



# Effects of Oxymethylene Ether in a Commercial Diesel Engine

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## Abstract

Oxymethylen Ether (OME) is a promising alternative fuel for diesel engines. It can be produced sustainably, and its combustion is clean and efficient. This study investigates the effects of different OME<sub>3-5</sub> mixtures on emissions and combustion. The measurements were done on a four-cylinder common rail commercial diesel engine equipped with an exhaust gas recirculation system (EGR). Five different blends of OME<sub>3-5</sub> and B7 diesel were applied with 0, 7, 15, 25 and 45 vol% OME<sub>3-5</sub> content at four loads. The NO<sub>x</sub>-PM trade-off was investigated at 11 EGR rates for each mixture at each load. Increasing OME<sub>3-5</sub> mixing ratio reduced the PM emission, improved the NO<sub>x</sub>-PM trade-off, and increased the brake thermal efficiency. The maximum achieved PM emission reduction was 86.8% for high loads. However, NO<sub>x</sub> emission increased, and also low heat capacity and viscosity can be a problem for real applications.

## Keywords

Advanced fuels, Oxymethylen Ether, NO<sub>x</sub>-PM trade-off, Sustainable mobility

## 1. Introduction

Global mobility has faced serious challenges in the last decades. The transportation sector has one of the largest shares in the worldwide greenhouse gas emissions, thus strict regulations are introduced all over the world (Török et al., 2005). The requirements of new legislation usually cannot be met with the use of conventional drives. Advanced internal combustion engine technologies and electrified drivetrains are expensive; therefore, the price of the new cars increase. This also drives the value of the used cars up. In most countries, the provoked high prices lead to the strong aging of the vehicle fleet, and thus newly developed technologies cannot spread widely. Advanced fuels offer a promising solution for these issues (Alahmer et al., 2022). If fuels can be produced that may result in carbon-neutral mobility and ensure low pollutant emission in existing engines, then the use of the old technologies become more eco-friendly (Zöldy et al., 2022). Thereby alternative fuels provide a great medium-term solution for this problem until the new sustainable transportation structure forms in the following few decades. There is already some progress in the market. For example in Sweden, hydrogenated vegetable oil (HVO) can be purchased and used in modified trucks (Soam et al., 2019).

Diesel engines have higher efficiency compared to gasoline engines; therefore, if higher soot and NO<sub>x</sub> emission can be diminished, it can still be a favorable fuel for commercial vehicles. There are many advanced fuels and additives described in the literature on diesel engines, such as the previously mentioned HVO. Recently, polyoxymethylene dimethyl ether, which is also called oxymethylene ether (OME) is one of the most recognized substances for compression ignition engines. It is an oligomeric compound containing oxygen, which has the molecule structure of CH<sub>3</sub>-O-(CH<sub>2</sub>-O)<sub>n</sub>-CH<sub>3</sub>, where *n* is the chain length, which highly affects the physico-chemical properties of the material. The compound is usually called dimethoxy methane (DMM) when the degree of polymerization is one (*n* = 1), but according to the common nomenclature, it is mostly labeled as OME<sub>1</sub> (Härtl et al., 2015). As the properties of this substance in Table 1 prove, it has a lower cetane number (CN) than 51, so it does not meet the requirements of EN590. The viscosity and the density of OME is also out of the bounds of this standard, thus this substance can only be used with additives, or as a blending component for fuels suitable for existing engines. The CN increases greatly with chain length, so excellent ignitability is provided at higher degrees of



polymerization. Still, viscosity remains under the lower limit, and the already high density increases further. The lower heating value (LHV) is nearly half of the B7 diesel fuel's LHV because of the high oxygen content. The oxygen content rises with chain length, which results in the diminution of the LHV (Pélerin et al., 2020).

Table 1. Fuel properties at different degree of polymerization (Pélerin et al., 2020; Liu et al., 2022; Omari et al., 2019; Norhafana et al., 2020)

Property	EN 590	B7 diesel	OME <sub>1</sub>	OME <sub>2</sub>	OME <sub>3</sub>	OME <sub>4</sub>	OME <sub>5</sub>	OME <sub>6</sub>
Lower heating value (LHV) [MJ/kg]	-	42.8	23.3	21	19.6	19	18.5	17.7
Cetane number (CN) [-]	>51	57.5	28	68	72	84	93	104
Density at 15 °C [kg/m <sup>3</sup> ]	820-845	832.6	860	980	1030	1070	1110	1140
Kinematic viscosity at 40 °C [mm <sup>2</sup> /s]	2-4.5	3.1	0.37	0.559	0.866	1.33	1.96	n.i
Boiling point [°C]	-	180-390	42	105	156	202	242	273
Flashpoint [°C]	>55	77	-32	12	54	88	115	169
Oxygen content [wt%]	-	0.8	42.1	45.2	47	48.1	48.9	49.5

To explore the possible practical uses of OME in existing engines, some important aspects need to be considered. The size of the fuel tanks should be increased due to the small LHV mentioned above. The different density requires the recalibration of the engine. The low viscosity results in poor lubrication properties, thus unmodified common rail systems may be damaged. The lubricity of OME<sub>3-6</sub> is acceptable, but OME<sub>1</sub> is really weak, so additives must be used to improve it. Cavitation might be another problem, because this substance has high saturation pressure. The OME is strongly polar due to its oxygen content; therefore, non-polar elastomers should be used in the fuel system. This means that the conventional fluorocarbon rubber sealings are not suitable for the application of OME, especially in the case of OME<sub>1</sub>, as it highly dissolves the sealing material. An alternative sealing material could be ethylene propylene diene rubber (Pélerin et al., 2020).

In addition to the appropriate properties for engine operation, safety is another important aspect. OME is non-toxic, and OME<sub>3-5</sub> has higher flashpoint than diesel fuel, so the usage is safe for the costumers. However, OME<sub>1</sub> has a flashpoint under -20 °C, which can lead to flaming hazards. The high vapor pressure of OME further increases this danger, but vapor escape can be impeded by sealed fuel tanks. This compound is non-biodegradable, and it is harmful for the ecosystem, thus the accidental release of the fuel into the environment must be avoided (Liu et al., 2022).

OME is usually produced from dimethyl ether (DME) or methanol. There are a lot of studies that investigate the application of these compounds as fuels, but they are toxic, so it is better to produce OME from them. Both DME and methanol can be produced from fossil resources, biomass or from CO<sub>2</sub> and H<sub>2</sub>. The well-to-wheel (WTW) greenhouse gas emission of OME mainly depends on the used resources. The WTW CO<sub>2</sub> equivalent emission of diesel fuel is 127 g/MJ. If OME is produced from coal-based methanol, this value is 228 g/MJ. If it is produced from natural gas-based methanol, then it is 136 g/MJ. This means that fossil OME production is worse than the use of conventional diesel. However, the WTW emission becomes significantly lower if the liquid is produced from renewable resources, because in this case WTW emission is equal to the well-to-tank emission, as the CO<sub>2</sub> released during combustion is part of a closed CO<sub>2</sub> cycle. If OME is made from residual forest-based methanol, then the WTW CO<sub>2</sub> equivalent emission is only 18 g/MJ (Wu et al., 2019).



OME has mostly positive effects on combustion and emission, depending on the degree of polymerization as well. The low CN of OME<sub>1</sub> is unfavorable, and it can lead to high pressure gradients during the premixed phase. The high volatility can also enhance the premixed flame and can reduce soot emission. However, the high CN of OME compounds with longer chain length results in good ignitability, thus the ignition delay (ID) is reduced. Therefore, the proportion of the premixed phase decreases, which reduces the combustion noise (Omari et al., 2019). The CN is so high, that even pre-injections can be eliminated. Another effect on the combustion is the decrease of the duration of combustion (DoC). This is the result of the oxygen content, because during the diffusion flame phase, less oxygen should diffuse from the air to the reaction zone. This shorter DoC can improve the indicated efficiency as well.

This oxygenate reduces soot formation so much, that it can be nearly zero when neat OME is applied. There are several reasons for that, but the main cause is the high oxygen content of the fuel. OH roots can easily be formed from the oxygen atoms of the molecule, and these help the oxidation of the soot. In addition to the O/C ratio, the H/C ratio also affects PM emission, since the higher H<sub>2</sub> content of the longer chains reduces the degree of soot formation. OME is a C1 fuel, thus the absence of C-C bonds also contributes to low PM emission. The molecule structure has another important positive effect on PM emission reduction: CO can be easily formed from the C-O bonds of the molecule, and this suppresses the formation of acetylene, which is a key compound for soot generation. Finally, good volatility can further reduce the PM emission, since it enhances air-fuel mixing. These effects abolish the NO<sub>x</sub>-PM trade-off for pure OME, but great improvements can be achieved even with small blends (Härtl et al., 2015).

Other emissions can be problematic. The oxygen content of the fuel rises the NO<sub>x</sub> emission because of the Zeldovich mechanism, but it also has a contrary effect. The shorter DoC arising from the oxygen content results in a shorter residence time at high temperature, thus this may reduce the NO<sub>x</sub> formation. Since the NO<sub>x</sub>-PM trade-off is minimized, extreme high EGR rates can be used to further reduce the NO<sub>x</sub> emission without the risk of high PM emission (Parravicini et al., 2021).

As mentioned above, the C-O bonds enhance the generation of CO, thus this emission may be high, but the oxygen content can help its oxidation. Methane emission can also be high, since there are methyl groups in the molecule. This compound has 25 times higher global warming potential than CO<sub>2</sub>, which must be reduced. The OME chain contains formaldehyde structures, thus carcinogenic formaldehyde emission can also emerge. These emissions are only high when a high EGR rate is applied. In addition to these, the HC emission can also increase: the small LHV leads to a longer duration of injection (DoI), which means that the start of injection (SoI) must be placed earlier for the same center of heat release (CoHR). The early SoI leads to enlarged wall wetting. To avoid the increased HC emission and oil dilution from this effect, the energy flow can be increased with higher rail pressure and with higher injector nozzle holes (Barro et al., 2018).

The exhaust aftertreatment system can be simplified if pure OME is used. PM emission is so low in this case that the application of diesel particulate filter (DPF) is not necessary. The eliminated NO<sub>x</sub>-PM trade-off allows EGR rates to be so high that even stoichiometric conditions can be achieved. Therefore, only a three way catalyst is enough in this extreme case. However, the increased methane and formaldehyde emission makes this solution problematic. Some improvement can also be achieved if OME is used only as a blending component. In this case, the DPF requires less frequent regeneration, thus the fuel consumption can be reduced (Wu et al., 2019).

In this research the effects of OME are investigated in a four cylinder commercial diesel engine. OME<sub>3-5</sub> is used, because it has better effects on the combustion than OME<sub>1</sub>, and its properties are more suitable for an unmodified common rail system. No additives were used, thus only lower mixing ratios (7, 15, 25 and 45 vol%) were applied to avoid possible engine damage. Combustion characteristics, NO<sub>x</sub> emission and PM emission were examined without EGR. Several EGR rates were applied with a HP-EGR system to study the NO<sub>x</sub>-PM trade-off of the blends. The investigation was carried out at 1400 rpm with 0, 100, 250 and 400 Nm loads. It was found that the OME mostly has positive effects on the engine operation.

## 2. Data and methods

### 2.1. The measurement system

The experiment was carried out in a Cummins ISBe 170 30 turbocharged, medium-duty commercial diesel engine. This Euro 3 level engine is equipped with a common-rail injection system, an intercooler, and a high-pressure EGR system. The engine was installed on an engine dynamometer in which all the necessary operating parameters were measurable. Temperature and pressure can be measured at several points of the gas exchange system. The main parameters of the engine are given in Table 2.

Table 2. Cummins ISBe 170 30 engine properties



Engine displacement	Bore	Stroke	Compression ratio	Rated effective power
3922 cm <sup>3</sup>	102 mm	120 mm	17.3	125 kW

The EGR rate is varied with a HP-EGR valve that can be controlled via CAN communication by a dSpace MicroAutoBox DS1401/1505/1506. The cylinder pressure was measured with an AVL GH13P piezoelectric sensor, which is connected to the seat of the glow-plug. To measure the crank angle position, an AVL 365C crank angle encoder was used with a resolution of 0.5 °CA. The combustion analysis was carried out with an AVL 612 Indi-Smart. The O<sub>2</sub> and NO<sub>x</sub> concentration was measured with a Continental UniNOx-Sensor, while opacity was measured with an AVL 439 Opacimeter. The emissions are not treated with catalysts, nor with DPF.

## 2.2. The applied mixtures

The used OME<sub>3-5</sub> fuel was provided by the Karlsruhe Institute of Technology (Haltenort et al., 2018). Table 3 gives the chemical components of the substance.

Table 3 OME<sub>3-5</sub> properties

OME <sub>1</sub>	OME <sub>2</sub>	OME <sub>3</sub>	OME <sub>4</sub>	OME <sub>5</sub>	OME <sub>6</sub>	Other compounds
0.16 wt%	0.34 wt%	45.55 wt%	27.26 wt%	12.73 wt%	5.61 wt%	8.35 wt%

The LHV of the substance can be estimated from the LHV of its OME<sub>n</sub> compounds the he other compounds are neglected:

$$(1) \quad LHV_{OME_{3-5}} = \frac{\sum_{n=1}^6 \gamma_{wt, OME_n} \cdot LHV_{OME_n}}{\sum_{n=1}^6 \gamma_{wt, OME_n}}$$

where

$LHV_{OME_{3-5}}$  is the lower heating value of the applied OME<sub>3-5</sub> [J/kg],

$LHV_{OME_n}$  is the lower heating value of each component [J/kg],

$\gamma_{wt, OME_n}$  is the mass fraction of each OME<sub>n</sub> component in the liquid [-].

Thereby, the LHV of the OME<sub>3-5</sub> is 19,164 MJ/kg. Density can be estimated similarly: the LHV must be replaced with the density in Equation (1). The calculated density of the OME<sub>3-5</sub> is 1059.26 kg/m<sup>3</sup>.

In the course of the measurements, 5 different blends were investigated: 0, 7, 15, 25, and 45 vol%. These can be converted into mass percentages by using the density of B7 diesel and OME<sub>3-5</sub>. Then, the LHV of the blends can be calculated with Equation (2).

$$(2) \quad LHV_i = \gamma_{wt,i} \cdot LHV_{OME_{3-5}} + (1 - \gamma_{wt,i}) \cdot LHV_{B7 \text{ diesel}},$$

where

$LHV_i$  is the lower heating value of the  $i^{\text{th}}$  blend [J/kg],

$LHV_{B7 \text{ diesel}}$  is the lower heating value of B7 diesel [J/kg],

$\gamma_{wt,i}$  is the mass fraction of OME<sub>3-5</sub> in the  $i^{\text{th}}$  blend [-].

The density of the blends can be calculated similarly as Equation (2). The kinematic viscosity of the B7-OME<sub>3-5</sub> blends was measured with a Cannon-Fenske viscometer (Csemány et al., 2022). The pure OME<sub>3-5</sub> viscosity was also measured: 1.187 mm<sup>2</sup>/sec. The properties of the blends can be seen in Table 4. The kinematic viscosity of the 7 vol% blend meets the requirements of EN590, but the 15 vol% blend is also near the required values. Further investigations should use additives to improve this property.



Table 4. Properties of the used blends

OME <sub>3-5</sub> [vol%]	OME <sub>3-5</sub> [wt%]	Density at 15 °C [kg/m <sup>3</sup> ]	Lower heating value [MJ/kg]	Kinematic viscosity at 40 °C [mm <sup>2</sup> /s]
0	0	832.6	42.8	3.1
7	8.74	852.41	40.73	2.321
15	18.33	874.16	38.47	1.788
25	29.78	900.09	35.76	1.557
45	51	948.20	30.75	1.401

### 2.3. The measurement methods

The previously described 5 different B7-OME<sub>3-5</sub> mixtures were studied on the test engine at 4 different loads with 11 different EGR rates, which resulted in 220 measurement points. The engine was warmed up with B7 diesel to 80 °C oil temperature before the experiment. The first measurement was done with pure B7, and then blends were applied with increasing OME<sub>3-5</sub> content. The fuel system was emptied after the measurement of each mixture and 300 g new mixture was used to flush it before the new measurements. The engine was conditioned to the new loads for one minute before the measurements of each load, and after that the 11 EGR rates were set. Each measurement with the new EGR rate lasted for 20 seconds. The first 10 seconds, and the last second were considered as a transient, thus the results of the measurement points are the average of the remaining 9 seconds of data. The EGR rate was set with the HP-EGR valve, and its position was varied between 0 and 100% with a 10% resolution. The investigation was carried out at no load (0 Nm), low load (100 Nm), medium load (250 Nm) and high load (400 Nm) at the engine speed of 1400 rpm.

The temperature of the combustion chamber can be estimated from the ideal gas law assuming that the medium in the chamber is air (Eriksson et al., 2017). The latent heat release rate is calculated from Equation (3) by neglecting heat loss. The released heat is the integral of the result of this equation.

$$(3) \quad \frac{dQ_b}{d\phi} = \frac{\kappa p}{\kappa-1} \cdot \frac{dV}{d\phi} + \frac{V}{\kappa-1} \cdot \frac{dp}{d\phi} - \frac{dQ_w}{d\phi},$$

where

$Q_b$  is released heat [J],

$\kappa$  is the adiabatic gas constant of air [-],

$p$  is the pressure in the combustion chamber [Pa],

$V$  is the volume of the combustion chamber [m<sup>3</sup>],

$Q_w$  is heat loss [J],

$\phi$  is crank angle [°CA].

NO<sub>x</sub> concentration is converted into NO<sub>x</sub> emission in g/kWh with the exhaust mass flow rate and the engine power. The exhaust mass flow rate can be calculated from engine geometry, dose and volumetric efficiency. PM emission is calculated from opacity (Lakshminarayanan et al., 2016). Firstly, filtered smoke number (FSN) has to be calculated from Equation (4).

$$(4) \quad N = 0.12 \cdot FSN^3 + 0.62 \cdot FSN^2 + 3.96 \cdot FSN,$$

where

$N$  is opacity [%],

$FSN$  is filtered smoke number [-].

After this, smoke concentration can be derived from Equation (5).



$$(5) \quad C_{smoke} = \frac{4.95}{0.405} \cdot FSN \cdot e^{0.38 \cdot FSN},$$

where

$C_{smoke}$  is smoke concentration [ $\text{mg}/\text{m}^3$ ].

The volumetric exhaust flow rate can be calculated from the exhaust mass flow rate and the pressure and temperature at the sampling point. As a simplification, the gas constant of air is used for the calculation. Then PM emission can be calculated from Equation (6).

$$(6) \quad PM = \frac{C_{smoke} \cdot \dot{V}_{exh}}{P_{mot}},$$

where

$PM$  is particulate matter emission [ $\text{g}/\text{kWh}$ ],

$\dot{V}_{exh}$  is volumetric exhaust flow rate [ $\text{m}^3/\text{h}$ ],

$P_{mot}$  is engine power [ $\text{W}$ ].

### 3. Results and Discussion

#### 3.1. Emissions

In this investigation, the emissions are specified to brake power, so the no load curves will not be presented, since they would be infinite. Figure 1 demonstrates the effects of the rising  $\text{OME}_{3.5}$  content on PM emission. The baseline measurement shows that the 400 Nm load generates drastically higher PM emission than other loads. Soot generation is reduced drastically by increasing the oxygenate portion. The extent of reduction is lower for the 100 Nm case, because its emission is already low, but for the 250 Nm and 400 Nm loads, the effect is significant. These latter two cases have a similar extent of PM emission diminution and only 15 vol%  $\text{OME}_{3.5}$  is enough for about 70% decrease. The higher mixing ratios only create a little more reduction. The 45 vol% blend reduced PM emission by 86.8%. This result was expected due to the considerable soot generation minimizing effect of the substance described in the introduction. There are similar results in the literature, Omari et al. (2017) could achieve 90% PM emission reduction with 35 vol%  $\text{OME}_1$  content.

Figure 2 presents  $\text{NO}_x$  emission as a function of the blending ratio. As expected, the  $\text{NO}_x$  emission increases with the rising oxygenate content due to the Zeldovich mechanism. However, the effect is moderate, the growth is only about 30% in the worst case. The increasing  $\text{NO}_x$  emission can also be reduced with EGR.

To study the possibilities of emission optimization, 11 EGR rates were applied to investigate the  $\text{NO}_x$ -PM trade-off. The results revealed that the trade-off change is similar for all loads, thus only the medium load is presented in Figure 3. The trade-off decreases with the increasing amount of  $\text{OME}_{3.5}$ . The test engine is Euro 3 level. If we consider the 5 g/kWh  $\text{NO}_x$  and 0.1 g/kWh PM emission limit, it is clear that aftertreatment is still needed, but the blends make it possible to have smaller catalysts or less DPF regeneration cycles.

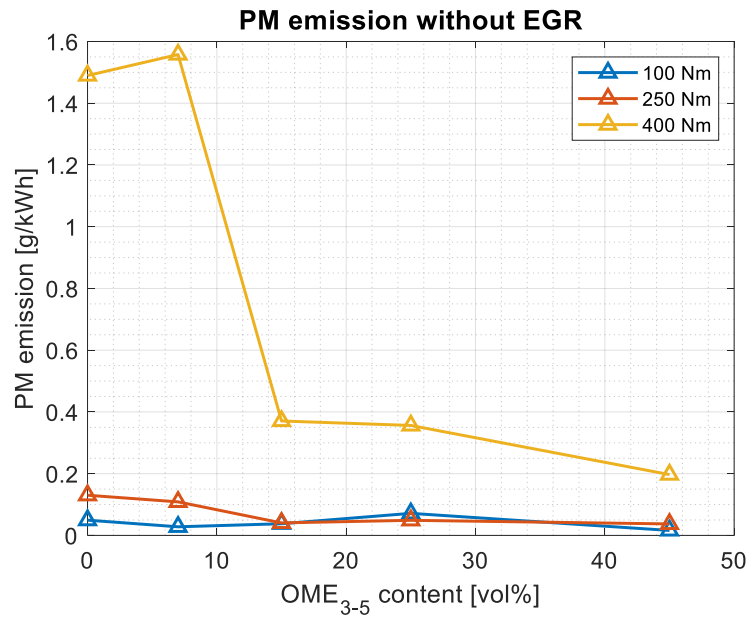


Figure 1. PM emission without EGR for the different mixtures at different loads

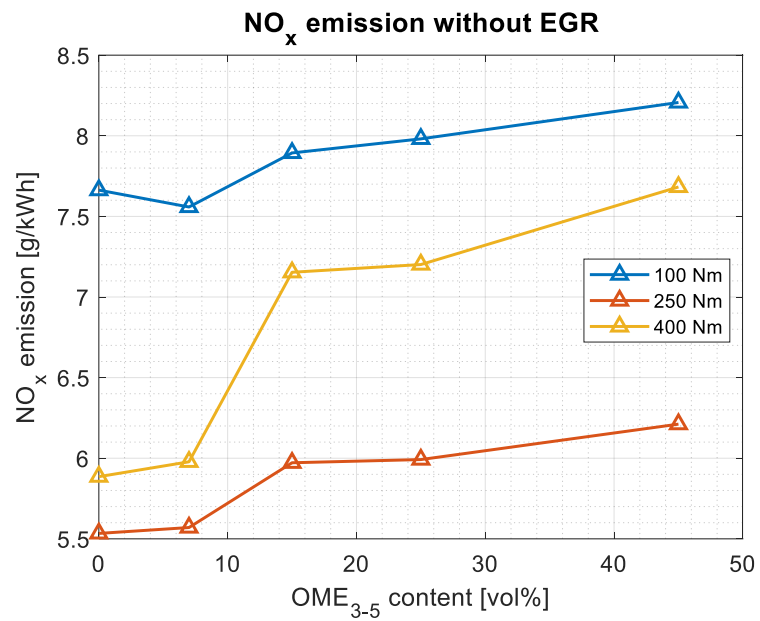


Figure 2. NO<sub>x</sub> emission without EGR for the different mixtures at different loads

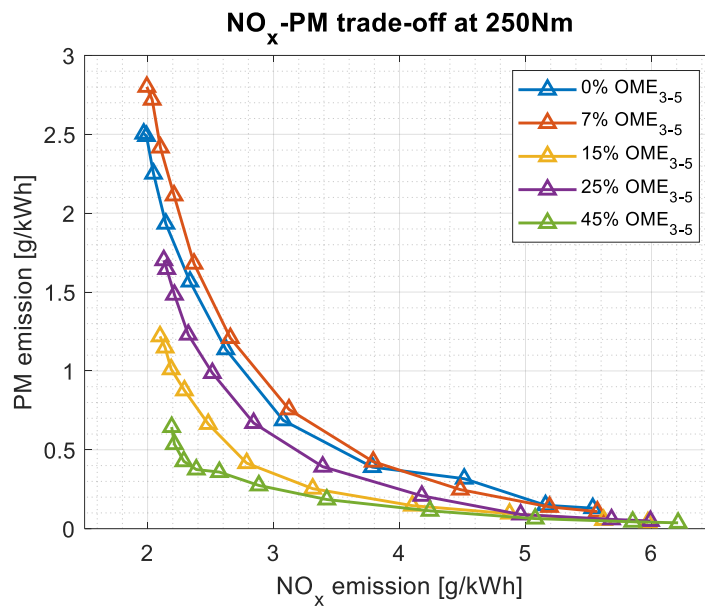


Figure 3. NO<sub>x</sub>-PM trade-off at 250 Nm with different EGR rates for each blend

### 3.2. Engine performance

The engine operated at fix duty points, thus the change in the performance can be illustrated only with the fuel consumption and the efficiency from our measurement data. Figure 4 presents the brake specific fuel consumption (BSFC) as a function of the OME<sub>3-5</sub> content. The LHV of the blends decreases with the increasing amount of oxygen, thus more fuel is required for the same power. The rising BSFC is an expected result. However, this is not a tremendous issue, because if OME<sub>3-5</sub> is produced from renewable resources, than the WTW CO<sub>2</sub> equivalent emission is still much lower than for B7 diesel. In terms of fuel costs, this is only a problem if the production of the substance cannot be made cost-effective. The only problem is the need for a larger fuel tank.

Figure 5 shows the change in brake thermal efficiency (BTE) at different loads. Higher OME blends had major effects, the BTE increased by about 8 percentage point when 45 vol% OME<sub>3-5</sub> was applied. This rise is an expected result, since most authors experience it, but it is usually around only 2-3 percentage points (Liu et al., 2017b). This significant difference may be due to the estimated LHV of the used substance. LHV measurement is necessary for proper calculations.

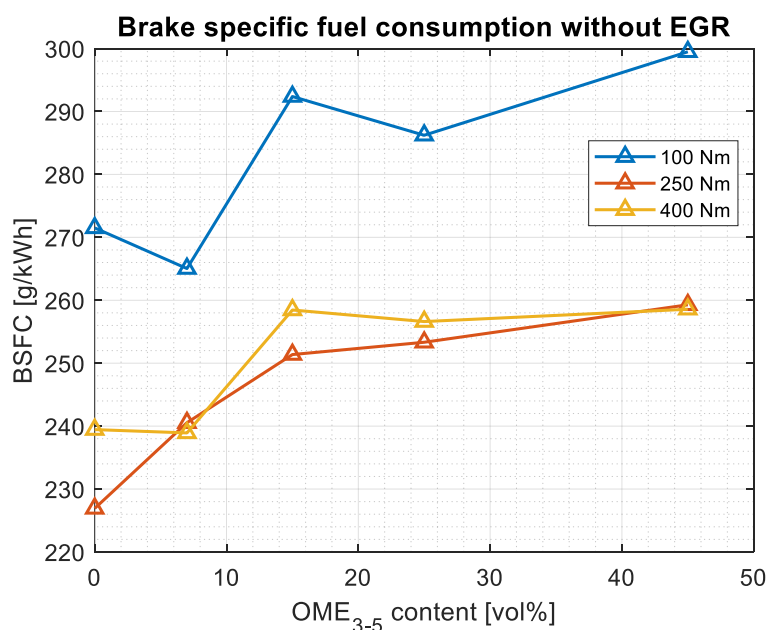


Figure 4. Brake specific fuel consumption without EGR for the different mixtures at different loads

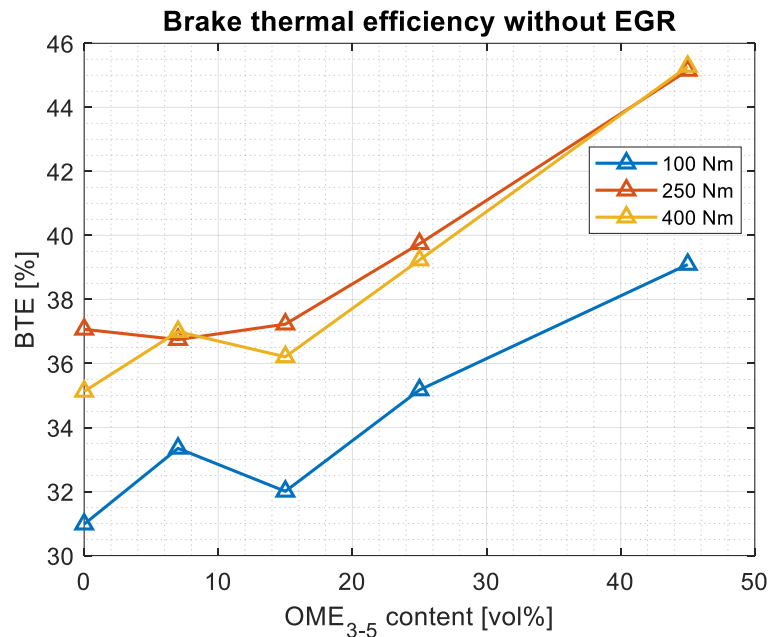


Figure 5. Brake thermal efficiency without EGR for the different mixtures at different loads

### 3.3. Mean combustion properties

In this section, the most important parameters of the combustion are presented. The results are the average of the measured duty cycles of each measurement case. The effects of OME<sub>3,5</sub> on the peak combustion temperature is demonstrated in *Figure 6*. The fuel's rising oxygen content helps the oxidation, thus a slight temperature increase can be observed. This also has an effect on the duration of combustion (DoC), which is presented in *Figure 7*. The diffusion phase of diesel combustion is a slow process, because the oxygen from the air has to diffuse to the reaction zone. However, if the fuel contains oxygen, it accelerates the burning process due to the lower need for external oxygen. The measured results are in line with this expectation. At 0 and 100 Nm the combustion is already short, and the proportion of the diffusion flame is not that large, thus the DoC remains nearly the same with increasing blending ratios. In contrast, the 250 and 400 Nm curves show a non-negligible DoC diminution as the OME<sub>3,5</sub> mixing ratio increases. The maximum decrease is around 5 °CA with the 45 vol% blend. In these cases, the diffusion phase is long enough to let the effects of the oxygen content prevail. The observed decrease is similar to the experiences of Liu et al. (2017a), who detected 10 °CA change in a single cylinder light duty diesel engine by adding 30 vol% OME<sub>3,4</sub> to the diesel fuel.

The peak combustion pressure gradient is another important parameter (*Figure 8*). The values remain below 6 bar/°CA which is a common upper limit for commercial diesel engines in order to avoid damages (Yin et al., 2021). The OME<sub>3,5</sub> has two main properties that affect the pressure gradient in the combustion chamber. The first is high CN, which shortens the ignition delay, thus reducing the proportion of the released heat during the premixed phase, because the fuel has less time to mix with the air. The second is the high volatility, which accelerates the mixing with air; therefore, it increases the proportion of the premixed phase, thus higher pressure gradients occur. These two contrary effects make differences in the combustion at different loads. At 0 Nm, the dose is so small that a notable part of the heat releases during the premixed phase, regardless of the little changes in the ignition delay. That is why high volatility has a more significant effect than the high CN, so the pressure gradient rises. At 100 Nm, the dose is larger, thus the heat released during the premixed phase can be effectively reduced by higher CNs. At 250 Nm, the effect becomes more significant. During the calibration of the ECU, the designers paid attention to keep the pressure gradient low as the load increases. This was achieved by retarding the SoI, which reduces ignition delay. Consequently, at 400 Nm the premixed phase is really small, and the peak combustion pressure gradient occurs at the diffusion phase. The oxygen content accelerates the diffusion flame, thus the peak pressure gradient rises slightly. This trend can be seen on the 400 Nm curve.

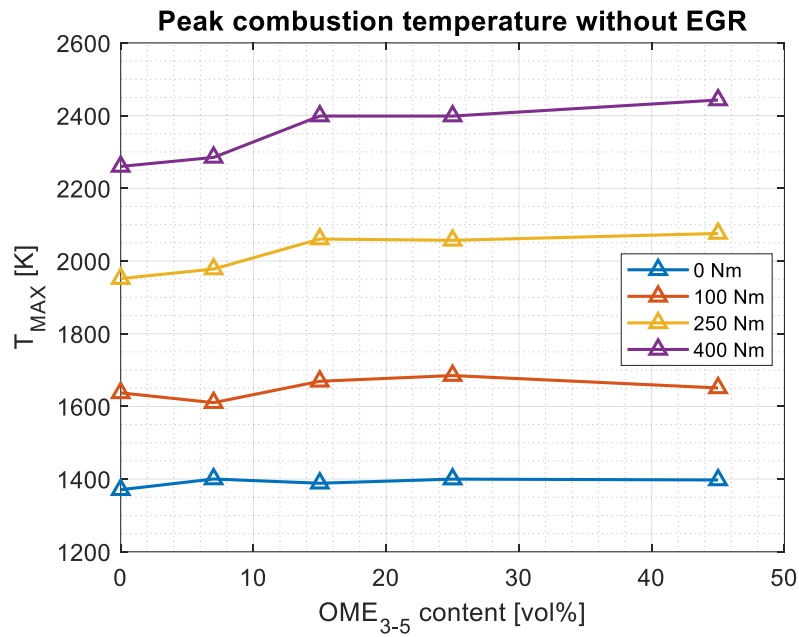


Figure 6. Peak combustion temperature without EGR for the different mixtures at different loads

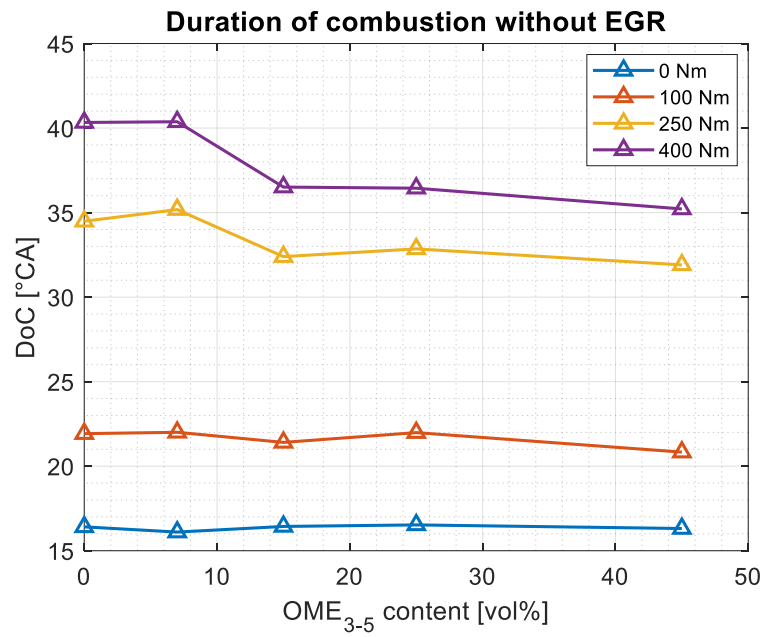


Figure 7. Duration of combustion without EGR for the different mixtures at different loads

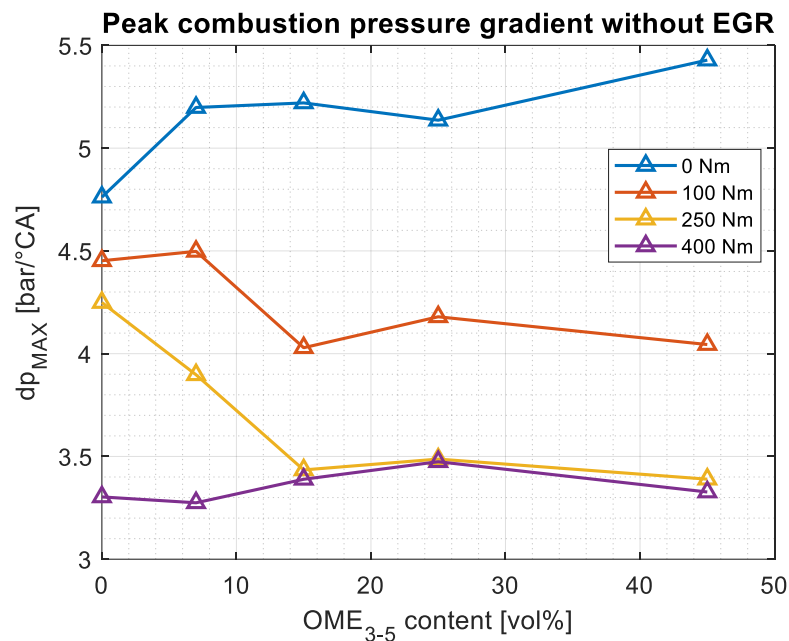


Figure 8. Peak combustion pressure gradient without EGR for the different mixtures at different loads

### 3.4. Heat release rates

In this section, the heat release rates (HRR) at the different loads are demonstrated, but to make them more clear, only the higher blends are plotted to the diagrams. Figure 9 shows the heat release rates of the 25 and 45 vol% blends compared to the reference pure B7 measurement at no load. It is discernable that at this small dose, the premixed phase is significant compared to the diffusion phase. The increasing OME<sub>3-5</sub> content has no significant effect on it, perhaps it is slightly increased. The diffusion phase also does not indicate significant changes, but due to the rising oxygen content, the burn-out phase clearly starts earlier for the 45% blend.

The 100 Nm results presented in Figure 10 show much more influence. The combustion of higher mixing ratios starts earlier because of the shorter ignition delay, as a result of the increasing CN. This clearly reduces the proportion of the premixed phase. The diffusion phase shows a different behavior than expected. The oxygen content accelerates the combustion there, thus the peak HRRs are larger in this phase for the higher OME<sub>3-5</sub> content. The 250 Nm data is similar to the 100 Nm data. The reduction of the premixed phase and the acceleration of the diffusion phase are also discernable, but the latter is not that significant. However, the 250 Nm load has longer DoC than the lower loads, thus a small acceleration can still make a notable reduction of DoC.

In the case of the 400 Nm load, only a little local maximum marks the premixed phase. However, this peak decreases because of the increasing CN. The diffusion phases are similar, but the burn-out phase starts earlier for the larger OME<sub>3-5</sub> content, just like at lower loads.

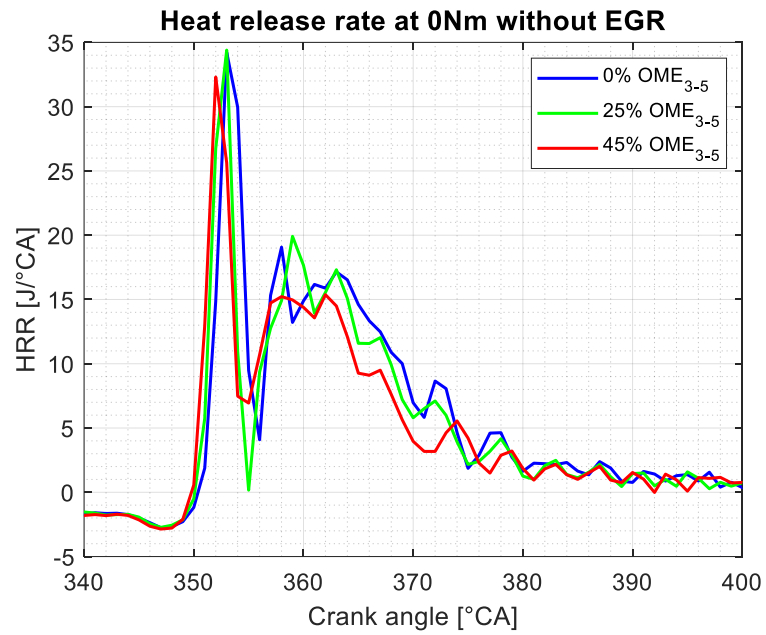


Figure 9. Heat release rate at 0 Nm load without EGR rate for different blends

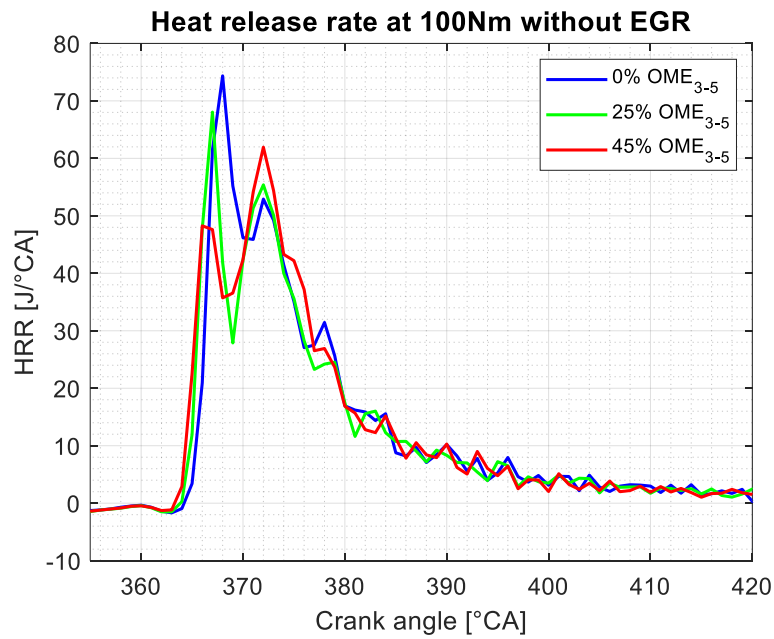


Figure 10. Heat release rate at 100 Nm load without EGR rate for different blends

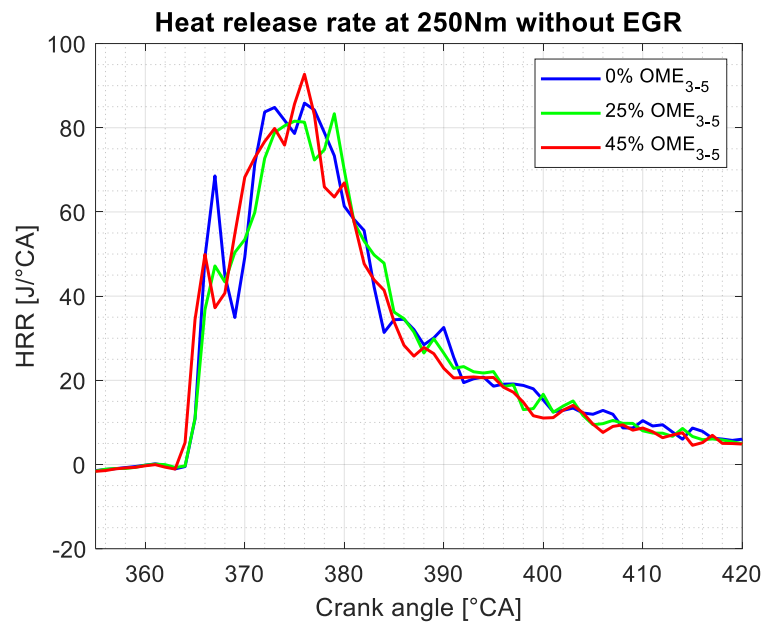


Figure 11. Heat release rate at 250 Nm load without EGR rate for different blends

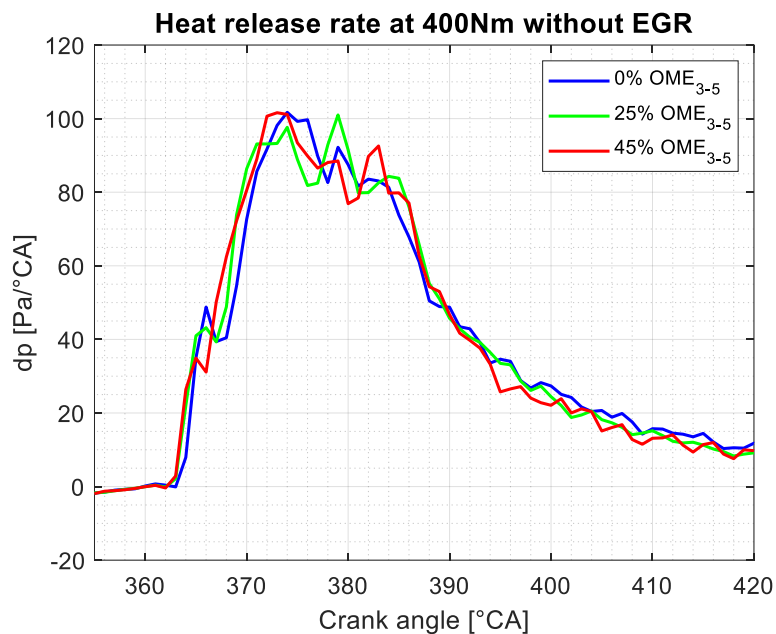


Figure 12. Heat release rate at 400 Nm load without EGR rate for different blends

#### 4. Conclusion

OME is a promising advanced fuel which can be produced from renewable resources, thus it diminishes the WTW CO<sub>2</sub> emission. In addition, this oxygenate is able to reduce soot emission greatly due to its high oxygen content, the lack of C-C bonds, and the C-O bonds present in the molecule structure. This enables the use of higher EGR rates, thus the NO<sub>x</sub> emission can also be reduced. As a consequence, this is an excellent alternative propellant for diesel engines. The combustion properties can also be improved due to the high CN of longer chain OMEs. However, there are still challenges to be solved if this fuel is to be applied at a large scale. Low LHV is a problem, because larger fuel tanks are needed. The low viscosity and the possible cavitation might damage the fuel system. Moreover, the commonly used sealing materials are incompatible with this polar fuel. Furthermore, methane and formaldehyde emissions may emerge when high EGR rates are used.

This work demonstrated the promising effects of OME<sub>3-5</sub> on the combustion and emission of a medium-duty commercial diesel engine. The reason behind using OME with higher degree of polymerization was that it has superior CN, and closer



viscosity to B7 diesel than OME<sub>1</sub>. During the investigations, we experienced the same benefits and demerits as described in the literature. The engine-out emissions could be effectively reduced. PM emission decreased by around 70% with only 15 vol% OME<sub>3-5</sub> blend for medium and high loads. The maximum reduction was 86.8% with the 45 vol% mixture for the 400 Nm load. This great decrease also diminishes the NO<sub>x</sub>–PM trade-off, so the costs of the exhaust aftertreatment can be decreased. In addition to better emissions, the BTE also increased notably, and the BSFC also increased due to the low LHV. The combustion also improved, because the high CN of the substance reduced the proportion of the premixed phase, while the oxygen content of the fuel reduced the DoC. The peak combustion temperature rose, which can also be another factor for the enhanced NO<sub>x</sub> generation, but this can be reduced with higher EGR rates as described previously. The peak pressure gradient had different behavior at different loads, but it did not exceed the defined knocking limit. The heat release rates also substantiated that combustion started earlier due to the shorter ignition delay resulting from the higher CN. This reduced the rate of heat release during the premixed phase. The high oxygen content slightly accelerated the combustion, thus the burn-out phase started earlier.

In conclusion, the OME is a promising fuel for compression ignition engines. However, its properties should be modified with additives in order to use it in existing vehicles. Still, the incompatibility with the commonly used sealing materials remains an issue. A possible solution could be the modification of future engines to make them able to operate with high OME blends, similarly to the Swedish example with HVO.

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### Abbreviations

BSFC, Brake Specific Fuel Consumption;  
BTE, Brake Thermal Efficiency;  
CN, Cetane Number;  
CO, Carbon Monoxide;  
CO<sub>2</sub>, Carbon Dioxide;  
CoHR, Center of Heat Release;  
DME, Dimethyl Ether;  
DMM, Dimethoxy Methane;  
DoC, Duration of Combustion;  
DPF, Diesel Particulate Filter;  
ECU, Engine Control Unit;  
EGR, Exhaust Gas Recirculation;  
FSN, Filtered Smoke Number;  
H<sub>2</sub>, Hydrogen;  
HC, Hydrocarbon;  
HP-EGR, High Pressure Exhaust Gas Recirculation;  
HRR, Heat Release Rate;  
HVO, Hydrogenated Vegetable Oil;  
ID, Ignition Delay;  
LHV, Lower Heating Value;  
NO<sub>x</sub>, Nitrogen Oxides;  
OME, Oxymethylen Ether;  
PM, Particulate Matter;  
SoI, Start of Injection;  
WTW, well-to-wheel;



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