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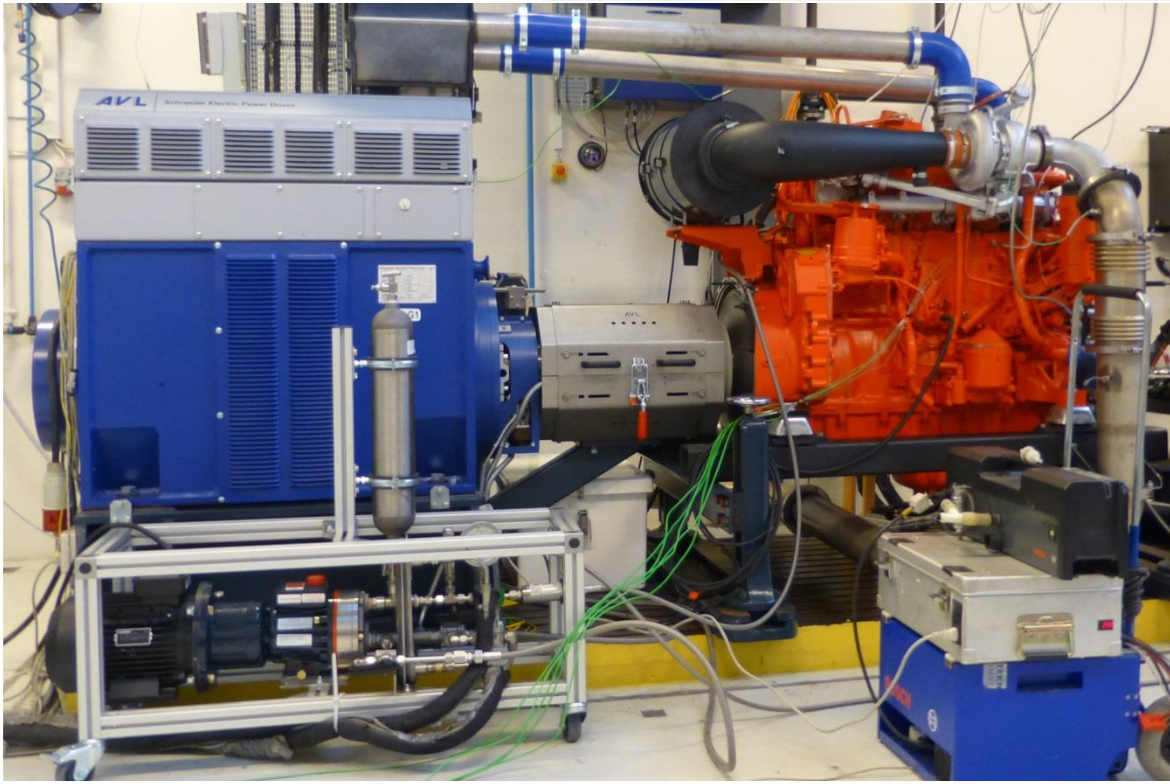
Testing of diesel fuel blends with methanol, ethanol and butanol



Prepared for the IEA AMF Annex 46:
Alcohol application in CI engines

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Summary

This report describes a comparative test of fuel blends with diesel and 10-30 % of methanol, ethanol and butanol. The engine has been run at 1500 rpm at 0, 25 and 50 % of its rated load.

In all tests, the injection timing was adjusted to maintain the same combustion timing for the fuel blends as the diesel reference, in order to minimize the effect of ignition delay on the formation of particulates. Since alcohols increase the ignition delay, neglecting this effect does not only result in increased smoke due to late combustion, but also substantially increased fuel consumption as well as difficulties with starting and running the engine unloaded.

Measurements on the particulate emissions has shown that the particulate number is reduced with increasing quantities of alcohol. The simplest alcohols ethanol and methanol gave the largest reductions, which where proportional to the fraction of alcohol in the blend. The best result was obtained with 20 % methanol and 10 % butanol as cosolvent. This blend reduced the particulate number up to 75 % in loaded operation, compared to the diesel reference. With 30 % ethanol, the reduction was up to 60 % in loaded operation. With 30 % butanol, a reduction of up to 40 % was found.

The gaseous emissions were found to be increasing with alcohol blends, but only in idle condition. The alcohol containing blends were found to increase emission of specific aldehydes, carbon monoxide and hydrocarbons. The higher cylinder and exhaust temperatures in loaded operation mean that the combustion is less sensitive to the fuel composition than at idle, and therefore only minor differences was found in loaded operation. The emission of nitrogen oxides was also affected, but no consistent increasing or decreasing trends were found.

Accurate measurements of the fuel consumption show that the brake thermal efficiency improves with increasing quantities of ethanol and methanol. Butanol does not appear to improve efficiency as significantly.

When preparing the diesel fuel blends, large differences in the miscibility of the three alcohols with diesel was clearly observable. Butanol could be blended into diesel without any visible separation or even discoloration. Ethanol did not form a homogeneous blend with cold diesel initially. After some circulation and heating of the blend, it eventually became clear even with 30 % ethanol. Methanol did not form a stable blend with diesel even when heated, but with the aid of butanol as cosolvent, a semi-stable blend was obtained, which in combination with a high circulation rate prevented the components from separating.

Background

The motivation for blending alcohol with diesel fuel is primarily to replace diesel as fuel, since this can help to reduce the increasing demand for diesel. An extra benefit is that the addition of oxygenated fuel can lead to a substantial reduction in the formation of particulate matter. The effect on the other undesired emissions in the exhaust such as nitric oxides, carbon monoxide and hydrocarbons is less well established, and therefore likely more dependent on the specific engine technology and operational conditions.

The use of diesel fuel blends with oxygenated components such as alcohols may be relevant in particular for older engines that do not comply with the newer standards for emissions. These engines are typically not equipped with advanced exhaust after treatment systems, which can reduce emissions of particulate matter and nitric oxides. Engines that are not built or adapted to comply with the strict road vehicle legislation are typically found in e.g. non-road machinery, railway locomotives, all sizes of marine engines and diesel generators. Emission from these engines are significant and sometimes the major sources of particulate matter and nitric oxides.

In many less developed countries, the legislation for emission control is either non-existing or not effective, due to the majority of vehicles and engines being old and poorly maintained. In these countries, the effect of blends with diesel and alcohols fuel could have a very large impact on the particulate emissions, as well as reducing the import of oil-derived diesel fuel while supporting local production of the alcohol required for the blends.

Methanol and ethanol are both inexpensive fuels that is widely used for blending with and even substituting gasoline. Blending these simple alcohols with diesel fuel is however more complicated, since such blends can separate in certain conditions such as low temperatures and presence of small quantities of water in the fuel. One approach to solving this problem is to produce emulsions of diesel and the alcohol, with the aid of surfactants. Such emulsions can be more stable at low temperatures and tolerant to water contamination, but can degrade at higher temperatures and may have a limited lifetime during storage. Emulsions are also complicated to produce, since the alcohol droplets are only few micrometers in diameter. Considering the effort required producing emulsions, blends may be a more attractive option as they can be prepared instantly when refueling a vehicle, and individual blend compositions may be available to the consumers depending on the climate, the engine configuration and other factors that may make a particular concentration of alcohol the best solution.

Outline of the experiment

The purpose of the test series presented in this report is to make a comparison of the emissions and combustion characteristics of the three alcohols methanol, ethanol and n-butanol, when used as minor fraction blending components with diesel. Standard diesel is also measured and used as reference.

The experiment was intended to test blends, which were prepared in batches with 10, 20 and 30 % alcohol by weight. This was performed with ethanol and butanol, while methanol was tested in combination with butanol at 10 % and 20 % concentrations, due to problems with obtaining a stable blend. A 30 % methanol blend was not tested, since it was clear that the fuel ignitability would become a problem during starting and idling.

The testing of the fuel blends was performed with a heavy-duty truck engine coupled to an engine dynamometer. The bench setup was operated at 1500 rpm at 0 %, 25 % and 50 % loads. Emissions and fuel consumption was measured when the engine had reached steady state.

The concentrations of gaseous and particulate emissions were measured with FTIR spectroscopy and a particle counter, respectively. The fuel consumption was measured with a precision scale.

Experimental setup

Fuel blends

	Fuel composition (in weight %)								
Diesel	90	80	70	90	80	70	90	85	70
Ethanol	10	20	30						
Butanol				10	20	30		5	10
Methanol							10	10	20
Name of blend	B10	B20	B30	E10	E20	E30	M10	M10 + B5	M20 + B10

Table 1: Composition of fuels in the test

Engine

The engine is a Scania model DC09 071A. It is a four stroke DI diesel with specifications as in table 1. The engine is equipped with turbocharger and intercooler.

Number of cylinder	5 in-line
Displacement	9.3 liters
Bore x stroke	130 x 140 mm
Compression ratio	16:1
Rated power and torque	226 kW and 1440 Nm @ 1500 RPM
Emission compliance	EU stage III a

Table 2: Engine specifications

The engine model is adapted for power generation at fixed speeds of 1500 or 1800 RPM. Due to the programming of the ECU being optimized for 1500 RPM, this speed was used for the test series.

The engine is connected to an AC dynamometer with a frequency controller, which controls the engine speed or torque as desired. It also measures the torque and power produced by the engine. Control of shaft torque was handled by the dynamometer, while the engine was operated in speed control mode. Since the dynamometer is limited to absorbing a torque of 700 Nm, the engine could only be tested at approximately half of the rated power.

ECU parameter control

The engine has previously been modified to run on experimental fuels. The original engine control unit has been replaced with a programmable MEDC 17 FLEX ECU unit from BOSCH, which allows full programmability and control of the parameters for injection. The ECU is monitored by a software named INCA on a remote laptop, from which injection parameters can be adjusted online.

The control for the EGR valve has not been implemented in the programmable ECU, so although present, the EGR is not used. The lack of EGR means that the intended suppression of NOx formation at idle and low load operation is not possible, and thus there is some potential for improving the emission performance obtained with the alcohol blends. It may also be possible to increase the inlet air temperature, such that the ignition delay is reduced. EGR is however only fitted on this particular engine model, whereas all models with higher power output, including the 6 and 8 cylinder versions, does not have EGR.

The control for the pneumatic waste gate control on the turbocharger waste gate has not been implemented in the ECU either. It is however not needed, since at medium load, the turbocharger does not reach the pressure at which the waste gate should be activated.

Injector technology

The engine is equipped with unit injectors (PDE). These injectors combine a pressure pump with a pressure activated injector nozzle in one unit. The injector pumps are driven by the camshaft in parallel with the valve train. Control of the nozzle opening is performed by closing a fuel bypass with a solenoid valve, thereby forcing the fuel through the injector nozzle.

The PDE injector technology, although a very reliable and cost-effective solution, may be considered outdated in a market where most road engines today are equipped with high-pressure common rail systems. It is however also engines with older injection technology and with little or no exhaust after treatment, that can benefit the most from new fuel formulations which can reduce emissions of particulate matter. In addition, older injector technologies is still being used in many applications where the precise control provided by the common rail is not required.

Injection timing

The timing of the injection is fully adjustable and can be changed while the engine is running. This was used to compensate for the longer ignition delay of the fuel blends with alcohol, such that the combustion took place at the same CAD for all fuels. After testing with diesel, it was decided to use the positions of peak heat release for premixed combustion in table 3.

	Idle	25 % load	50 % load
Start of injection CAD BTDC	11	12	12
Peak of premixed heat release CAD ATDC	10	5	3

Table 3: Injection timing and position of premixed heat release peak with standard diesel fuel

The injection angles that were initially chosen may be considered late for diesel, but the concern was that injection angles would become too advanced with the low cetane blends, particularly those containing methanol. Table 4 displays the values for Start of Injection (SOI) that was used to compensate for the ignition delay.

SOI CAD BTDC	Diesel	B10	B20	B30	E10	E20	E30	M10	M10 + B5	M20 + B10
Idle	11	12	12	13,5	11	15	18	11	13	20
25 %	12	12	13	15	12	14	17,5	12	14	17
50 %	12	12	12	13	12	13	14,5	12	13	14

Table 4: Start of injection (SOI) with the various alcohol diesel blends.

By maintaining a fixed position of the premixed combustion, some effects on the emissions related to retardation of the combustion was avoided, such as increased particulate formation and reduced nitrogen oxide formation. A constant combustion timing also makes a comparison of the brake thermal efficiency more reasonable.

Fuel system

The original fuel system on the engine was used in combination with a 20-liter tank, which was placed on a precision scale.

The fuel system feeding the unit injectors is comprised of a low-pressure pump driven by the crankshaft, a fuel filter and a fuel rail that distributes fuel to the cylinder heads. A backpressure valve opening at 4.5 – 5 Bars directs fuel into the return line and back into the fuel tank. This system turned out to function well, since the fuel was subjected to both powerful circulation and heating, which helps to keep the alcohol from separating from the diesel.

Cylinder pressure measurements

Cylinder pressure is measured on one cylinder. This produces accurate information about the ignition delay as well as the shape and peak of the heat release curve. The peak of the premixed combustion is used to adjust timing, since this peak is the most consistent and visible part of the heat release curve which is displayed.

The pressure measurements contain valuable information regarding the timing and duration of the combustion. The influence of alcohols on the ignition delay is of particular importance in this study, as well as the influence on the premixed combustion.

Test procedure

Test scheme

All tests were performed at 1500 RPM. The engine loads tested were 0, 25 and 50 % for each fuel combination. In order to ensure that all measurements were performed consistently and without using the fuel batch, a time scheme was set up for the testing of each fuel combination.

Load [%]	Brake torque [Nm]	Brake power [kW]	Fuel cons. est. [kg/h]	Time at steady state [min]	Fuel cons. exp. [kg]
Initial warmup	0	0	5	30	2.5
0	0	0	4.4	15	1.1
25	350	55	15.6	10	2.6
50	700	110	22.6	10	3.8

Table 5: Time scheme for testing

All testing of each alcohol fuel was completed in one session. The engine was first started and warmed up with standard diesel. The sequence in table 5 was then completed with standard diesel to make a reference measurement. After completing the sequence, the engine was stopped and the first fuel blend with 10 % concentration of alcohol was prepared. The sequence was then run again with the fuel blend. This was repeated with increasing concentrations of 20 % and 30 % of the same alcohol, except for methanol where butanol was used as cosolvent.

After each run of the load sequence shown in table 5, the engine was allowed to idle for 5 minutes to cool the turbocharger, pistons and engine oil, before it was stopped. The engine was further cooled in the time it took for refueling to a new concentration, such that each measurement could start with conditioning the engine to the same temperature before testing.

The required quantities for the refilling of the fuel tank to 10 %, 20 % and 30 % concentrations were calculated in a spreadsheet, based on the remaining fuel quantity in the engines fuel system, connecting lines and the fuel tank.

Measurements of emissions and fuel consumption were performed when concentration levels of NO and NO2 had stabilized. The temperatures of cooling water, engine oil, inlet/exhaust and the turbocharger pressure were monitored and logged manually. The log files confirmed that oil and cooling water temperatures were increasing equally with the change in load levels in all the tests, which means that the engine friction should be constant as well.

Fuel measurement setup

Fuel consumption was measured on a digital scale during intervals of 6 minutes with constant load. As the scale output is in kg with two decimals, care had to be taken in the measurement. The time was started on the change of the last digit on the scale, and stopped again on the first change of the last digit occurring after 6 minutes. The uncertainty when using this method is an estimated 5 seconds or about 1.4 % for the consumption of the given fuel quantity measured at idle. With the engine loaded at 25 % and 50 %, the fuel consumption is much higher and therefore the uncertainty is reduced to about 3 seconds, which is 0.8 %.

In order to get stable readings from the scale, it was necessary to isolate it from floor vibrations by placing it on a heavy metal plate on top of a tall foam matt. Vibrations in the fuel forward and return lines were removed by fixing the lines with rubber-insulated pipe fixtures.

Emission measurement setup

The gaseous emissions were measured with an ANTARIS IGS FTIR from Thermo Scientific. The emissions were measured non-diluted and non-condensed through a sample line at 180 °C. The species included in the calibration of the instrument are listed in table 6.

Component	Name	Cal. range
Water	H2O	0.5 – 25 %
Carbon dioxide	CO2	0.1 – 20 %
Carbon monoxide	CO	1 - 10,000 ppm
Nitric oxide	NO	1 - 10,000 ppm
Methane	CH4	1 - 10,000 ppm
Ammonia	NH3	1 - 1000 ppm
Nitrogen dioxide	NO2	1 - 100 ppm
Nitrous oxide	N2O	1 - 100 ppm
Sulfur dioxide	SO2	1 - 100 ppm
Acetylene	C2H2	1 - 100 ppm
Ethene	C2H4	1 - 100 ppm
Ethane	C2H6	1 - 100 ppm
Propene	C3H6	1 - 100 ppm
Propane	C3H8	1 - 100 ppm
1,3 butadiene	C4H6	1 - 100 ppm
Iso-butylene	C4H8	1 - 100 ppm
N-Pentane	C5H12	1 - 100 ppm
Benzene	C6H6	1 - 100 ppm
Iso-octane	C8H18	1 - 100 ppm
Formaldehyde	CH2O	1 - 100 ppm
Acetaldehyde	CH3CHO	1 - 100 ppm
Total hydrocarbons	THC	FID equivalent[1]
Non-methane hydrocarbons	NMHC	FID equivalent
Total NOx	NOx	NO + NO2

Table 6: List of measured species

The emission of particulate matter was measured with an AVL 489 Advanced Particle Counter. The instrument is a CPC type counter. The functional principle is to dilute the raw gas, dry the particles in a heated chamber, dilute the hot sample (which also cools it) and then condense evaporated n-butanol onto the particles. The particles are then illuminated by laser and counted by photo detection. The instrument is capable of detecting particle sizes down to a mean diameter of 23 nm. Particles of VOC are not measured, since they will be evaporated and diluted before the detection chamber.

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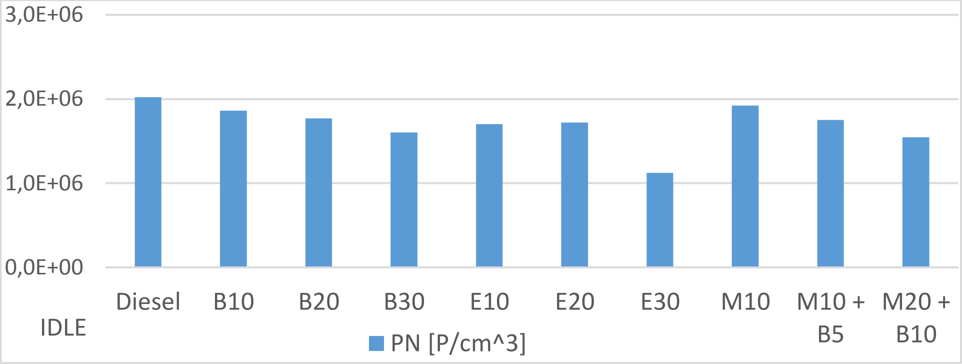
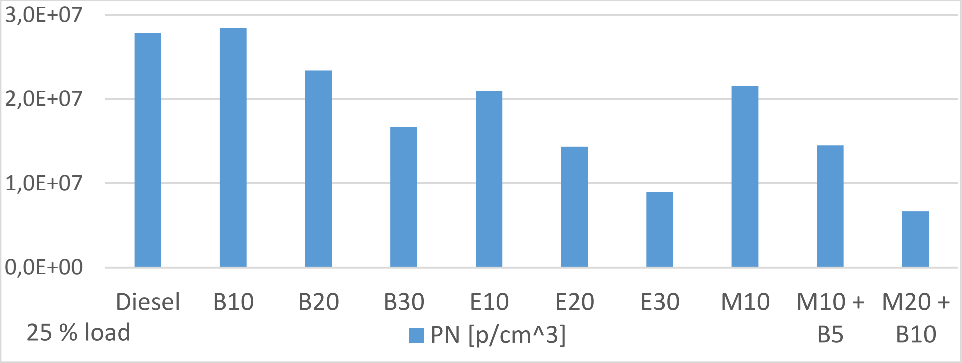
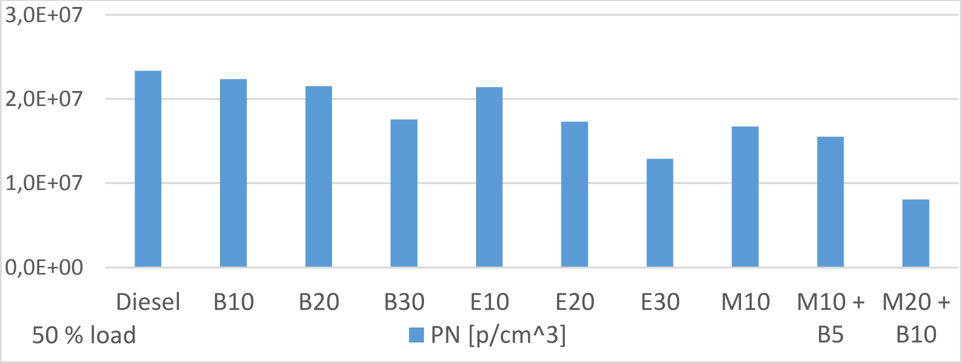
[1] The hydrocarbons in the table are used to calculate a value that is equivalent to the response of a standard FID instrument, which has output in propane ppm.

Measurements

Particulate number



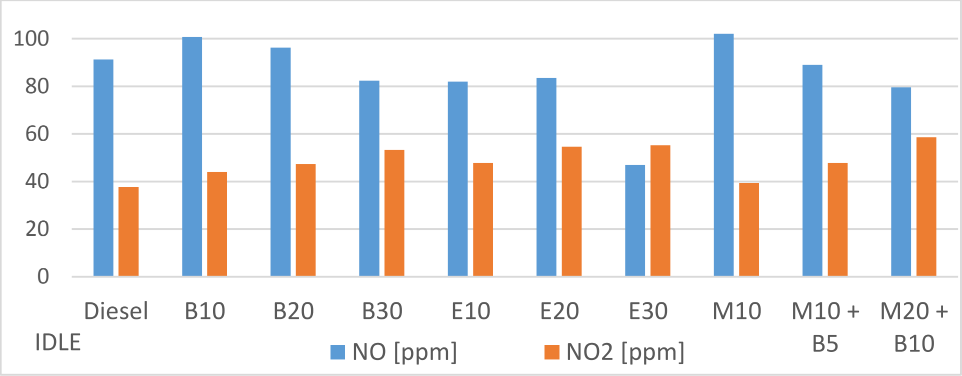


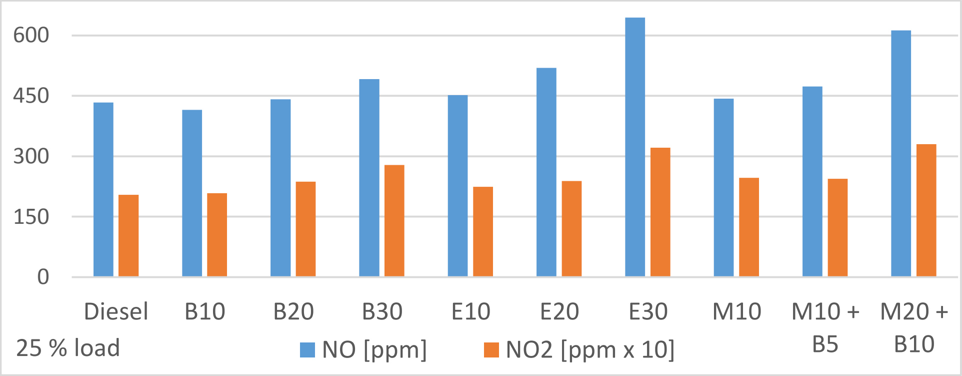


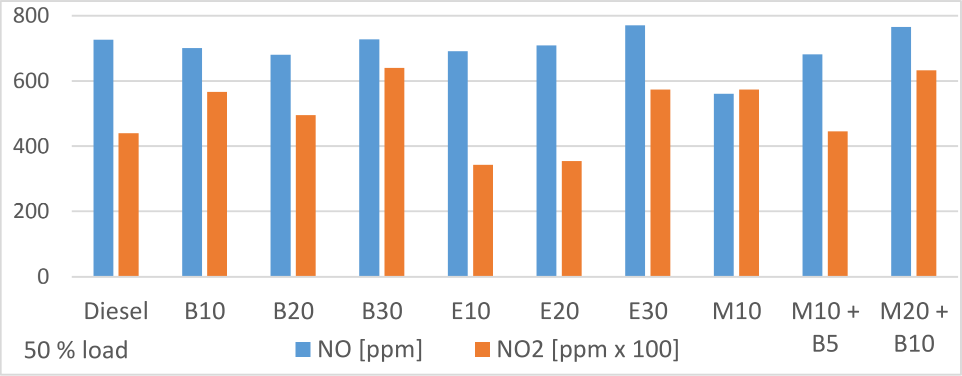
The formation of particulates at idle appear to be only moderately affected by the addition of alcohols. However, the reference level is already quite low in idle operation, less than 10 % of the levels in loaded operation. With 30 % E, the PN is reduced to about half of the reference level, which is quite significant considering that the NOx formation is reduced as well (next page).

At 25 % and 50 % load, the particulate concentration increases approx. 10-15 times compared to idle. The formation of particulates is greatly reduced with addition of alcohols. The reduction is most effective with methanol and ethanol. The addition of 5 % butanol to the 10 % methanol blend appears to improve the reduction obtained with 10 % methanol only. Since butanol only has a minor effect on particulate formation at 10 % concentration, the combined effect of methanol and butanol on particulate formation could be caused by a more homogeneous fuel mixture.

Nitrogen oxides



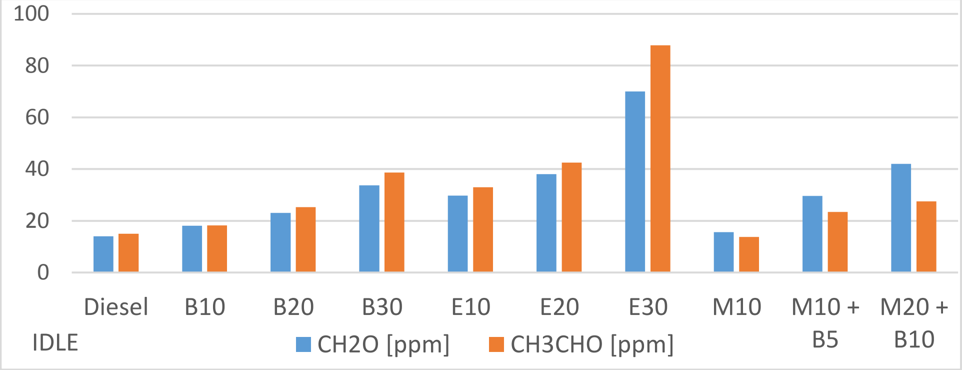


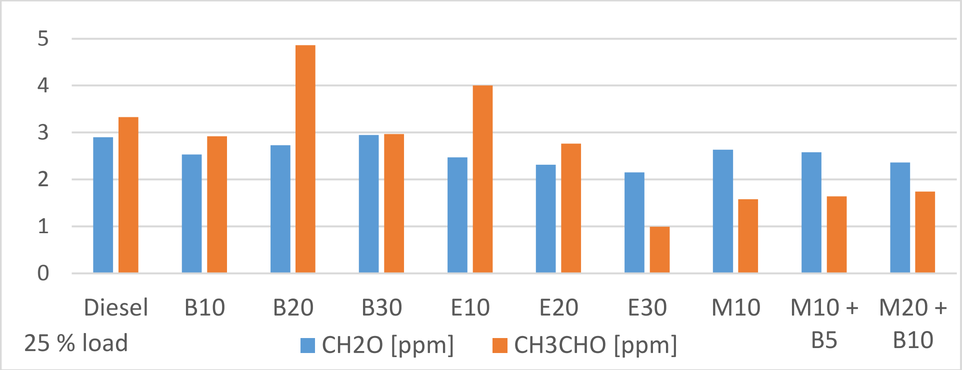


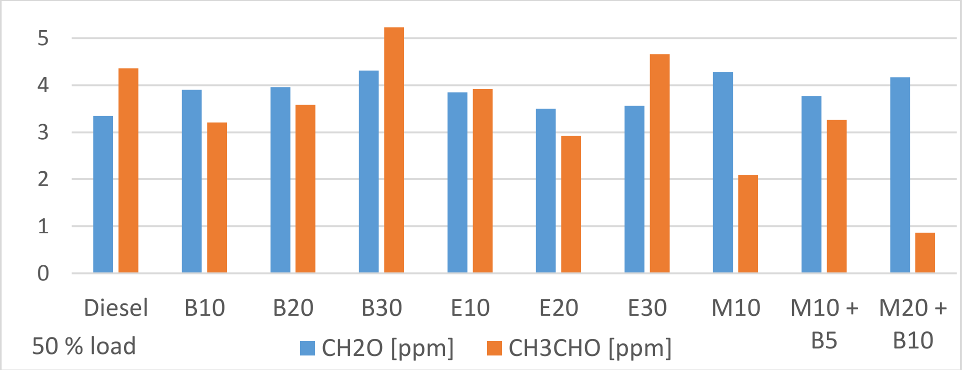
In idle, the emissions of NO and NO2 are moderately affected by the addition of alcohols. The level of total NOx is very constant, except with 30 % E, in which test the premixed combustion was suppressed. It appears that the balance between NO and NO2 is changed towards NO2 with increasing percentage of alcohol, which indicates that the combustion products are being cooled more when alcohol is present in the fuel.

At 25 % load, NO2 levels are reduced to approx. 5 % of the total NOx emission. Nitrogen oxides are moderately increasing with increasing amounts of alcohol. The increase is stronger with methanol and ethanol. At 50 % load, the NO2 concentration is reduced to less than 1 % of the total NOx emission. There is a weak effect on NO emission with ethanol and a somewhat stronger effect with methanol, where a low concentration of methanol is lowering the NO and the higher concentration is increasing it again. A possible explanation for the effect of alcohol at 25 % load and, to some extend 50 % as well, may be that the heat release rate in the premixed and mixing controlled combustion phases are increasing with increased concentration of alcohol, due to a higher volatility of the fuel combined with a longer ignition delay. The increased heat release rate results in an elevation of the combustion temperature and hence the NO formation.

Aldehydes



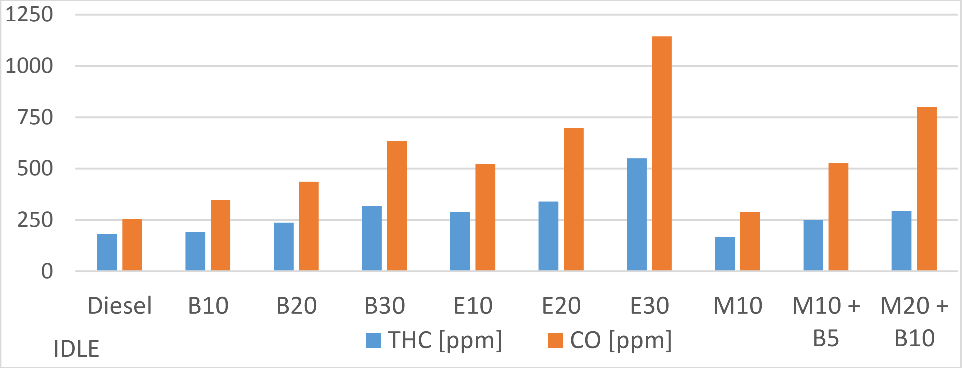


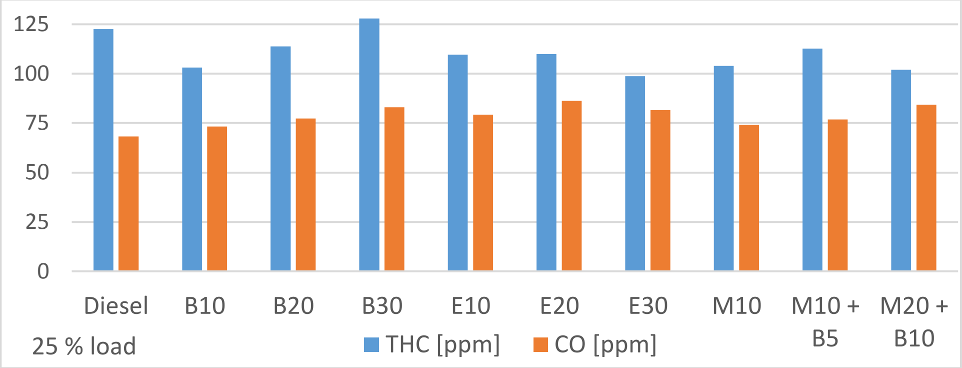


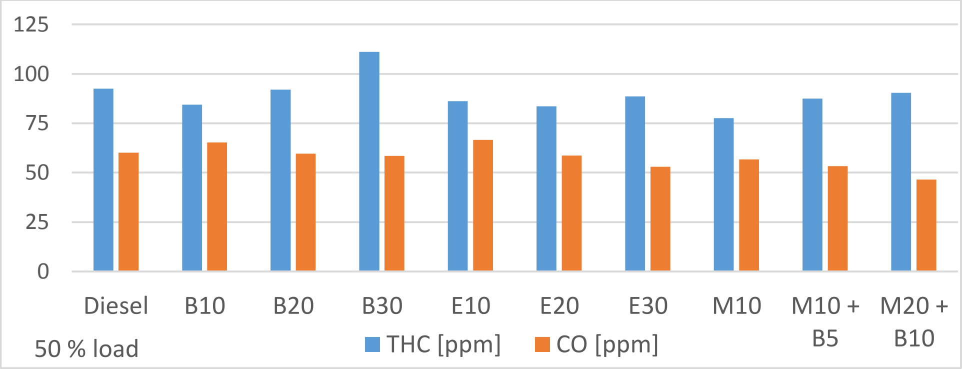
In idle, the formation of formaldehyde and acetaldehyde are significantly increasing with the addition of alcohols. An increase in formaldehydes is also known from SI engines operating on ethanol and methanol. The largest formaldehyde increase is seen with the 30 % E blend, which had poor premixed combustion. Butanol and methanol result in less formaldehyde formation than ethanol.

Aldehydes are generally much lower in loaded operation, due to the high temperatures in the combustion chamber. The emission levels of aldehydes do not appear to be increasing by alcohol addition, as was observed in idle condition. The aldehyde emission at 50 % load appears higher than that observed at 25 % load. However, as the levels are still all below 5 ppm, these emissions are of minor importance.

Hydrocarbons and carbon monoxide



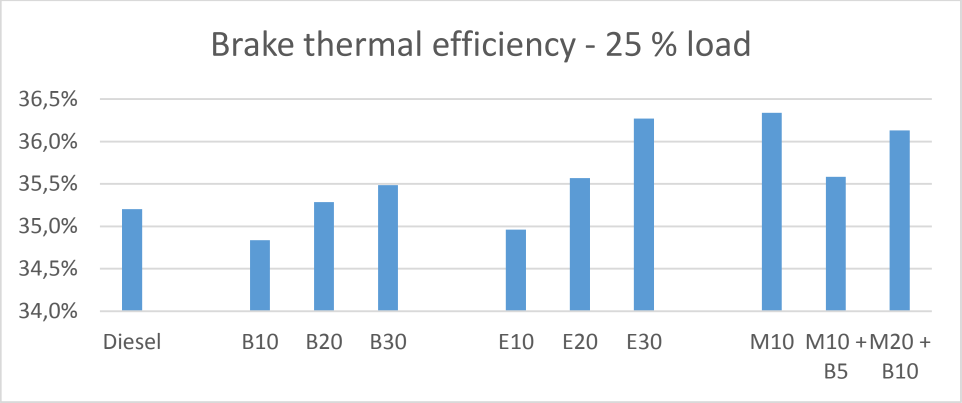


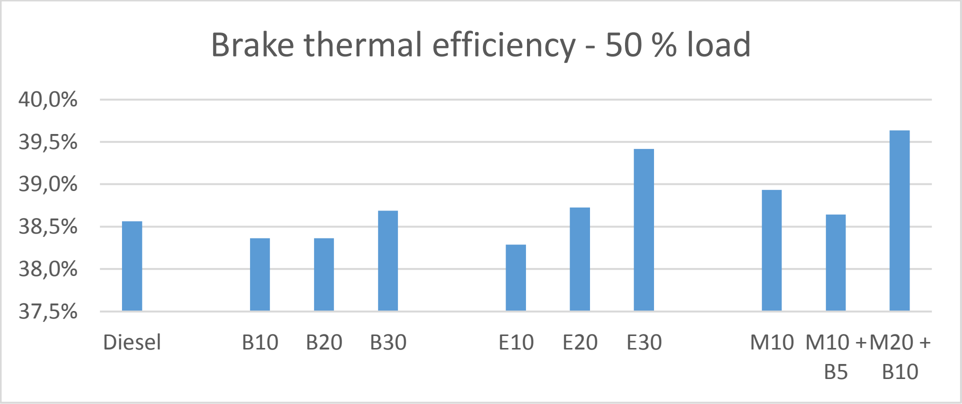


In idle condition, the emission of carbon monoxide and hydrocarbons are increasing significantly with the addition of alcohols. The large increase in CO indicates that the combustion is being less efficient with increasing amounts of alcohol in the blend.

The emissions of hydrocarbons and carbon monoxide are generally low in loaded operation, which is a consequence of the higher combustion temperatures. There is no obvious effect on the emissions by the addition of alcohols when the engine is running loaded.

Brake thermal efficiency





The calculation of brake thermal efficiencies in loaded condition are clearly demonstrating that the efficiency is affected with the alcohol blends.

Butanol does not appear to have as strong an effect as ethanol or methanol, but it is also the alcohol with the lowest ratio of oxygen to carbon, and more similar to a straight chain alkane than the two simpler alcohols.

Ethanol provides a large increase in thermal efficiency with 20 % and 30 % concentration in the blend, but the efficiency is actually decreasing when only 10 % ethanol is used.

Methanol also provides a large increase in thermal efficiency. The trend is strong when looking at the difference between M10 + B5 and M20 + B10 alone. The result with pure methanol compared to the combination with 5 % butanol is however indicating that butanol has a strong influence on the way that methanol behaves in the combustion of the fuel blend.

It must be remembered however, that although care was taken in adjusting the combustion timing with the purpose of comparing the emissions of the fuel blends, there may remain a large potential for optimizing fuel consumption, not only by proper injection timing, but also by the use of fuel additives to restore the cetane number.

Conclusion

Blending of the simple alcohols methanol, ethanol and butanol with diesel can contribute to a significant reduction in particulate matter formation. This may be used to reduce emissions of particulate matter from engines that are not fitted with particulate filters or other means of capturing the particulate matter.

The most effective alcohols for reducing particulate formation are methanol and ethanol. Butanol does not have as great potential as a single blending component, but it may be an important cosolvent for methanol and thereby assist in a more efficient particulate reduction.

Emission of other harmful components such as aldehydes, carbon monoxide and unburned hydrocarbons are mainly increasing when the engine is not under load. These emissions may need to be handled by oxidizing catalysts, if improvements to the fuel composition and engine tuning are not enough to reduce these emissions to an acceptable level. The same emissions are however not increasing from the reference diesel at higher loads, which indicates that the engine is not very sensitive to the presence of alcohol in the fuel, when the combustion temperature is higher.

The formation of nitrogen oxide is slightly increasing at 25 % load with the use of alcohol blends, possibly due to an increased fraction of the fuel burning in premixed combustion and therefore an overall faster combustion at elevated temperatures. At 50 % load however, it appears that there is little difference between the diesel reference and the alcohol blends. Alcohol blends can therefore not contribute to emissions of nitrogen oxides.

The lower heating value of the fuel is reduced with alcohol blends, and the brake specific fuel consumption is therefore increasing. By measuring the fuel consumption and calculating the lower heating value of the fuels, it was however found that the brake thermal efficiency of the engine is actually increasing significantly when using alcohol blends at 25 and 50 % load. This effect may be due to faster combustion and possibly a reduction in heat losses. The thermal efficiency is however strongly dependent on the timing of the combustion, which in this experiment was monitored and advanced to match the diesel reference measurements. If alcohol blends are used without proper adjustment of injection timing, it is more likely that the thermal efficiency will decrease due to the prolonged ignition delay.