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Investigation of combustion and emission performance of Hydrogenated Vegetable Oil (HVO) diesel

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Abstract

Hydrogenated Vegetable Oil (HVO) diesel fuels have the potential to provide a reduced carbon footprint for diesel engines and reduce exhaust emissions. Therefore, it is a strong candidate for transport and diesel powered machines including electricity generators and other off-road machines. In this research, a waste cooking oil derived HVO diesel was investigated for its combustion and emission performance including ignition delays, size segregated particulate number emissions and gaseous emissions. The results were compared to the standard petroleum diesel. A EURO5 emission compliant three litre, direct injection, intercooled IVECO diesel engine equipped with EGR was used which has a maximum power output of 96kW. The engine was equipped with an integrated DOC and DPF aftertreatment system. Both the upstream and downstream of the aftertreatment emissions were measured. The tests were conducted at different RPM and loads at steady state conditions. A DMS500 particle size measurement instrument was used for measuring particles between 5 nm and 1000nm. The engine was instrumented with a number of thermocouples so that the engine conditions were closely monitored. Gaseous emissions were measured using a HORIBA 7100 series gas analyzer. The results showed that HVO reduced particulate numbers significantly at the upstream of the aftertreatment system. The particle number emissions were not much different between HVO and standard diesel at the downstream of the aftertreatment system due to the low particle number concentrations.

Introduction

The wide application of modern diesel engines inevitably consumes the limited fossil derived diesel fuel and contributes to the air pollution. The research by Kavalov, B. and Peteves, S.D., [1] showed that the increasing automotive diesel consumption in the EU can lead to problems such as potential energy supply risk, higher diesel fuel costs and most importantly air quality issues. The exposure to diesel exhaust can cause asthmatic diseases and damage to the lung function [2]. Therefore, finding solutions to relieve the heavy reliance on petroleum diesel and reduce the pollutants' emissions can be necessary.

Hydrogenated vegetable oil (HVO) can either be derived from waste cooking oil or animal fats and thus can be deemed as renewable energy resources. In the process of refining HVO, oxygen is removed by the hydrogen added at the isomerization stage, leaving the HVO free of aromatics, which contributes to Polycyclic Aromatic Hydrocarbons (PAH) emissions [3,4]. A previous study by Sugiyama, K., et al, [5] showed that HVO with zero aromatics would produce lower hydrocarbon and PM emissions than petroleum diesel. Another researcher, E Zervas [6] reports on the PM emissions from aliphatic fuels compared to diesel, and there doesn't tend to be much difference at low loads indicating there is little difference between the total particle number and the distribution of the sizes. This is because the reduced sulphur content, such as in aliphatic fuels, should decrease the particle number, since sulphur is key in the nucleation mode. Therefore, the control of the nucleation-mode must come from another source. Zervas [6] denotes this to carbon condensation.

For diesel engines, the most concerned emissions are NOx and particulate emissions. The advantage of HVO fuel lies on its potential on particle and THC emissions. From the research of Bhardwaj, O.P., et al.in 2013 [7], the pure HVO can reduce up to 50% of particle emissions in comparison with fossil diesel. HVO also achieves the lowest soot accumulate rate on the diesel particle filter (DPF) when compared with the FAME fuel or diesel fuel. [8] However, studies of HVO's performance on NOx doesn't show a very significant advantage in comparison with diesel. From Mizushima, N et al [9], NOx emissions from HVO fuel are almost the same as diesel fuel. Millo, F et al, in 2013[10], also reported the similar level of NOx for the blended HVO B30 fuel with diesel fuel. The results showed a similar outcome: the HVO B30 fuel reduces the CO and HC emissions significantly, but the NOx emission was nearly the same.

This paper presents the particulate and gaseous emissions from a HVO diesel fuel derived from waste cooling oil. The combustion performance (ignition delay and engine power) was also investigated. The results were compared to standard diesel fuel. The efficiency of diesel particle filter (DPF) on particle removal was determined.

Experimental

Test engine and control system

An IVECO 3.0 L direct injection diesel engine compliant with Euro 5 emission legislation and fitted with a turbocharger and an intercooler and EGR system was used, Table 1 shows the specifications of the engine.

Table 1. Specifications of the test engine.

Parameters	Values
Engine type	Diesel 4 stroke
Total displacement; liter	3
Number of cylinder	4 in line
Injection type	Direct & High pressure common rail
Injection pressure; bar	1600
Injection sequence	1-3-4-2
Bore; mm	88
Stroke; mm	94
Maximum power;	96 kW@3100-3500rpm
Maximum torque;	300 Nm@1300-3100rpm
Aftertreatment system	DOC+DPF (closed wall-flow type filter)
EGR	Yes

The engine is connected to a 100kW AC dynamometer. The engine and dynamometer were controlled via a software system -DSG system, which is used to control the engine rpm and engine throttle position, and to monitor and log the experiment data, including engine rpm, engine torque, engine emissions, and temperatures at specific locations of the engine.

In-cylinder pressure and crank angle measurement

An AVL in-cylinder pressure transducer and crank angle measurement system was installed to the engine to acquire the pressure data from one of the cylinders. It consists of the pressure transducer, AVL amplifier, and AVL software. The pressure transducer is connected to one combustion cylinder of the engine on one side, and inputs the signals to the amplifier. The AVL amplifier receives two types of signals from the experiment engine: one is the pressure signal from the cylinder; the other is the crank angle signal from the crank angle encoder. Thus, the AVL acquires the data both in combustion cylinder pressure and crank angle degree. During the measurement, the amplifier receives signals from the engine and passes them to the AVL Indicom software via one Ethernet cable connected between the amplifier and computer. The software will normally record 100 combustion cycles' data.

AVL system provides the combustion PV (Pressure-Volume) diagram, combustion P-crank angle diagram, ignition delay, and heat release.

Fuels

The standard Ultra Low Sulphur Diesel (ULSD) complying with EN590 and HVO diesel (Neste Renewable Diesel) supplied by NESTE which meets EN 15940:2016 for paraffinic diesel fuels were used for testing. Some selected properties for both fuels are shown in table 2.

Table 2: Selected fuel properties

Property	**Ultra Low Sulphur Diesel**	**HVO**
Kinematic viscosity at 40ºC; mm^2/s	~2.7	2.8
Density at 15ºC; kg/m^{-3}	~0.84	0.78
Cetane number	>51	78.8
NCV; MJ/kg	44	44
Sulphur; mg/kg	<10	<1
Water; mg/kg	<100	34
Flash point; ºC	66	84
Cloud point; ºC		-31
Aromatics; wt%		0.3
Hydrogen; wt%		15.2

Emissions measurement

The Horiba MEXA 7100 gas analyzers were used to measure the concentration of CO, CO_2, O_2, THC, NO, NOx and air to fuel ratio. It was controlled by the DSG system during the experiment, and the data was logged by the DSG system.

DMS 500 was used to measure the particle size distribution of the engine exhaust gas. It was controlled by an independent computer and logged its' own data with that computer during the experiment.

No DPF regeneration event was observed during the measurements.

The whole system set up and test conditions

Figure 1 shows the whole system set up for the engine, dynamometer and measurements systems.

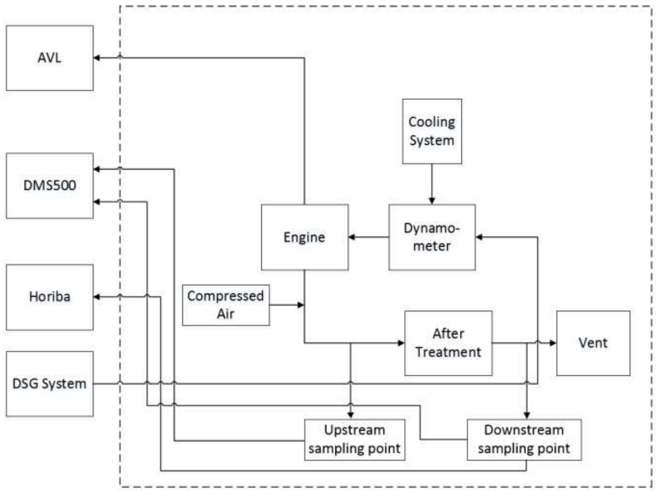

Figure 1: Schematic view of engine and testing system set up

The Horiba MEXA 7100 and DMS 500 were connected to both the upstream and downstream of the engine exhaust aftertreatment system. To optimize the accuracy of experiment data, the engine was tested at 9 selected stable condition stages. The selected engine working condition was based on bench marking experiment and is shown in the table 3 below. The diesel fuel experiments were taken first as the baseline. Then the engine was purged with pure HVO fuel before the HVO fuel tests. Approximately 10 litres of HVO fuel was used to purge the fuel system.

Table 3. Engine rpm, throttle position and power parameters

Stage of experim ent	Engine rpm	Throttle position (%)	Engine power (kW)	Exhaust temperature - Post DPF (°C)
1	1000	30	6	176
2	1000	40	14	265
3	1000	50	17	353
4	1600	40	7	377
5	1600	50	17	344
6	1600	60	29	391
7	1900	50	15	398
8	1900	60	25	391
9	1900	70	39	413

Results and discussions

Comparison of particle size distribution between diesel and HVO at the downstream of DPF

Both HVO fuel and diesel fuel were measured for their particle size distribution from the upstream and downstream of the engine exhaust aftertreatment system using DMS 500. The instrument measuring frequency was set to 2 Hz, and for each engine working condition, the data logging time was 5 minutes. The average readings were taken and reported. Error bars (one standard deviation) were calculated and found to be in a range of $1x10^3$ to $2x10^4$ p/cm^3.

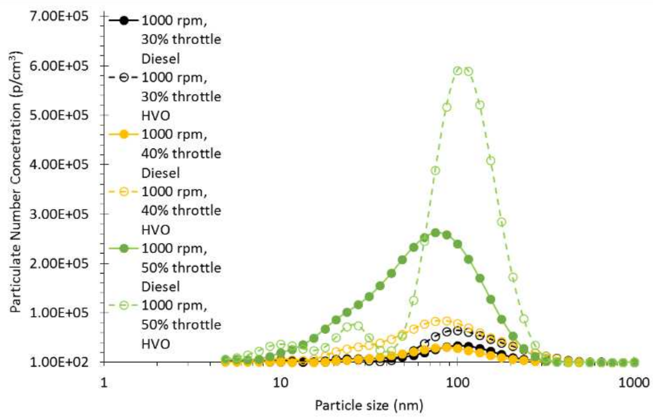

Figure 2: Particle size distribution from downstream of the aftertreatment system at 1000 rpm engine working condition.

Figure 2 shows the particle size distribution from downstream of the aftertreatment system (DPF) at the 1000 rpm engine working condition. The particles generated from HVO fuel and diesel fuel were very close at 30% and 40% throttle positions. However, the HVO fuel produced more large particles (~100 nm) and less nano particles (10 nm) when the throttle increased to 50%. The nano particles are known to pose more hazards to human health since they can penetrate and deposit to the lungs and alveolar membrane.

When the engine rpm increased to 1600 and 1900, from Figure 3 and Figure 4, it can be found that the particle size distribution and number concentrations from HVO fuel and diesel fuel are very similar. All of them were close to the detection limit of the instrument (10^{-3} ~ 10^{-4} p/cm^3). Despite the diesel fuel showing a slightly lower PN emission at 1600 rpm, 40% throttle engine condition, the PN performance from the two types of fuels was nearly the same at the 1900 rpm engine working condition.

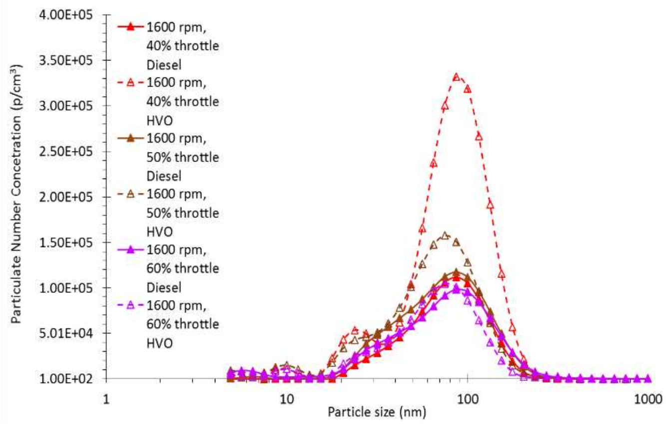

Figure 3: Particle size distribution from downstream of the aftertreatment system at 1600 rpm engine working condition

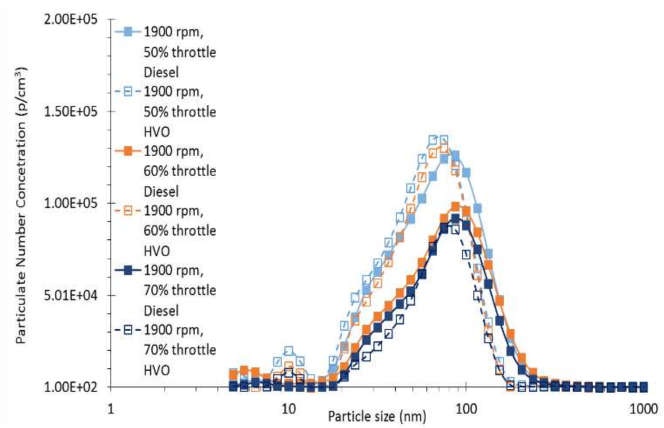

Figure 4: Particle size distribution from downstream of the aftertreatment system at 1900 rpm engine working condition

In general, the PN emissions and size distributions from the HVO fuel and diesel fuel are close in value, based on the measurements at the engine downstream of the aftertreatment system. This matches up with the study from Kim, D., et al, [11] on light duty vehicle test, which was taken at engine downstream of the aftertreatment system.

Particle size distributions for diesel and HVO at the upstream of DPF

As the PN emissions and size distributions from downstream were under the effect of DPF, in order to analyze the particle generated direct from HVO fuel and diesel fuel combustion, the measurements were taken at the engine upstream of DPF position.

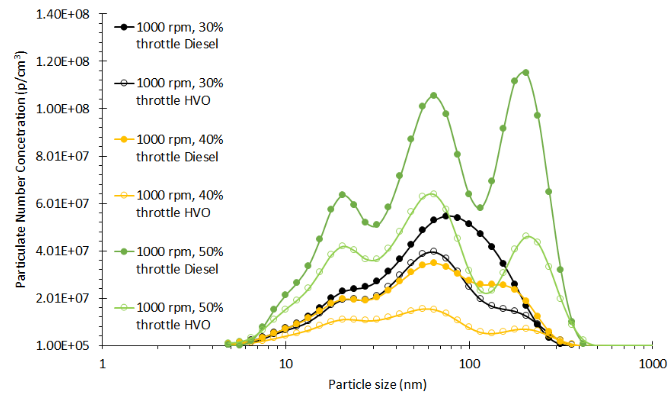

Figure 5: Particle size distribution from upstream of the aftertreatment system at 1000 rpm engine working condition

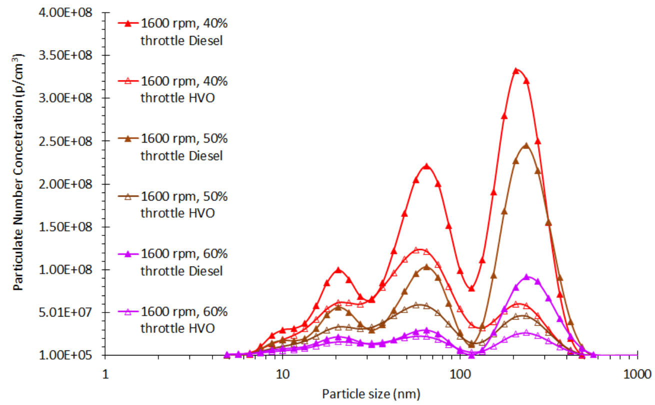

Figure 6: Particle size distribution from upstream of the aftertreatment system at 1600 rpm engine working condition

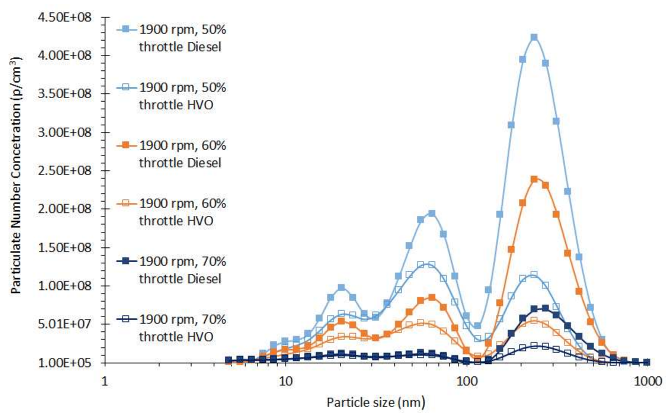

Figure 7: Particle size distribution from upstream of aftertreatment system at 1900 rpm engine working condition

From figures 5, 6, and 7, it can be seen that the HVO fuel produced significantly less particles, at all the engine working conditions at the engine out or upstream of the aftertreatment system, indicating that the HVO fuel is much cleaner than petroleum diesel fuel. This accords with the findings by Erkkilä, K., et al on HVO tests on heavy duty vehicle. [12]

Comparison of particle size distributions between upstream and downstream of DPF

Particle size distributions and number concentrations were compared between upstream and downstream of the aftertreatment system for diesel (figures 8-10) and HVO (figures 11-13). Combined with figures 2-7, it can be seen that the characteristics of particle size distributions were changed across the DPF. The particle distributions upstream were tri-modal with peaks at around 20 nm, 70 nm and 230 nm. The peak around 230 nm was the largest. The particles downstream of the DPF showed dominantly a monomodal distribution with the mode size at around 80 -100 nm. This demonstrated that the DPF was the very efficient removing relatively large particles (~230 nm) and very small nanoparticles (~20nm) and less efficient removing particles at a size around 80-100 nm. Nevertheless, the efficiency of DPF at all three modes was over 99%. Those relatively large particles (~230 nm) are agglomerated particles while the 20 nm range particles are nucleation mode particles including carbonaceous materials and unburned hydrocarbons.

Particle number concentrations were significantly reduced by the DPF across the whole size range. Particle concentrations downstream of the DPF were at a magnitude of 10^3 to 10^4 in general, which reached the instrument's detection limit. The efficiency of DPF is very high, which was shown in figures 14 and 15 and will be discussed later.

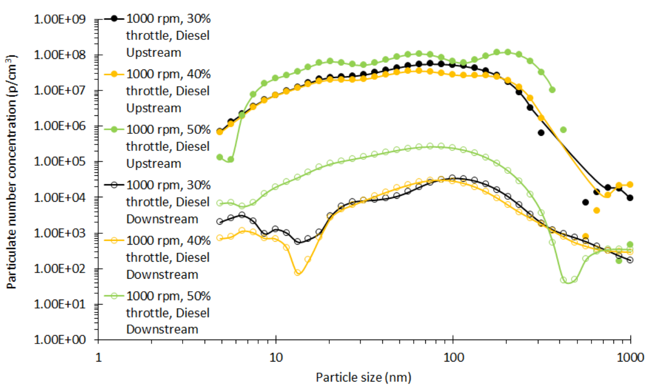

Figure 8: Particle size distributions from diesel fueled engine upstream and downstream of the aftertreatment system at 1000 rpm engine working condition

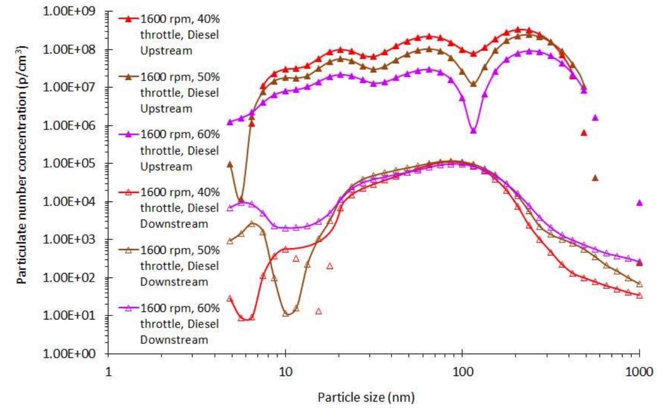

Figure 9: Particle size distributions from diesel fueled engine upstream and downstream of the aftertreatment system at 1600 rpm engine working condition

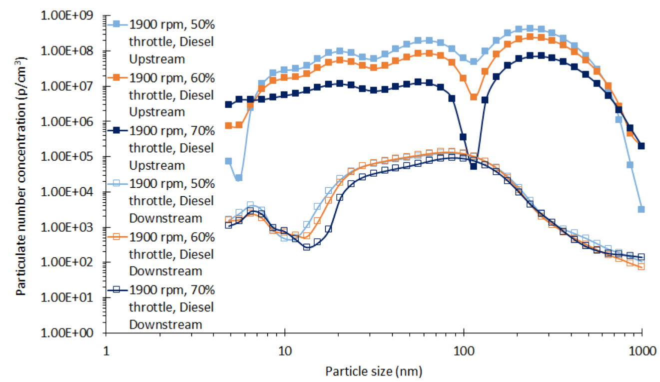

Figure 10: Particle size distributions from diesel fueled engine upstream and downstream of the aftertreatment system at 1900 rpm engine working condition

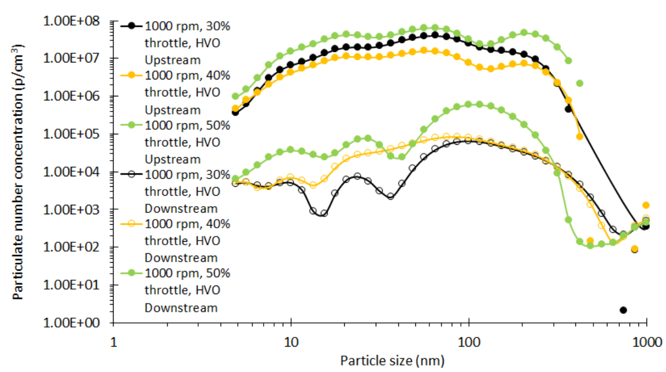

Figure 11: Particle size distributions from HVO fueled engine upstream and downstream of the aftertreatment system at 1000 rpm engine working condition

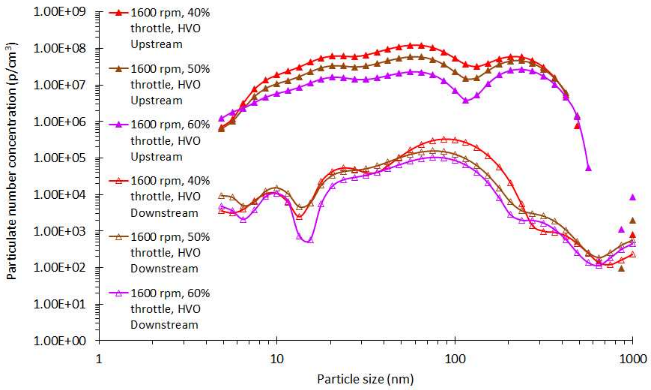

Figure 12: Particle size distributions from HVO fueled engine upstream and downstream of the aftertreatment system at 1600 rpm engine working condition

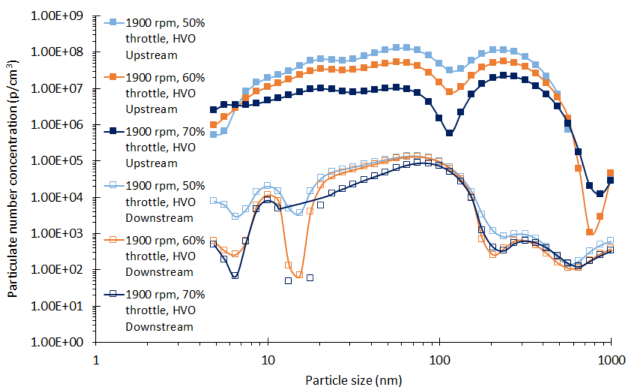

Figure 13: Particle size distributions from HVO fueled engine upstream and downstream of the aftertreatment system at 1900 rpm engine working condition

Total PN

Particle number concentrations were summated for the whole measurement range (total PN). Table 4 below shows total PN for diesel and HVO fuels at upstream and downstream of the aftertreatment system. The results show that particle number concentrations from the HVO diesel were in general half of that fossil diesel produced at engine out. The particle concentrations downstream of the DPF between two fuels were not discernable as the values approached the instrument's detection limit. The efficiency of the DPF in terms of total particle numbers were also obtained and discussed in table 5 in the next section. Though the DPF efficiency for the removal of particulates was over 99% for both fuels at all testing conditions, the much lower engine out particulate emissions from the HVO diesel compared to the standard diesel will lead to less frequent DPF regenerations.

Table 4. Total PN comparison for upstream and downstream of the aftertreatment system for diesel and HVO fuel

		Diesel		HVO	
Rpm	Throttle	Upstream	Downstream	Upstream	Downstream
1000	30%	4.53E+07	1.98E+04	3.13E+07	3.91E+04
1000	40%	3.31E+07	1.82E+04	1.45E+07	6.50E+04
1000	50%	1.09E+08	4.07E+05	6.14E+07	2.86E+05
1600	40%	2.29E+08	5.79E+04	1.00E+08	1.56E+05
1600	50%	1.36E+08	7.14E+04	5.51E+07	9.07E+04
1600	60%	4.98E+07	6.25E+04	2.56E+07	5.81E+04
1900	50%	2.67E+08	8.15E+04	1.18E+08	8.22E+04
1900	60%	2.67E+08	8.30E+04	5.45E+07	7.05E+04
1900	70%	3.75E+07	5.25E+04	1.67E+07	4.16E+04

DPF efficiency

With the PN distribution data from upstream and downstream of the engine exhaust, the DPF efficiency can be calculated using the formula:

$$\text{DPF efficiency } \% = \frac{\text{PN upstream} - \text{PN downstream}}{\text{PN upstream}} \times 100\%$$

Equation 1

Where:

PN: Particle Number Concentration (p/cm^3)

Upstream: Measurements taken before the aftertreatment system

Downstream: Measurements taken after the aftertreatment system

The calculated DPF efficiency is shown in Table 5. The filter was very effective for particle removal for both HVO fuel and diesel fuel. This provides an explanation to the similar PN emissions at downstream of the aftertreatment system for HVO and diesel.

The DPF efficiency was further analyzed based on particle size at nine engine working conditions for both fuels respectively as shown in Figure 14 and 15. The results show that the efficiency of the DPF across the whole particle size range was nearly 100% for most of the size ranges for both fuels except a few data points where the particle size was at 6 nm, 100 nm, 400 nm, 600 nm, 700 nm and 900 nm. The engine out particle number concentrations were relatively low at these size points, while the downstream concentrations at these points were not proportionately lower (could be due to instrument sensitivity as the data were close to the detection limit). Thus the DPF efficiency at these points was slightly lower and dropped to ~90%.

Table 5. The DPF efficiency of HVO fuel and Diesel fuel

RPM	Throttle position	DPF efficiency of HVO fuel	DPF efficiency of diesel fuel
1000	30.00%	99.87%	99.96%
1000	40.00%	99.55%	99.94%
1000	50.00%	99.53%	99.63%
1600	40.00%	99.84%	99.97%
1600	50.00%	99.84%	99.95%
1600	60.00%	99.77%	99.87%
1900	50.00%	99.93%	99.97%
1900	60.00%	99.87%	99.94%
1900	70.00%	99.75%	99.86%

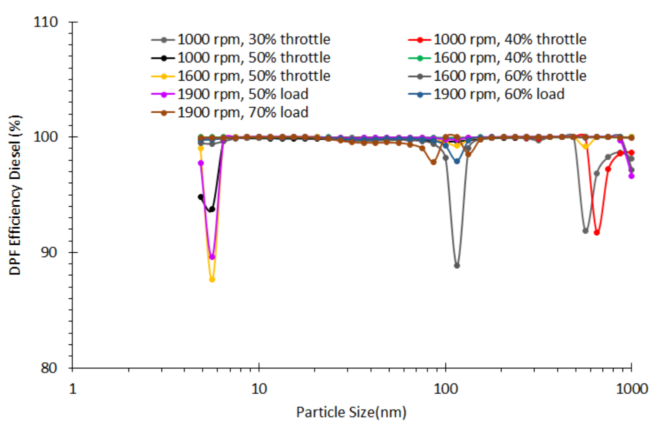

Figure 14: DPF Efficiency (%) for Diesel fuel as a function of particle size

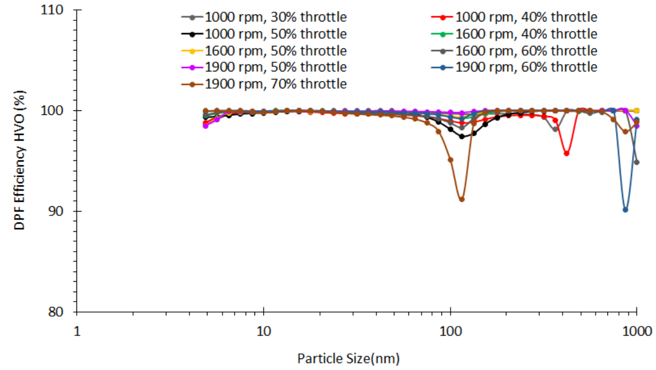

Figure 15: DPF Efficiency (%) for HVO fuel as a function of particle size

The HVO fuel can reduce engine out particulate and THC emissions effectively in comparison with petroleum diesel fuel, however, it doesn't show a significant improvement in NOx emissions (figures 16-18). Therefore, future applications of HVO must utilize the HVO's advantage in lower particulate and hydrocarbon emissions and to improve its' performance in NOx emissions. One possible method of using HVO fuel on diesel engines can be using a smaller DPF while adding a SCR (Selective Catalytic Reduction) system. Because the HVO fuel generates less engine out particulate, the smaller DPF and/or less frequent regeneration of DPF is required. The reduced demand for DPF regeneration will reduce the fuel consumption that is used for regeneration. Since the required size of DPF has been reduced, there will be the chance to install SCR, in the engine aftertreatment system, which can reduce the NOx emission effectively. The combination of smaller DPF and SCR can optimize the HVO's advantage in particle and hydrocarbon emissions whilst improve its' NOx reduction performance as well. From Seo, J's research in 2011, the SCR efficiency was 69.4% to 75.7% for the tested DPF+SCR aftertreatment on diesel engines [13]. Another method of emission control for HVO application can be fuel injection parameters optimization. Aatola, H, et al. demonstrated that the pure HVO can reduce up to 6% of NOx, and 35% of smoke, and has the potential to acquire even lower emissions if the fuel injection parameters have been optimized [14].

NO, NO_2 and NOx emissions

NO, NO_2 and NOx emissions were measured for the HVO fuel and diesel fuel at the downstream of the aftertreatment system as shown in figures 16-18. NOx emissions were at similar levels between the HVO and diesel fuels at nine engine working conditions. There are a few conditions where the HVO fuel reduced NO emissions. However, increases in NO_2 emissions by the HVO fuel were observed at several engine working conditions. From the research by Happonen, M., et al, [15] the proper adjusting of engine parameters can improve HVO's NOx emission performance.

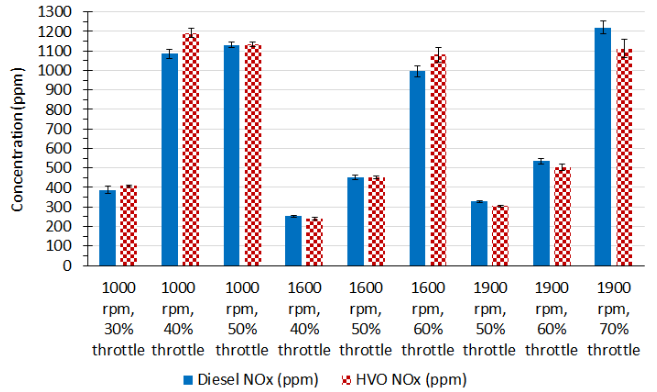

Figure 16: NOx emission from Diesel and HVO fuel at downstream of the aftertreatment system.

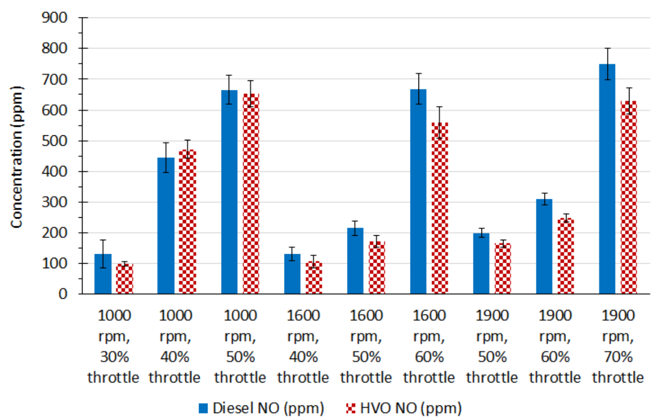

Figure 17: NO emission from Diesel and HVO fuel at downstream of the aftertreatment system.

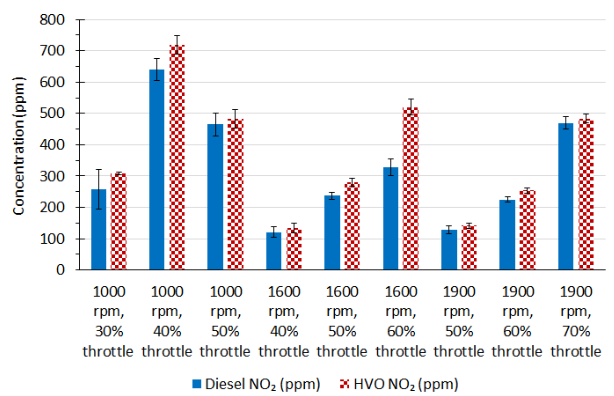

Figure 18: NO_2 emission from Diesel and HVO fuel at downstream of the aftertreatment system.

CO, CO_2 and THC emissions

The CO, CO_2 and THC emissions from the HVO fuel and diesel fuel are shown in Table 6 and Table 7. It can be found that CO and CO_2 emissions were quite low and close for two types of fuels but the HVO showed much lower THC emissions. This is due to the zero-aromatic characteristic of the HVO fuel, and conforms to the finding by Sugiyama, K., et al [5] in their HVO emission tests on a diesel engine, showing that HVO can reduce the hydrocarbon emissions, and the research from Pflaum, H., et al [16].

Table 6. CO, CO_2 and THC emissions downstream of the exhaust aftertreatment system from HVO fuel

Engine power (kW)	CO_2 [%vol]	CO (L) [ppm]	THC [ppmC_1]
15.49	9.00	0.00	6.18
23.57	10.00	0.00	7.00
26.27	11.00	0.00	5.85
22.56	8.11	0.00	5.00
31.54	9.00	0.00	4.00
44.14	9.00	0.00	4.00
32.18	9.00	0.00	4.00
43.08	9.00	0.00	3.00
56.02	9.00	0.00	4.00

Table 7. CO, CO_2 and THC emissions downstream of the exhaust aftertreatment system from diesel fuel

Engine power (kW)	CO_2 [%vol]	CO[ppm]	THC [ppmC]
14.88	9.00	0.00	26.55
22.69	10.00	0.00	73.79
26.03	12.00	0.93	90.41
21.28	8.61	0.00	7.84
31.01	9.00	0.05	7.18
43.30	9.77	2.20	12.21
31.89	9.00	2.00	13.95
42.82	9.00	2.00	8.93
56.28	9.00	3.43	7.48

Ignition delay analysis

The ignition delay was calculated from the P (Pressure) - crank angle diagram, where the crank angle change between start of injection and start of combustion can be directly measured. Utilization of engine rpm can then convert the crank angle changing range to ignition delay time in millisecond (ms). The ignition delay time of HVO fuel and diesel fuel is shown in the figure 17, where it can be found that at lower engine rpm the ignition delay for HVO is shorter due to it obtains high cetane number [7], however, with the increasing of engine rpm, the ignition delay time became closer between two fuels, and at 1900 rpm, the ignition delay was almost the same between HVO and diesel.

$$\text{ID (ms)} = \frac{\text{CA (SOC)} - \text{CA(SOI)}}{720^{\circ}} \times t_{cycle}$$

Equation 2

Where

CA: Crank Angle (°)

ID: Ignition delay time (ms)

SOC: Start of Combustion

SOI: Start of Injection

t_{cycle}: Cycle time for 2 revolutions (ms)

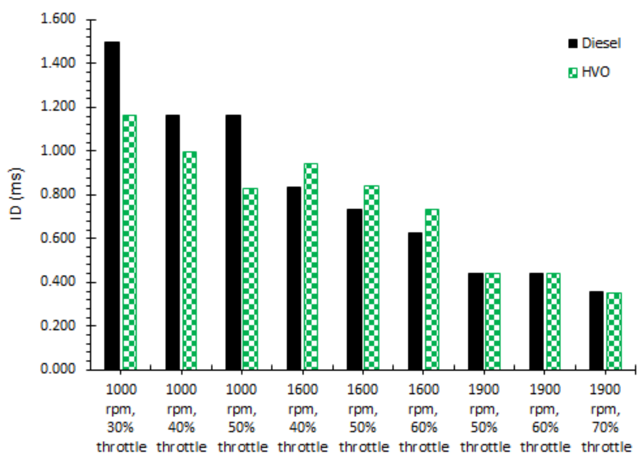

Figure 19: The ignition delay time of HVO fuel and Diesel fuel

Conclusions

The comparison tests were made between the HVO fuel and standard ultra-low sulphur diesel fuel using a EURO5 emission compliant, 3 liter, direct injection, intercooled IVECO diesel engine equipped with EGR and an integrated DOC and DPF aftertreatment system, to investigate their emission and combustion performance. From the test results following conclusions can be made:

- PN emissions from the HVO diesel at the upstream of the aftertreatment system (engine out emissions) were significantly lower (~50% or more) than that from diesel fuel due to its zero-aromatics and straight chain characteristics. Lower engine out particulate emissions from the HVO diesel leads to lower loading of DPF and thus less frequent DPF regenerations.
- PN emissions at the downstream of the aftertreatment system showed the similar levels for both the HVO and standard diesel fuels due to the high efficiency of DPF, which reduced diesel particulate number emissions to a similar level with that from the HVO fuel.
- The HVO diesel shows a lower NO emission in most of the selected engine test conditions, but overall NOx emissions were close to the diesel fuel.
- The HVO diesel shows a lower THC emission as it's burned more completely with straight chain and branched paraffin molecule structure and free of aromatics.
- The ignition delay of the HVO diesel was shorter than the standard diesel at a lower rpm because of the high cetane number characteristic but tends to be the same with the diesel ignition delay with an increase of rpm.
- In general, the DPF efficiency from the HVO fuel test and diesel test are both very high, all above 99%.

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Definitions/Abbreviations

A/F: Air Fuel ratio
CA: Crank Angle
EGR: Exhaust Gas Recirculation
FAME: Fatty Acid Methyl Ester
HVO: Hydrogenated Vegetable Oil
DOC: Diesel Oxidation Catalyst
DPF: Diesel Particle Filter
ID: Ignition Delay
PM: Particulate Matter
PN: Particle Number
PV: Pressure-Volume
SCR: Selective Catalytic Reduction
SOC: Start of Combustion
SOI: Start of Injection
t_{cycle}**:** Cycle time for 2 revolutions (ms)
ULSD: Ultra Low Sulphur Diesel
THC: Total hydrocarbon