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Samenvatting

HVO (Hydrotreated Vegetable Oil) is een drop-in alternatief voor gewone, meestal fossiele, dieselbrandstof. HVO wordt op de markt gebracht vanwege de lagere koolstofintensiteit in vergelijking met gewone dieselbrandstof, maar men claimt vaak dat het gebruik van HVO ook zou resulteren in lagere emissies van fijnstof (PM) en stikstofoxiden (NO_x) uit de uitlaat van dieselmotoren. Literatuur levert bewijs dat voor oudere motoren aanzienlijke reducties van PM-emissies kunnen worden verwacht wanneer motoren op HVO draaien. Voor de impact op NO_x vertonen individuele gevallen gemengde effecten van nul tot reducties tot ongeveer 20%. Er wordt gerapporteerd dat de effecten afnemen wanneer er een goed werkend emissiereductiesysteem aanwezig is, zoals een DPF (Diesel Particle Filter) om de uitstoot van fijnstof te verminderen of een NO_x-reductiekatalysator (SCR, Selective Catalytic Reduction) om de NO_x-uitstoot te verminderen. Dit bewijs is voornamelijk beschikbaar voor voertuigen op de weg, maar over het algemeen zijn er voor niet-wegmotoren niet veel onderzoeksgegevens.

Daarom heeft het Nederlandse Ministerie van Infrastructuur en Waterstaat TNO gevraagd om onderzoek te doen naar het effect van HVO op de emissies van verontreinigende stoffen van moderne Stage V-motoren, de nieuwste generatie niet-voor-de-weg-bestemde dieselmotoren met en zonder emissiereductiesysteem. Een literatuurstudie en metingen zijn uitgevoerd om meer inzicht te krijgen in het effect van HVO op de emissies van verontreinigende stoffen van deze Stage V-motoren. Gegevens van emissiemetingen helpen ook om het Nederlandse emissiemodel voor niet-wegmobiele machines te verbeteren.
De emissies van verontreinigende stoffen van twee Stage V-dieselgeneratoren en een lichtmast, met een motorvermogen van respectievelijk 216 kW, 17,5 kW en 8 kW, werden gemeten. De motor met 216 kW heeft zowel een SCR als DPF, de andere twee motoren hebben geen SCR en DPF vanwege minder strenge emissielimieten voor de wettelijke vermogenscategorie. Tijdens de metingen werd gebruikgemaakt van gewone diesel en HVO van twee verschillende leveranciers. De resultaten van de emissiemetingen met de verschillende brandstoffen zijn onderling vergeleken.

Op basis van de metingen en literatuur werd geconcludeerd dat HVO over het algemeen geen of een verwaarloosbaar effect heeft op de deeltjes- en NO_x-uitstoot van een Stage V-motor met een goed functionerende SCR en DPF.

Voor Stage V-dieselmotoren die geen strenge emissielimieten hebben en daardoor geen uitlaatgasnabehandeling hebben, leidt het draaien op HVO tot lagere deeltjesemissies. Voor dieselmotoren zonder uitlaatgasnabehandeling kunnen lagere NO_x-emissies niet altijd worden geclaimd. Of HVO effect heeft op NO_x-emissies en de mate van het effect, hangt af van de technische motoreigenschappen en bedrijfsomstandigheden.

Uit de metingen bleek dat de twee verschillende HVO's geen significant effect hebben op de NO_x- en PM-emissies uit de uitlaat van de 216 kW Stage V-motor van de generatorset in vergelijking met gewone fossiele diesel. De motor maakt gebruik van een DPF (Diesel Particulate Filter) en SCR om deze emissies te verminderen, wat gemiddeld resulteert in emissies die laag zijn in vergelijking met die van dieselmotoren zonder deze emissiecontrolesystemen.

Voor twee Stage V-motoren met een laag vermogen (8 kW en 17,5 kW), die geen uitlaatgasnabehandeling hebben vanwege de minder strenge limieten voor de toepasselijke vermogenscategorie van niet-wegmotoren, resulteerden de HVO's in een reductie van de PM-emissies van ongeveer 23%, maar de HVO's hebben verschillende effecten op de NO_x-emissies: voor de 8 kW-motor werd geen significant effect gevonden, terwijl voor de 17,5 kW-motor een reductie van ongeveer 18% werd waargenomen bij gebruik van HVO. Verschillende onderzoeken en emissietests hebben al aangetoond dat het effect van HVO op NO_x-emissies afhankelijk is van motorkarakteristieken, zoals injectiestrategie en EGR (Exhaust Gas Recirculation) en motorbelasting.

Summary

HVO (Hydrotreated Vegetable Oil) is a drop-in alternative for regular, mostly fossil, diesel fuel. HVO is marketed for its lower carbon intensity compared to regular diesel fuel, but the use of HVO is also often claimed to result in lower pollutant emissions of particulate matter (PM) and nitrogen oxides (NO_x) from the exhaust of diesel engines. Literature provides evidence that for older engines significant reductions of PM emissions can be expected when engines run on HVO. For the impact on NO_x, individual cases show mixed effects from zero to reductions up to about 20 %. The effects are reported to diminish when a well-functioning emissions reduction system is present, such as a DPF (Diesel Particle Filter) to reduce particulate matter emissions or a NO_x reduction catalyst (SCR, Selective Catalytic Reduction) to reduce NO_x emissions. This evidence is mainly available for on-road vehicles, but in general, for non-road engines, there is not much research data.

Therefore, the Dutch Ministry of Infrastructure and Water management asked TNO to investigate the effect of HVO on the pollutant emissions of modern Stage V engines, the latest generation of non-road diesel engines with and without emission reduction system. A literature study and measurements have been conducted to increase the understanding of the effect of HVO on pollutant emissions from these Stage V engines. Data of emission measurements also help to improve the Dutch emissions model for non-road mobile machinery.

The pollutant emissions of two Stage V diesel gensets and a light pole, with an engine power of respectively 216 kW, 17.5 kW and 8 kW were measured. The engine with 216 kW has both an SCR and DPF, the other two engines do not have an SCR and DPF due to less stringent emission limits for the regulatory power category. During the measurements, regular diesel and HVO of two different suppliers was used. The results of the emission measurements with the different fuels were compared.

Based on the measurements and literature it was concluded that in general, when a Stage V engine has a well-functioning SCR and DPF, HVO will have no or a negligible effect on particulate matter and NO_x emissions.

For Stage V diesel engines which do not have stringent emissions limits, and as a result do not have exhaust gas aftertreatment, running on HVO leads to lower particulate emissions. For diesel engines without exhaust gas aftertreatment, lower NO_x emissions cannot always be claimed. Whether or not HVO has an effect on NO_x emissions, and the level of the effect, depends on technical engine characteristics and operating conditions.

The measurements showed no significant effect of the two different HVO's on the NO_x and PM emissions from the exhaust of the 216 kW Stage V engine of the genset compared to regular fossil diesel. The engine uses a DPF (Diesel Particulate Filter) and SCR to reduce these emissions, which on average results in emissions that are low compared to those of diesel engines without these emission control systems.

For two low powered Stage V engines (8 kW and 17.5 kW), which have no exhaust gas aftertreatment due to the less stringent limits for the applicable power category of non-road engines, the HVO's resulted in a reduction of the PM emissions of about 23%, but the HVO's have different effects on the NO_x emissions: for the 8 kW engine no significant effect was found, while for the 17.5 kW engine a reduction of about 18% was observed when using HVO. Different studies and emission tests have already shown that the effect of HVO on NO_x emissions depend on engine characteristics, such as injection strategy and EGR (Exhaust Gas Recirculation) and engine load.

Contents

Abbreviations

Abbreviation	Meaning
Bsfc	Brake specific fuel consumption
CO	Carbon monoxide
CO_2	Carbon dioxide
DEF	Diesel Emission Fluid (AdBlue)
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particle Filter
ECT	Engine Coolant Temperature
ECU	Engine Control Unit
EFM	Exhaust Flow Meter
EGR	Exhaust Gas Recirculation
EGT	Exhaust Gas Temperature
FAME	Fatty Methyl Ester
HEFA	Hydro-processed Esters and Fatty Acids
HVO	Hydrotreated Vegetable Oil
NO_x	Nitrogen Oxides
NRE	Non Road Engine
NRMM	Non Road Mobile Machinery
OBD	On-Board Diagnostics
PM	Particulate Matter
PN	Particle Number
PEMS	Portable Emissions Measurement System
ppm	parts per million
SCR	Selective Catalytic Reduction
SEMS	Smart Emissions Measurement System
THC	Total Hydro Carbons

1 Introduction

1.1 Background

HVO (Hydrotreated Vegetable Oil) is often marketed as renewable diesel and, next to its lower indirect CO_2 emissions, it is often claimed that while using HVO diesel engines emit less pollutants than when fossil diesel is used. In particular, reductions of NO_x and particulate matter emissions are mentioned. Literature provides evidence that for older engines significant reductions of PM emissions can be expected when engines run on HVO, but for NO_x individual cases show mixed effects from zero to small reductions. The effects are reported to diminish when emissions reduction systems are present, such as a DPF to reduce particulate matter emissions or a NOx reduction catalyst (SCR) to reduce NO_X emissions. The evidence is mainly available for diesel engines in on-road vehicles, but for diesel engines in non-road applications there is not much research data

1.2 Objectives

The main objective of the investigation is to compare the pollutant emissions NO_x and particulate matter of modern Stage V (the latest generation of non-road diesel engines) diesel engines running on HVO and regular diesel. The hypotheses to be tested is that HVO reduces the level of exhaust gas emissions of NO_x and Particulate Matter (PM)/ Particulate Number (PN) of a diesel engine without exhaust gas aftertreatment and a diesel engine with exhaust gas after treatment: Selective Catalytic Reduction (SCR) to reduce NO_x emissions and Diesel Particulate Filter (DPF) to reduce particle emissions. Other objectives are to determine emissions levels of Stage V engines and to determine the dependencies in the application of generator sets and light poles for different regulatory EU NRMM Non-Road Engine power categories, which do and which don not require SCR and DPF to comply with the NRMM regulation (*Regulation - 2016/1628 - EN - EUR-Lex*, n.d.) to improve the emission factors used in emission models. This work is performed on behalf of the Dutch Ministry of Infrastructure and Water Management.

1.3 Approach

The selected approach is to measure the gaseous emissions and particulate matter emissions from the exhaust on three Stage V gensets, one with and two without exhaust gas aftertreatment system. This on regular diesel and on HVO from two different suppliers and for different engine load conditions. The latter to cover for the different possible real world conditions of use of the gensets from engine start, stand-by with idling engine to delivering full power.

1.4 This report

Chapter 2 provides information on HVO and the effect on pollutant emissions based on literature. In **chapter** 3, the measurements and test methods are described with the test programme, the test engines, fuels and instruments used. In **chapter** 4, the results of the programme are presented and in **chapter** 5 the results are discussed. **Chapter** 6 contains the conclusions of the investigation.

2 HVO and direct exhaust emissions

Hydrotreated Vegetable Oil (HVO) is a drop-in biofuel that can be used pure or blended with regular, mostly fossil diesel, in compression ignition engines. HVO can be produced from a number of feedstocks including vegetable oils, waste cooking oils, animal fats and crude tall oil. In the 2020s HVO is mostly produced by an oleochemical process using hydrogenation and refining and results in a mixture of mostly paraffinic hydro-carbons. HVO is also referred to as HEFA (hydro-processed esters and fatty acids) or Renewable Diesel (*Renewable Hydrocarbon Fuels*, n.d.), (*Alternative Fuels*, n.d.).

The carbon intensity of renewable diesel is lower than fossil diesel. This is an important reason for commercialization of the fuel as an alternative to fossil diesel. The carbon intensity of HVO however depends on the feedstock (*Renewable Hydrocarbon Fuels*, n.d.). In 2021, HVO is the second largest commercial renewable diesel alternative world-wide behind biodiesel and the third largest biofuel behind ethanol and biodiesel. (Renewables 2021 - Analysis and Forecast to 2026, 2021).

HVO from most feedstocks overall has almost similar chemical properties as synthetic or fossil diesel. The fuel has to meet the EN15940 standard and Fuel Quality Directive 2009/30/EC Annex 2, which allow it to be used in diesel engines. Most common differences with fossil diesel are usually a lower density compared to fossil diesel. Furthermore, HVO is free from sulphur, oxygen and aromatic hydrocarbons, and commonly has a higher cetane number than regular diesel. HVO has a lower viscosity, a lower cloud point and better storage and cold flow properties than FAMEs. (Kuronen et al., 2007). These properties make HVO a suitable fuel for utilisation in compression ignition engines as used in transportation, construction, shipping or rail roading. Compared to FAME, the lubricity of base HVO is poorer and additives have to be used to increase lubrication properties.

Aside from reduced indirect CO_2 emissions it is also often claimed that HVO leads to lower pollutant emissions from the exhaust of diesel engines compared to fossil diesel. Various studies report about the measured effects of HVO in compression ignition (diesel) engines on the tail-pipe emissions PM/PN, NO_x, CO and THC. Some of these studies also report about the measured effects of HVO on species such as PAH (Poly-Aromatic Hydro-carbons). Hereafter, the literature findings are summarized for engines without and with exhaust gas aftertreatment.

Engines without exhaust gas aftertreatment

Many studies report lower tail-pipe particulate matter (PM), solid particle number (PN), carbon-monoxide (CO), black carbon and total hydro-carbons (THC) emissions with HVO or paraffinic diesel in compression ignition engines, engine out or for engines *without* exhaust gas aftertreatment, (Na et al., 2015), (Dobrzyńska et al., 2020), (Kousoulidou et al., 2014), (Bugarski et al., 2016, 2017), (Mikkonen et al., 2012; Pirjola et al., 2017, 2019), (Happonen et al., 2012), (Murtonen et al., 2009), (Happonen et al., 2012), (Rantanen et al., 2005).

Some studies reported similar results for non-road diesel engines (McCaffery et al., 2022), (Bugarski et al., 2016).

Regarding NO_x, a number of studies reported significantly lower emissions with HVO (Laurikko et al., 2014), (Murtonen et al., 2009), (Happonen et al., 2012). According (Mikkonen et al., 2012). NO_x emissions did reduce on average for 32 trucks and buses, but (Mikkonen et al., 2012) reported no or a very small effect for 8 passenger cars. (Bohl et al., 2018), (Dimitriadis et al., 2018), (Sugiyama et al., 2011) concluded that the effect on NO_x emissions is small or non-present with the application of a post fuel injection strategy as is the case for most modern or more complex diesel engines, and the application of EGR. Also engine load seems to impact the effect of the fuel on NO_x emissions: (Bohl et al., 2018) reports that effects diminish at higher loads and (Pflaum et al., 2010) reports that effects are more pronounced at lower loads. It must be noted that current market diesel, which is the reference in this investigation, is required to have a minimum share of bio-diesel of up to 7%. This bio-diesel, usually FAME, contains oxygen. The oxygen present in neat FAME or blends is known to increase engine out NO_x emissions. This means that the share of B7 can, depending on its atomical composition, also slightly increase the engine out NO_x emissions.

Engines with exhaust gas aftertreatment

For diesel engines *with* exhaust gas aftertreatment, effects on emissions depend on the type of aftertreatment used and the efficiency of reducing emissions: (Suarez-Bertoa et al., 2019) reported no effect on emissions of PM/PN and NO_x on Euro 6b diesel cars. These cars have catalytic NO_x reduction systems (SCR or NO_x trap) as well as Diesel Particle Filters to reduce PM/PN and NO_x emissions. (Pirjola et al., 2017) reported a reduction of NO_x emissions of an agricultural tractor equipped with SCR but the SCR did not run at a very high efficiency. (Ligterink et al., 2023) reported a reduction of the NO_x emission of 11 to 17% with HVO of a Stage IIIB engine equipped with SCR in a passenger train, but also in this case the SCR did not work optimally. (Hartikka et al., 2012) explained that lower absolute emission reductions with HVO with more recent heavy-duty engines as used in trucks and buses, such as EURO IV, V and VI, are to be expected due to the use of exhaust gas aftertreatment systems and the more precise and complex control strategy of the engine. Mata et al. reported a slightly lower NOx emission when running on HVO for a Euro VI-D bus during the cold start phase.

Some investigations have tested HVO on different engines to gain an understanding of its combustion and exhaust formation behaviour. The reductions of emissions observed are mainly attributed to the high Cetane Number (lower ignition delay time), the lack of aromatics compared to fossil diesel and the lack of oxygen compared to bio-diesel or bio-diesel blends. It was also reported that HVO could allow tuning the injection control to achieve an optimum, where PM, NO_x and fuel consumption are reduced compared to basic settings at regular fossil diesel (Pflaum et al., 2010), (Happonen et al., 2012), (Bohl et al., 2018).

Table 2.1: Overview of effects of HVO on diesel emissions PM/PN and NO_x based on literature.

	Without aftertreatment	With aftertreatment DPF in case of PM/PN and SCR in case of NO_x
PM/PN	Significant reductions up to 50%, but typically around 20-30%	No reductions in between regenerations. The amount and duration of regenerations may decrease due to the lower ‘engine out’ PM emissions.

	Without aftertreatment	With aftertreatment DPF in case of PM/PN and SCR in case of NO_x
NO_x	No reduction up to 20% reductions depending on engine load and engine type/technology.	If a small reduction is present from the engine, this is significantly reduced by the functionality of the SCR. Only at sub-optimal SCR performance, engines emitting less NO_x may still show a small NO_x reduction.

3 Method

3.1 Test approach

The initial approach selected is to measure the gaseous emissions and particulate matter emissions from the exhaust of two Stage V diesel engines in two gensets, one engine with and one without exhaust gas aftertreatment system. The test are conducted on regular diesel fuel and on HVO. The latter from two different suppliers. Test are conducted at different, mainly steady engine load conditions. This to cover for the different possible real world conditions of use of the gensets from engine start, stand-by with idling engine to delivering full power. A third Stage V engine without an exhaust gas aftertreatment system was added later.

The test data obtained, should give indications on the effects of the fuel on emissions. Moreover, the data helps to demonstrate effects of HVO fuel for a better common understanding of these effects on emissions.

The test approach, however, has some limitations for drawing conclusion about the use of HVO in diesel engines as the tests are limited to:

- Mainly stationary loads;
- Three non-road engines. Nevertheless, engines with different engine power and complexity were chosen. Two engines are of a simple construction:
  - a naturally aspired, mechanically controlled engine without any form of exhaust gas aftertreatment, with an engine power in the low power range, Non-Road Engine (NRE) category 2 (9.5 and 15kW stand-by power),
  - and one turbo-charged electronically controlled engine in a higher power range NRE category 6 (197 kW stand-by power), which has e exhaust gas aftertreatment (SCR and DPF).
- All engines do not use EGR. Effects may depend on engine control, but mainly for electronic controlled with EGR, ignition timing and (pre-) injection strategy.

3.2 Fuels

For the test programme regular market EN590 diesel (B7) is chosen as a reference. Two EN15940 HVO fuels from different suppliers are selected for the comparison with the standard diesel, see Table 3.1 for a number of specifications. The three fuels differ in terms of density, heat of combustion per kg and litre and composition. Remarkable is the difference in volumetric energy density of the two HVO's, one being lower and one being higher compared to the regular diesel

Another B7 diesel and a third HVO were added for a later test programme to run tests on a third test object because the PM measurement on one of the two initial test objects failed. For these fuels, no analyses is available.

Table 3.1: A number of specifications of the three fuels that were used for the test programme: a regular fossil diesel and two HVO's each from a different supplier.

Standard			Diesel B7 OK	HVO1 Neste	HVO2 Full tank
ISO12185	Density@15C	g/mL	0.819	0.7832	0.8084
ISO4264	Cetane Index calculated	[-]	>56.5	>56.5	>56.5
ASTM D240	Gross Heat of Combustion	MJ/kg	46.165	46.465	47.395
	Gross Heat of Combustion Calculated	MJ/l	37.809	36.391	38.314
ISO8217	Calculated Carbon Aromaticity Index CCAI	[-]	779	741	768
ASTMD5291M	Carbon	Wt%	83.8	83.2	83.3
	Hydrogen	Wt%	13.2	13.7	13.4
	Nitrogen	Wt%	3	3.1	3.3
	Oxygen	Wt%	<0.1	<0.1	<0.1
EN12916	DAH (Di-Aromatic Hydrocarbons)	Wt%	<1.0	<1.0	<1.0
	MAH (Mono-Aromatic Hydrocarbons)	Wt%	<7.9	<6.0	<6.0
	TAH+ (Tri+ Aromatic Hydrocarbons)	Wt%	0.1	0.1	0.2
	PAH (Polycyclic Aromatic Hydrocarbons)	Wt%	<1.0	<1.0	<1.0
	TAH (Total Aromatic Hydrocarbons)	Wt%	<8.7	<8.7	<7.0

Figure 3.1: Samples of the three test fuels, from left to right: regular, fossil diesel B7 from OK, a 100% HVO from Neste (HVO1) and a 100% HVO from Full tank (HVO2).

3.3 Machinery/engines

Table 3.2, Table 3.3 and Table 3.4 provide the most relevant specifications of the test objects, two diesel-powered genset and a diesel-powered light pole.

3.3.1 200 kVA genset

The genset is relatively fresh with only 386 running hours. The average fuel consumption indicates that the average engine load was low and around 20%.

Table 3.2: Specifications of the 200 kVA genset with non-road engine with emissions control. Data from genset plate, engine plate and (*Specification Sheet B6.7-G18 EU Stage V and Tier 4 Final 0063351.Pdf*, n.d.).

NRMM type	Generator set 200kVA prime
NRMM Brand and ID	Bruno for Aggreko, plant no. XEML080, model FQ225cv
Engine brand	Cummins Inc.
Type	B6.7 G18
Date of manufacturing	18mar22
Engine specifications	6.7 l, Inline 4-Cycle Diesel, Turbocharged & Charge Air Cooled
NRMM category, Stage V	NRE-v/c-6 , EU Stage V, EPA Tier4F
EC code (engine plate)	e5 EC6/D V-1099, EU family U313
Emissions control systems	Single module DOC, DPF, SCR
Emissions control information (engine plate)	ECS (Emissions Control System) DDI (Direct Diesel injection) ECM (Engine Control Module) TC (Turbo Charger) CAC (Charge Air Cooler)
DEF tank capacity [l] (tank plate)	113.5
Engine power rating [kW] @ 1500 min^{-1}	Prime 216, stand-by 197
Generator rating [kVA]	200
Generator prime rating [kW] (power factor 0.8) Generator cont. rating [kW] (power factor 0.8)	160 144
Running hours at test start [h], # starts	386, 92
Fuel used [l], average FC [l/h]	4007, 10.4

Table 3.3: Power, fuel and DEF (Diesel Emission Fluid, AdBlue) specifications from the Cummins engine (*Specification Sheet B6.7-G18 EU Stage V and Tier 4 Final 0063351.Pdf*, n.d.)

Generator rating	Load	Engine power	Fuel consumption	DEF (AdBlue)	DEF (AdBlue) - % of fuel
	[%]	[kW]	[l/h]	[l/h]	[%]
Stand-by	100	216	51	5.9	12%
Prime	100	197	46	5.3	12%
	75	148	34	3.7	11%
	50	98	23	2.1	9%
	25	49	14	1	7%
Continuous	100	177	41	4.7	11%

Figure 3.2: The diesel-powered genset at the test site.

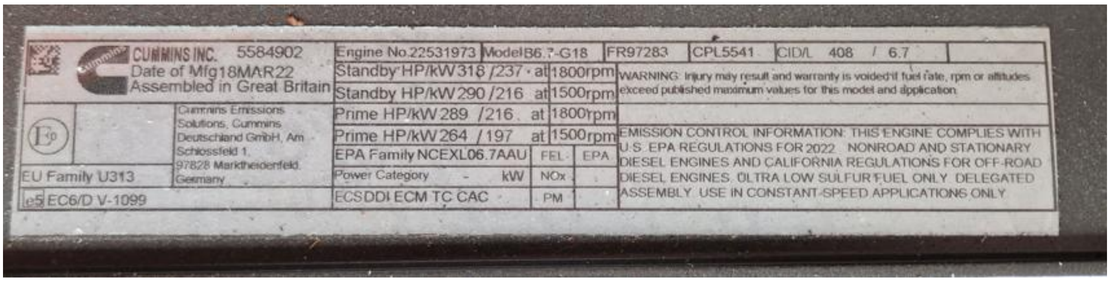

Figure 3.3: Engine plate of the Stage V Cummins diesel engine of the genset.

3.3.2 7 kVA light pole

During its lifetime, the engine of the light pole ran at a low average load of 1.2 kW according to the display.

Table 3.4: Specifications of the 7 kVA genset with non-road engine without emissions control system.

NRMM type	Light pole, low power generating set
NRMM Brand and ID	E-power 3535-22
Engine brand	Kubota
Type	D1105-BG-EF02 (2022)
Family	JKBXL01.5BCC
Engine specifications,	1.123 l, inline 3 cylinder, diesel
NRMM category, Stage V	NRE-v/c-2, EU Stage V
EC Code	(e1) EC2/D V-0039
Emissions control systems	-
Engine power rating [kW]	9.5 stand-by, 8.4 continuous
Generator rating [kVA]	Prime 7, stand-by 7.5
Running hours at test start [h], work [kWh], average power [kW]	1124, 1376, 1.2kW
Fuel used [l], average FC [l/h]	n.a., n.a.

Figure 3.4: The diesel-powered light pole at the test site.

Figure 3.5: Engine plate of the Stage V Kubota diesel engine of the light pole.

3.3.3 17.5 KVA genset

Table 3.5: Specifications of the 17.5 kVA genset with non-road engine without emissions control system.

NRMM type	Genset
NRMM Brand and ID	Genpower QAS20 s5
Engine brand	KUBOTA
Type	V2203M-E4BG
Family	EAC ASF370892, 09/2022
Engine specifications	2.2 l, inline 4 cylinder, diesel
NRMM category, stage	NRE2, EU Stage V
EC Code	n.a.
Emissions control systems	No exhaust gas aftertreatment
Engine power rating [kW]	Prime 14, Stand-by 15
Generator rating [kVA]	Prime 17.5, Stand-by 18.7
Running hours at test start [h], work [kWh], average power [kW]	n.a.
Fuel used [l], average FC [l/h]	n.a., n.a.

Figure 3.6: The diesel-powered 17.5 kVA genset.

3.4 Test programmes

Table 3.6, Table 3.7 and Table 3.8 provide the test programmes as conducted with the three test objects. The programmes contained a D2 cycle and an additional zero load point to measure emissions over the entire load range and to compare the weighted cycle result with the applicable limit value which accounts for a formal type approval test. Additionally, three load points over the engine load range were selected, each point to be repeated three times. This is done to be able to compare emissions running on the different fuels over three typical loads: zero load, medium load and high load. For the low-powered engines without after treatment we tried to find a smoke point and test just above it. For the tests on the three load points and the D2 cycle, each load point was run long enough such that exhaust gas temperatures and emissions are stabilized. The latter is especially important for the SCR-equipped engine because SCR temperature stabilization can take some time and impacts emissions levels substantially.

Table 3.6: Test programme for the 200kVA genset with 216 kW non-road engine with emissions abatement (SCR, DPF)

Date (2023)	Programme part	Remarks
22-6	Commissioning	Various load points
22-6	D2-cycle (diesel only)	100, 75, 50 25, 10%, (+0%)
23-6	SCR light-off (diesel only)	Stepwise increasing and de-creasing load from 0% to ~30%
26-6	Diesel: 3x3 load points	0, 35, 70%
27-6	HVO 1: 3x3 load points	0, 35, 70%
27-6	HVO 2: 3x3 load points	0, 35, 70%

Table 3.7: Test programme for the 7kVA light pole / genset with 8 kW non-road engine without emissions abatement.

Date (2023)	Programme part	Remarks
28-6	Commissioning	Various load points
28-6	D2-cycle (diesel only)	100, 75, 50, 50, 25, 10%, (0%)
28-6	Load steps (diesel only)	0 to 80%
29-6	Diesel: 3x3 load points	0, 35, 80
29-6	HVO 1: 3x3 load points	0, 35, 80%
29-6	HVO 2: 3x3 load points	0, 35, 80%

A third test object was added to the programme at a later stage because the PM emissions of the 7 kVA light pole could not be determined due to an error of the scale that was used to weigh the filters. Table 3.7 shows the test programme for the third test object.

Table 3.8: Test programme for the 14 kVA genset with 17 kW non-road engine without emissions abatement.

Date (2024)	Programme part	Remarks
22-8	Diesel: 3x3 load points	0, 36, 93%
22-8	D2-cycle (diesel only)	100, 75, 50, 50, 25, 10%, (0%)
23-8	HVO 3: 3x3 load points	0, 36, 93%

3.5 Instruments

A Portable Emissions Measurement System (PEMS) has been used to measure the regulated gaseous emissions NO_x, (T)HC, CO and the non-regulated gaseous emissions NO, NO_2 and CO_2 of the 200 kVA genset and the 7 kVA light pole . A Smart Emissions Measurement System (SEMS) was added to record the engine data and additional NO_x sensor data and exhaust gas temperature on both machines. SEMS with a calibrated NO_x sensor was used for emissions measurements of NO_x, O_2 (to calculate CO_2) from the exhaust of the 17.5 kVA genset. The NPET was added to measure Particle Number emissions but the instrument failed during the first measurements. A partial flow dilution system with filters was added to collect particulate matter and to determine PM mass emissions.

Table 3.9: Instruments used and TNO's identification number to track instrument status.

Instrument	Remarks	TNO TUI nr.
PEMS EFM	Portable Emissions Measurement System Exhaust Flow Meter	60150508
SEMS	Smart Emissions Measurement System	94017847
NPET	Nano particle emissions tester. Failed at the first measurements. Erratic high readings, also with ambient air.	94003989

Instrument	Remarks	TNO TUI nr.
PF PM	Partial flow dilution gravimetric measurement. TNO developed set-up. Two mass flow controllers control dilution air flow and total sample flow. The dilution probe is heated and temperature controlled to avoid condensation. 47 mm filter holder with Pallflex PTFE / glass fibre filters and quartz filters.	N/A

PEMS is the formally prescribed instrument for off-cycle type-approval testing and in-service conformity testing Euro VI certified engines in heavy-duty vehicles, Euro 6 dtemp and later passenger cars and in-service monitoring of Stage V non-road mobile machinery. The PEMS used for the programme is a Horiba OBS-ONE GS11.

Figure 3.7: PEMS (Portable Emissions Measurement System), a Horiba OBS-one GS11.

Figure 3.8: Exhaust Flow Meter (EFM) of the PEMS as mounted on the genset.

SEMS is a sensor-based autonomous emissions measurement system developed by TNO (Heijne, V. et al., 2016). SEMS is used in the programme to measure and analyse the tail-pipe NO_x emissions and a range of engine parameters to be able to determine engine load and engine and genset status. The SEMS uses a calibrated automotive NO_x/O_2 sensor, an ammonia sensor and a data-acquisition system to record the sensor data and data from the engine ECM at a sample rate of 1Hz. The system can operate autonomously and wakes up at ignition/key-on. The recorded data is sent hourly to a central data server.

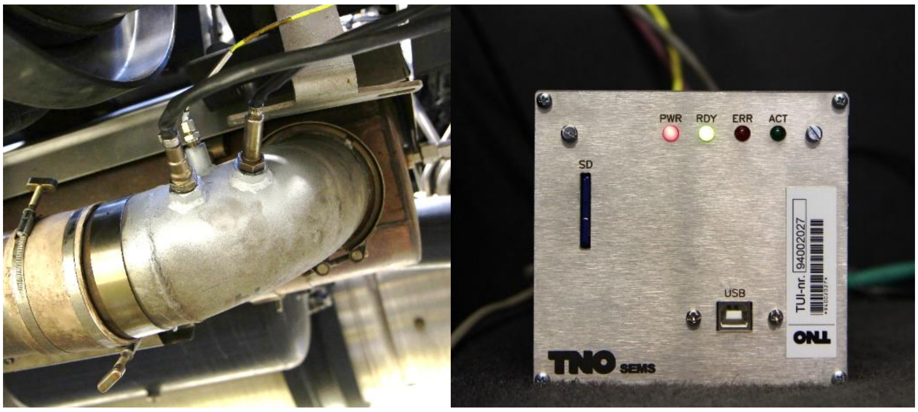

Figure 3.9: SEMS. *Left*: calibrated NO_x-O_2 sensor, NH_3 sensor and temperature sensor mounted in the tail-pipe of a lorry. *Right*: autonomously running data recording unit with hourly data transmission to a central server via GPRS.

A set-up with partial flow dilution gravimetric measurement was used to collect particulate matter on a filter medium. The set-up is shown in Figure 3.6. Flows for dilution were controlled by means of calibrated Bronkhorst mass flow controllers. 47mm Pallflex glassfibre/ptfe and quartz filters were used, the latter to be able to analyse the particulate matter composition.

A load bank, see Figure 3.10, was used to apply stable loads to the gensets.

Figure 3.10: Load bank used to put load to the gensets and light pole.

4 Results

4.1 Results 200 kVA Genset

4.1.1 Gaseous emissions

A number of gaseous emissions were measured for the three fuels at three engine loads with the Portable Emissions Measurement System (PEMS) and SEMS was used to record engine data and the NOx sensors from the engine. Each load point was measured three times to assess repeatability of the test.

The average emissions levels of the fuels can be compared at each of the three engine load points. Figure 4.1 shows the NO_x emissions for the three fuels at three measured loads of the 200 kVA genset. Each load point was measured three times. The emission is highest at 0% engine load (stabilized idling). This is caused by the fact that the SCR does not reach working temperature at that load, see paragraph 4.1.4 about SCR 'behaviour'. At 35 and 70% engine load the NO_x emissions are clearly lower. The small differences between the different fuels seem to be caused by differences in SCR efficiency, also at 0% load, which indicates that there can be still some low SCR activity at this low load. HVO1 shows a significant difference but this seems to be caused by a slightly higher SCR efficiency. There are no significant differences in exhaust gas temperature post-SCR (~135 °C) that could explain differences in SCR efficiency at 0% load. See Figure 4.11 for the average SCR efficiencies.

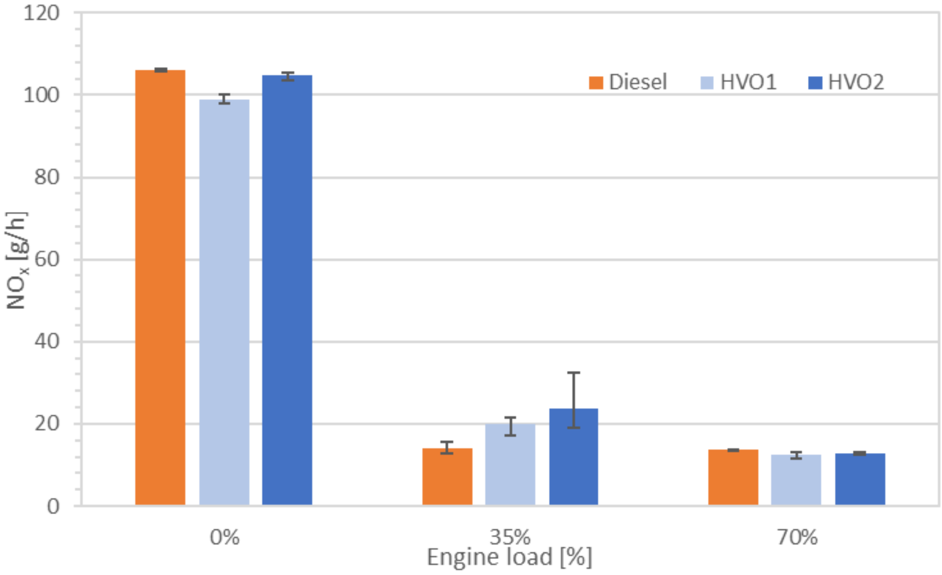

Figure 4.1: NO_x emission for the three fuels at three measured loads of the 200kVA genset. Each load point was measured three times. The bar represents the average of three measurements, the error bars represent the minimum and maximum of the measurements. At working temperature the SCR system reduces the NO_x emissions which lead to the lower NO_x emissions at 35 and 70% load. Some variation in SCR efficiency seems to cause the small variations in NO_x emissions.

A number of the measurements of NO concentration showed deviations with unstable readings. This means that the NO and NO_2 fractions cannot be determined reliably but NO_x can be. Also the measurements of the CO concentrations showed deviations with negative measurement values due to which the CO emissions cannot be determined reliably.

The total hydro-carbon emissions are lower for the two HVOs at low load and this trend is also observed at the higher load points where mainly HVO2 shows a large difference with HVO 1 and the regular diesel.

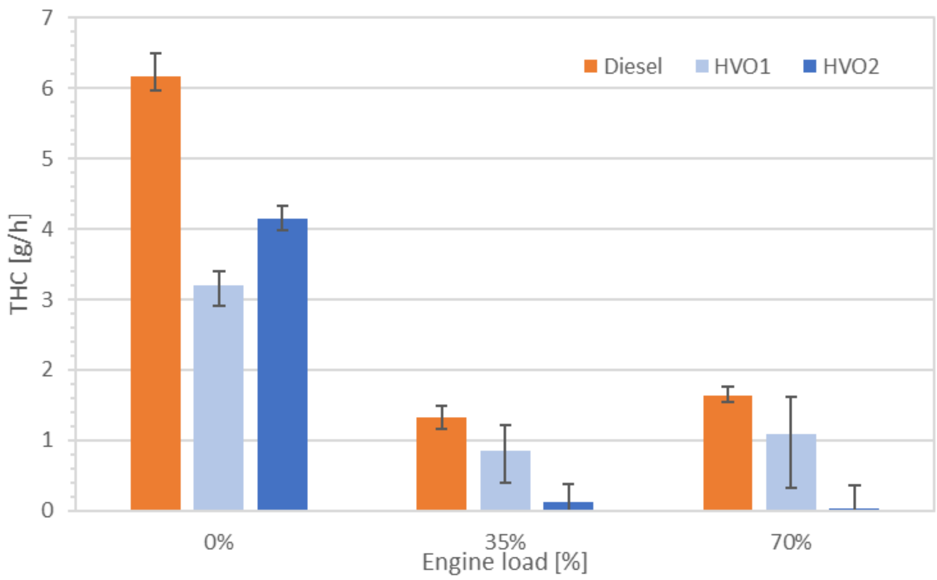

Figure 4.2: THC emissions for the three fuels at three measured loads of the 200kVA genset. Each load point was measured three times. The bar represents the average of three measurements, the error bars represent the minimum and maximum of the measurements.

The ISO 8178 D2 test cycle was conducted to quickly check the engines NO_x emissions level and to gain insight of NO_x levels over the five modes of the test cycle. The weighted work-specific NO_x emissions are below the limit of 0.4 g/kWh (Stage V, category NRE-v/c-6, 130 ≤ Net power ≤ 560 kW) which applies for this engine type as tested over the formal EU type approval test procedure. Note that the D2 cycle ran for this investigation is not entirely done according formal type approval procedures. Type approval testing involves testing on an engine test bed in an emission testing laboratory.

Table 4.1: NO_x results over the applicable D2 test cycle.

D2 mode	D2 weighting factor	Engine power	NO_x	D2 NO_x
	[-]	[kW]	[g/h]	[g/kWh]
B7 100%	0.05	191	23	
B7 75%	0.25	160	17	
B7 50%	0.3	101	11	
B7 25%	0.3	49	9	
B7 10%	0.1	15	201	
D2 NO_x				0.32

4.1.2 Fuel consumption and CO_2 emission

Figure 4.3 shows the CO_2 emission for the three fuels at three engine loads. With HVO1 the CO_2 emission is measured to be the lowest and with HVO2 the highest. The theoretical CO_2 emission per litre of fuel used is lowest for HVO1 and highest for the diesel. This is only inline with the low CO_2 emission of HVO2. Differences between diesel and HVO2 are a few precent and small.

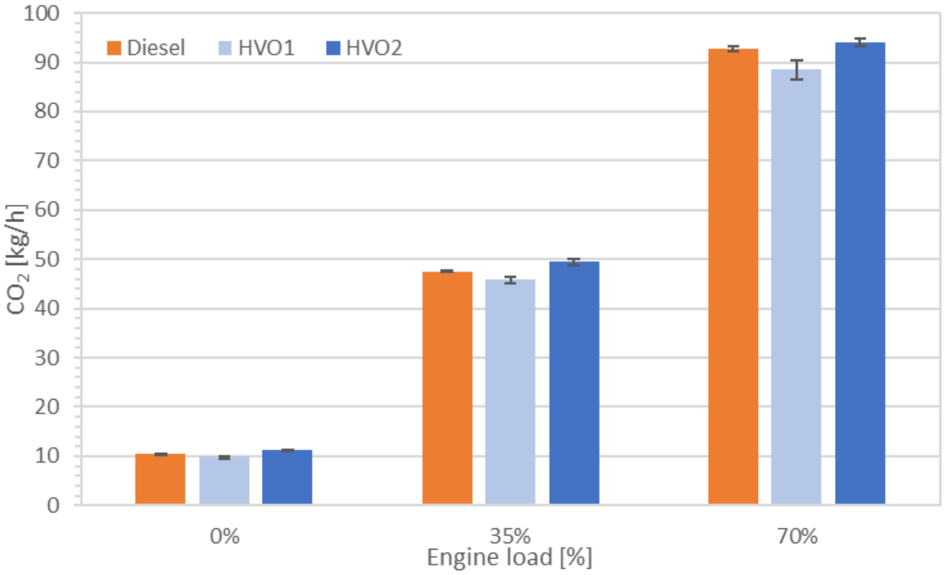

Figure 4.3: CO_2 emission for the three fuels at three measured loads of the 200kVA genset. Each load point was measured times. The bar represents the average of three measurements, the error bars represent the minimum and maximum of the measurements.

Figure 4.4 shows the fuel consumption for the three fuels at three engine loads. The fuel consumption is determined from the measured CO_2 THC and CO mass emission (PEMS), the measured fuel C-content and density of the fuels. Both HVO's lead on average to a slightly higher, 1 to 4 % FC. Based on fuel volumetric energy content one would expect HVO1 to have higher FC than diesel and HVO2 a lower FC compared to diesel. So HVO2 seems to be too high which is in line with the observation of the CO_2 emission of HVO2 which seems to be higher than one would expect based on fuel properties. A higher FC and CO_2 emission than expected could be explained by a higher engine load, but according to the noted load bank settings and calculated engine power from the engine this is not the case.

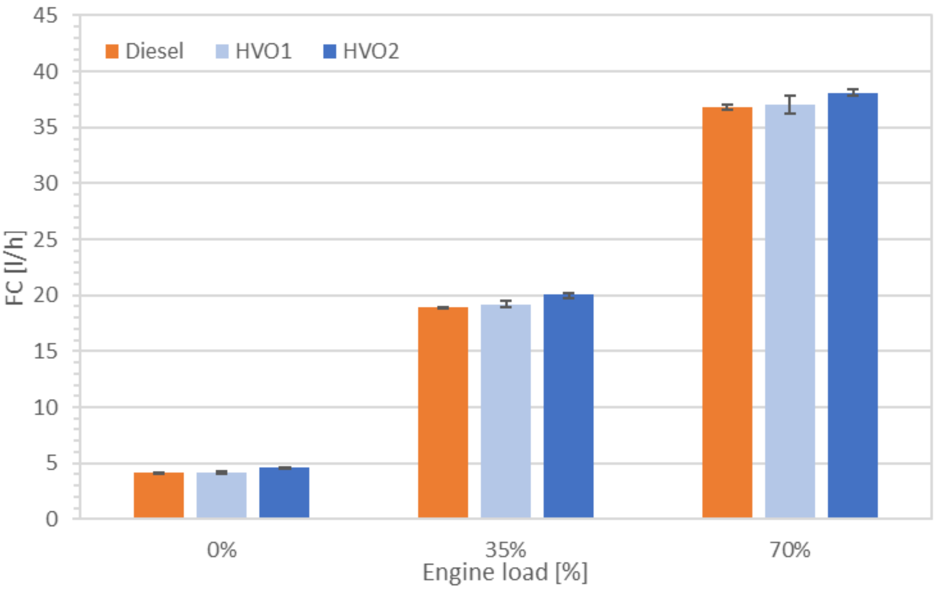

Figure 4.4: Fuel consumption for the three fuels at three engine loads. Each load point was repeated three times. The error bars show the minimum and maximum consumption.

4.1.3 Particulate matter emission

Particulate Matter emissions were measured on Teflon filters and on quartz filters. The latter to be able to measure the elemental carbon (EC) and organic carbon (OC) fractions and species from the filter medium.

The filters were sampled over a combination of engine loads as the sample time was to be kept high enough to collect sufficient PM on a filter. This was needed as the engine has a diesel particulate filter, leading to low tailpipe particle emission. For the D2 cycle the engine loads per load point used are 90, 75, 50, 25, and 0% for each load. The engine loads and sample times per load point used for the comparison of the different fuels are 0, 35 and 70% and 30, 20 and 20 minutes respectively for those points, all with warm stabilized engine.

4.1.3.1 Filter

The average level of particulate matter emissions ranges from 3 to 8 mg/kWh. This is well below the limit of 15 mg/kWh which applies for the D2 cycle and regulated test conditions. Hourly emissions rates range from 200 to 470 mg/h. PM emissions per fuel vary between measurements. This poor repeatability may be caused by the low sampled mass on the filter. There is no clear trend regarding the emissions levels of the different fuels.

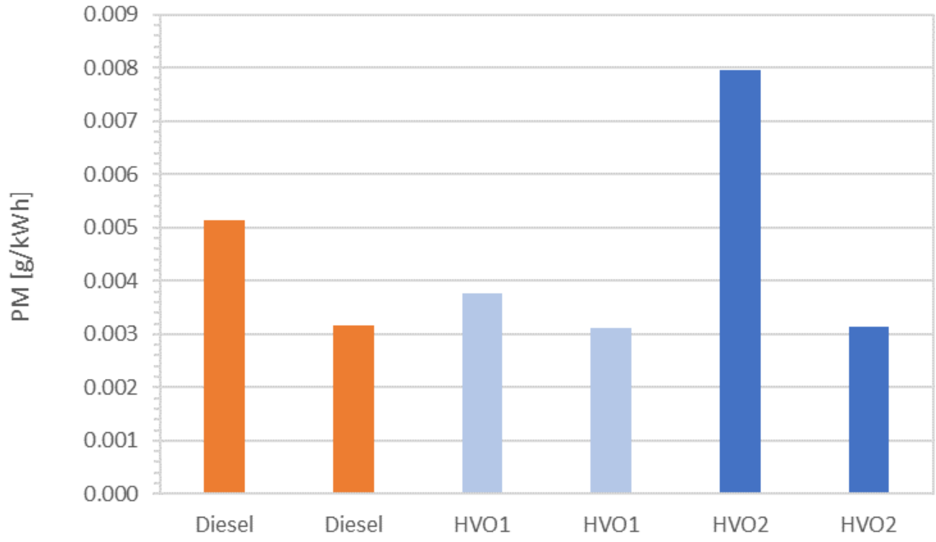

Figure 4.5: Work-specific PM emissions for the three different fuels as sampled on one filter over three engine loads, 0, 35 and 70% respectively. Each test was repeated once.

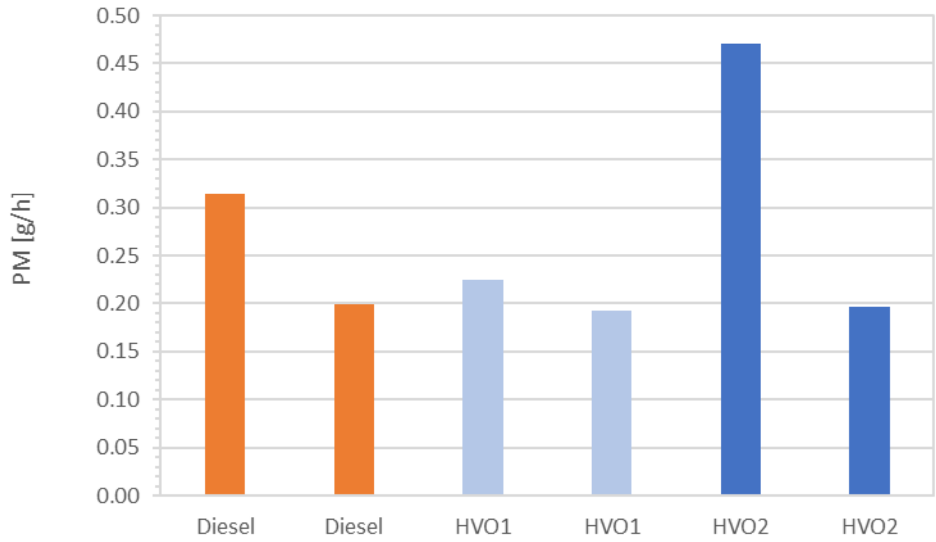

Figure 4.6: PM emission rates for the three different fuels as sampled on one filter over three engine loads, 0, 35 and 70% respectively. Each test was repeated once.

4.1.3.2 Quartz filter

PM sampled on the quartz filter results in higher PM values than when sampled on the Teflon filter. This may be caused by the difference in filter medium. Both HVO's have a slightly lower PM emission.

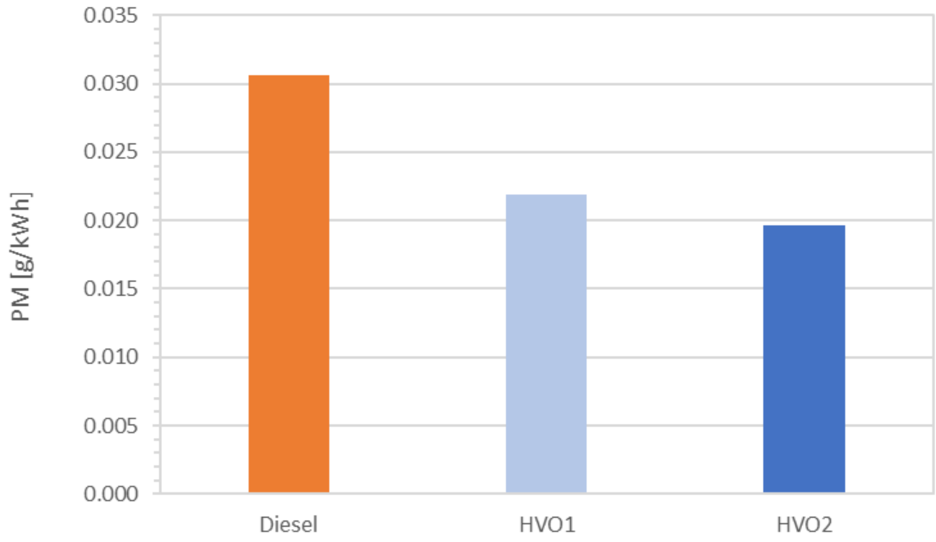

Figure 4.7: Work-specific PM emissions for the three different fuels as measured on quartz filters. PM was sampled on one filter over three engine loads, 0, 35 and 70% respectively.

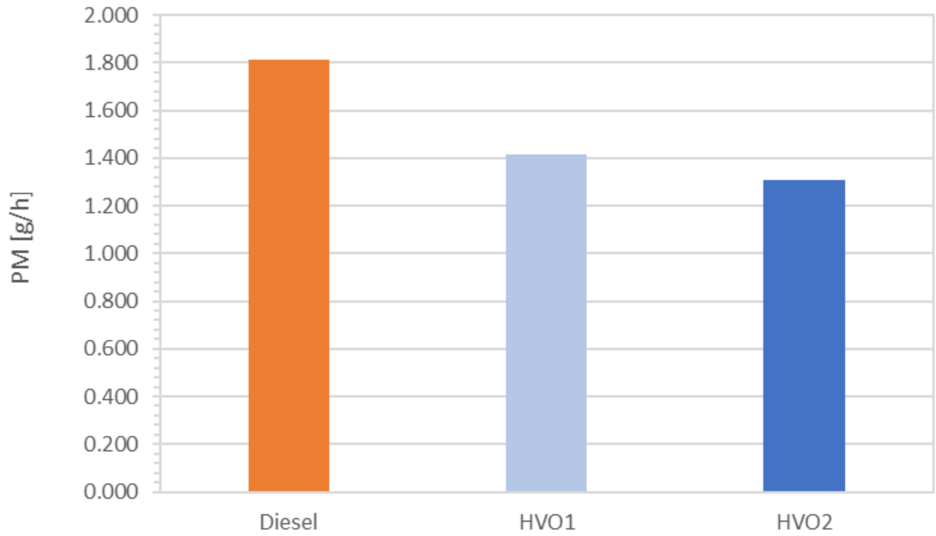

Figure 4.8: PM emissions rates for the three different fuels as measured on quartz filters. PM was sampled on one filter over three engine loads, 0, 35 and 70% respectively.

4.1.4 SCR 'behaviour'

Figure 4.9 shows NO_x concentrations upstream the SCR catalyst (SEMS-US (only provides signal when warmed up), engine NO_x sensor), downstream of the catalyst (PEMS-GA), the exhaust gas temperature post-SCR and the engine torque for a load cycle going from low load to a higher load in steps (up to 25%) and back with the same steps. This load cycle has been done to investigate SCR behaviour at low load and specifically to determine the light-off point of the SCR.

Going up in engine load the NO_x concentration downstream of the SCR follows the NO_x concentration upstream of the SCR, until the engine runs at 20% load and post SCR temperature has just increased to above 200 °C.
At that point the NO_x concentration downstream of the SCR at 20% load decreases from 450 ppm until almost stable just below 100 ppm. When the load increases another 5% from 20 to 25% the NO_x concentration decreases further to around 10-20 ppm.

When load is decreased in steps. NO_x concentrations increases again, first slightly from, but when post SCR temperature drops below 200 °C NO_x concentration increases again. The SCR light-off lies around 20% load and 200 °C post SCR exhaust gas temperature, at decreasing load steps not all load points were stabilized.

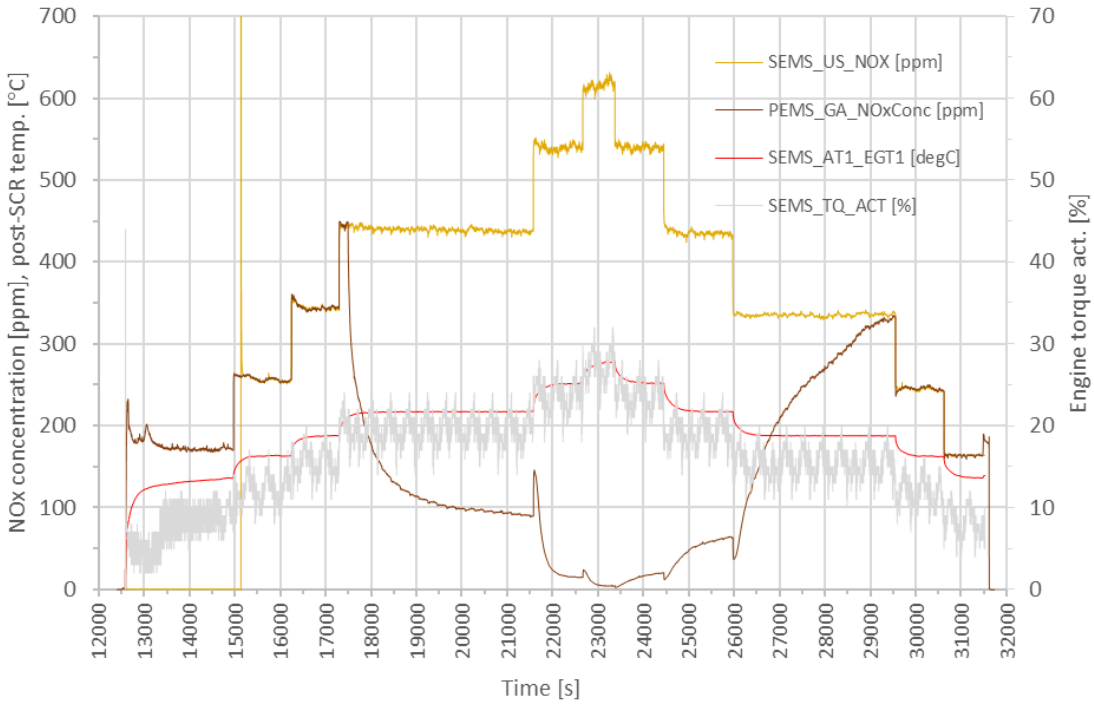

Figure 4.9: Graph showing the change of NO_x concentrations, exhaust gas temperature post SCR and engine torque in response to step load changes going from zero to 25% engine torque and back.

Figure 4.10 shows the absolute NO_x emissions over the (same) low load steps. When the SCR does not work at loads from 0 to 20 % the NO_x emission goes from 30 to 90 mg/s. Running a few minutes at 20% load the NO_x emission starts to drop to about 20 mg/s. Increasing the load further the NO_x emission drops further to below 5 mg/s. At the same loads and at stabilized conditions, NO_x emissions are roughly the same at increasing and at decreasing loads. An exception is the 20% load where NO_x emissions are somewhat lower compared to the 20% load at increasing load steps. This is possibly due to the SCR, which still has some ammonia stored to reduce the engine out NO_x a bit more at that point. The load point was not fully stabilized, so in the end NO_x emission level will probably become more or less the same.

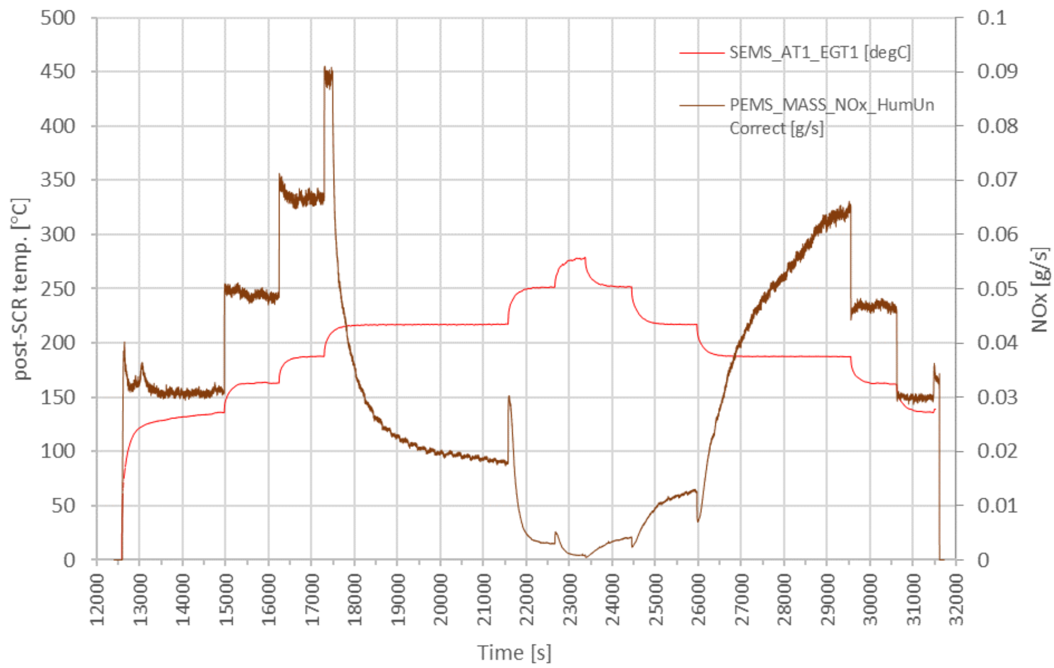

Figure 4.10: Graph showing the change of the NO_x mass emission in response to step load changes going from zero to 25% engine torque and back.

Figure 4.11 shows the SCR efficiency, which is about a few percent at the lowest load. SCR efficiency reaches values of just above 95% at 35% engine load which lies above the SCR light-off which seems to lie between 15 and 20% engine load. At 70% engine load SCR efficiency increases further to 98-99%.

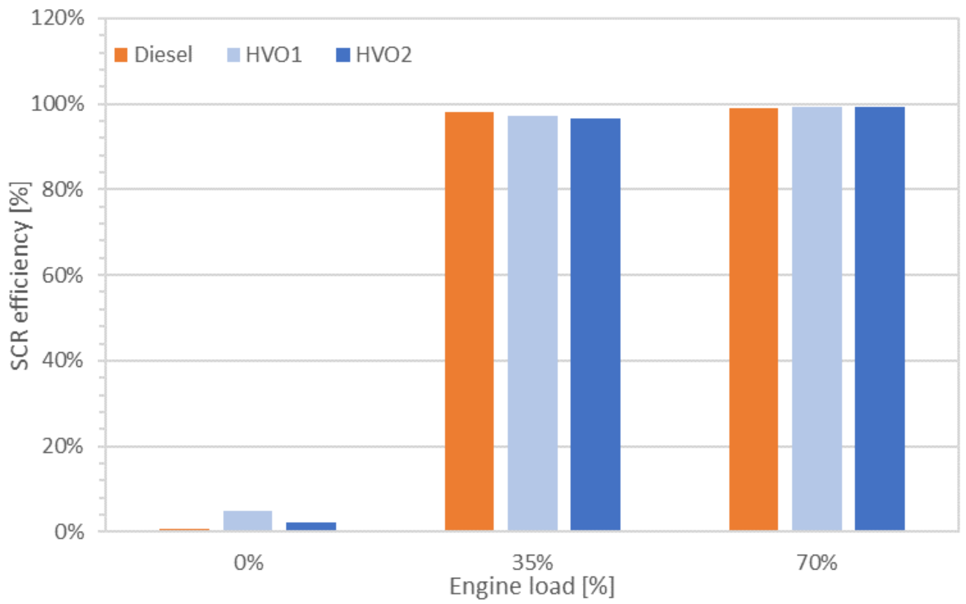

Figure 4.11: SCR efficiency at three different engine loads as determined from the NOx sensor upstream of the SCR catalyst and the NOx measured post SCR catalyst.

4.1.5 Engine data

Data from the engines ECU was recorded and used for the data-analyses.
Such data are not only necessary for analyses of the test results. Insight in the usability of the signals is also needed for the Dutch programme EMPK (Emissions monitoring and periodic Inspection) for mobile machinery, because monitoring and inspection based on available data of machinery is considered (2023).

Data of interest are:
- Fuel rate [l/h];
- Engine speed and torque (actual % engine torque, friction torque and reference torque [Nm]) which enables calculation of engine brake power [kW];
- AdBlue consumption and tank level [%];
- NO_x concentration upstream and downstream of SCR catalyst [ppm] to determine catalyst activity and calculate tail-pipe NO_x emissions levels.

Figure 4.12 shows a sample of recorded ECU signals. Engine speed, torque and fuel rate and the derived calculated engine power show some periodicity. Engine speed has an amplitude around 1500 rpm which is smaller than 10 rpm but most of the times about 5 rpm, with a period of about 400 seconds. Engine torque also shows some change over time but with a less clear pattern. Fuel rate has a very clear block pattern where the amplitude becomes smaller at a smaller fuel rate and has a period of about 130 seconds. The change in engine torque and speed over time result in a somewhat unstable calculated engine power. Changes in engine torque and fuel rate do not seem to be directly related, which is unexpected because engine torque output is a direct result from the controlled fuel quantity. Also engine speed and fuel rate do not seem to be directly related.
Given the unstable signals and unexpected behaviour we have doubts about the quality of the engine data. Roughly, the calculated engine power levels are in line with what one would expect based on the setpoints of the load bank. But because the generator losses over the load range are not known, it is not possible to make a direct comparison.

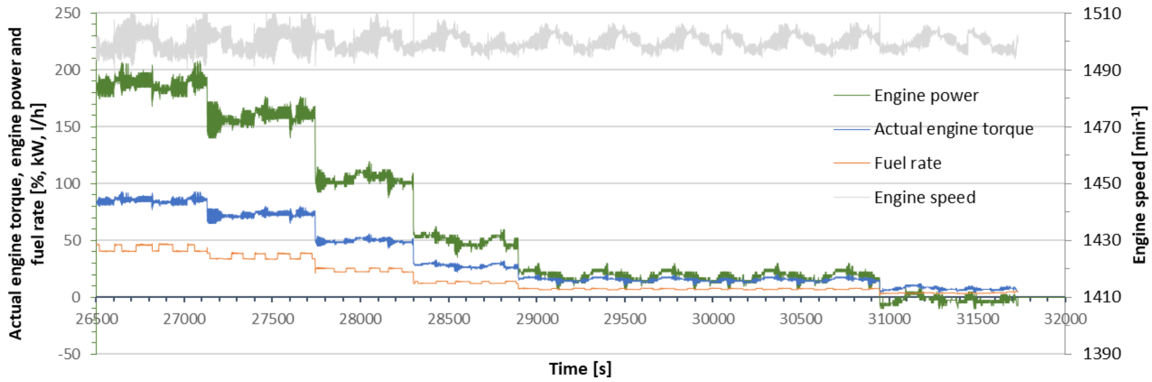

Figure 4.12: Part of the dataset showing recorded engine data of the D2 cycle with engine load going stepwise from maximum to 10% and additionally a zero load. The signals engine speed, power and fuel rate show some periodicity.

Figure 4.13 shows the load bank power setting versus engine power calculated from the recorded ECU data. There is roughly a 5% difference which is due to the loss of power over the generator (generator efficiency).

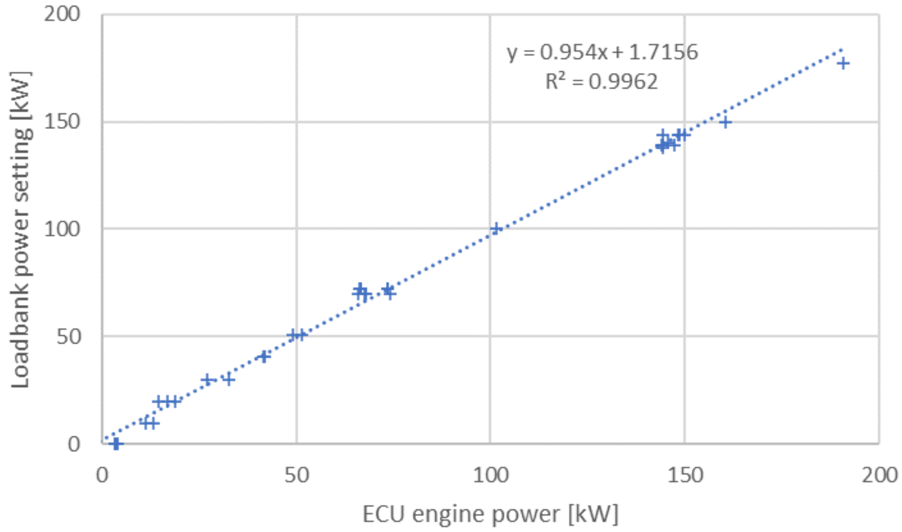

Figure 4.13: Comparison of calculated power from recorded ECU signals and the load bank power settings.

Figure 4.14 shows brake-specific fuel consumption versus engine power as specified by the OEM, calculated from recorded ECU engine data (fuel rate, engine power) and based on PEMS measurement data (CO_2 emissions, fuel carbon content and ECU engine power). The values indicate the plausibility of measured values and are roughly in line, with ECU data based bsfc 5-20 g/kWh lower than OEM specification and PEMS CO_2 based bsfc 10-20 g/kWh higher and differences thus maximal about 10% maximal.

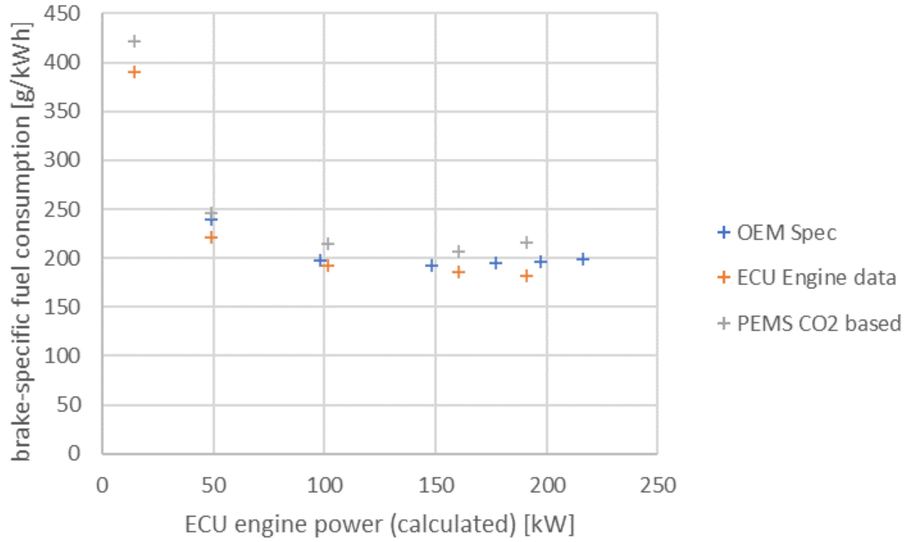

Figure 4.14: Brake-specific fuel consumption versus engine power as specified by the OEM, calculated from recorded ECU engine data (fuel rate, engine power) and based on PEMS measurement data (CO_2 emissions, fuel carbon content and ECU engine power).

Figure 4.15 shows fuel consumption versus engine power as specified by the OEM, calculated from recorded ECU engine data (fuel rate, engine power) and based on PEMS measurement data (CO_2 emissions, fuel carbon content and ECU engine power).

Data correlate well, PEMS CO_2 based fuel consumption is about 10% higher than OEMS spec and ECU based data.

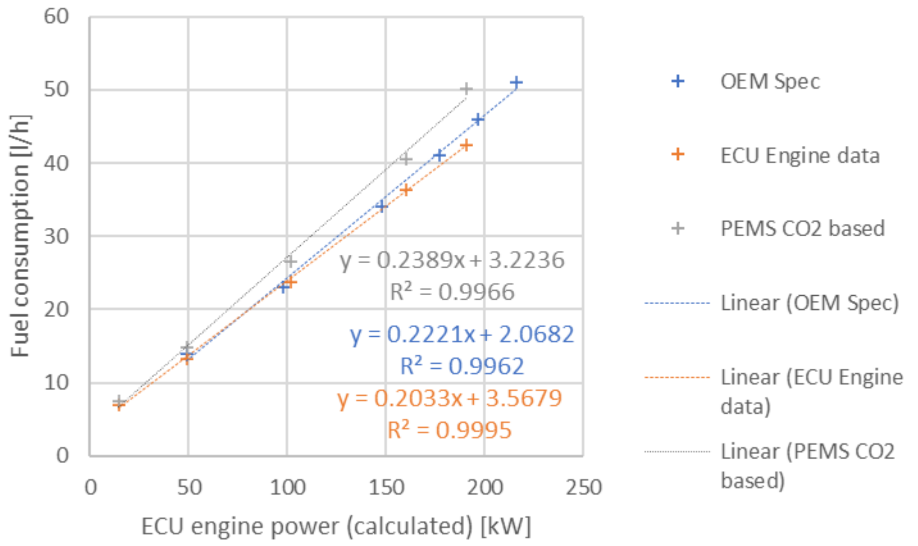

Figure 4.15: Fuel consumption versus engine power as specified by the OEM, calculated from recorded ECU engine data (fuel rate, engine power) and based on PEMS measurement data (CO_2 emissions, fuel carbon content and ECU engine power).

Figure 4.16 shows the relation between specified AdBlue consumption and engine power going from 2 l/h per 100 kW from 0-50% load increasing a little to about 2.6 l/h per 100 kW at 200kW.

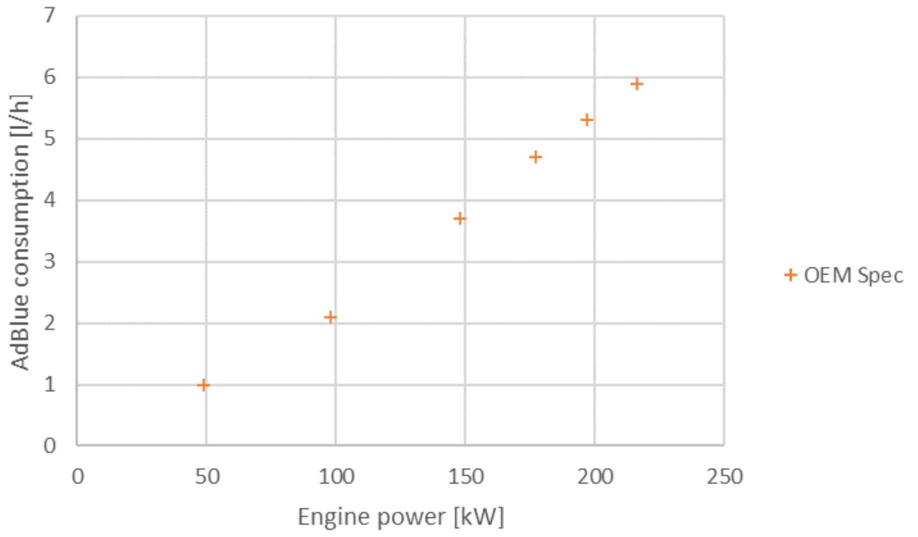

Figure 4.16: Relation between AdBlue consumption and engine power as specified by the engine OEM.

Figure 4.17 shows the relation between AdBlue consumption and fuel consumption as specified by the engine OEM which is roughly 0.11-0.13 l AdBlue per liter fuel.

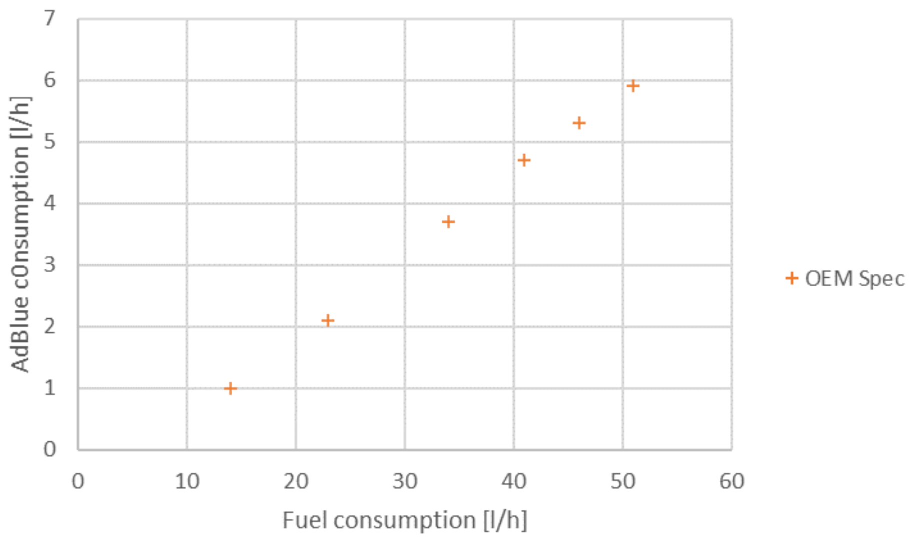

Figure 4.17: Relation between AdBlue consumption and fuel consumption as specified by the engine OEM.

A.1.1 AdBlue consumption

During the measurements the AdBlue level was noted and combined with the total fuel used which was broadcasted by the ECM (Engine Control Module), see Table 4.2.
This enables a rough calculation of the amount of AdBlue per fuel used. On average 0.11 liter of AdBlue was used per liter of fuel. This is in line with the AdBlue consumption as specified by the engine original equipment manufacturer, who specified 0.7 to 0.12 liter AdBlue per liter fuel, going from low to high load.

Table 4.2: Noted DEF (AdBlue) level and total fuel used and the calculated volume of DEF per volume of fuel.

Date, time	Engine total fuel used (ECM)	DEF (AdBlue) level (Genset display)	DEF (AdBlue) level (based on 113.5 l tank capacity)	
	[l]	[%]	[l]	
26-06, 09:37:00	4059	41%	47	
26-06, 13:53:00	4133	30%	34	
26-06, 16:23:00	4162	30%	34	
27-06, 09:59:00	4186	25%	29	
27-06, 12:13:00	4220	25%	29	
27-06, 14:38:00	4246	20%	22	
27-06, 17:54:00	4297	18%	21	
Fuel, AdBlue used [l]	238		26	
Liter AdBlue / liter fuel				0.11

Figure 4.18 shows the relation between noted ‘AdBlue tank level’ and ‘fuel used’. The relation implies an AdBlue consumption which is in line with the specified consumption of 0.07-0.12 litre of AdBlue per litre fuel.

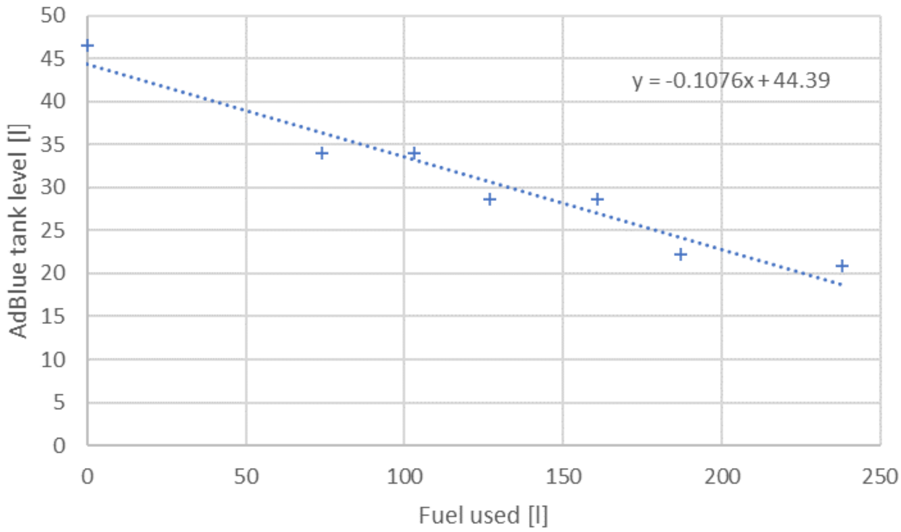

Figure 4.18: Relation between noted ‘AdBlue tank level’ and ‘fuel used’.

4.2 Results 7 kVA light pole

4.2.1 Gaseous emissions

Figure 4.19 shows hourly NO_x emission rates for three load points which are repeated three times. Absolute emissions increase from low to high load which is commonly known for diesel engines without emission control. The average of measured NO_x emissions of HVO1 is lower than that of the regular diesel and HVO2, where HVO2 has on average the highest NO_x emissions. Differences are small, maximal about 6% between HVO 1 and 2. But the difference are not considered significant.

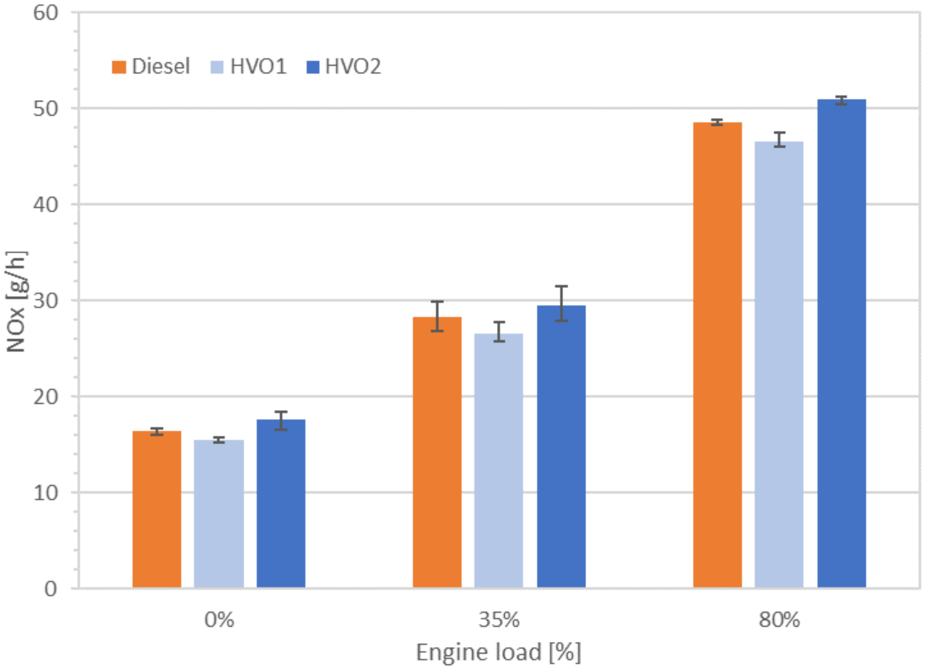

Figure 4.19: NO_x emission for the three fuels at three measured loads of the 7 kVA light pole. Each load point was three measured times. The bar represents the average of three measurements, the error bars represent the minimum and maximum of the measurements.

Figure 4.20 shows the NO_2 emission for the three fuels at three measured loads of the 7 kVA light pole. The average of measured NO_2 emissions of HVO1 is lower than that of the regular diesel and HVO2, where HVO2 has on average the highest NO_2 emissions, but in general the level of NO_2 and the fraction in NO_x is very low.

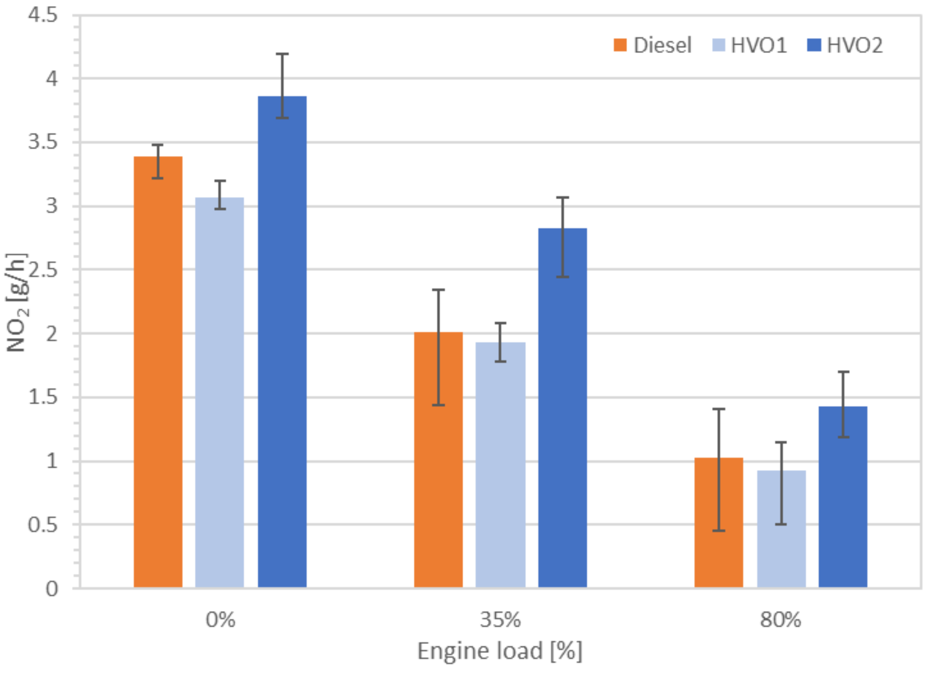

Figure 4.20: NO_2 emission for the three fuels at three measured loads of the 7 kVA light pole. Each load point was measured three times. The bar represents the average of three measurements, the error bars represent the minimum and maximum of the measurements.

Figure 4.21 shows the NO emission for the three fuels at three measured loads of the 7 kVA light pole. The average of measured NO emissions of HVO1 is lower than that of the regular diesel and HVO2, where HVO2 has on average the highest NO emissions.

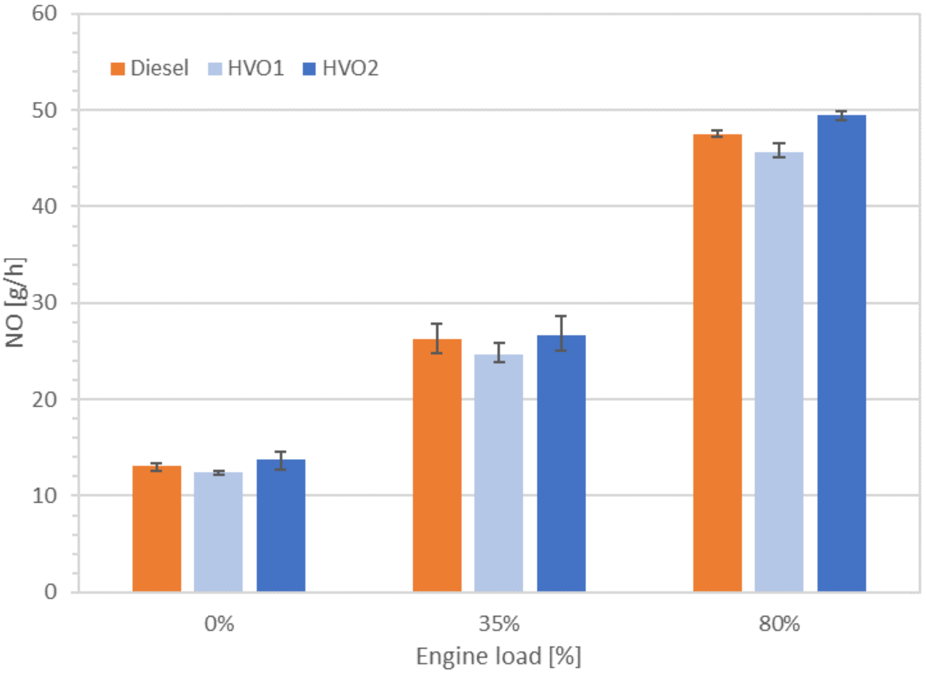

Figure 4.21: NO emission for the three fuels at three measured loads of the 7 kVA light pole. Each load point was measured three times. The bar represents the average of three measurements, the error bars represent the minimum and maximum of the measurements.

Figure 4.22 shows the hourly CO emission for the three fuels at three measured loads of the 7 kVA light pole. The spread between measurements is large. There seems to be no significant effect for HVO versus diesel given the large spread but the trend is comparable to the trend of the total hydro-carbon emissions, see Figure 4.23.

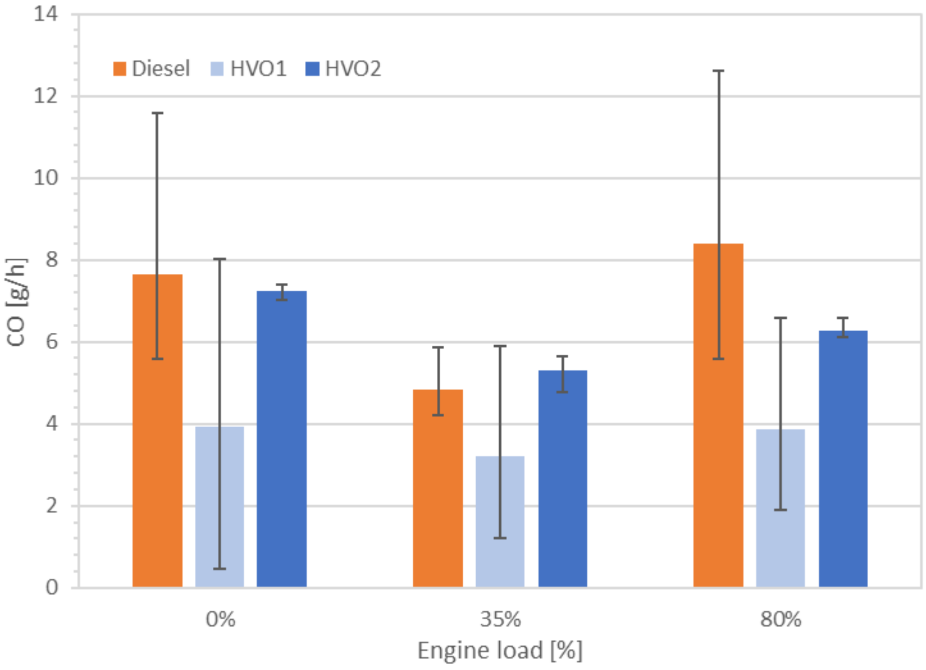

Figure 4.22: CO emission for the three fuels at three measured loads of the 7 kVA light pole. Each load point was measured three times. The bar represents the average of three measurements, the error bars represent the minimum and maximum of the measurements.

Figure 4.23 shows the hourly THC emission for the three fuels at three measured loads of the 7 kVA light pole. CO emissions and THC emissions show a comparable trend, but is more significant for THC and for THC both HVO's lead to lower emissions. Because HVO generally lead to lower PM emissions compared to fossil diesel, they also could lead to lower other emissions that indicate incomplete combustion such as CO and THC. For THC the differences are considered more certain because the spread is smaller between the individual measurements especially for HVO 2 and the 80% load point.

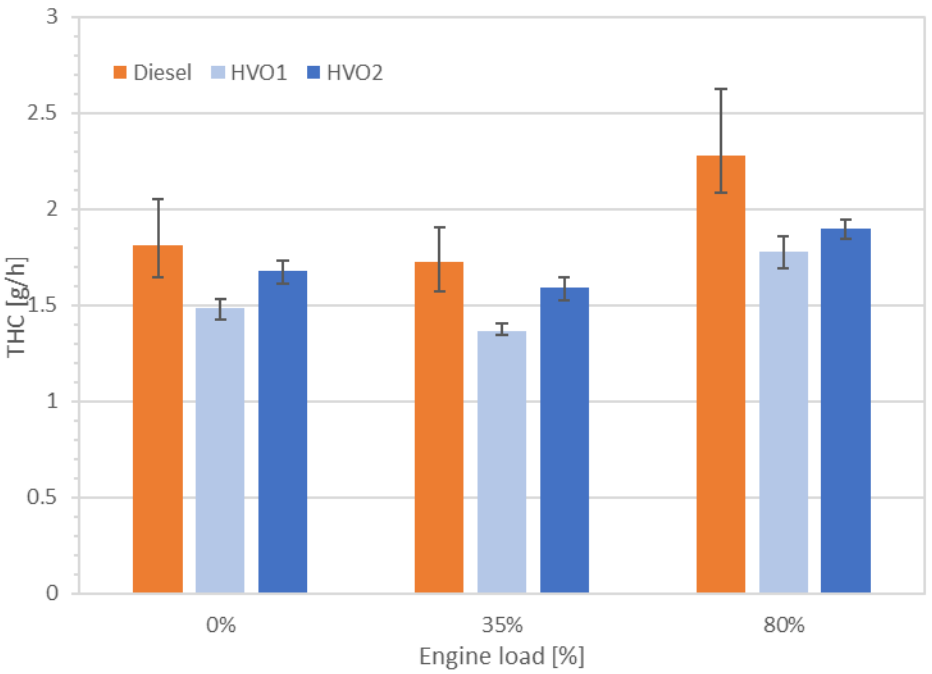

Figure 4.23: THC emission for the three fuels at three measured loads of the 7 kVA light pole. Each load point was measured three times. The bar represents the average of three measurements, the error bars represent the minimum and maximum of the measurements.

4.2.2 Particulate matter emission

The particulate matter emissions could not be determined for this machine, because of an instrument error of the scale used to weigh the filters. Therefore, during another test programme, with the same partial flow diluted PM sampling instrument, a comparable genset was tested. This test was performed with normal diesel fuel and 100% HVO (from a different supplier than the previous mentioned HVOs) to measure the effect of HVO on PM emissions. NO_x emissions could also be evaluated. The results are shown in paragraph 4.3.

4.2.3 Fuel consumption and CO_2 emission

Figure 4.25 shows the CO_2 emission for the three fuels at three engine loads. With HVO2 the CO_2 emission is measured to be the lowest and with HVO1 slightly higher at 80% and lower at 35% than diesel. HVO2 has the lowest energy specific CO_2 value (g of CO_2 formed per Joule of energy at complete combustion of the fuel), followed by HVO1. Based on this one would expect the CO_2 emission to be slightly lower for HVO1 compared to diesel which is not the case for the 80% load.

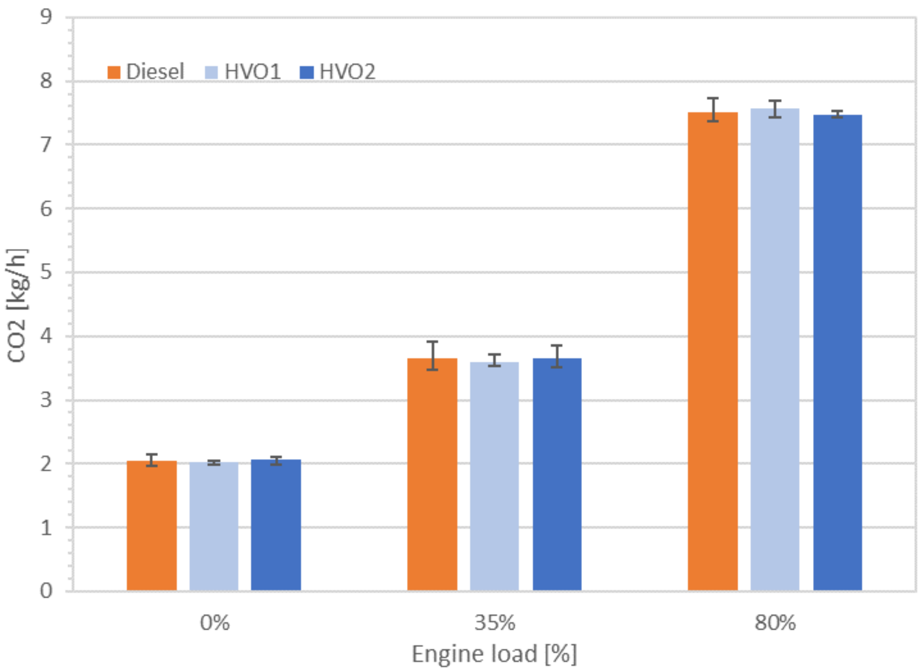

Figure 4.24: CO_2 emission for the three fuels at three measured loads of the 7 kVA light pole. Each load point was measured three times. The bar represents the average of three measurements, the error bars represent the minimum and maximum of the measurements.

Figure 4.25 shows the fuel consumption for the three fuels at three engine loads. The fuel consumption is determined from the measured CO_2 mass emission (PEMS), the measured fuel C-content and density of the fuels. HVO1 indeed has higher FC at 80% but the other way around at 35% load. For HVO2 one would expect lower FC at 80% compared to diesel which is correct at 35% load. Based on fuel volumetric energy content one would expect HVO1 to have higher FC than diesel and HVO2 a lower FC compared to diesel.

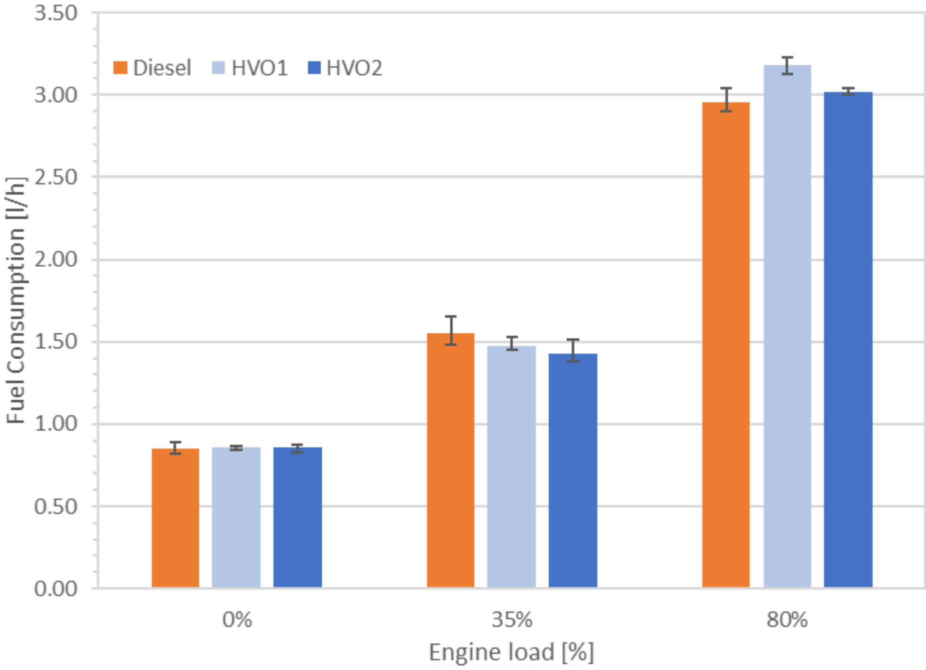

Figure 4.25: Fuel consumption for the three fuels at three measured loads of the 7 kVA light pole. Each load point was measured three times. The bar represents the average of three measurements, the error bars represent the minimum and maximum of the measurements.

4.3 Results 17.5 kVA genset

4.3.1 NO_x emissions

The NO_x emissions where determined over the ISO-8178 D2 test cycle which is the test cycle that is to be used for formal type approval testing. The NO_x emission over the D2 cycle is somewhat higher than the applicable limit of 7.5 g/kWh which applies for HC+NO_x combined. Note that the D2 cycle ran for this investigation is not entirely done according formal type approval procedures. Type approval testing involves testing on an engine test bed in an emission testing laboratory. NO_x emissions increases with engine load.

Table 4.3: NO_x emissions over the D2 cycle.

D2 mode	D2 WF	Power	NO_x	NO_x	NO_x
	[-]	[kW]	[g/kWh]	[g/h]	[g/kWh]
D2 100	0.05	14	5.1	71	
D2 75	0.25	11	6.6	72	
D2 50	0.3	7	9.6	67	
D2 25	0.3	4	11.5	49	
D2 10	0.1	1	28.2	28	
D2 weighted					8.51

Figure 4.26 shows repeated measurements over three load points of regular B7 diesel and HVO. There is a clear reduction of NO_x emissions over the three load points of on average 18%.

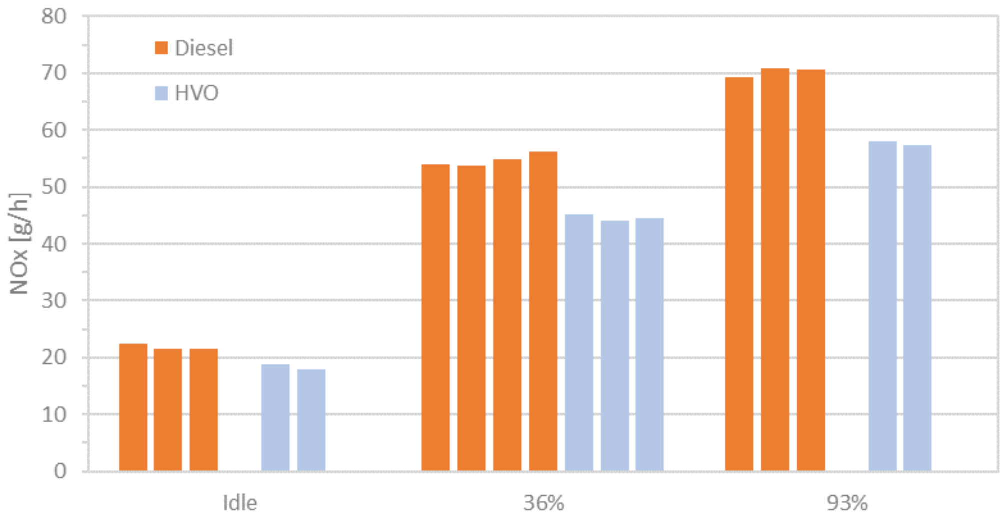

Figure 4.26: NO_x emissions for repeated tests with b7 diesel and HVO, over three engine loads.

4.3.2 Particulate matter emission

Table 4.4 shows PM emissions over the D2 cycle. Hourly PM rates increase with engine load and increase sharper going from 75 to 100%. At 0.09 g/kWh the work-specific PM is well below the limit of 0.4 g/kWh. Note that the D2 cycle ran for this investigation is not entirely done according formal type approval procedures. Type approval testing involves testing on an engine test bed in an emission testing laboratory.

Table 4.4: PM emissions over the D2 cycle.

D2 mode	D2 WF	Power	PM	PM	PM
	[-]	[kW]	[g/kWh]	[g/h]	[g/kWh]
D2 100	0.05	14	0.19	2.62	
D2 75	0.25	11	0.08	0.84	
D2 50	0.3	7	0.08	0.54	
D2 25	0.3	4	0.09	0.36	
D2 10	0.1	1	0.36	0.36	
D2 weighted					0.094

Figure 4.27 shows repeated measurements of PM over three load points of regular B7 diesel and HVO. There is a reduction of PM emissions over the three load points of on average 23%. PM emissions vary between repeated measurements and we argue that this variation is caused by the fact that measurements are done in the field. Generally, PM measurement in the field are more prone to small disturbances causing measurement variation.

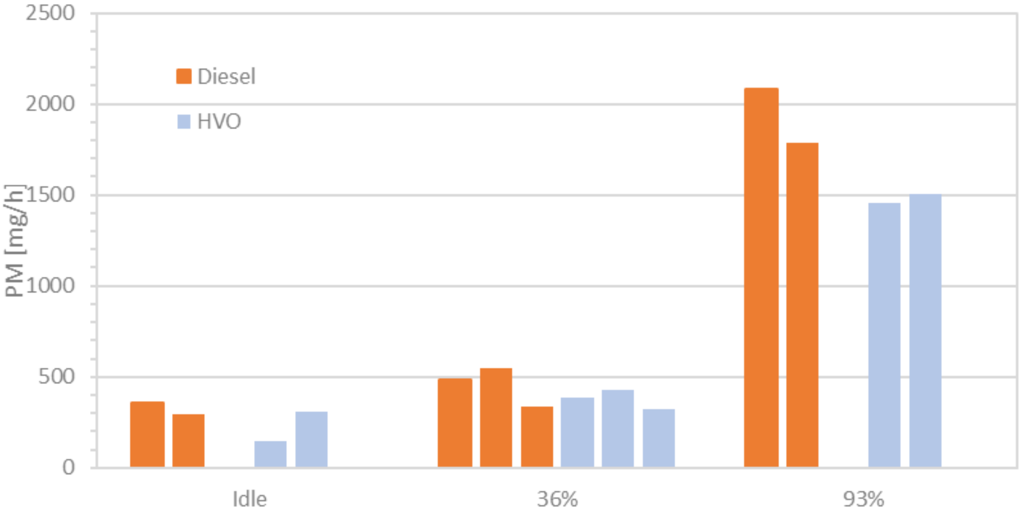

Figure 4.27: PM emissions for repeated tests with b7 diesel and HVO, over three engine loads.

5 Discussion

Genset with 216 kW Stage V engine *with exhaust gas aftertreatment*

The measurements did not show a measurable effect of the two HVO's on PM emissions from the exhaust compared to regular fossil diesel. This is due to the high filtration efficiency of the DPF. Particulate matter emissions levels are generally low for the tested fuels and engine loads, as typically seen for diesel engines with a well-functioning diesel particle filter. When running the engine on HVO, the particulate matter concentrations before the DPF might decrease compared to regular fossil diesel and lead to a lower frequency of DPF regenerations, but this was not investigated.

The measurements did not show a measurable effect of the two HVO's on NO_x emissions from the exhaust. This is due to the high efficiency of the SCR when it is at operating temperature. Measurements also did not show a significant effect of both HVO's on the NO_x emissions when the efficiency of the SCR is low.

Below the engine load of 25%, the NO_x emission increases substantially due to the lower load and the temperature of the SCR which is becoming too low to reduce NO_x with high efficiency. When running below an engine load of 20%, the SCR does not reduce NO_x anymore. To reduce NO_x emissions, running at lower engine loads, like idling, for longer periods of time should be avoided. Or a genset with a lower power rating could be selected if possible.

The NO_x emission over the D2 cycle is 0.32 g/kWh, which is below the limit value (0.4 g/kWh for NO_x) for non-road engines of this power category. Over the load range, NO_x emissions are well-controlled by the SCR above 20% load. Hourly emissions rates are 9-23 g/h, depending on the engine load point. Light-off of the SCR, meaning the catalyst has sufficiently high temperature to reduce NO_x with ammonia, starts around 15-20% engine load. Below the SCR light-off, at a 10% engine load, we measured 201 g/h of NO_x.

Gensets with 8 and 17.5 kW Stage V engine *without exhaust gas aftertreatment*

HVO leads to a significant reduction of the PM emissions of the 17.5 kW Stage V engine of about 23% compared to regular fossil diesel. This is expected based on other investigations where HVO was tested in diesel engines without exhaust gas aftertreatment, see chapter 2. HVO is known to reduce PM emissions from these diesel engines without DPF. For the smaller 8 kW engine, the PM measurements did not succeed due to a malfunction of the weighing scales, but for this engine a significant reduction of the total hydro-carbon emissions were observed.

Both engines falls in the lower power category of the EU NRMM Stage V regulation.
This category has higher emissions limits for PM, NO_x and no limit for PN (Particle Number) compared to medium powered (56-560 kW) non-road engines. The less stringent regime for low powered engines does not require the use of DPF and SCR to control these emissions. Without any form of aftertreatment the use of HVO therefore leads to lower PM emissions. THC emissions which are usually caused by incomplete combustion also seem to decrease somewhat when running on HVO.

8 kW engine

For one tested HVO, a lower average NO_x emission was measured, for the other HVO we observed the opposite, namely a higher NO_x emission than for diesel was measured. Differences with diesel are in the range of 5-7% increase or decrease. Variation of tests overall was a bit lower (better), but we argue that the observed differences are not significant. Engine power was controlled with a load bank, ECU engine power showed ripple. Engine power and load bank power correlate well but show deviations of a few percent. Also the measured CO_2 emissions and FC are not exactly in line with the expectation based on fuel properties. We therefore cannot conclude that the HVO's had an effect on NO_x emissions.

17.5 kW engine

For the 17.5 kW engine, a reduction of NO_x of on average 18% was observed when using HVO.

Different investigations show varying results for the effect of HVO on NO_x, see chapter 2. Some mention that an effect on NO_x emission depends on engine load and injection strategy: NO_x reductions are measured at lower engine loads and for engines with simple injection strategies without pre-injection or EGR. The measured 8 kW engine was tested at low load and is supposed to have a simple injection strategy and as such one could expect a reduction of NO_x. This was not clearly observed however for one engine while it was observed for the other (17.5 kW) low-powered engine.

Absolute NO_x emission levels of simple diesel engines without aftertreatment, such as the 8 kW and 17.5 kW engines used in the light pole and genset generally increase with the size of the engine and the engine load at which the engine is running.

We measured the PM-mass emissions of the 17.5 kW engine over a load range from 10 to 100% and observed a sharper increase of PM emissions above 75%. We argue that at high loads PM formation increases due to an increase of the local oxygen shortage in the combustion chamber.

6 Conclusions

HVO (Hydro treated Vegetable Oil) is a drop in replacement for regular fossil diesel fuel which is marketed for its lower carbon intensity but also often claimed to result in lower pollutant emissions from the exhaust of diesel engines. Therefore, the criteria air pollutant emissions of three gensets with Stage V diesel engines were measured running the engines on two different HVO's and on regular fossil diesel.

In general, when a Stage V engine has a well-functioning exhaust gas aftertreatment (SCR and DPF), HVO will have no or a negligible effect on NO_x and particulate matter emissions. For Stage V engines, which do not have stringent limits and as a result do not have exhaust gas aftertreatment, running on HVO leads to lower particulate matter emissions. For these diesel engines, without exhaust gas aftertreatment lower NO_x emissions cannot always be claimed, however. Whether or not HVO has an effect on NO_x emissions and the level of the effect depends on engine characteristics and running conditions.

The measurements showed no significant effect of two different HVO's on the NO_x and PM emissions from the exhaust of the 216 kW Stage V engine of the genset compared to regular fossil diesel. The engine uses a DPF (Diesel Particulate Filter) and SCR (Selective Catalytic Reduction) to reduce these emissions, which on average results in emissions which are low compared to those of diesel engines without these emission control systems.

For two low powered Stage V engines (8 kW and 17.5 kW), which have no exhaust gas aftertreatment due to the less stringent limits for the applicable power category of non-road engines, HVO resulted in a reduction of about 23% PM for the 8 kW engine for which the PM measurement succeeded. Also for this engine a significant reduction of total hydrocarbon emission was observed.

However, the HVO's have different effects on the NO_x emissions: for the 8 kW engine we found no significant effect, while for the 17.5 kW engine we did observe a reduction of about 18% when using HVO. Different studies and emission tests have already shown that the effect of HVO on NO_x emissions depend on engine characteristics and running conditions.

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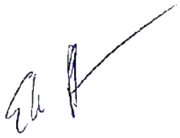

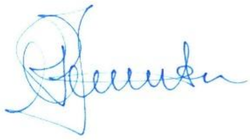

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