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Effects of Crude Tall Oil Based Renewable Diesel on the Performance and Emissions of a Non-Road Diesel Engine

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Effects of Crude Tall Oil based renewable diesel on the performance and emissions of a non-road diesel engine

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Abstract

Environmental concerns and government policies aiming to increase biofuel shares have led to the search for alternative fuels from a variety of renewable raw materials. The development of hydrotreated vegetable oil (HVO) type fuels has been strong in the Nordic countries, partly due to the early use of tall oil from the forest industry as feedstock. An innovative production process to convert crude tall oil (CTO) – a residue of pulp production – into high-quality renewable diesel fuel was developed by a Finnish forestry company UPM. Paraffinic, high cetane and low aromatic CTO renewable diesel allows efficient and clean combustion, resulting in reductions of local air pollution in addition to not releasing any new CO₂ into the atmosphere during their combustion. This research investigated the influence of CTO renewable diesel on the performance and exhaust emissions of a non-road diesel engine. The examined fuels were neat CTO renewable diesel (BVN) and a blend of BVN and fossil diesel fuel oil (DFO) (50/50% v/v). Neat DFO served as the reference fuel. During a thorough test bench campaign, the engine was driven with the loads of the ISO 8178-4 C1 test cycle. The test engine had no exhaust after-treatment system, and no engine modifications or parameter optimizations were made during the tests. CTO renewable diesel proved to be beneficial in terms of CO, HC and particle number (PN) emissions. With neat BVN, a reduction of 9 % for CO, 10 % for HC, and 10% for PN compared with DFO were observed. The beneficial trends were most evident at low loads. Renewable fuel also slightly reduced brake specific NO_x emissions. CTO renewable diesel proved to be a high-quality, sustainable alternative to fossil diesel and fully compatible with existing non-road diesel engines.

1. Introduction

Today, heavy-duty road transportation and non-road applications are almost entirely powered by internal combustion engines (ICE) in which the petroleum-derived liquid fuels are burned [1, 2]. Diesel engines are recognized as superior power sources among the ICE family due to their fuel efficiency, strength and durability [3]. Liquid fossil fuels have become the predominant transport fuel due to their high energy density and ease of distribution and storage, and a vast global infrastructure has been built over the past century to support this system [4].

At the same time, there is a global understanding of the need to reduce emissions of air pollutants and greenhouse gas (GHG) emissions, encouraging the development and adoption of alternative energy

sources. In September 2020, the European Commission decided on increasingly stringent GHG emission reduction targets. The new goal is to reduce EU GHG emissions by at least 55% by 2030, compared to 1990 levels [5]. This is a substantial increase from the earlier target of 40%. This level of ambition for the next decade is expected to set Europe on a balanced pathway to becoming climate neutral by 2050 – an economy with net-zero GHG emissions.

Climate strategies will inevitably affect the design solution of non-road mobile machinery (NRMM) and heavy-duty vehicles (HDV). Although internal combustion engines are still undergoing continuous further improvements with, e.g., advances in combustion technologies [6], the sole increase of energy efficiency of the conventional technology will not be sufficient by itself to meet the current emissions target levels. Therefore, alternatives not relying exclusively on the combustion of fossil fuels will undoubtedly be required [7].

All solutions are needed to achieve climate targets. Indeed, powertrain electrification is a growing trend in light-duty vehicle applications [7]. Electrification of heavy equipment is, however, still in its infancy. This segment will also be the most difficult to electrify due to the high energy demand [8]. The energy density of today's batteries is not even close to that of diesel fuel [7], and the expected large battery capacities would burden vehicle weight and reduce the payload capacity. In addition, the cost would be high and the charging time long. For non-road machinery operating for extended periods far away from charging infrastructure, the issue of battery technology is even more complicated. There are also doubts whether the global lithium resources will be able to sustain the simultaneous mass electrification of both light and heavy segments [9]. Moreover, concerns of the human toxicity impacts associated with the extraction of metals needed for batteries are growing [2].

Based on the above arguments, robust and efficient diesel engines are expected to continue to power heavy machinery and HDV to a large extent for decades to come [2,4,6,8]. As the GHG reductions of the required magnitude cannot be achieved through energy efficiency measures alone, a large-scale deployment of advanced liquid biofuels is needed in parallel [8]. There is a huge potential to significantly and realistically improve the sustainability of IC engines in the short- and medium-term through the development and deployment of renewable liquid fuels. Extensive existing distribution infrastructure can support such initiatives without modification or investment [4].

Hydrotreating vegetable oils or waste animal fats is a sustainable way to produce high-quality bio-based diesel fuel [10]. To clarify the

distinction between first-generation biodiesels (fatty acid methyl esters, FAME), these fuels are referred to as ‘renewable diesel’ [11]. Renewable diesel is chemically identical to its petroleum counterpart, making it a complete drop-in replacement for fossil diesel fuel [12]. It works on all diesel engines without blending limits or modifications to the engines or fuel distribution infrastructure.

Renewable diesel overcomes many of the sustainability issues associated with first-generation biofuels. Notably, they do not compete with food resources, as they are produced from non-food crops, including agricultural and forest residues, dedicated energy crops, and industrial wastes [13, 14]. Moreover, paraffinic, high cetane, sulfur- and aromatic-free renewable diesel does not have the detrimental effects typical for ester-type biodiesels, such as deposit formation, storage stability problems, or poor cold properties [10]. Major CO₂ savings are based on the fact that the production of biofuels from organic waste results in fuels that contain only biogenic carbon [15], i.e., atmospheric carbon that was captured via biomass growth. Combustion of these fuels is considered carbon-neutral, as it does not release any new CO₂ into the atmosphere.

The development of renewable HVO type diesel fuels has been active in recent years, and many studies have confirmed the emissions benefits of HVO type fuels. Considerable reductions in engine-out CO, unburnt HC, and particulate matter (PM) emissions have been reported by [16–19]. For example, Kuronen et al. [16] examined neat HVO on two heavy-duty engines and two city buses. The reference fuel was sulfur-free EN 590 diesel fuel. For HVO, PM was reduced by 28–46%, CO by 5–78%, and HC by 0–48%. In [19], a non-road diesel engine was driven with different fuel blends of traditional fossil diesel fuel and CTO based renewable diesel. With neat renewable diesel, a reduction of 21% in HC, 15% in CO, and 27% in PN compared with fossil diesel was reported. The main reasons for reduced CO and HC emissions were assumed to be the low aromatic content and the higher cetane number of the CTO renewable fuel, also suggested by [20].

The reductions in NO_x emissions from using HVO are reported more inconsistently in the open literature, with considerable reductions reported by some researchers, while others [19,21,22] did not measure meaningful differences between the fuels. Both NO_x reduction and improvements in PM formation using HVO have been reported, e.g., by [10, 23]. Nylund et al. [23] examined 17 city buses and found average reductions of 10% for NO_x, 30% for PM, 30% for CO, and 40% for unburned HC when switching from regular diesel to 100% HVO. In [10], smoke emissions were reduced by 35% with HVO without any modifications to the engine control. At the same time, a 6% decrease in NO_x emissions was detected. Bohl et al. [24] reported a simultaneous NO_x reduction of 10% and PM reduction of 36% after optimizing injection parameters.

The present study aimed to investigate how HVO-type renewable fuel affects a high-speed, non-road diesel engine’s performance and exhaust emissions. The renewable BVN was studied as neat and restrictedly as a 50% blend with conventional fossil diesel. Neat low-sulfur DFO served as the reference fuel. During a thorough test bench campaign, the engine was driven at eight steady state load points which were based on the loads of the ISO 8178-4 standard’s non-road steady-state cycle C1. The test engine had no exhaust after-treatment system, meaning that raw engine-out emissions were recorded during the experiments. In addition to gaseous emissions, PN emissions and particle size distributions (PSD) were determined. All fuels were studied with similar engine settings, and no engine modifications or parameter optimizations were made during the tests.

2. Experimental setup

The engine experiments were performed by the University of Vaasa at the IC engine laboratory of the Technobothnia laboratory unit in Vaasa, Finland.

2.1 Fuels

The studied HVO was BioVerno supplied by a Finnish forestry company UPM. The fuel batch examined in this study represents UPM’s normal commercial production. UPM’s renewable diesel production process is based on hydrotreatment of CTO, a wood-based residue of the chemical pulping process. CTO is a mixture of fatty acids with a carbon chain of 16 to 20 carbons (36–58%), rosin acids (10–42%), and sterols and neutral substances (10–38%). The composition varies depending on many factors, such as tree species and the growing cycle and age of the tree, geographical location, time of the year, and the pulping conditions. [25]

The production process of CTO-based renewable diesel fuel is presented in Figure 1. At first, crude tall oil – an organic, water-immiscible liquid from a pulp mill – is purified from solid particles, elements and metals, and other contaminants. These impurities have to be reduced to ppm level or less to ensure the hydrogenation catalysts’ functionality. Hydrotreatment is carried out in the biorefinery’s hydrotreatment unit at a pressure range of 2–12 MPa and a temperature range of 280–430 °C. The actual hydrotreating is performed in a plug flow reactor using catalysts capable of simultaneous hydro-deoxygenation, hydrodesulfurization, isomerization, hydrogenation, and cracking. Next, the remaining hydrogen sulfide and incondensable gases are removed. Finally, the hydrotreated CTO “raw diesel” containing mid-distillate diesel components and lighter naphtha components is distilled, i.e., fractionated to renewable diesel and naphtha. [25] Table 1 shows the main specification of the three studied fuels and also lists the limits of the European diesel specification EN 590.



Figure 1. CTO-based renewable fuel production process.

Table 1. Properties of the test fuels analyzed by ASG Analytik-Service GmbH.

Parameter	Test method	Unit	DFO	BVN-DFO 50/50	BVN	Specification EN 590:2014	
						min	max
Cetane Number	DIN EN 17155	-	57.5	61.5	65.2	51.0	-
Cetane Index	DIN EN ISO 4264	-	57.0	63.4	71.2	46.0	-
Density (15°C)	DIN EN ISO 12185	kg/m ³	836	826	815	820	845
PAH content	DIN EN 12916	% (m/m)	2.7	1.4	0.1	-	8.0
Total aromatics	DIN EN 12916	% (m/m)	23.8	12.9	2.0	-	-
Sulphur content	DIN EN ISO 20884	mg/kg	7.9	<5	<5	-	10
Flash Point	DIN EN ISO 2719	°C	67.5	73.0	77.0	>55	-
Carbon residue (10% Dist.)	DIN EN ISO 10370	% (m/m)	<0.10	<0.01	<0.1	-	0.30
Ash Content (775°C)	DIN EN ISO 6245	% (m/m)	<0.001	<0.001	<0.001	-	0.1
Water content	DIN EN ISO 12937	mg/kg	32	19	21	-	200
Total contamination	DIN EN 12662	mg/kg	<12	<12	<12	-	24
Copper strip corrosion	DIN EN ISO 2160	Korr.Grad.	1	1	1	-	1
FAME content	DIN EN 14078	% (V/V)	<0.1	<0.1	<0.1	-	7.0
Oxidation stability		g/m ³	<1	<1	<1	-	25
filterable insolubles	DIN EN ISO 12205	g/m ³	<1	<1		-	-
adherent insolubles		g/m ³	<1	<1		-	-
HFRR (Lubricity at 60°C)	DIN EN ISO 12156	µm	<460	<460	<460	-	460
Kin. Viscosity (40°C)	DIN EN ISO 3104	mm ² /s	3.3	3.4	3.5	2.0	4.5
% (V/V) recovery at 250°C		% (V/V)	22.7	19.8	15.9	-	<65
% (V/V) recovery at 350°C	DIN EN ISO 3924	% (V/V)	93.4	93.1	92.2	85	-
95% (V/V) recovery		°C	354	358	372	-	360
CFPP	DIN EN 116	°C	-12	-14	-14	-	*
Manganese (Mn)	DIN EN 16576	mg/l	<0.5	<0.5	<0.5	-	2.0
Surface tension (20°C)	DIN EN 14370	mN/m	28.3	28.1	27.9	-	-
Calorific value, lower	DIN 51900-2	MJ/kg	42.8	43.2	43.4	-	-

* According national specifications

The BVN-DFO blend fully met the requirements of the EN 590. For neat BVN, however, the density was slightly below the minimum limit of 820 kg/m³, and 95% distillation slightly exceeded the maximum of 360°C defined in EN 590. The PAH content of BVN and the blend was significantly lower than that of DFO. The cetane number – an ignitability indicator for diesel fuels – of BVN and the blend was higher than that of the reference fuel. A high cetane number is advantageous in terms of cold start, noise and emissions [26].

2.2 Engine

The experiments were performed with a four-cylinder, turbocharged, intercooled non-road diesel engine, equipped with a common-rail fuel injection system. The test engine was mounted on a test bench and loaded with a Horiba eddy-current dynamometer WT 300. A Horiba SPARC controller platform was used to control engine speed, torque and throttle. The engine was not equipped with exhaust gas after-treatment devices, meaning that raw engine-out emissions were recorded during the experiments. The main specification of the test engine is given in Table 2.

Table 2. Test engine specification.

Engine	AGCO POWER 44 AWI
Cylinder number	4
Bore (mm)	108
Stroke (mm)	120
Swept volume (dm ³)	4.4
Rated speed (rpm)	2200
Rated power (kW)	103
Rated maximum torque at rated speed (Nm)	446
Maximum torque at 1500 rpm (Nm)	560

2.3 Analytical procedures

The measurement setup for regulated gaseous emissions consisted of typical type-approval grade methods: a non-dispersive infrared (NDIR) analyzer to record CO and CO₂ concentrations, a chemiluminescence detector (CLD) for recording NO_x, and a heated flame ionization detector for HC. In addition, several unregulated gaseous compounds were recorded using a Fourier transformation infrared (FTIR) analyzer. PN and PSD were measured using an engine exhaust particle sizer (EEPS) spectrometer. Prior to emission measurements, the analyzers were calibrated according to the instrument manufacturer's instructions. The brake-specific emissions results were calculated from the recorded data of the pollutant concentrations according to the ISO 8178 standard.

For the determination of the exhaust PN, the raw exhaust was sampled. The sample was diluted with a rotating disc diluter (MD19-E3, Matter Engineering AG) using a constant dilution ratio of 60:1. For the EEPS, the diluted sample was further diluted by purified air with a dilution ratio of 2:1. Thus, the overall dilution ratio was 120:1. The sample flow rate of EEPS was adjusted at 5.0 dm³/min before the measurement. Periods of three minutes were chosen for the PN and size distribution results, during which the total concentration of particles was as stable as possible. Mean values with standard deviations were calculated from the particle numbers measured during these three-minute time intervals. For gaseous emission, only momentary values at the time of measurement for each load point were available. Therefore, due to the lack of continuous measurement data, the standard deviations of gaseous emissions could not be determined.

Table 3 summarizes the methods and instruments adopted for the measurements. The schematic representation of the experimental setup is shown in Figure 2.

Table 3. Analytical instruments.

Parameter	Measuring device	Technology
NO _x	Eco Physics CLD 822 M hr	Chemiluminescence
CO, CO ₂	Siemens Ultramat 6	NDIR
HC	J.U.M. VE7	HFID
O ₂	Siemens Oxymat 61	Paramagnetic
PN and PSD	TSI EEPS 3090	Spectrometer
Smoke	AVL 415 S	Optical filter
Unregulated gaseous emissions	Gasetm DX4000	FTIR
Air mass flow	ABB Sensyflow P	Hot-film anemometer
Cylinder pressure	Kistler KiBox	

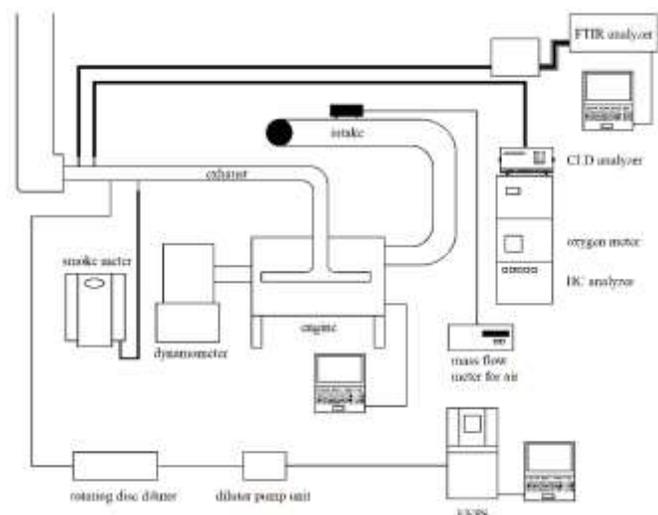


Figure 2. Experimental set-up.

The sensor data were collected using software made in the LabVIEW system-design platform. In addition to gaseous and PN emissions, the recorded quantities included engine speed and torque and several fluid temperatures and fluid pressures, such as temperatures of cooling water, intake air and exhaust gas, and intake air and exhaust pressures. The engine control functions were monitored with AGCO SISU Power WinEEM4 software. No engine parameter optimizations were applied during the tests, and all fuels were studied using similar engine settings. Engine warm-up and measurement procedures were identical for all fuels.

For combustion analysis, the heat release rate (HRR) and the mass fraction burned (MFB) were determined based on the in-cylinder pressure data, measured with a piezoelectric Kistler 6125C pressure sensor. The signal was filtered and amplified by a charge amplifier and transferred to a Kistler KIBOX combustion analyzer. A Kistler 2614B1 crank angle encoder recorded the crankshaft position. To smooth out irregular combustion, the cylinder pressure data were averaged over 100 consecutive cycles.

HRR and MFB were calculated using the AVL Concerto data post-processing tool. The average values of in-cylinder pressures and the Thermodynamics2 macro with a calculation resolution of 0.2°CA were used to calculate HRR values. Thereafter, the HRR curves were filtered with a DigitalFilter macro and a frequency of 4,000 Hz. For MFB results, the cylinder pressure values were first filtered, and after that, the macro was used. For MFB calculations, the pressure values were not averaged to determine the standard deviations for 100 consecutive cycles.

2.4 Experimental matrix

Performance and emission measurements were conducted at eight steady state load points following the modes of the ISO 8178-4 C1 test cycle. The C1 cycle is also referred to as the non-road steady cycle (NRSC). The test engine's rated speed was 2200 rpm, and the intermediate speed was chosen to be 1500 rpm. At idle, the engine speed was 860 rpm. Table 4 lists the loading points or modes, the corresponding engine speeds, loads and torques, and the NRSC weighting factors (WF) for the different modes.

Table 4. Experimental matrix.

Mode	1	2	3	4	5	6	7	8
Speed (rpm)	2200	2200	2200	2200	1500	1500	1500	860
Load (%)	100	75	50	10	100	75	50	0
Torque (Nm)	446	334	223	45	560	420	280	1
WF	0.15	0.15	0.15	0.1	0.1	0.1	0.1	0.15

Before initiating the measurements, it was always waited that the engine run had stabilized. The main criteria were that the intake air and exhaust gas temperatures were stable.

3. Results and discussion

3.1 Measurement conditions

The range of ambient temperature variation was 2–4°C between the test runs. The relative humidity ranged from 13 to 18%. The ambient pressure was 97 kPa for the blend and 100–101 kPa for DFO and BVN during the measurements. The ambient conditions were not considered to noticeably affect the results as they were very similar for each fuel.

3.2 Combustion analysis

Maximum cylinder pressures for DFO and BVN were very similar at all speed and load configurations. The BVN-DFO blend consistently showed slightly lower peaks of cylinder pressure compared to the other two fuels. Figure 3 depicts cylinder pressure at rated speed at 75% load. Maximum cylinder pressure at this point for DFO and BVN was 106 bar and for the blend 105 bar. Nonetheless, the pressure curves were very similar, indicating that combustion propagated quite similar way with all three fuels.

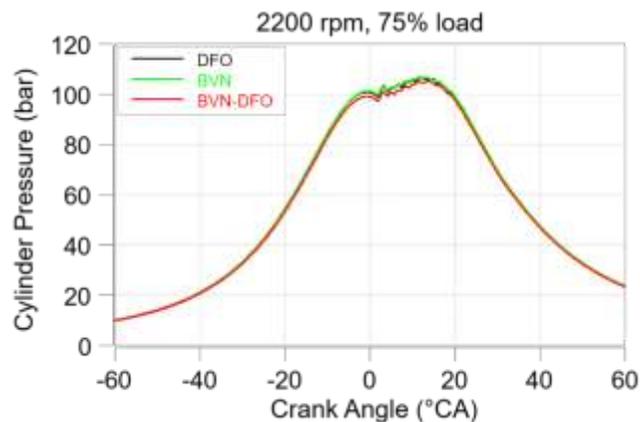


Figure 3. Cylinder pressure against crank angle at rated speed at 75% load for the studied fuels.

Table 5. Mass fraction burned, standard deviations and combustion durations at rated speed at 75% load and intermediate speed at 50% load.

	MFB 10%	Stdev	MFB 50%	Stdev	MFB 90%	Stdev	CD
	°CA	°CA	°CA	°CA	°CA	°CA	MFB10-90% °CA
Mode 2							
DFO	8.0	0.090	17	0.12	32	0.47	24
BVN-DFO	8.0	0.095	17	0.12	33	0.48	25
BVN	7.8	0.094	17	0.11	32	0.39	24
Mode 7							
DFO	8.7	0.063	14	0.078	27	0.27	18
BVN-DFO	8.7	0.065	14	0.089	27	0.32	19
BVN	8.6	0.072	14	0.078	27	0.24	18

Table 5 illustrates 10%, 50%, and 90% MFB points for each fuel at rated speed at 75% load and intermediate speed at 50% load. Standard deviations of crank angles at MFB 10%, MFB 50% and MFB 90%, calculated from 100 consecutive engine cycles, are also given. BVN had the earliest crank angle positions of MFB 10% at both load points. This was consistent with the highest cetane number of BVN and presumably a shorter ignition delay. The latest MFB 90%, and a shade longer combustion duration (CD), was measured for the BVN-DFO blend. This was also evident in the cylinder pressures, which were slightly lower with the blend than with the other fuels (Fig. 3). Otherwise, no significant differences in combustion durations were detected, defined herein as the crank angle duration from MBF 10% to MBF 90%. MFB 50% values were very similar for all fuels studied.

Figure 4 illustrates HRR at rated speed at 75% load. No pilot injection was used at this load point. Despite the differences in cetane numbers (Table 1), the HRR curves were quite similar for all fuels studied. A slightly lower peak in premixed combustion was observed for BVN and the blend compared to DFO.

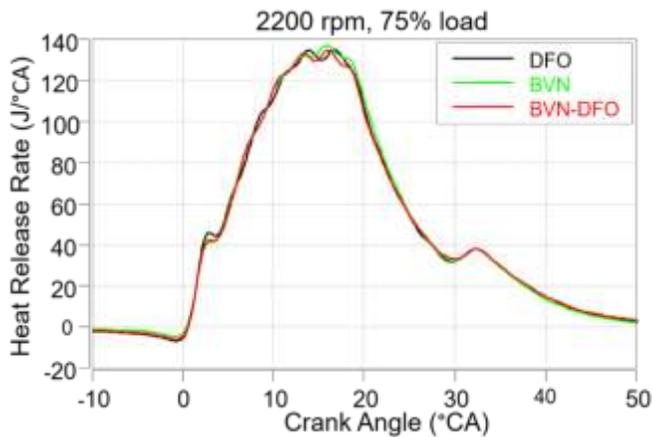


Figure 4. HRR as a function of crank angle at rated speed at 75% load for the studied fuels.

3.3 Efficiency

The engine brake thermal efficiency (BTE) was very similar for all fuels at all load and speed configurations. Figure 5 illustrates the efficiency at intermediate speed. At a brake mean effective pressure (BMEP) of 16 bar, the BTE varied from 40.5% for blend to 40.8% for BVN and DFO.

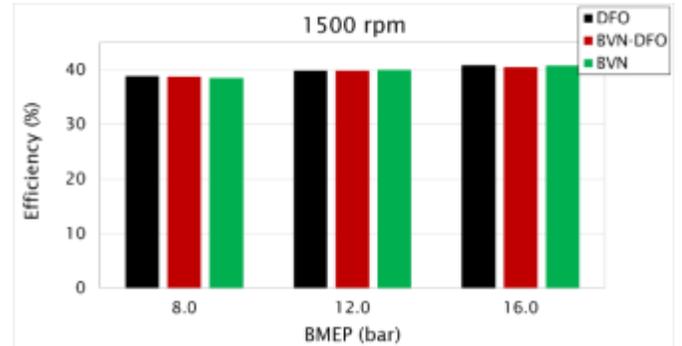


Figure 5. Engine brake thermal efficiency against engine load at intermediate speed.

3.4 Gaseous emissions

Over the eight-mode cycle, both BVN and BVN-DFO blend slightly reduced NO_x emissions, as shown in Figure 6. The largest reduction was achieved with the blend emitting 3.4% less NO_x than the baseline DFO. With BVN, the NO_x reduction was 2.6% compared to fossil diesel. Throughout the cycle with weightings, the NO_x for DFO was 7.9 g/kWh, for BVN 7.7 g/kWh and for blend 7.6 g/kWh, also showing that the engine was tuned for high NO_x – and high efficiency – and intended for the later use of an efficient catalyst system for clear NO_x reduction.

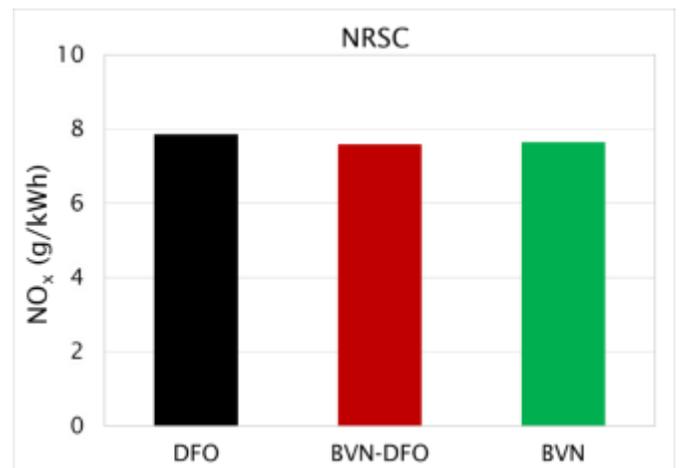


Figure 6. Cycle-weighted NO_x emissions for the studied fuels.

The improved NO_x outcome with BVN could be explained by the fuel properties. NO_x formation is reduced with fuels having lower aromatic content as aromatic compounds have higher adiabatic flame temperature and thereby produce higher local combustion temperatures [27, 28]. In the case of the BVN-DFO blend, the lower NO_x could be attributed to a slightly longer combustion duration resulting in lower cylinder pressure and temperature peaks.

In general, HC and CO emissions are low for lean-burn engines. However, the use of CTO-based renewable diesel reduced them further compared to conventional diesel fuel, as shown in Fig. 7. Throughout the cycle with weightings, the CO emissions were 0.24 g/kWh for neat BVN, 0.26 g/kWh for BVN-DFO blend and 0.27 for DFO. Compared to fossil diesel, the percentage reduction for neat BVN was 9%.

Quite similar trend was observed for HC emissions. BVN and the blend produced the lowest HC, 0.12 g/kWh for both fuels. DFO's HC emissions were 0.14 g/kWh. The percentage reduction for neat BVN was 10% compared to fossil diesel. The reason for lower HC emissions were assumed to be the better ignitability of HVO, limiting the overmixing effect. The absence of aromatics can also be expected to reduce HC emissions in the exhaust gas [24].

HC and CO emissions for all fuels were well below the EU Stage V and US Tier 4 emission limits for non-road engines (0.19 g/kWh for HC and 5.00 g/kWh for CO).

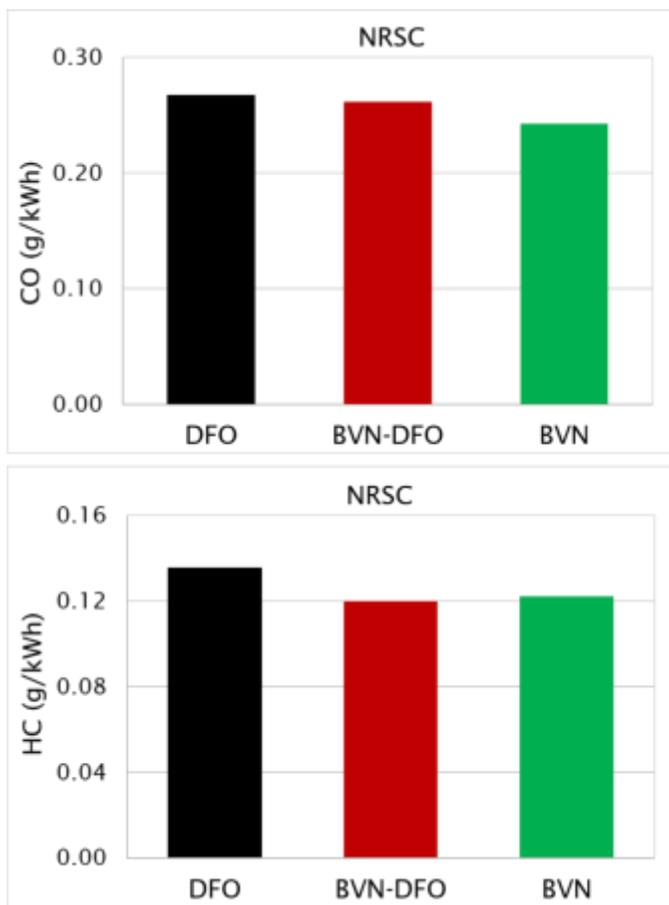


Figure 7. Cycle-weighted CO and HC emissions with the studied fuels.

Figure 8 summarizes the percentage changes in regulated emissions. DFO forms the baseline. In addition to gaseous emissions, relative changes in particle numbers are presented. PN results are discussed in more detail in Section 3.5.

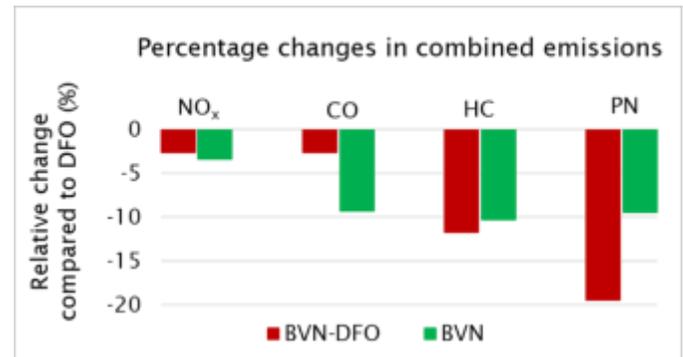


Figure 8. Relative changes in cycle-weighted brake specific emissions. DFO forms the baseline.

From the recorded unregulated gaseous emissions, nitrous oxide (N₂O) concentrations were low at all loads and almost equal for all three fuels. N₂O generally ranged from 0.4 to 0.8 ppm, but at full load at 1500 rpm, it was 0.1 ppm.

The wet exhaust methane (CH₄) contents were also low at all loads. The highest concentrations were recorded at 10% load at 2200 rpm (0.9 ppm for DFO, 0.6 ppm for the blend, and 0.7 ppm for BVN) and at half load at 2200 rpm (0.4 ppm for DFO, <0.1 ppm for the blend, and 0.3 ppm for BVN). At higher loads, CH₄ content was always below 0.1 ppm for all fuels.

The wet exhaust formaldehyde concentrations peaked at half load at 2200 rpm (3.0 for DFO and the blend, and 2.2 for BVN). Otherwise, it varied between 0.1 and 2.1 ppm, BVN having the lowest formaldehyde concentration at all loads.

Overall, with regard to unregulated emissions, the differences between fuels were negligible, and the recorded levels were close to the measuring accuracy.

3.5 PN emission and smoke

The effect of CTO-based renewable diesel on PSD at four different load points is shown in Figure 9. The averages of PN concentrations are presented as data points and combined with lines. The shaded area depicts the standard deviation. One peak of the bimodal PSD was detected at a particle diameter of 10 nm, the other at approx. 35 nm, even though the latter was not observed at all loads.

At higher loads, no consistent trend was observed in PSD between the fuels. In contrast, at idle, both BVN and the blend resulted in a clear reduction of nuclei mode (10 nm) PN emissions. This can be explained by near-zero sulfur and low aromatics content of BVN, also concluded by [29]. Marasri et al. [30] also pointed out that, at low temperatures, lower density fuel might be more easily atomized, vaporized, and mixed with air in the combustion chamber, leading to improved combustion.

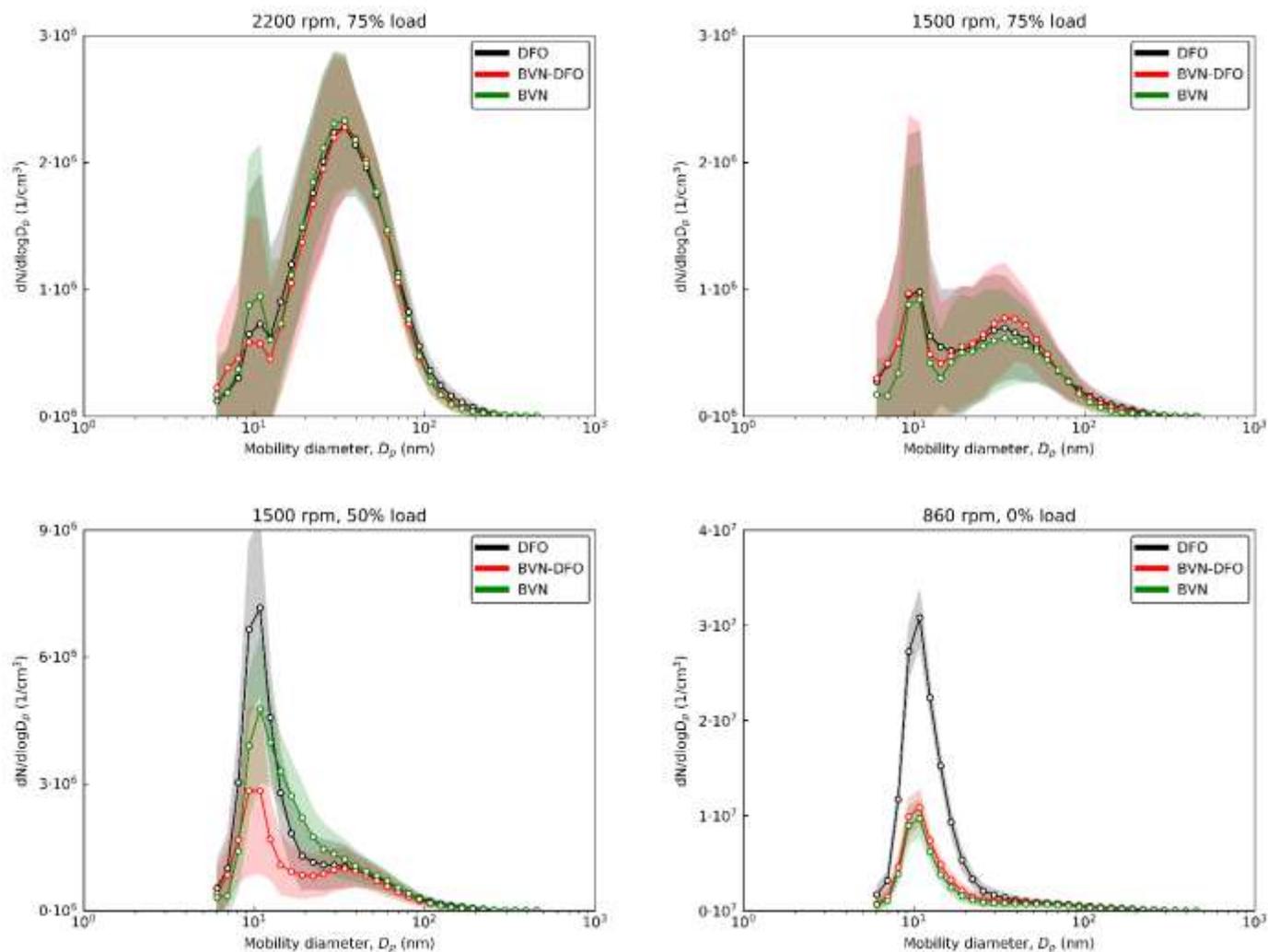


Figure 9. Particle size distributions at high load and low load conditions.

Fig. 10 depicts the weighted total PN emission within the size range of 5.6–560 nm over the eight-mode test cycle following the NRSC. When looking at these results, the blend was the most beneficial. Fueling with the BVN-DFO blend produced a total particle number (TPN) reduction of 20% compared with DFO. With neat BVN, TPN decreased by 10% compared with reference fuel.

The main reason for decreased PN was interpreted to be the beneficial hydrocarbon structure and low aromatics content of CTO renewable fuel. The more complete combustion was assumed to be due to the higher H/C ratio, also concluded by [31, 32]. Furthermore, BVN’s aromatic free composition implies that less PAH, acting as soot precursors, are formed [33, 34]. On the other hand, as shown by [35], high-cetane fuels can also lead to lower soot emissions as a result of improved ignition quality and, thus, cleaner combustion.

With all fuels, smoke was low at all loads. For DFO, filter smoke number (FSN) values varied from 0.01 to 0.07, for the blend from 0.02 to 0.05, and for BVN from 0.01 to 0.05.

In the present study, the engine settings were not optimized for the combustion of paraffinic fuel. Further reductions in exhaust emissions

could be achieved by adjusting engine parameters to take advantage of the properties of paraffinic fuel, as evidenced by [10,24,36].

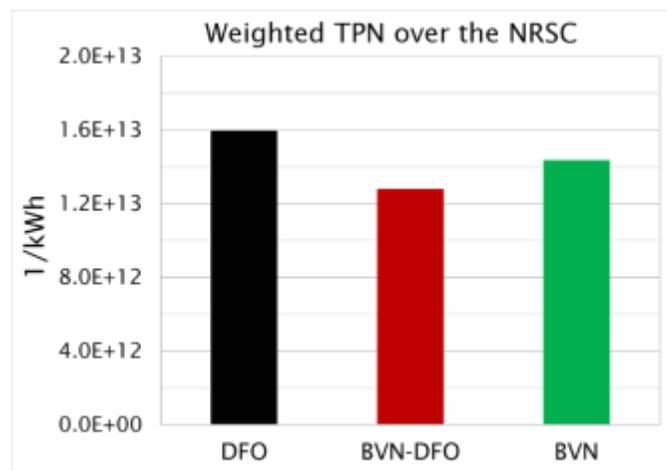


Figure 10. Total PN emission within the particle size range of 5.6 to 560 nm, weighted over the eight-mode cycle.

4. Conclusions

This study investigated the effect of CTO-based renewable diesel fuel on the performance and exhaust emissions of a non-road diesel engine over the eight-mode steady state cycle that followed a standardized NRSC driving cycle C1. A combustion analysis was performed as well. Renewable diesel was studied as neat and as a 50% blend with conventional fossil diesel. Neat DFO served as the baseline fuel. All fuels were studied with similar engine settings, and no engine parameter optimizations were made during the tests.

Based on the performed research work, the main conclusions were:

- According to the combustion analysis, combustion propagated quite similar way with all three fuels. BVN and the blend generated a shade lower peaks of premixed combustion. MFB 50% values were, however, very similar for all fuels.
- The engine brake thermal efficiency was almost identical for all fuels throughout the load-speed range of the test engine.
- Over the eight-mode cycle, both BVN and BVN-DFO blend reduced NO_x emissions by approx. 3% compared to fossil DFO.
- The cycle-weighted CO emissions reduced by 9% with BVN and 3% with the blend. HC emissions reduced by 10% with BVN and 12% with the blend. The reason for lower HC emissions were assumed to be the better ignitability of CTO renewable fuel.
- The wet exhaust gas concentrations of nitrous oxide, methane, and formaldehyde were negligible with all fuels.
- Fueling with the BVN-DFO blend produced a TPN reduction of 20% compared with the reference fuel. With neat BVN, TPN decreased by 10% compared with DFO. The main reason for decreased PN was interpreted to be the beneficial hydrocarbon structure and near-zero sulfur and low aromatics content of CTO renewable fuel.

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Abbreviations

BMEP	brake mean effective pressure
BTE	brake thermal efficiency
CH₄	methane
CLD	chemiluminescence detector
CA	crank angle
CD	combustion duration
CFPP	cold filter plugging point
CO	carbon monoxide
CTO	crude tall oil
DFO	diesel fuel oil
EEPS	engine exhaust particle sizer
EU	European Union
FAME	fatty acid methyl ester
FSN	filter smoke number
FTIR	Fourier-transform infra-red
GHG	greenhouse gas
HC	total hydrocarbons

HDV	heavy-duty vehicles
HFID	heated flame ionization detector
HFRR	high frequency reciprocating rig
HRR	heat release rate
HVO	hydrotreated vegetable oil
ICE	internal combustion engine
ISO	International Standard Organization
MFB	mass fraction burned
N₂O	nitrous oxide
NDIR	non-dispersive infra-red
NO_x	oxides of nitrogen
NRMM	non-road mobile machinery
NRSC	non-road steady cycle
PAH	polyaromatic hydrocarbons
PM	particulate matter
PN	particle number
PSD	particle size distributions
TPN	total particle number
WF	weighting factor