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BIOFUELS AND E-FUELS USED IN A MULTI-FUEL-ENGINE AS SOLUTION FOR RAPID REDUCTION OF GREENHOUSE GAS IMPACTS OF NRMM ENGINES

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ABSTRACT

In the non-road mobile machinery (NRMM) sector, long operating hours combined with specific high-load operating conditions place high performance requirements on the propulsion system.

The established propulsion systems in the field of NRMM meet these requirements through diesel engines powered by liquid fuels with high energy density – a requirement which cannot be met by current battery electric drive systems. However, in order to reduce fossil CO₂ emissions as fast as possible, fuels produced from regenerative sources must be introduced for these purposes, which also have to be compatible with existing vehicle fleets.

These requirements were addressed in the project presented here through the development of a multi-fuel engine concept, which is suitable for the fully flexible use of pure rapeseed oil in any blending ratio with diesel fuel. In addition to the use of rapeseed oil/diesel blends, also the use of rapeseed oil/e-fuel blends (using hydrated vegetable oil – HVO – and oxymethylene ether – OME) has been investigated. For existing vehicles, such concepts could also provide the opportunity of retrofit solutions. The flexible use of vegetable oil, diesel fuel and e-fuels makes the customer independent of current fuel availability. As a prototype, a John Deere 4045 engine was optimized for the use of vegetable oil. In addition to the development of a DPF regeneration concept suitable for vegetable oil, the project focused on the potential for emission reduction and the impact on engine efficiency.

Keywords: Non-road mobile machinery (NRMM), agricultural machinery, internal combustion engine (ICE), e-fuels, rapeseed oil, straight vegetable oil (SVO), oxymethylene ether (OME), hydrated vegetable oil (HVO), multi-fuel operation, fuel blending, DPF regeneration, emission reduction

NOMENCLATURE

AI50	combustion center (50% mass fraction burned)
ATDC	after top dead center
BEV	battery electric vehicle
BTE	brake thermal efficiency
CNG	compressed natural gas
CO	carbon monoxide
CO ₂	carbon dioxide
DPF	diesel particulate filter
DOC	diesel oxidation catalyst
EAT	exhaust gas aftertreatment
ECU	engine control unit
EGR	exhaust gas recirculation
EOI	end of injection
FAME	fatty acid methyl ester
FCEV	fuel cell electric vehicle
FID	flame ionization detector
FTIR	Fourier-transform-infrared- spectroscopy
HC	hydrocarbons
HICE	hydrogen internal combustion engine
HVO	hydrated vegetable oil
NO _x	nitrogen oxides
NRMM	non-road mobile machinery
OME	(poly-)oxymethylene ether
PM	particulate matter
PTO	power take off
SOI	start of injection
SVO	straight vegetable oil
HEV	hybrid electric vehicle (var. types)

1. INTRODUCTION

To mitigate the anthropogenic effects of climate change, greenhouse gas emissions must be reduced rapidly. The main focus should be to avoid the use of fossil fuels. In the field of mobile machinery, several potential solutions are currently under investigation and development. For the private vehicle sector, battery electric vehicles (BEVs) appear to be the most appropriate solution for many applications. A battery electric powertrain might also be used for light on-road commercial vehicles (e.g. hub to hub distribution). In other applications of commercial vehicles, such as agriculture, forestry, or construction machinery – often referred to as “non-road mobile machinery” (NRMM) – battery electric drives still fail to meet the requirements for several typical use cases.

This is also due to the characteristics of the NRMM sector, where mobile machinery and equipment are used for commercial purposes. The applications may be classified according to power requirements and work shift or operating time. The requirements to the vehicles and their propulsion systems range from vehicles or machines with relatively low power demand and short operation times (e.g. small tractors in agriculture or light construction machinery) to large machines with huge power requirements and almost non-stop operating times (e.g. in mining applications). In the field of NRMM, diesel engines are currently the “state of the art” powertrain, meeting the above requirements by the use of liquid fuels with high energy density. However, to reduce anthropogenic greenhouse gas emissions, alternative non-fossil energy sources need to be considered. Besides the above mentioned battery electric drives on the one side and advanced diesel-powered drives on the other, potential solutions are hybrid electric drives (HEVs), renewable and synthetic drop-in fuels (e.g. vegetable oil or liquid e-fuels) or hydrogen powered drives (either fuel cell electric vehicles – FCEV – or hydrogen internal combustion engines – HICE) [1–4].

To find the most suitable energy source for each application, it is essential to analyze all the possibilities, their potential, and the potential speed of introduction and market penetration. For heavy-duty equipment, the power and energy density of the drive system is a limiting factor. A comparison between diesel engines and their alternatives in terms of package space required to store the same amount of energy shows an increase by a factor of 17 for hydrogen-powered drives (FCEV and HICE) and by a factor of 23 for BEVs [1]. As a result, completely new vehicle concepts will be required for many applications in order to integrate the alternative energy storage and drive systems, which is a major hurdle in terms of market acceptance and speed of introduction. Further current challenges associated with battery electric or hydrogen-fueled powertrains are the need for setting up a new infrastructure, and also the frequency and the duration of recharging or refueling, which might become unacceptable for certain applications.

To avoid these drawbacks and to accelerate the adoption of non-fossil energy sources, renewable or synthetic fuels could be used in existing diesel powertrains. In this case, the advantages

of diesel engines and of liquid fuels can be maintained, but without increasing greenhouse gas emissions.

If renewable fuels with properties similar to diesel are used, the existing vehicle fleet might profit as well, either by simply replacing fossil fuels by compatible renewable fuels, or through retrofitting the existing vehicles and engines to run on new fuels. This might contribute to the required rapid reduction in greenhouse gas emissions. For new vehicles, a potential approach is the development and deployment of a multi-fuel engine concept as described in the following. This concept was developed particularly for the use in agricultural machinery.

1.1 Multi-Fuel engine concept

The acceptance of alternative energy sources by the customers is key for a rapid reduction of greenhouse gas emissions and needs to be paid particular attention in the concept finding phase for new concepts. The primary goal of the multi-fuel concept is to allow customers to refuel their vehicle from a (defined) range of different fuels at any time, regardless of the resulting mixture in the fuel tank. A potential renewable fuel to be considered for application in agriculture is rapeseed oil, belonging to the group of straight vegetable oils (SVO). In addition to the potential for reducing greenhouse gas emissions, a further advantage of rapeseed oil or rapeseed oil blends as fuels for agricultural machinery is the chance of decentralized oil (thus fuel) production with a very short supply chain.

Starting from a series NRMM diesel engine as the basis for the study, some minor adjustments first needed be carried out to qualify the engine for the use the higher viscosity rapeseed oil. In addition to the exchange of fuel hoses and the use of increased tube diameters, an important step was the development of an optimized operation strategy for the exhaust gas aftertreatment (EAT) system [5–7]. This was followed by investigations of the combustion behavior in order to understand and exploit the potential of the fuel for emission reduction [5]. As a result, the combustion parameters were adjusted for optimum combustion performance for each possible diesel / rapeseed oil blend.

As a next step, the potential of replacing the diesel component with oxymethylene ether (OME) or hydrogenated vegetable oil (HVO) was studied as a measure for mitigating the emissions (greenhouse gases and pollutants) originating from the diesel component in the mixture. Using a fuel blend of rapeseed oil and an e-fuel also provides the opportunity to disconnect local food production from (fossil) fuel availability and to provide a wider variability in the fuel supply, making this important sector more resilient with respect to potential international crises, fuel shortages and cost increases. The potential emission reduction opportunities and the adjustment of the combustion for different variations of rapeseed oil / e-fuel blends are presented in this paper.

2. BACKGROUND

2.1 Fuels

Fossil diesel fuel

The material structure of diesel fuel is a mixture of various hydrocarbon compounds. The main components of this mixture are n- and iso-alkanes, alkenes, alkynes, cycloalkanes and aromatic hydrocarbons [8]. Cycloalkanes and aromatic hydrocarbons are the precursors for soot formation [9]. The diesel fuel used in this study complies with the European standard DIN EN 590, which allows a content of up to 7 vol-% of fatty acid methyl esters (FAME).

Rapeseed oil

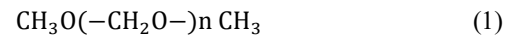
In contrast to the material structure of diesel fuel, pure rapeseed oil is a triacyl glyceride, which means that it consists of a glycerin molecule with three added fatty acid chains [8]. Rapeseed oil contains almost no aromatics, which reduces the formation of soot. The idea of CO₂ reduction through the use of rapeseed oil is justified by its potential to realize a closed CO₂ cycle, as the carbon content of the oil stems from ambient CO₂ absorbed by the plants. Furthermore, pure rapeseed oil is biodegradable and can therefore be used in environmentally sensitive areas (as food production and agriculture in general). In Western Europe and particularly in Germany, rapeseed is the most important oil plant and thus the most commonly used vegetable oil for fuel supply [10]. Rapeseed is also an important element of crop rotation in agriculture and promotes biodiversity [11]. In Germany, for example, about two thirds of the rapeseed plants are processed into high-protein feed for livestock. To produce such feed, the plants are pressed exclusively mechanically. Rapeseed oil is a by-product of this feed production and is therefore readily available, avoiding land use competition with food production [10]. To ensure its fuel properties, rapeseed oil is standardized in DIN 51605.

Hydrated vegetable oil (HVO)

Hydrating of vegetable oil is an approach to produce a regenerative fuel with similar properties as fossil diesel fuel. In this process, vegetable oil is converted into a mixture of paraffinic hydrocarbons. This mixture is free of sulfur and aromatics [10, 12]. The properties of HVO are very similar to fossil diesel fuel. Therefore, HVO can be used with relatively small adaptations in logistics, engine combustion and EAT strategies. Nonetheless, the hydration process is energy intensive, and to create a fully renewable fuel, the use of energy from renewable sources is essential. To ensure its fuel properties, HVO is standardized in DIN 15940.

Oxymethylene ether (OME)

OME is a fully synthetic diesel alternative based on the following structural formula:



The oxygen bridges connecting the carbon atoms avoid direct carbon-to-carbon bonds, which are one of the sources of soot formation during combustion. This property leads to soot-free combustion without particle formation. The absence of soot-forming elements in the fuel creates the opportunity to mitigate the so-called soot-NO_x trade-off [13, 14].

OME may be produced from a synthesis reaction using hydrogen and CO₂ as primary sources. If the supplied hydrogen is produced from renewable energy (e.g. water electrolysis using solar energy) and the CO₂ is extracted from the atmosphere (also using energy from renewable sources), the OME produced is completely CO₂-neutral [13].

The physical properties of OME depend on the chain length. A blend of OME₃, OME₄ and OME₅, called OME₃₋₅, was used in the experimental studies conducted as part of this research, due to its increased similarity to fossil diesel fuel, in contrast to shorter-chain OME [14]. To ensure its fuel properties, OME will be standardized according to DIN SPEC 51699.

Comparison of fuel properties

Table 1 provides an overview of the physical properties of all fuels used in this study.

property	unit	diesel fuel	rapeseed oil	HVO	OME ₃₋₅
density	kg/m ³	833	920	780	1067
kinematic viscosity (40 °C)	mm ² /s	2.72	35.5	3.01	1.188
heating value	MJ/kg	41.4	37.1	43.5	20.7
boiling range _{10-90 % mass fraction}	°C	230-340	300-340	270-280	160-200
volumetric energy density	kWh/l	9.6	9.6	9.4	5.6
cetane number	-	54.2	44	74.3	71.4
carbon	kg/kg	0.865	0.774	0.855	0.439
hydrogen	kg/kg	0.136	0.117	0.154	0.086
oxygen	kg/kg	-	0.109	-	0.409

TABLE 1: PHYSICAL PROPERTIES OF DIESEL FUEL (EN 590) RAPESEED OIL (DIN 51605) HVO (DIN 15940) AND OME (DIN SPEC 51699)

Diesel fuel is the comparative fuel for all investigations, as it is currently used in many conventional NRMM engines. Rapeseed oil is an unrefined biofuel that can be produced locally and processed decentral so that it is available in fuel quality. A fuel supply that is independent of suppliers could be ensured by using rapeseed oil as a fuel in agriculture. Variable refueling of a vehicle with diesel and/or rapeseed oil is thus a first step in a multi-fuel concept with market acceptance. HVO and OME were selected for the investigation of a further admixture of e-fuels to rapeseed oil. HVO is a diesel substitute fuel that has diesel-like properties. It is characterized by a comparatively high cetane number and high energy density, also in comparison to diesel fuel. In contrast to FAME, the use of HVO is harmless in terms of material compatibility [15]. These properties only apply to a limited extent to the use of OME. It has a reduced energy density and is relatively incompatible with other materials. However, OME is a soot-free diesel fuel with a high cetane number, so that fuel properties could be particularly influenced by blending it with other fuels.

2.2 Previous investigations

Rapeseed oil has been investigated as a substitute energy source for tractors by Dieringer et al. [16] and Düsseldorf [17]. In the research work of Dieringer, the aim was to use vegetable oil in an EU Stage IIIA tractor engine with a retrofitted DPF/DOC. The lower calorific value of the vegetable oils tested resulted in a 15 % reduction in full load power. Modified ECU software was not deployed during the tests. Particulate matter (PM) and hydrocarbon (HC) emissions were reduced when rapeseed oil was used [16]. Düsseldorf et al. [17] investigated the use of rapeseed oil in an engine with an EAT system for Stage IIIB and Stage IV emission standards. To ensure that the investigated engine comply with the Stage IV emissions standard, the use of a DPF was necessary. The standard approach for regenerating a DPF in diesel operation is late post-injection. The late-injected diesel fuel does not participate in combustion and thus will be converted in the DOC. This process contributes to the exhaust temperature rising to over 600 °C. At such high temperatures, the soot stored in the DPF oxidizes to CO₂. Düsseldorf tested such a diesel-type regeneration process using rapeseed oil. However, using this strategy with rapeseed oil led to significant engine oil dilution. To mitigate oil dilution, additional components were required for DPF regeneration. Düsseldorf investigated external HC dosing units and catalytic burners to achieve the required exhaust gas temperatures in DPF. In addition, he also examined a dual-fuel approach using different gaseous fuels (diesel + compressed natural gas (CNG), rapeseed oil + CNG). The investigations resulted in a reduction of PM and NO_x emissions, while CO and HC emissions increased due to the methane slip.

Emberger et al. [8] investigated the emission performance of different vegetable oils in tractors. The emission results showed lower specific PM, CO and HC emissions but higher specific NO_x emissions at medium and high load operating points. In idle operation, the products of incomplete combustion (CO, HC, PM) were higher for vegetable oil. The poorer

conditions for mixture preparation led to an increased ignition delay, which was supposed to be the reason for incomplete combustion in idle mode and low load operation.

None of the previous investigations examined the potential in emission reduction through adaption of the combustion parameters to the combustion properties of rapeseed oil fuel. The previous investigations used the original diesel data from the ECU. Therefore, the full potential has never been exploited in these studies.

3. EXPERIMENTAL SETUP

The engine studied on the test bench is a John Deere JD4045 engine, which is typically used in agricultural machinery. This is a 4-cylinder engine with a common rail injection system and a two-step turbocharging system, producing 110 kW of maximum power. Some further technical details of the engine are presented in Table 2.

The fuel injection system is supplied by a dual-piston high pressure pump and uses solenoid injectors to inject the fuel directly into the combustion chamber. The engine is equipped with two exhaust gas turbochargers arranged in series. The second turbocharger has a wastegate for passive boost pressure control. The compressed air passes through an intercooler before being supplied to the intake system. The engine is equipped with a high-pressure exhaust gas recirculation (EGR) line, containing an electrically actuated EGR valve and an EGR cooler.

	value	unit
max. effective power	110	kW
max. torque (@ 1600 rpm)	580	Nm
nominal speed	2100	rpm
displacement	4.5	dm ³
compression ratio	17.3:1	-
bore diameter	106.5	mm
stroke	127.0	mm
valves per cylinder	4	-
emission standard	EU stage V	-

TABLE 2: TECHNICAL DETAILS OF TEST ENGINE

The engine was equipped with cylinder pressure indication sensors on all four cylinders and lambda sensors on each exhaust port. Additionally, gas temperature is measured close to the exhaust ports. By this, the combustion and the equal distribution between the different cylinders can be compared against various properties. The exhaust gas components CO and NO_x were analyzed via the FTIR principle using a Horiba MEXA 6000-FT. To detect THC, O₂ and CO₂ in the exhaust (and the latter also in intake manifold to determine the real EGR rate), a Horiba MEXA 7100-DEGR was used. The sampling point for the exhaust gases was located downstream of the second turbine and upstream of the DOC. Particle emissions were analyzed using a photoacoustic measurement principle with an AVL Microsoot Sensor. To understand the combustion potential of the fuels and

mixtures, several discrete mixtures were chosen. Table 3 shows the investigated fuel mixtures and their composition.

name	composition (m/m)
D100	100 % diesel fuel
R25D75	75 % diesel fuel & 25 % rapeseed oil fuel
R50D50	50 % diesel fuel & 50 % rapeseed oil fuel
R75D25	25 % diesel fuel & 75 % rapeseed oil fuel
R100	100 % rapeseed oil fuel
R90HVO	90 % rapeseed oil fuel & 10 % HVO
R75HVO	75 % rapeseed oil fuel & 25 % HVO
R50HVO	50 % rapeseed oil fuel & 50 % HVO
R90OME	90 % rapeseed oil fuel & 10 % OME
R75OME	75 % rapeseed oil fuel & 25 % OME
R50OME	50 % rapeseed oil fuel & 50 % OME

TABLE 3: INVESTIGATED FUEL MIXTURES AND THEIR COMPOSITION

4. RESULTS AND DISCUSSION

The standard limited emissions for diesel engines are HC, CO, NO_x, and PM emissions. HC and CO emissions can be reduced relatively easily in a DOC due to the high percentage of oxygen in the exhaust gas. PM and NO_x emissions are more critical and typically exhibit a trade-off behavior. The formation of both pollutants is directly dependent on the EGR rate of the engine. In order to illustrate the influence of rapeseed oil on the critical pollutants, Figure 1 shows the differential deviations between rapeseed oil and diesel fuel in terms of EGR rate, NO_x and PM emissions.

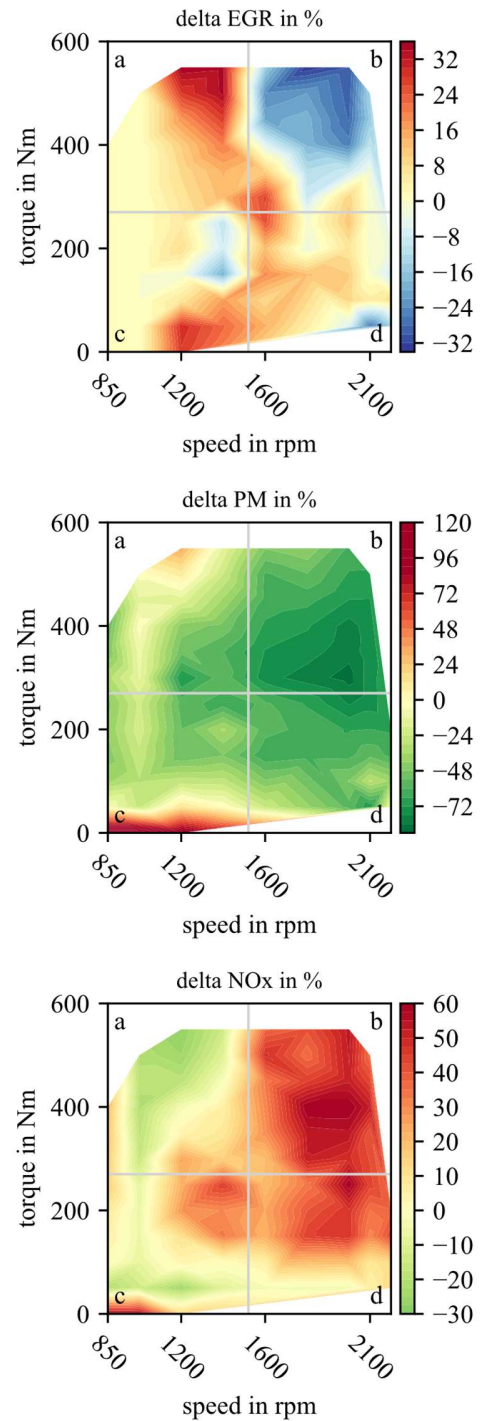


FIGURE 1: DIFFERENTIAL COMPARISON OF REAL EGR RATE, NO_x AND SOOT EMISSIONS BETWEEN DIESEL AND RAPESEED OIL OPERATION

The first diagram of Figure 1 shows the differential deviations of the measured EGR rate resulting from the use of rapeseed oil when the ECU is not modified. The measured EGR rate in rapeseed oil operation varies between approximately

30 % lower and approx. 30 % higher values compared to diesel operation. In the low speed and high torque range (quadrant a), the EGR rate tends to be higher, while in high speed and high torque range (quadrant b), the measured rate tends to be lower than in diesel operation. In the low speed and low torque range (quadrant c), there are areas where rapeseed oil tends to have lower EGR rates and areas where it tends to have higher EGR rates than in diesel operation. There is no clear trend in the high speed and low torque range (quadrant d). However, this operating range is the least interesting when considering the engine operation requirements of a NRMM vehicle.

The second diagram shows the differential deviations of the PM emissions. At first glance, it can be seen that the PM emissions in rapeseed oil operation are lower than in diesel operation almost over the entire engine operating map. Only in a narrow range of low speed and very low torque (lower range in quadrant c), an increase in PM emissions can be observed. A slight increase in PM emissions is also obvious in a small area at low speed and high torque (1200 rpm and >500 Nm).

The third diagram shows the differential deviations in NO_x emissions. The region of low speed and high torque (a) shows a slight decrease in NO_x emissions. However, the high speed and high torque range (b) exhibits a significant increase in NO_x. This increase is due to the reduced EGR rate in this map region (first diagram, b). The increase of NO_x emissions can also be observed at medium torque over almost the entire speed range. Only in a small area of the low speed and low torque range there is a slight decrease.

The differential comparison between diesel and rapeseed oil with the standard diesel data set shows that the use of rapeseed oil has a different impact depending on the region of the engine map. The observed change in real (measured) EGR rate is a major influencing parameter which directly affects PM and NO_x emissions. In order to understand the full potential of the different fuels and to judge their suitability in normal operation, specific operating points need to be analyzed and optimized. For this purpose, four stationary operating points were selected. The operating points were chosen in the regions with the largest differences between the two fuels. These operating points are visualized in the engine map in Figure 2.

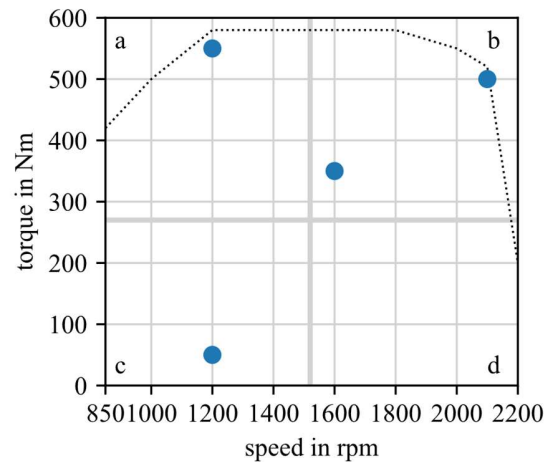


FIGURE 2: INVESTIGATED OPERATING POINTS IN THE ENGINE MAP

The first point (quadrant c) is an operating point with low speed and low torque (1200 rpm/50 Nm). At this operating point the EGR rate is about 25 % higher with rapeseed oil compared to Diesel. Contrary to the common assumption, the use of rapeseed oil leads to an increase in PM emissions at this low load point. The second point (quadrant a) is an operating point with low speed and high torque (1200 rpm/550 Nm). This operating point also shows an increase in EGR rate and PM emission. Low speed and high torque operation is required for certain tractor work applications, such as when a specific speed on the power take off (PTO) shaft is needed. The third operating point is an operating point at medium speed and medium torque (1600 rpm/350 Nm), which is right in the middle of the engine map, with EGR rate almost unchanged. PM emissions are reduced and a small increase in NO_x emission is observed. The last point examined is the operating point of nominal power with high speed and high torque (2100 rpm/500 Nm). The EGR rate is decreased when using rapeseed oil, which leads to an increase in NO_x emission but also reduced PM emissions.

Rapeseed oil / diesel blends

Figure 3 shows the PM-NO_x trade-off plots for a variation in EGR rate for the four operating points investigated. To improve comparability between the fuels, a single injection was chosen. The center of combustion (AI50) of the displayed operating points was kept at 8 ° after top dead center (ATDC). The emission values refer to specific emissions (in [g/kWh]).

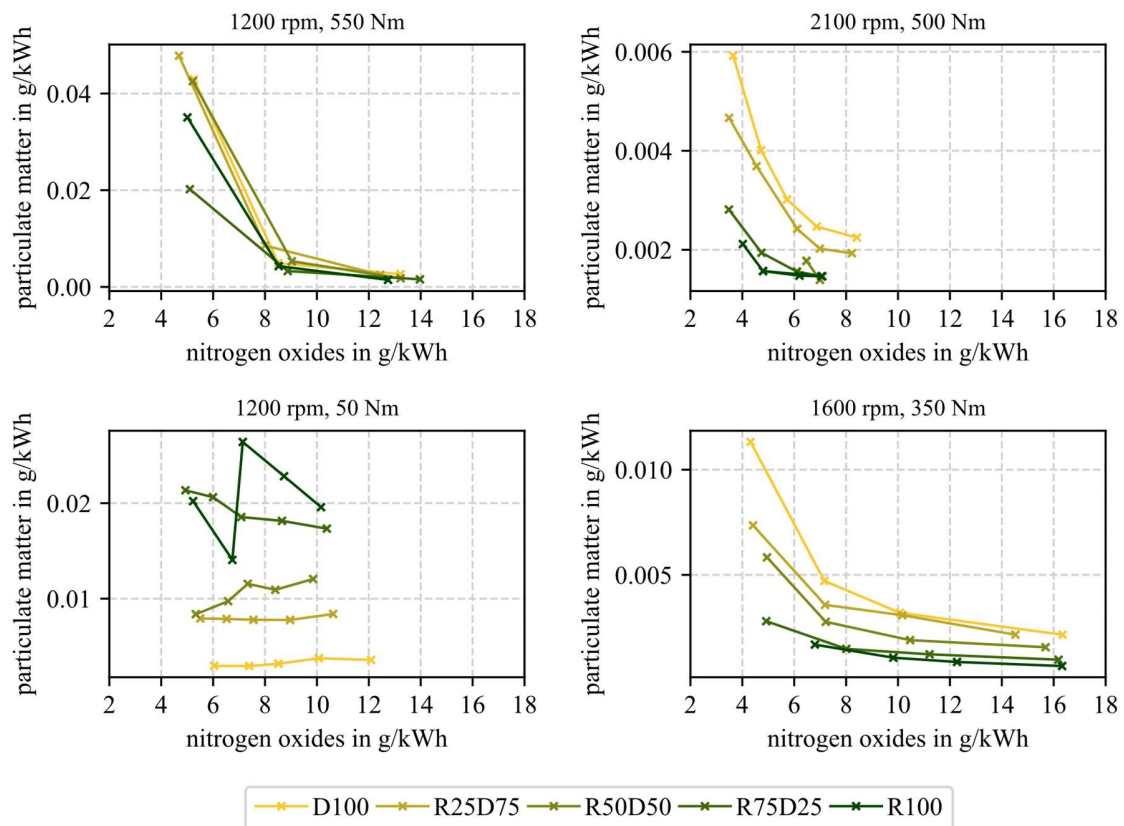


FIGURE 3: PM-NO_x TRADEOFF IN ALL OPERATING POINTS FOR ALL INVESTIGATED RAPESEED OIL DIESEL BLENDS

With increasing EGR rate, PM emission also increase and NO_x emissions decrease. This behavior in emission formation describes the typical PM-NO_x trade-off as it is well-known from diesel operation. The comparison of the fuel blends in Figure 3 shows a reduction in PM emissions with increasing rapeseed oil share for the operating points at high and medium load. PM emissions decrease with the increasing share of rapeseed oil since rapeseed oil is less prone to particulate formation than diesel due to the lack of aromatics in the fuel. In contrast to this, the low load operating point of 1200 rpm & 50 Nm shows an increase of PM emission with increasing rapeseed oil share. None of the fuels investigated shows the characteristic trade-off behavior in this low load operating point; the PM emissions are almost constant for all studied EGR rates, while NO_x emissions decrease with increasing EGR rate. An exception to this is the R100 measurement series. As the EGR rate increases, the PM emissions fluctuate significantly. This shows a high sensitivity of rapeseed oil in particle formation with fluctuating environmental conditions during low load operations. In terms of NO_x formation, smaller differences can be observed between the blends. However, the behavior observed in previous studies – particularly the phenomenon of rapeseed oil tending to increase NO_x formation – cannot be confirmed based on these measurements.

In order to help understand the different influence of rapeseed oil in the operating points of the present study, the heat release rates are studied. Figure 4 shows the heat release rate of D100, R75D25 and R100 at 1600 rpm/350 Nm. The rail pressure for each fuel was 166 MPa.

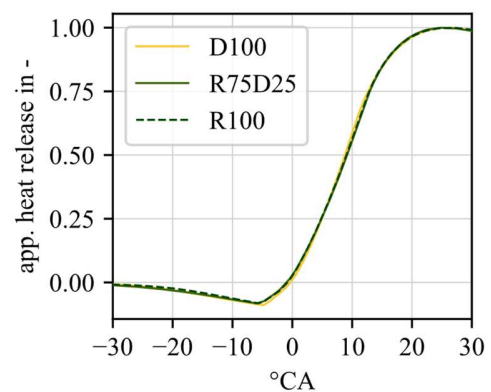


FIGURE 4: HEAT RELEASE RATE D100, R75D25 AND R100 (1600 RPM, 350 NM)

The heat release curves in Figure 4 show that there is no difference in ignition delay for any of the fuels shown. The center

of combustion of R75D25 and R100 is 1 °CA later than that of D100. The end of combustion (90 % heat release) is identical for all fuels studied. The difference in the heat release curve can be attributed to the different behaviour of the injector due to the viscosity of the fuel blend. The change in viscosity causes a delay in fuel injection, so that the center of combustion is reached late. To further evaluate the potential of rapeseed oil blends, Figure 5 shows the brake thermal efficiency as a function of EGR rate for all fuel blends.

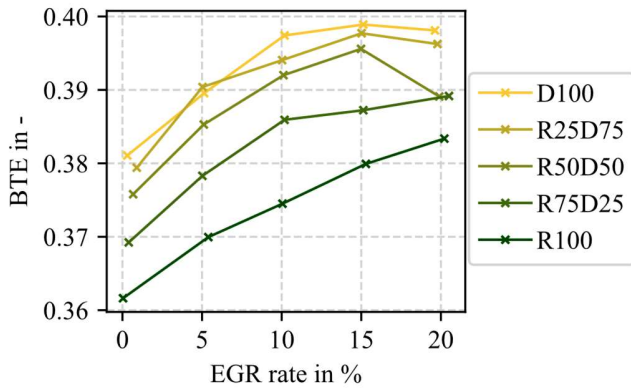


FIGURE 5: BRAKE THERMAL EFFICIENCY FOR ALL FUELS (1600 RPM, 350 NM)

It is obvious from the figure that thermal efficiency increases with increasing EGR rate. The underlying effect is the reduction of throttling at higher EGR rates. Thermal efficiency decreases as the share of rapeseed oil is increasing. The biggest difference between D100 and R100 is about 2 % BTE, which means that with blends containing rapeseed oil, emission of pollutants and greenhouse gases can be reduced with a small decreasing effect on the BTE. The PM-NO_x trade-off displayed in Figure 3 confirms that EGR rates higher than 15 % are possible with R75D25 and R100 to further reduce NO_x emissions without reaching the PM emission levels of pure diesel fuel. At EGR rates > 15 %, the brake thermal efficiency for this fuel is expected to increase further.

In order to explain the different impact of rapeseed oil on NO_x and PM emissions at the low load operating point, Figure 6 shows the heat release rate for D100, R50D50, R75D25 and R100 at 1200 rpm and 50 Nm. SOI and EOI are also displayed (identical for all fuels).

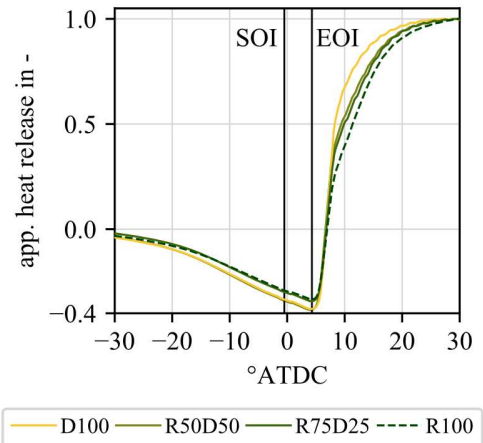


FIGURE 6: HEAT RELEASE RATE D100, R50D50, R75D25 AND R100 (1200 RPM, 50 NM)

Similar to the 1600 rpm/350 Nm operating point, the heat release curves show no difference in ignition delay between the fuels. The first 30 % of the heat release occurs at the same rate for all fuels. However, from 30 % on the fuels start to exhibit a different behavior. The higher the proportion of rapeseed oil in the fuel, the more likely the heat release rate slows down. Two different hypotheses are conceivable to account for the reduced heat release with rapeseed oil. One possibility is the retarded fuel injection for rapeseed oil despite the same SOI timing (referring to injector actuation). This is due to the higher viscosity of rapeseed oil, leading to different hydraulic behavior within the injector. The second possibility is the available amount of combustible air-fuel mixture of the corresponding phases of combustion. The different evaporation characteristics and increased boiling point of rapeseed oil might lead to delayed mixture preparation.

While SOI is identical for all fuels, EOI differs about 0.5 °CA between diesel and rapeseed oil. As obvious from Figure 6, the injection of all fuels ends before the start of combustion. Therefore, the slower combustion of rapeseed oil cannot be attributed to the difference in injector behavior. The desired amount of fuel is injected into the combustion chamber before combustion starts. This leads to the assumption that the described effect of slowed-down combustion is due to the mixing behavior of rapeseed oil.

The low enthalpy in the combustion chamber at this operating point amplifies the effects of the fuel properties. To minimize the effects, it is necessary to increase the enthalpy in the combustion chamber. This could be achieved by increasing the injection pressure. Figure 7 shows the effect of increasing the injection pressure on pollutant emissions.

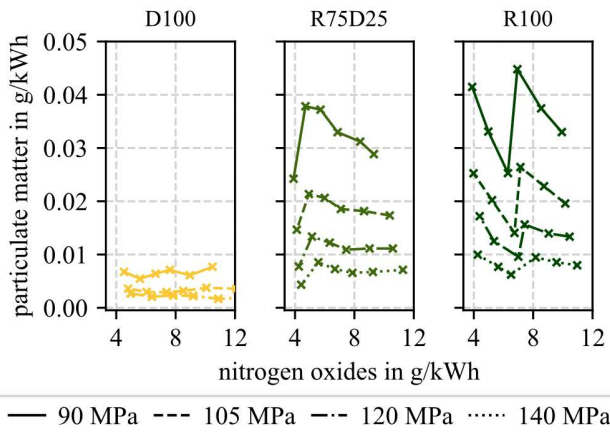


FIGURE 7: INFLUENCE OF INCREASING INJECTION PRESSURE ON PM AND NO_x EMISSIONS (1200 RPM, 50 NM)

Figure 7 shows that with increasing injection pressure, the specific PM emissions of R100 and R75D25 decrease. The emissions of pure rapeseed oil do not reach the low emission value of D100, but it reaches the same scale. The effect of increased injection pressure on particulate formation (reduction of emissions) is larger for rapeseed oil than for diesel fuel. The increase of injection pressure of D100 from 90 MPa on 105 MPa improves PM emissions only slightly. A further increase in the injection pressure has no notable effect on the PM emissions with D100. For injection pressures above 105 MPa, emissions remain on a constant level.

The PM emissions of R100 show a jump in the trade-off curve at 7 g/kWh NO_x and for R75D25 at 4 g/kWh NO_x. This is the result of varying ambient conditions such as humidity. At this operating point, it appears that the PM formation of rapeseed oil reacts sensitively to these influences. Figure 7 shows that increased injection pressure also reduces this sensitivity.

Increasing the injection pressure requires a higher mechanical power input at the high-pressure pump. In order to be able to assess the influence of the injection pressure increase on brake thermal efficiency, Figure 8 shows the efficiency for D100, R75D25 and R100 at 105 and 140 MPa rail pressure, respectively.

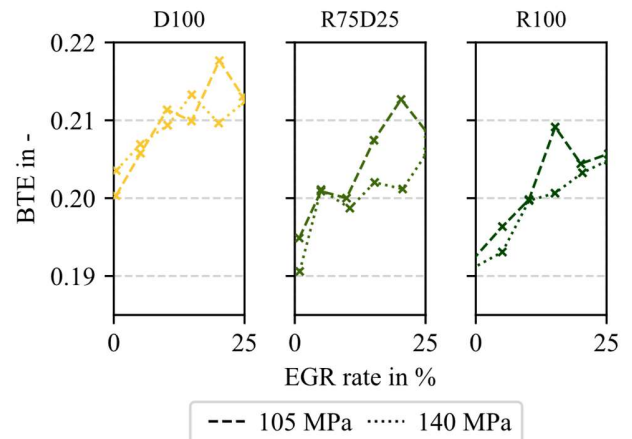


FIGURE 8: INFLUENCE OF INCREASING INJECTION PRESSURE ON BRAKE THERMAL EFFICIENCY (1200 RPM, 50 NM)

Brake thermal efficiency is around 20 % for all of the three fuels for this low-load operating point. Thermal efficiency remains almost constant despite the increased rail pressure. Obviously, the losses due to higher required pump power are compensated by improved combustion quality. In addition, the increase in injection pressure even lowers the PM emission level for fuel blends with high rapeseed oil content. Thus, the use of rapeseed oil in this operation range has a high potential for improvement with adapted application parameters.

Rapeseed oil / e-fuel blends

In continuation of the above investigations, the diesel share in the fuel blends was replaced by two different e-fuels – HVO and OME. Three blends were investigated for each of the e-fuels tested. The proportion of HVO or OME was increased from 10 to 25 to 50 mass percent in the mixture. To compare the potential of the fuel blends and their effects on combustion and emissions, a single injection was chosen for all blends. Figure 9 shows the effect of the described blends on PM and NO_x emissions with a variation of the EGR rate for all four operating points.

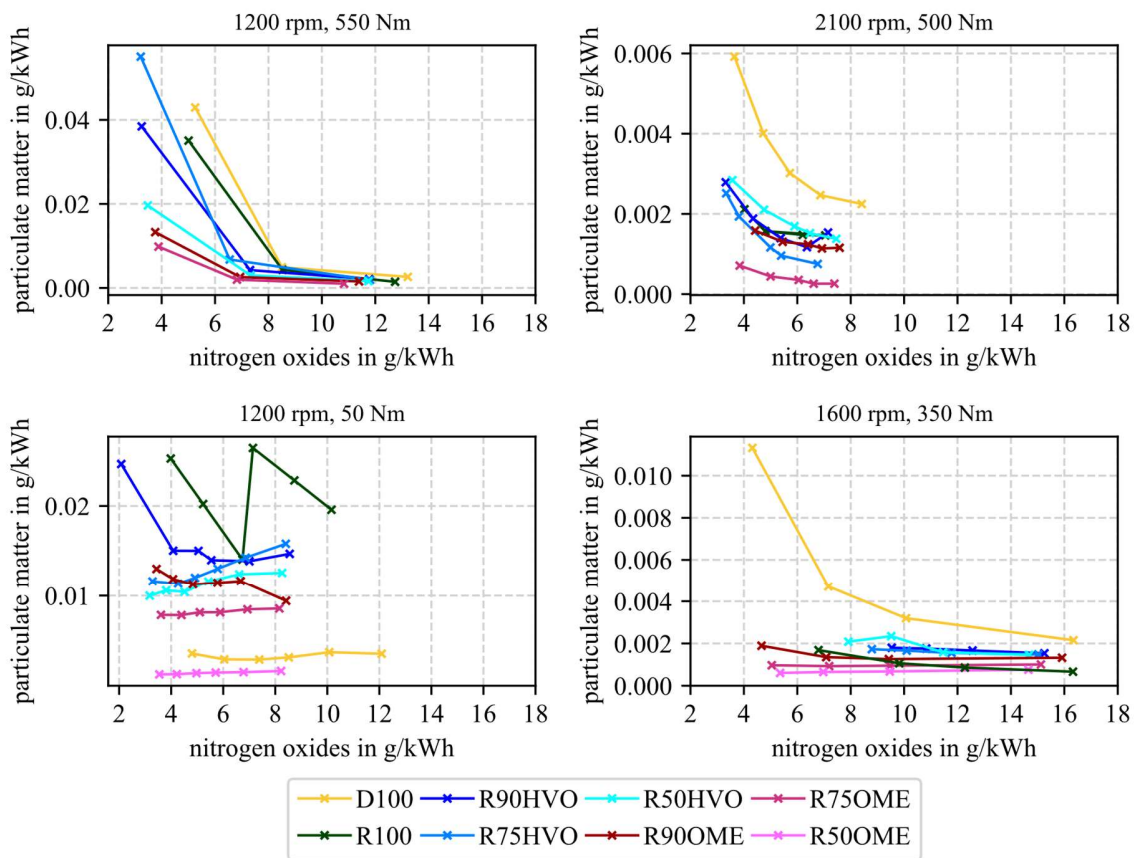


FIGURE 9: NO_x/PM TRADEOFF IN ALL OPERATING POINTS WITH RAPESEED OIL/E-FUEL BLENDS

At the high load operating points (1200 rpm/550 Nm and 2100 rpm/500 Nm), it was not possible to achieve the desired load with the R50OME blend. The reduced energy density of OME leads to the effect that the available time for fuel injection is not enough to inject the required mass of R50OME. To use a 50 % (m/m)-blend of OME and rapeseed oil in these two operating points, an adaptation of the injector would be required.

1200 rpm and 50 Nm

At low engine speed and low load, the e-fuel blends reduce PM emissions compared to pure rapeseed oil. All three HVO blends are in the same range in terms of PM emissions. The R90OME blend is also in the same PM emission range. One of the main influences on the emission formation at this low load operating point appears to be the evaporation behavior of the fuels. HVO exhibits similar evaporation temperatures to rapeseed oil, which results in comparable PM emissions from these blends. The evaporation temperature of OME is closer to the evaporation range of diesel. As the share of OME in the blend is further increased, PM emissions decrease. The PM emissions of the R50OME blend are similar to D100. Fuel injection is complete for all fuels before combustion starts.

As shown in the previous comparison of rapeseed oil/diesel blends, R90HVO also shows a jump in PM emission between 2

to 4 g/kWh NO_x. This is also a result of sensitivity to ambient conditions at low load.

1600 rpm and 350 Nm

The trade-off curves of all rapeseed oil/e-fuel blends are flattened compared to the trade-off curve of D100. The PM emissions of the blends are lower compared to D100. The less distinct trade-off behavior of the blends allows the use of higher EGR rates than in diesel operation. This makes it possible to further reduce NO_x emissions without increasing PM emissions compared to D100 operation. R75OME and R50OME show no trade-off behavior up to an EGR rate of 15 %.

1200 rpm and 550 Nm

At 1200 rpm and 550 Nm between 0 % and 5 % EGR rate, all fuel blends are in the same range of PM emission. Above 5 % EGR rate, PM formation is the same for D100, R100, R90HVO and R75HVO, but higher than for R50HVO, R90OME and R75OME. This operating point is a critical point in terms of emission formation due to the low excess air share. The air-fuel ratio at EGR rates close to 10 % reaches the soot limit for all fuels and the engine operation becomes unstable.

2100 rpm and 500 Nm

All of the investigated fuels show a trade-off behavior at this operating point. PM emissions from D100 are highest and the PM emissions from all HVO blends and R90OME are in the same range as R100. At EGR rates up to 15 %, R75HVO shows slightly lower PM emissions than R100, R90HVO and R50HVO. R75OME shows a further reduction in PM emissions. Emissions from R75OME at the highest EGR rate (25%) are lower than PM emissions from rapeseed oil at all EGR rates.

On the whole, it appears that the use of rapeseed oil/e-fuel blends results in a reduction in NO_x emissions compared to

D100. The formation of NO_x is sensitive to variations in air fuel ratio and the resulting amount of local excess air in the combustion chamber. In order to clarify whether the reduction in NO_x emissions is a fuel property or related to the air-fuel ratio, Figure 10 shows the correlation between air-fuel ratio and NO_x emissions.

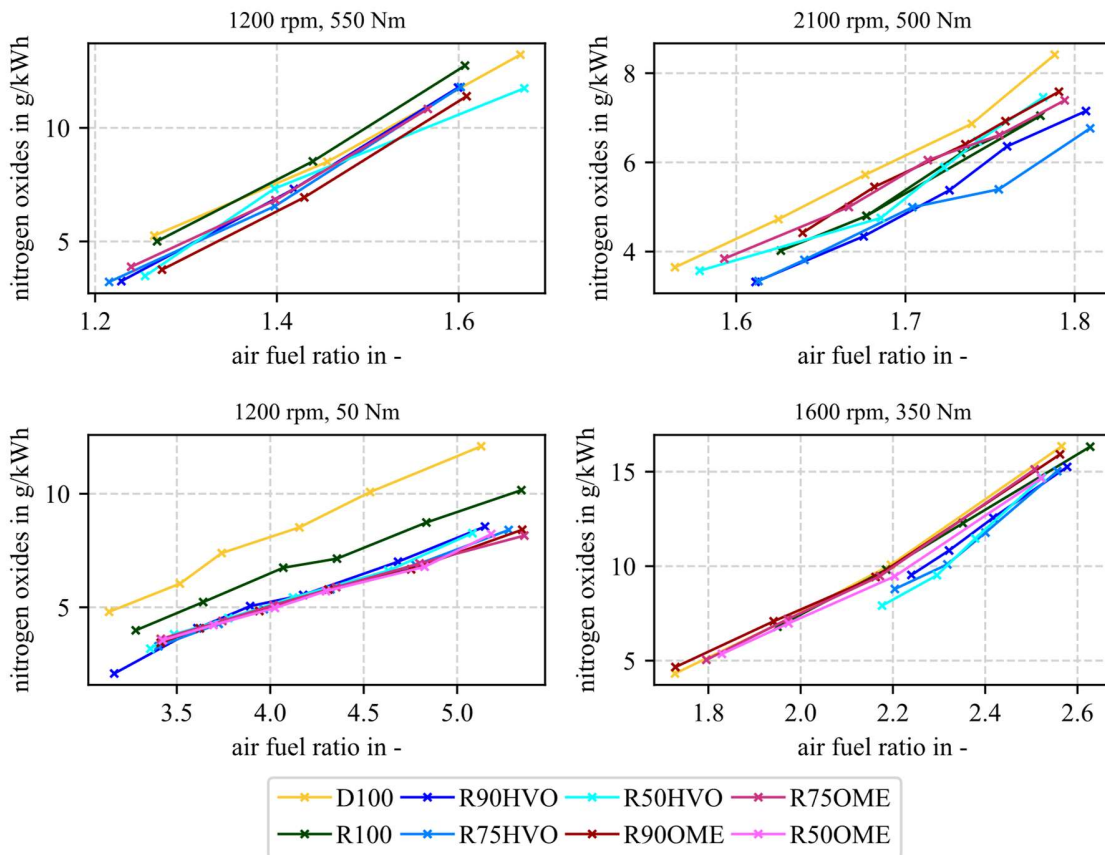


FIGURE 10: NO_x EMISSIONS IN RELATION TO THE AIR FUEL RATIO

Rapeseed oil/e-fuel blends cause a reduction in NO_x emission compared to D100 at all the operating points investigated. A difference between OME and HVO blends is visible at the 1600 rpm/350 Nm and 2100 rpm/500 Nm operating points. At these operating points, HVO blends show a reduced formation behavior in NO_x emissions than OME blends. A difference in NO_x formation between D100 and R100 is visible at the 1200 rpm/50 Nm and 2100 rpm/500 Nm operating points.

A possible explanation for the varying NO_x emissions are differences in combustion temperature, cylinder pressure and cylinder pressure gradient. Increases of these parameters lead to an increased formation of thermal NO_x. Apparent heat release rates are used as an indicator of these physical parameters to explain a possible difference in NO_x formation. This comparison is shown in Figure 11.

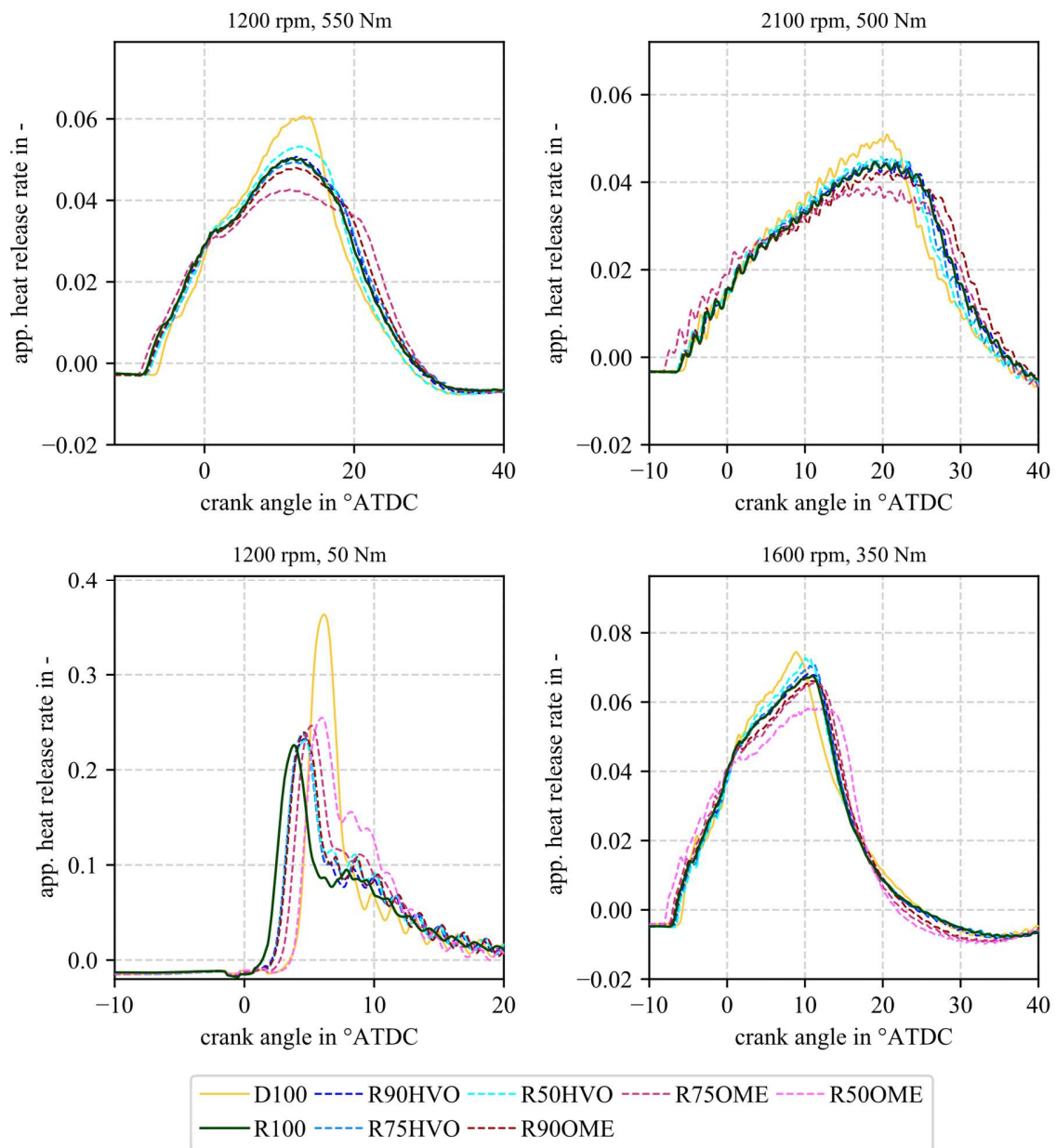


FIGURE 11: HEAT RELEASE RATES IN ALL OPERATING POINTS

At the operating point 1200 rpm/50 Nm, the heat release rate shows a significant peak for D100, which is a plausible reason for increased NO_x emissions. A possible reason for this peak is the lower viscosity of diesel fuel in combination with a volumetric energy density in the upper range of the fuel blends. These properties lead to a slightly later SOI timing combined with a reduced injection duration.

All other operating points also show a peak in apparent heat release rate of D100, but in the cases of the 1600 rpm/350 Nm and 1200 rpm/550 Nm operating points, this peak does not result in increased NO_x emissions. In these operating points, the NO_x emissions of D100 and R100 remain identical. At the moment,

there is no hypothesis which explains the difference in NO_x formation of D100 and R100 because of their properties in combustion. Possible reasons could be overlapping effects. This needs further investigations.

Another phenomenon seems to be the NO_x formation of HVO and OME. At medium and high loads, HVO tends to a reduced NO_x formation in comparison to the OME blends, but the gradients of the heat release are increasing with HVO share. In contrast to this, gradients are decreasing with the OME share.

Due to this behavior, Figure 12 shows a comparison of the maximum cylinder pressure between 1600 rpm/350 Nm and 2100 rpm/500 Nm.

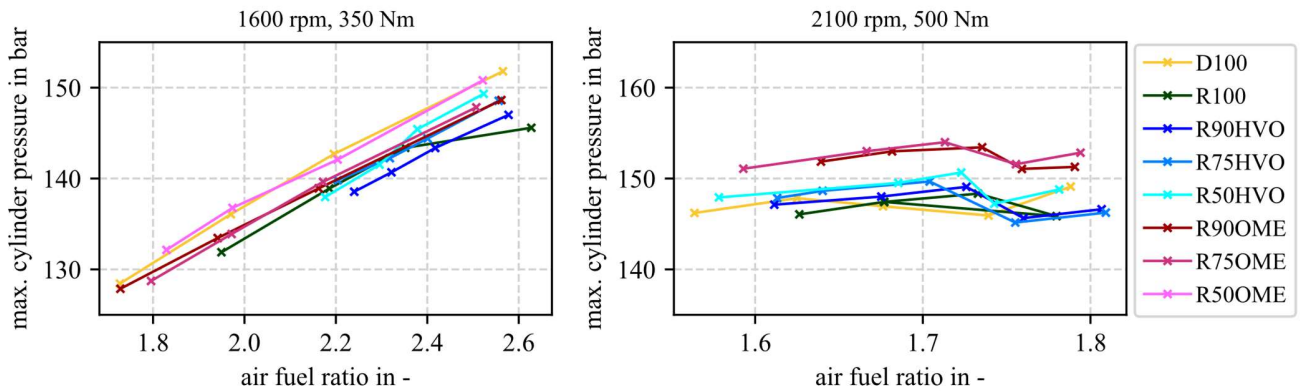


FIGURE 12: MAXIMUM CYLINDER PRESSURE

The graphs of Figure 12 show, that the maximum cylinder pressure of the OME blends is higher than the pressure of the HVO blends. OME has a lower energy density than HVO, so to achieve the same energy content for combustion, a longer injection duration is required. A longer injection duration with same AI50 requires an earlier SOI timing and results also in a later EOI timing. At these operating points, combustion therefore starts earlier as the energy density of the fuel blends decreases. This leads to an increased heat release share during the compression stroke. As a result, peak pressures are higher.

The described effect has a larger influence on emission formation at operating points with high engine speed, as the time for mixture preparation/combustion is shortened. Therefore, this effect is less pronounced for the operating points at 1200 rpm.

The comparison of the maximum cylinder pressure also does not explain the increased NO_x formation of D100 at 2100 rpm.

In order to obtain an overview of the influence of the different fuel blends on the brake thermal efficiency (BTE), Figure 13 shows the efficiency as a function of the air fuel ratio.

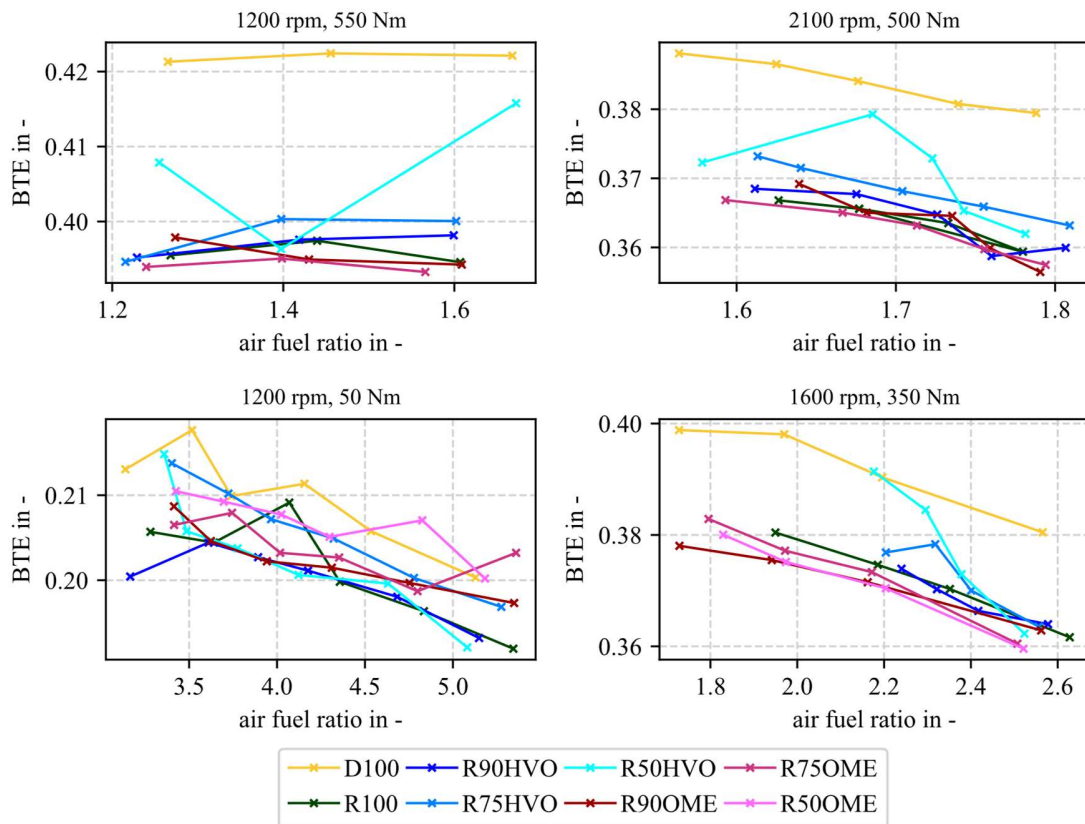


FIGURE 13: BRAKE THERMAL EFFICIENCY OVER AIR FUEL RATIO

The comparison of BTE confirms the effects which are shown in the heat release rates. All investigated fuel blends show a slight decrease in BTE compared to D100, due to an increased combustion duration. Compared to R100, BTE tends to rise with increasing HVO content. BTE of the OME blends is in the same range for all blends and slightly lower in comparison to the HVO blends.

However, the operating point of 1200 rpm/50 Nm is an exception, with the spread of the BTE between all fuel blends being much smaller. The increase of the OME share leads to an improvement in BTE, resulting in R50OME reaching the same level as D100. Since the PM emissions of R50OME are also reduced at this operating point compared to all other fuel blends, a high OME share indicates improved combustion at low load operation.

5. CONCLUSION

The fuels and fuel blends investigated in this study proved their suitability for use in diesel engines. These fuels could be used both in existing vehicles and machines or in new vehicles through minor conversions and thus appear to be capable of providing a fast solution for reducing the greenhouse gas impact of NRMM engines. For the full potential of the fuels to be exploited, the ECU application needs to be adapted.

Especially at medium and high loads, an increase of the rapeseed oil share in the fuel leads to improved EGR compatibility. As a result, engine throttling can be reduced so that the engine does not suffer any efficiency disadvantage. At the same time, nitrogen oxides are reduced without a disadvantage in particulate emissions. The use of rapeseed oil/e-fuel blends does not deteriorate the fuel properties compared to rapeseed oil. In some cases, additional improvements could be achieved.

A special behavior was observed at low load, where the low combustion chamber enthalpy leads to a deterioration of the particle emission with increasing rapeseed oil content in the HVO blends. Due to their comparatively high boiling range, mixture preparation deteriorates. Vehicle operation at low load thus leads to put increased stress on the particulate filter. This is particularly unfavorable, as particulate filter regeneration with SVO is a particular challenge. The results of the project show that it is possible to find operating parameters which largely compensate for these disadvantages through the targeted application of fuels. In the entire process, no negative influence on the BTE could be observed.

Another important finding relates to the nitrogen oxide formation behavior of rapeseed oil and of the fuel blends, differing only slightly one from the other. In contrast to the results of previous studies, the new measurements show that under thermodynamically identical conditions, the tendency of rapeseed oil to form nitrogen oxides is even lower than that of diesel fuel.

These findings represent an important step in the development of a multi-fuel concept. This implies the necessity of fuel detection so that the full fuel potential is not only

demonstrated on the test bench but can also be used in real operation.

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