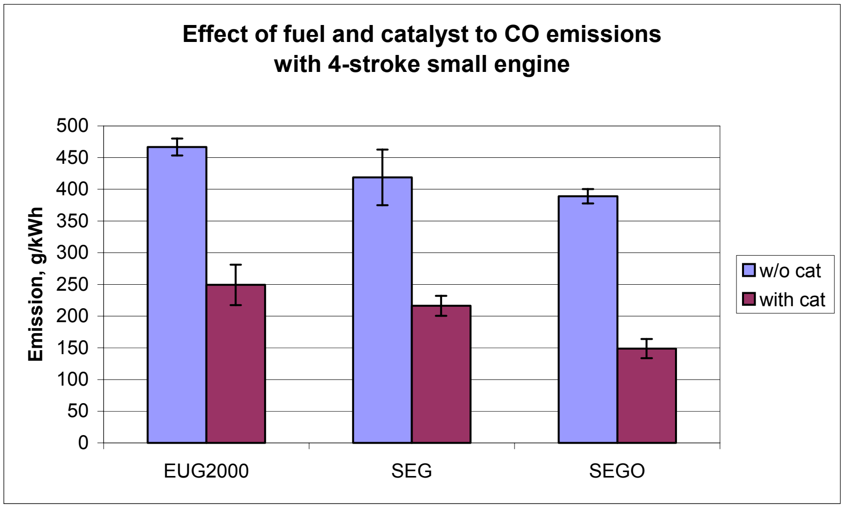


Figure 11. CO emissions from the four-stroke engine.

The particle emission levels were very low, as can be expected when measuring a four-stroke gasoline engine. Although the collection time and volume of samples was maximised, the collected masses were normally less than 1 mg over the cycle. Figure 12 shows that the standard deviation of the mass emission was rather high, partly due to low weight of the samples and partly to the accuracy of the sampling method. However, it seems that SEG and SEGO produce less particle mass than EUG2000. It is difficult to make any conclusions how the catalyst affects the particle mass because the differences are rather small with and without catalyst and the standard deviations are high.

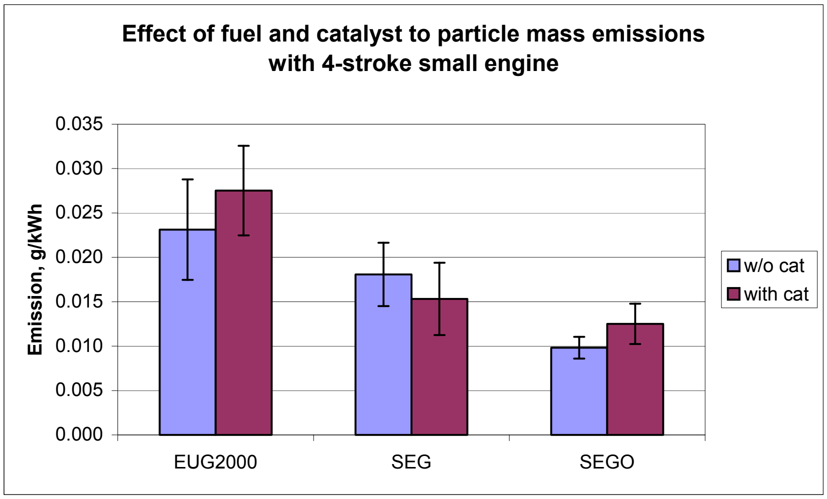


Figure 12. Particle mass emissions from the four-stroke engine.

Figures 13 and 14 present the differences on average emission levels measured from small gasoline engines. The presented values are averages of the results measured with different fuels.

CO emissions from both engines are high and the difference is relatively low (Figure 13). The HC emission level of the four-stroke engine is almost 20 times lower than the level of the two-stroke engine. The main reasons for high HC emissions from the two-stroke engine are scavenging loses and the fact, that the lubrication oil is mixed into the fuel.

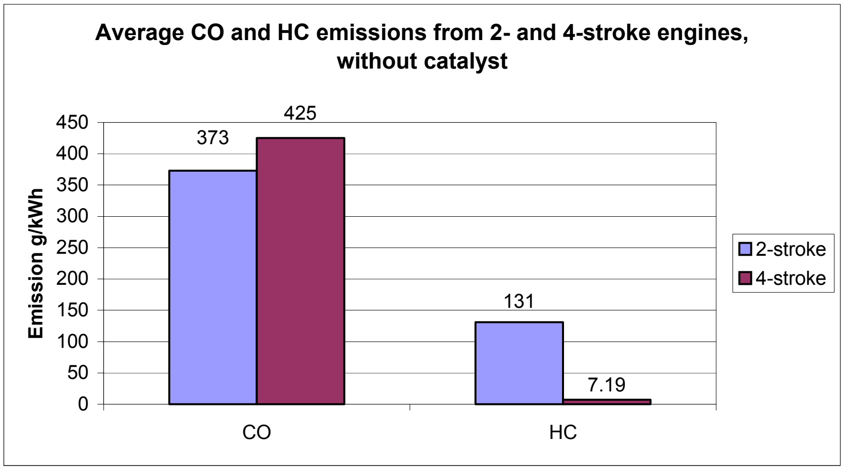


Figure 13. Average CO and HC emissions from two- and four-stroke engines.

Figure 14 presents NO_x and PM emissions from the mentioned engines. The four-stroke engine produces about two time higher NO_x emissions than the two-stroke engine. However the NO_x emissions from both engines are relatively low. The PM emission from the two-stroke engine is more than a hundred times higher than form the four-stroke engine. This can be explained by the unburned fuel and lubrication oil, in the two-stroke engine's exhaust gases.

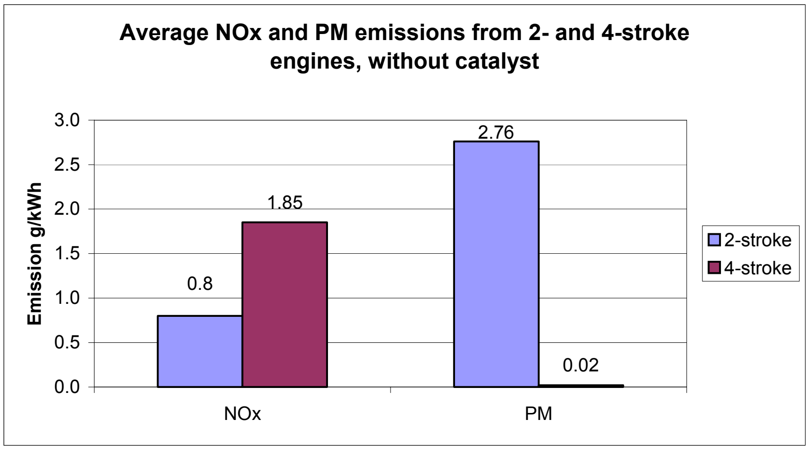


Figure 14. Average NO_x and PM emissions from two- and four-stroke engines.

2.5 SUMMARY

The results of small gasoline engine measurements indicate that a good quality fuel has a positive effect on engine exhaust emissions. Regarding NO_x and particle mass emissions, both engines gave lower results with SEG and SEGO fuels compared to EUG2000. With four-stroke engine, also CO and HC emissions were lower with the alkylate gasolines. In overall emission results the SEGO turned out to produce lower emission levels than SEG with both engines. With the two-stroke engine, the fuel did not have a clear effect on CO emissions, and also the changes in HC emission levels were relatively low. It is difficult to say how much the fluctuations in air/fuel ratio (the engine was not stable) affected the CO and HC results in the two-stroke engine measurements. Small engines typically use “rich” air/fuel mixture, and this is why a small change in air/fuel ratio could cause a significant change in CO and HC levels. The theoretical air demand depends on the fuel composition. When, for example, substituting SEG with SEGO using fixed carburettor settings, the mixture is leaned out due to the oxygen content of the fuel. However, in the measurements the performance of the engine itself varied so much that it obscured the differences between the fuels.

The sulphur content of fuel seemed to be the main factor, which affected the particle mass emission from these engines. EUG2000, which had the highest sulphur content, also gave the highest particle mass emissions with both engines. The particle mass emissions were very high from the two-stroke engine and very low from the four-stroke engine. For the two-stroke engine, the greater part of the particle mass is made up of heavy unburned hydrocarbons originating from the lubricating oil.

The two-stroke engine, when operated with catalyst, basically gave lower emissions than without catalyst, although the reductions in emission levels were lower than expected probably due to variations in lambda values. The CO levels were a bit higher with SEG and SEGO compared to EUG2000, but this could be due to the lower lambda value. SEG with catalyst gave the lowest NO_x emissions, whereas SEGO with catalyst gave clearly the lowest particle mass emissions.

The catalyst (with air injection) for the four-stroke engine turned out to be very efficient. The conversion ratio of the catalyst was at lowest with CO (45-60 %) and at highest with NO_x (>90 %). The effect of the catalyst on particle emissions was close to zero.

3 DIESEL ENGINES

3.1 TEST PROCEDURES AND MEASUREMENT EQUIPMENT

The diesel engines were tested for regulated exhaust emissions at VTT according to the ISO 8178 C1 test procedure. During the test cycle the engine is driven at rated and intermediate speed on different engine load levels. The last mode of a total of eight modes is idling. Figure 15 presents the test cycle. In addition to the regulated exhaust emissions, some unregulated emissions were measured.

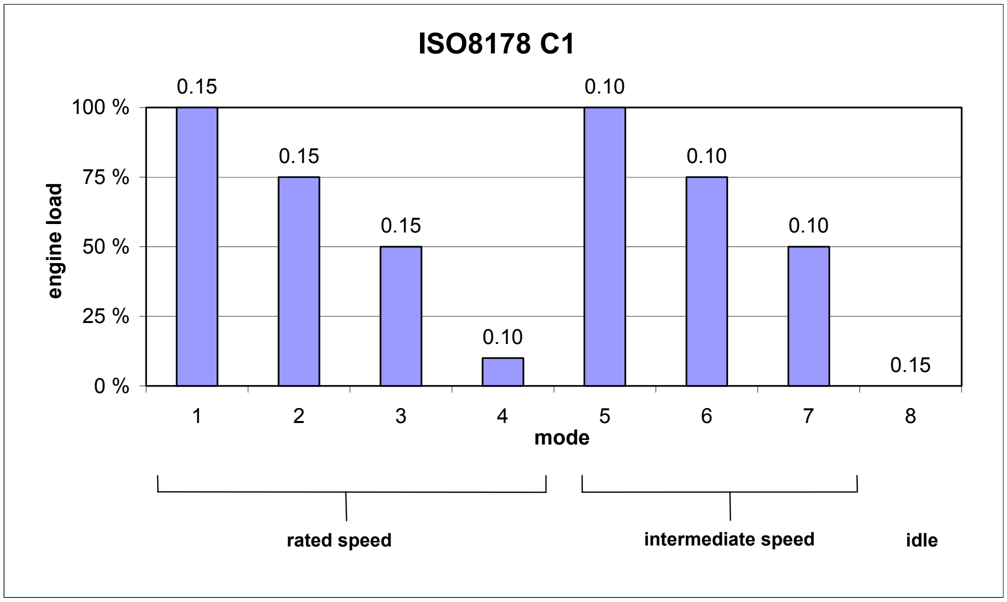


Figure 15. Cycle for diesel engine emission measurements. Weighting factors of modes are marked above the columns.

All equipment used for measuring the regulated emissions (CO, HC, NO_x and particle) conform to the specifications for measurement systems given in standard ISO8178. The equipment used in the tests is presented in Table 4.

Table 4. Equipment used in the tests at VTT.

Equipment/function	**Manufacturer/type**	**Remarks**
engine dynamometer	Zöllner B-300	eddy-current, 260 kW
dyno control & data acquisition	AVL Puma Test Assistant 5	
regulated emissions	BOO Instrument	
particle sampler	AVL MDT 474	mini-dilution tunnel
particle filter papers	Pallflex TX40HI20WW70	∅ 70 mm

An eddy-current engine dynamometer by Zöllner and a "PUMA Test Assistant" control system by AVL were used for running and controlling the test engine. The regulated gaseous emissions were measured from raw exhaust gas with an analyser system by BOO Instrument AB. The system includes analysers from different manufacturers (Table 5). The fuel consumption was measured with an AVL 733S fuel balance.

Table 5. Analysers used for gaseous emission measurements

Gas	**Manufacturer**	**Model**	**Principle**
CO	Maihak	Unor 610	NDIR
CO_2	Maihak	Unor 610	NDIR
NO_x	Ecophysics	700 ELHT	HCLD
HC	J.U.M. Engineering	JUM109A	HFID

Particle mass samples were collected using an AVL Mini Dilution Tunnel 474. The samples were collected on ∅ 70 mm Pallflex TX40HI20WW filters. Filter smoke number (FSN) was measured with an AVL 415 SmokeMeter.

3.2 FUELS

The diesel engines were tested with five different fuels. Three base fuel qualities were selected: fuel corresponding to today's minimum requirements for non-road fuels, a current on-road diesel fuel and a fuel corresponding to the requirements for on-road diesel fuel in the future. The main fuel variables were sulphur, aromatics and polyaromatics (Table 6). As the use of biocomponents is in general interest, also two blends with biodiesel (RME) were studied.

The selected fuels were:

- LFO, light fuel oil, S ≅ 2000 mg/kg
- EUD2000, automotive diesel fulfilling the EU year 2000 specifications, S < 350 mg/kg
- EUD2005, reformulated high quality automotive diesel, S < 50 mg/kg
- BIO5, mixture of EUD2005 and RME, RME ratio 5 vol-%
- BIO30, mixture of EUD2005 and RME, RME ratio 30 vol-%

Table 6. The specifications of fuels used in the diesel engine measurements.

Property	**LFO**	**EUD2000**	**EUD2005**	**BIO5**	**BIO30**
Sulphur, mg/kg	1860	293	35	33	25
Density 15 °C, kg/m^3	858.7	849.8 1)	835.5	837.9	849.3
Viscosity 40 °C, mm^2/s	3.61	3.42	3.10	3.03	3.34
Cetane number	52.4	51.6	57.0	54.6	53.3
Total aromatics, vol-%	36.4	25.7	19.2	< 19.2	< 19.2
Polyaromatics (Di+Tri+), wt-%	6.8	5.1 2)	1.9	< 1.9	< 1.9

1) slightly over the EU2000 requirement of < 845 kg/m^3

2) unit of the value is vol-%

In the EU Stage 2 engine LFO gave the highest power and torque values. With Bio30 the power and torque values were at lowest, but the difference to LFO was 4,3 % at rated power and 3,2 % at maximum torque.

3.3 PRE-EU STAGE 1 EMISSION LEVEL ENGINE

The selected engine (MY 1985) represents old non-road diesel engine technology. However, for its time the engine was modern, as it is turbocharged. The reason to include this kind of engine was that similar engines are still common in use, due to the long life span of diesel engines in work machinery applications. Table 7 presents the specifications of the engine.

Table 7. Specifications of pre-EU Stage 1 engine.

Engine manufacturer	Valmet
Engine type	411 DS, year model 1985
Number of cylinders	Four
Displacement	4.4 litre
Power output	70 kW at 2200 rpm, 375 Nm at 1450 rpm
Injection pump	Mechanical in-line pump
Compression ratio	16:1
Combustion system	direct injection, turbocharged

3.3.1 Measurement matrix

Five different fuels were tested in the engine. With each fuel at least three tests were carried out to ensure the reliability of the results. The regulated emissions and some unregulated emissions were measured in all tests. Table 8 presents the measurement matrix.

Table 8. Measurement matrix for the pre-EU Stage 1 engine.

Fuel	Regulated	Aftertreatment
LFO	CO, HC, NOx, PM	no
EUD2000	CO, HC, NOx, PM	no
EUD2005	CO, HC, NOx, PM	no
Bio5	CO, HC, NOx, PM	no
Bio30	CO, HC, NOx, PM	no

3.3.2 Regulated emission results

Figure 16 presents the gaseous emissions from the pre-EU Stage 1 engine with different fuels. The CO and HC emissions are presented multiplied by a factor of 10. The differences between fuels are relatively low. There was some drifting in the performance of the engine itself over the measurement period (Figure 17). For this reason, the fuel effects on CO and NO_x emissions are not significant. With Bio30 fuel the HC result is some 10 % lower than with LFO.

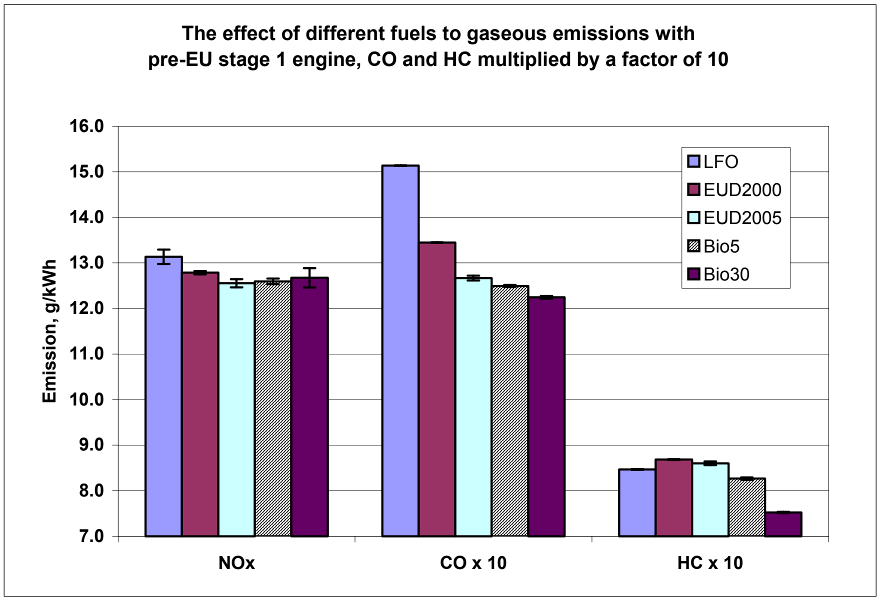


Figure 16. The regulated gaseous emissions with the pre-EU Stage 1 engine, CO and HC multiplied by a factor of 10.

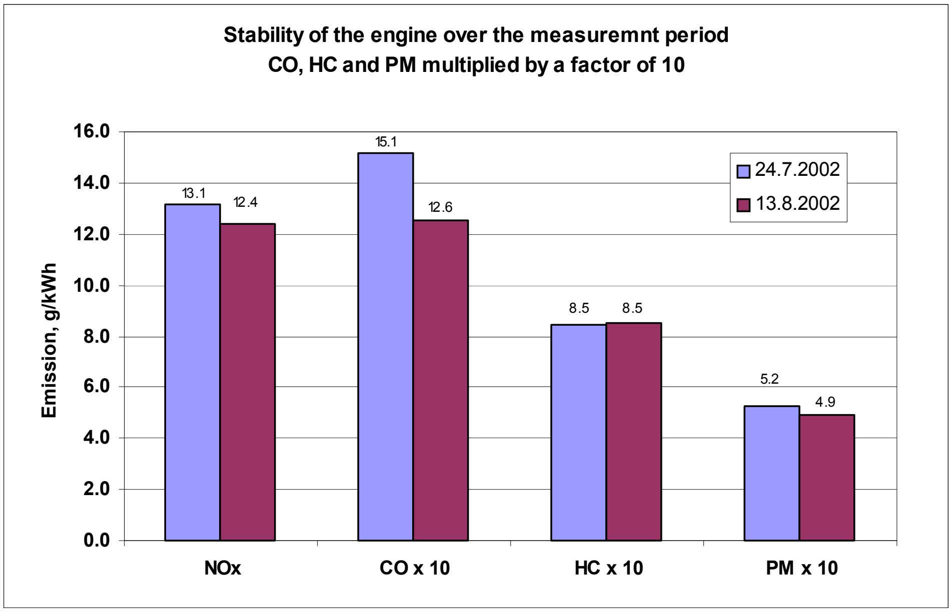


Figure 17. Engine stability over the measurement period measured with LFO.

The fuel quality has a clear effect to the particle mass emissions. The emission level is highest with LFO and lowest with Bio5 fuel (Figure 18). The difference between these fuels is some 30 %. The particle mass emission starts to increase with Bio30 fuel compared to Bio5 fuel, so with this engine optimum RME content is something between 5 and 30 %. It seems that the sulphur content of the fuel correlates with the particle mass emissions.

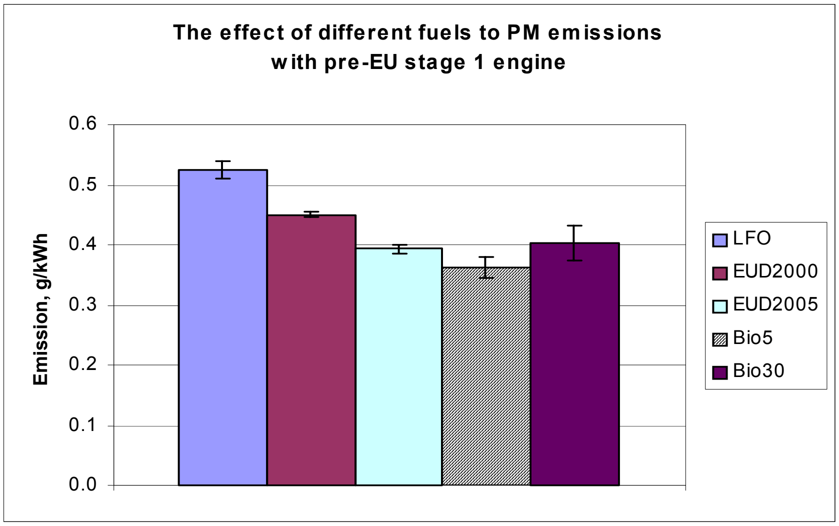


Figure 18. The particle mass emissions with pre-EU stage 1 engine.

3.4 EU STAGE 2 EMISSION LEVEL ENGINE

The selected engine represents "up to date" non-road diesel engine technology. The engine is designed to meet EU Stage 2 emission levels, which came into effect in the year 2002. The specifications of the engine are presented in Table 9.

Table 9. The specifications of the EU Stage 2 engine.

Engine manufacturer	Sisu Diesel
Engine type	44 EWA, model year 2002
Number of cylinders	Four
Displacement	4.4 litre
Power output	104 kW at 2200 rpm, 565 Nm at 1500 rpm
Injection pump	Electrically controlled electric rotary pump
Compression ratio	18,5:1
Combustion system	direct injection, turbocharged, intercooled

3.4.1 Measurement matrix

Five different fuels were tested in the new engine. Some fuels were also tested in combination with an oxidation catalyst. With each fuel/aftertreatment combination at least three tests were carried out to ensure the reliability of the results. The regulated emissions, and some unregulated emissions were measured during each test. Table 10 presents the measurement matrix.

The measurements with oxidation catalyst were done with fuels EUD2005 and BIO30. The oxidation catalyst used with the engine was manufactured by Kemira Metalkat Oy. The precious metals used were Pt, Pd and Rh, and the precious metal loading was 1.41 g/dm^3. The volume of the catalyst was 2.31 dm^3 and the cell density was 300 cpi.

Table 10. The measurement matrix for the EU Stage 2 engine.

Fuel	**Regulated**	**Aftertreatment**
Bio5	CO, HC, NOx, PM	no
LFO	CO, HC, NOx, PM	no
EUD2000	CO, HC, NOx, PM	no
EUD2005	CO, HC, NOx, PM	no
Bio30	CO, HC, NOx, PM	no
Bio30	CO, HC, NOx, PM	oxidation catalyst
EUD2005	CO, HC, NOx, PM	oxidation catalyst

3.4.2 Regulated emission results

Over the measurement period, the engine has stayed quite stable. The biggest drift (11 %) was with HC. For the other measured components the drift was less than 5 %. Figure 19 presents the changes in emissions over the measurement period. Bio5 fuel was used as reference fuel when evaluating engine stability.

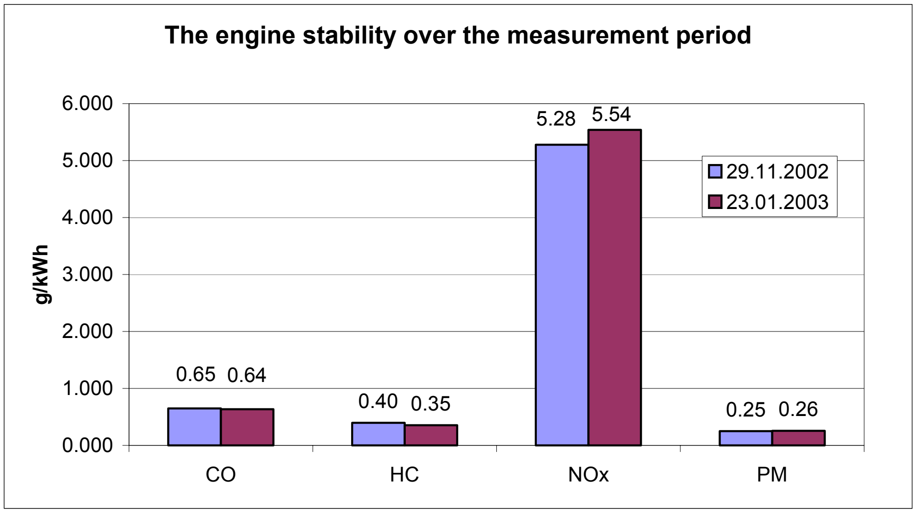


Figure 19. Engine stability over the measurement period (Bio5).

The fuel effect on gaseous emission was generally only marginal. What is worth noting is that EUD2005 and Bio5 produced some 10 % less NO_x than LFO. Like in the case of the pre-EU Stage 1 engine, the Bio30 fuel produced less HC than the other fuels. The difference to LFO was some 25 %. Figure 20 presents the emission results of the Stage 2 engine.

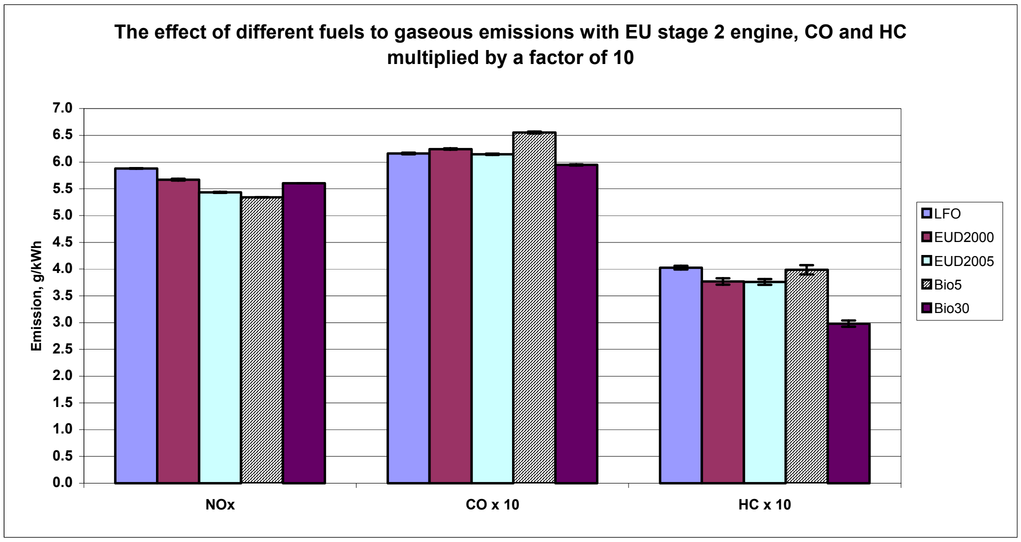


Figure 20. The regulated gaseous emissions with EU Stage 2 engine, CO and HC multiplied by a factor of 10.

As expected, particle mass emissions were highest with LFO. Compared to LFO, EUD2000, EUD2005 and Bio5 all reduced particle mass emissions some 25 %. With a clear margin Bio30 fuel produced the lowest mass emissions, some 40 % lower than with LFO. Figure 21 presents the emission results.

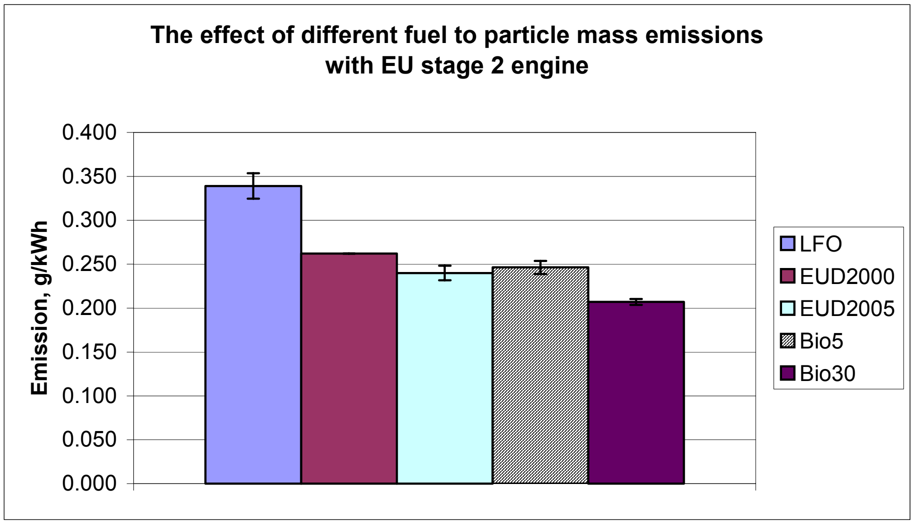


Figure 21. Particle mass emissions with EU stage 2 engine.

It is well known that an oxidation catalyst cuts down CO and HC emissions (Figure 22). In this case the reduction in CO was some 85 % (Bio30 and EUD2005). HC dropped some 60 %. The catalyst did not affect the NO_x emissions. Also the changes in particle mass emission were low. With EUD2005 there was no detectable changes with the catalyst, and with Bio30 the catalyst decreased particle mass emission by 7 %. With an older engine, with higher PM emissions and “wet” particles, the catalyst might have been more effective for PM reductions.

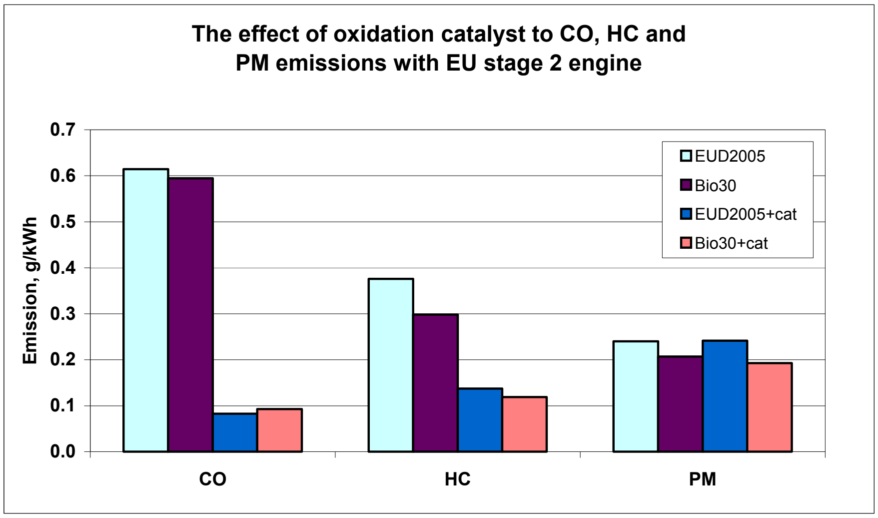


Figure 22. The effect of the oxidation catalyst on CO, HC and PM emissions.

Figure 23 presents the differences on average emission levels measured from diesel engines with five different fuels. It gives an indication how the engine technology has reduced exhaust emissions. The gaseous emission levels are at least two times higher with the pre-EU Stage 1 engine than with the EU Stage 2 engine. The reduction in particle mass emissions is some 40 %.

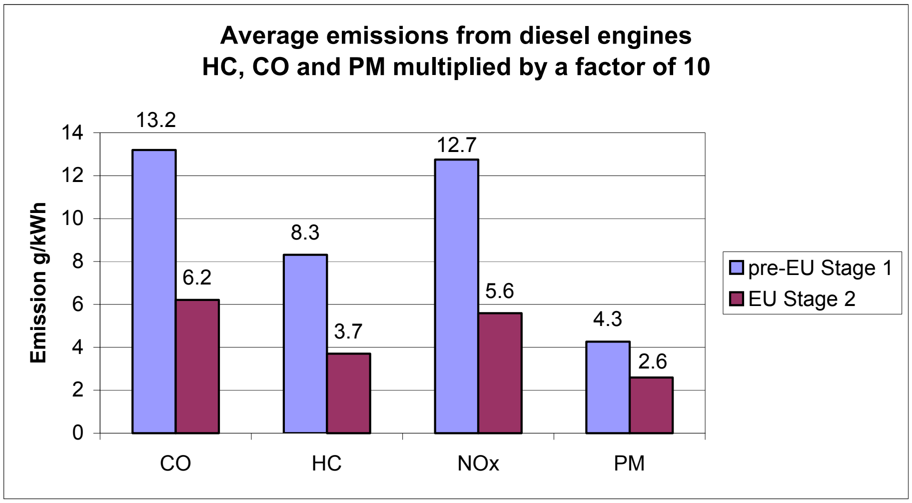


Figure 23. Average emissions from diesel engines HC, CO and PM multiplied by a factor of 10.

3.5 SUMMARY

The main concerns regarding diesel engine emissions are particles and NO_x. Also health effects of particles are gaining more attention. This study gives quite a clear testimony that it is possible to reduce particle emissions from non-road diesel engines by improving fuel quality, whether the engine is old or "up-to-date". The fuel effects on gaseous emissions are marginal with both engines tested. On the other hand, the effect on particle mass emissions is obvious. The main factor, which seems to affect the particulate emissions, is sulphur content of the fuel. In addition it can be noted that the polyaromatics content of fuel plays an important role when the health effects of particles are taken into account.

With the pre-EU Stage 1 engine the particle mass emission reduction was highest (30 %) with Bio5 compared to LFO. LFO produced the highest mass emissions. With the EU Stage 2 engine the difference between best and worst fuel (Bio30 vs. LFO) was as much as 40 %.

The oxidation catalyst tested on the EU-Stage 2 engine was very efficient. The conversion rate for CO was 85 % (Bio30, EUD2005) and 60 % for HC. The catalyst did not have a significant effect on the particle mass or NO_x emissions.

4 CONCLUSIONS AND DISCUSSION

This project has shown that fuel quality (e.g. low sulphur, low aromatics) makes a difference to the exhaust gas emissions from non-road engines. The results obtained with gasoline and diesel engines are encouraging. With small gasoline engines the fuel quality generally lowered all exhaust emission, although the reduction of gaseous emissions in some cases was relatively low. With the four-stroke gasoline engine the reductions in all emissions were obvious. The diesel engine results show that it is possible to achieve significant reductions in particle emissions by using a fuel with good quality. The use of catalyst turned out to be an efficient way to reduce emissions from these engines. The only exception was the two-stroke engine with catalyst. The results obtained with this combination were not as good as expected.

The design of small gasoline engines is very simple and that's why the specific emissions are high. The means for reducing exhaust emission by improving engine technology are limited, because this type of engines needs to be low-priced, reliable and light weighted. This study indicates that one easy way to reduce emissions is to use a fuel with good quality. When combining a good quality fuel and a catalyst, the outcome is generally the best.

A couple of observations regarding problems related to measurement procedures were made whilst running the small engines in laboratory conditions. As discussed, these engines use air/fuel –ratio lower than stoichiometric air/fuel –ratio. This means, that small changes in air/fuel –ratio can have a notable impact on HC and CO emission levels. If the theoretical air demand of fuels vary a lot, there is a possibility that the changes in air/fuel ratio over-rule or strengthen the effect of fuel on CO and HC emissions. This awakes a question: Should the engine adjustments be optimised for different fuels? And if constant adjustments are used, which should be the reference fuel for these settings? In general, small engines are very unstable, and this presents extra challenges to the measurements.

Today's non-road diesel engines require certain functional fuel properties, such as high cetane number, a good fuel lubricity etc. The legislation in many countries allows the use of low quality fuels in non-road machinery. This study has proven that it would be beneficial also from an environmental point of view to use fuels with good quality (meaning low sulphur, low aromatics etc.). One would suppose that also the engine manufacturers would benefit if better fuel qualities were to be used in non-road machinery. This would, for example, give more opportunities to get the engine's NO_x emissions lower without aftertreatment systems.

In the case of small two-stroke engines there is much room for improvement of emission performance. In the case of non-road diesel engines, adopting the existing engine technologies from on-road applications could be one way to decrease the emission levels. However, in this case high quality diesel fuel is needed. Combining advanced engine technology and low sulphur, low aromatics fuel would lead to the greatest emission benefits. If needed, low sulphur fuels also enables the use of exhaust gas aftertreatment devices.