

Bachelor's thesis

Mechanical and Production engineering

ENPOS13

2017

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# EXHAUST EMISSION RESEARCH OF OFF-ROAD DIESEL ENGINES IN THE FIELD AND LABORATORY

–CASE: Health relevant and energy efficient  
regulation of exhaust particle emissions (HERE)



BACHELOR'S THESIS | ABSTRACT

TURKU UNIVERSITY OF APPLIED SCIENCES

Mechanical and Production engineering

2017 | 48 Pages

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# EXHAUST EMISSION RESEARCH OF OFF-ROAD DIESEL ENGINES IN THE FIELD AND LABORATORY

-CASE: Health relevant and energy efficient regulation of exhaust particle emissions (HERE)

This Bachelor's thesis was commissioned by Turku University of Applied Sciences. The aim of the thesis is to report the results of on-road measurements in Suolahti and passive regenerations at Turku University of Applied Sciences. During the laboratory measurements comparisons are made between Stage 5 and Tier 4 final emission standards, as well as on how Neste Renewable diesel (NRD) and EN590 DFO-fuel behave during passive regeneration.

A van from Tampere University of Technology was used in the field measurements. The tractor pulled a trailer with the van and aggregator on it. In addition to field measurements, laboratory measurements were performed. In the laboratory measurements, a cycle similar to on-road measurements was performed for a total of eight hours.

The formation of emissions was measured successfully in the field measurements and measurement data was delivered to Tampere University of Technology. In the laboratory measurements the DPF was able to fill up with soot for every passive regeneration. DPF got regenerated passively with NRD and DFO with both emission standard softwares. The difference between NRD and DFO was clear in exhaust backpressure and PM emissions in exhaust gas.

KEYWORDS:

Emissions, Diesel engine, Emission standards, HERE

Jussi Saarikallio

# OFF-ROAD DIESELMOOTTORIEN PAKOKAASUPÄÄSTÖTUTKIMUS KENTÄLLÄ JA LABORATORIOSSA

-CASE: Health relevant and energy efficient regulation of exhaust particle emissions (HERE)

Tämä opinnäytetyö tehtiin Turun ammattikorkeakoululle. Opinnäytetyössä raportoidaan Suolahdessa suoritetuista jahtausmittauksista, sekä Turun ammattikorkeakoulussa suoritetuista passiivisista regeneroinneista. Laboratoriomittauksissa vertailtiin miten Stage 5 ja Tier 4 Final päästöstandardit, sekä Neste Renewable diesel (NRD)-polttoaine ja EN590 DFO-polttoaine käyttäytyvät passiivisen regeneroinnin aikana.

Jahtausajoissa käytettiin Tampereen Teknillisen korkeakoulun pakettiautoa. Mittauksissa pakettiauto sekä aggregaatti olivat lavetilla traktorin perässä. Jahtausajojen lisäksi tehtiin mittauksia laboratoriossa. Laboratoriomittauksissa käytettiin jahtausajojen kaltaista sykliä, jota ajettiin yhteensä noin kahdeksan tuntia.

Jahtausajoista saatiin mitattua päästöjen muodostumista onnistuneesti, ja mittausdata toimitettiin Tampereen Teknilliselle Korkeakoululle. Laboratoriomittauksissa DPF saatiin täyttymään noesta ennen jokaista passiivista regenerointia. DPF regeneroitui passiivisesti NRD:llä sekä DFO:lla molemmilla päästöraja – ohjelmistolla. Ero NRD:n ja DFO:n välillä oli selvä pakokaasujen vastapaineessa sekä nokihiukkasissa.

ASIASANAT:

Päästöt, dieselmoottori, päästöstandardit, HERE

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## LIST OF ABBREVIATIONS AND SYMBOLS

Abbreviation	Explanation of abbreviation
AT	AFTER-TREATMENT
CO	CARBON MONOXIDE
CO <sub>2</sub>	CARBON DIOXIDES
DFO	DIESEL FUEL OIL
DOC	DIESEL OXIDATION CATALYST
DPF	DIESEL PARICULATE FILTER
H <sub>2</sub> O	DIHYDROGEN OXYGEN, WATER
HC	HYDROCARBON
kW	KILOWATT
kWh	KILOWATT-HOUR
N <sub>2</sub>	NITROGEN
NH <sub>3</sub>	AMMONIA
NO	NITROGEN OXIDE
NO <sub>2</sub>	NITROGEN DIOXIDE
NO <sub>x</sub>	NITROGEN OXIDES
NRD	NESTE RENEWABLE DIESEL
PM	PARTICULATE MATTER
PPM	PARTS PER MILLION
SCR	SELECTIVE CATALYTIC REDUCTION
TDC	TOP DEAD CENTRE

## INTRODUCTION

This thesis contains diesel engine emission measurements in the laboratory and in the field. These measurements were conducted in cooperation with Valtra, Tampere University of Technology and the Finnish meteorological institute. The goal of the field measurements was to measure emissions when the tractor is used for its designed purpose. The goal of the laboratory measurements was to investigate if DPF could regenerate without any post-injection fuel.

Health relevant and energy efficient regulation of exhaust particle emissions (HERE) identifies and analyzes particle emissions on engines. Particles are a health risk and can be reduced by many methods. The aim of the HERE-project is to identify methods to reduce exhaust particle emissions that are approved by the health authorities without reducing engine performance and increasing fuel consumption. The HERE-project is conducted with Tampere University of Technology, the Finnish meteorological institute, VTT Technical Research Centre of Finland, the Laboratory of Applied Thermodynamics, AGCO Power, Dekati Oy, Dinex Ecocat Oy, Neste Oyj, Pegasor Oy, Wärtsilä Oy and The Finnish Funding Agency for Technology and Innovation (Tekes.) The HERE-project started in March 2013 and runs until the end of 2017.



# 1 DIESEL ENGINE EMISSIONS

## The diesel engine

The diesel engine is a piston engine which is mainly used for heavy-duty prime movers. Diesel engines are usually four-stroke engines, however two-stroke engines are usually used for ships etc. The engines come in two main types: direct injection engines and ones with indirect injection, where the fuel is injected into the precombustion chamber. The fuel atomizes and mixes with the air in the combustion chamber, which is heated in compression. The mixture is ignited due to the heat. (Lehtinen & Rantala 2012, 218)

### 1.1 The formation of emissions

Combustion engines exhaust gas emissions always contain carbon dioxide ( $\text{CO}_2$ ), nitrogen ( $\text{N}_2$ ) and harmless water steam ( $\text{H}_2\text{O}$ ). It is theoretically impossible to reduce these emissions for engines which burn hydrocarbon. Particulate matter (PM), carbon monoxide (CO) and unburned hydrocarbons (HC) are emissions which are formed as a result of pollutants from the engine and fuel, or from incomplete combustion. (Lehtinen & Rantala 2012, 43-47)

$\text{NO}_x$  and particulate emissions are common for diesel engines. Nitrogen in combustion air oxidizes to NO and  $\text{NO}_2$ . Oxidation occurs in the part of the fuel jet where the mixture ratio is near stoichiometric and in high temperatures. Nitrogen oxides are mostly formed on low speeds and higher engine loads. Particulate emissions are formed in the parts of fuel jet where  $\lambda$  is less than 0.5. Particulates in exhaust gases are formed in the colder parts of combustion. Particulates are mainly small carbon particles. (Lehtinen & Rantala 2012, 43-47)

### 1.2 Emission standards

New Stage 5 standards are the follower of old Tier 4 Final standards. Stage 5 is scheduled to step in in 2019. The proposed Stage 5 suggests that engines  $>130\text{kW}$   $\text{NO}_x$  is reduced from 0.4 to 0.015 g/kWh and PM from 0.02 g/kWh to 0.015 g/kWh. Stage 5 engines will contain both SCR and DPF. (Dieselnet 2016)

Table 1 Tier 4 emission standards for nonroad engines. (Dieselnet 2016)

Engine Power	Year	CO	NMHC	NMHC+NO <sub>x</sub>	NO <sub>x</sub>	PM
37 ≤ kW < 56 (50 ≤ hp < 75)	2008	5.0 (3.7)	-	4.7 (3.5)	-	0.3 <sup>b</sup> (0.22)
	2013	5.0 (3.7)	-	4.7 (3.5)	-	0.03 (0.022)
56 ≤ kW < 130 (75 ≤ hp < 175)	2012- 2014 <sup>c</sup>	5.0 (3.7)	0.19 (0.14)	-	0.40 (0.30)	0.02 (0.015)
130 ≤ kW ≤ 560 (175 ≤ hp ≤ 750)	2011- 2014 <sup>d</sup>	3.5 (2.6)	0.19 (0.14)	-	0.40 (0.30)	0.02 (0.015)

b - 0.4 g/kWh (Tier 2) if manufacturer complies with the 0.03 g/kWh standard from 2012

c - PM/CO: full compliance from 2012; NO<sub>x</sub>/HC: Option 1 —50% engines must comply in 2012-2013; Option 2 —25% engines must comply in 2012-2014, with full compliance from 2014.12.31

d - PM/CO: full compliance from 2011; NO<sub>x</sub>/HC: 50% engines must comply in 2011-2013

Table 2 Stage V emission standards for nonroad engines. (Dieselnet 2016)

Category	Ign.	Net Power	Date	CO	HC	NO <sub>x</sub>	PM	PN
		kW		g/kWh				1/kWh
NRE-v/c-4	CI	$37 \leq P < 56$	2019	5.00	4.70 <sup>a,c</sup>		0.015	$1 \times 10^{12}$
NRE-v/c-5	All	$56 \leq P < 130$	2020	5.00	0.19 <sup>c</sup>	0.40	0.015	$1 \times 10^{12}$
NRE-v/c-6	All	$130 \leq P \leq 560$	2019	3.50	0.19 <sup>c</sup>	0.40	0.015	$1 \times 10^{12}$
NRE-v/c-7	All	$P > 560$	2019	3.50	0.19 <sup>d</sup>	3.50	0.045	-

<sup>a</sup> HC+NO<sub>x</sub>

<sup>b</sup> 0.60 for hand-startable, air-cooled direct injection engines

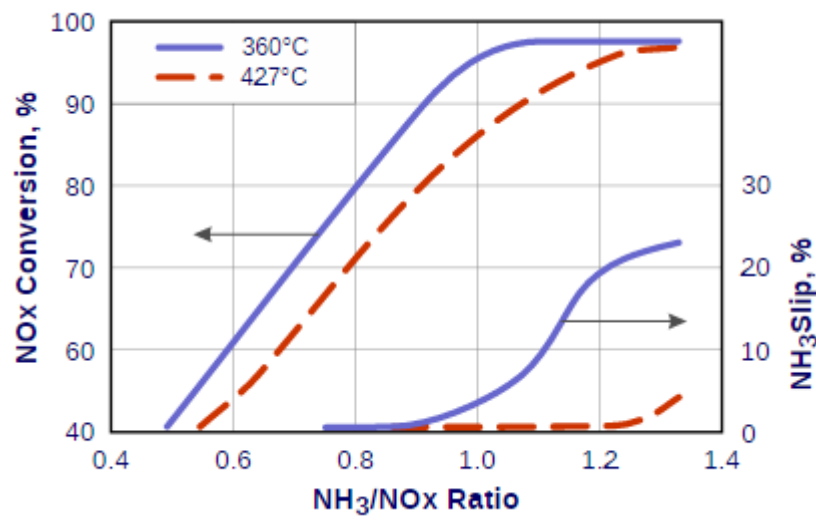
<sup>c</sup> A = 1.10 for gas engines

<sup>d</sup> A = 6.00 for gas engines

### 1.3 Reducing emissions in diesel engines

#### SCR

The SCR (**S**elective **C**atalytic **R**eduction) system uses a NO<sub>x</sub> storing system which, if necessary, is regenerated with through post-injection product, CO<sub>2</sub>. Reductive reaction in SCR catalytic converter is produced by spraying reaction fluid among exhaust gases. The reaction fluid is a mixture of urea and chemically purified water. Ammonia (NH<sub>3</sub>) reacts with the NO<sub>x</sub> and the result is harmless N<sub>2</sub> and H<sub>2</sub>O. In commercial vehicles, NO<sub>x</sub> can be reduced approximately 85% with SCR catalytic converter. (Lehtinen & Rantala 2012, 268)



Picture 1 NO<sub>x</sub> conversion and ammonia slip. (Dieselnet 2016)

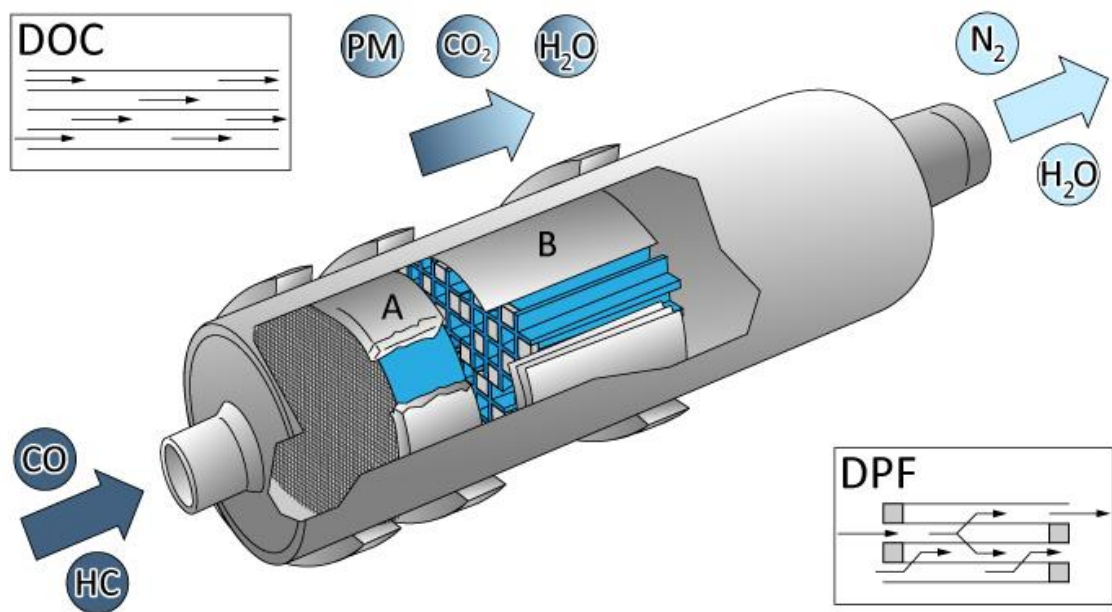
## DOC

The DOC (**D**iesel **O**xidation **C**atalytic) reduces CO and HC emissions with residual oxygen of the exhaust gases to H<sub>2</sub>O and CO<sub>2</sub>. This is possible by expensive metal coatings. The exhaust gases are routed to channels. The channel walls consist of a ceramic or metal substrate covered in a catalyst wash coat containing precious metal (platinum or palladium.) (Majewski 2016)

## DPF

DPF (**D**iesel **P**articulate **F**ilter) captures diesel particulates to prevent their release to the atmosphere. DPF uses a wall-flow principle, where the exhaust gases are forced to pass through of porous and dense ceramic wall material. The particles in exhaust gases are trapped to the pores on the wall. The remaining soot will clog the DPF quickly, unless the particles get oxidized, whereby the DPF cleans itself or is “regenerated.” (Majewski & Khair, 2006, 459-460)

Regeneration refers to the oxidation of soot in DPF, or burning. Soot burns itself at approx. 400 – 600 °C. When DPF oxidates itself it is called passive regeneration. Passive regeneration is the only method to oxidate if exhaust gas temperature are high enough for sufficiently long period. This is very uncommon in heavy-duty diesel engines. (Majewski & Khair, 2006, 462-463)



Picture 2 After-treatment systems: DPF + DOC by Cummins. (Gonzalez 2016)

## 2 FIELD MEASUREMENTS

This chapter presents similar on-road measurements as performed, facilities and measurement devices used in field measurements. This chapter also contains engine details and fuel and lubrication used in the measurements. Test procedure for on-road measurements and lifting measurements are presented at the end of chapter.

### 2.1 Facilities

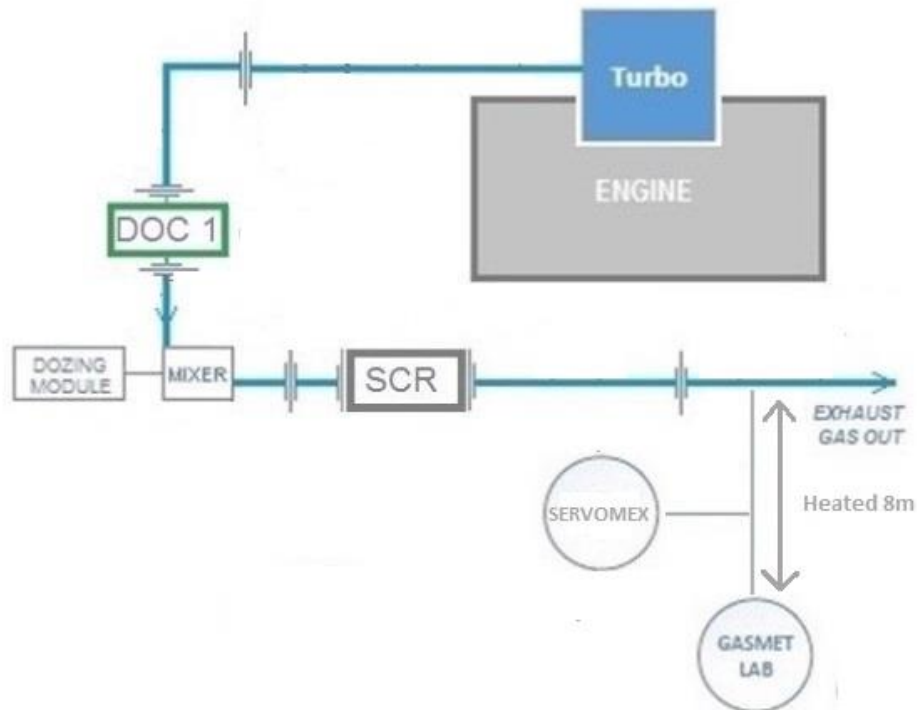
The facilities in the field measurements were located near Valtra's factory in Suolahti. The aim of the field measurements was to know more about emissions for off-road vehicles in real use. The field measurements were conducted with the Finnish Meteorological Institute and Tampere University of Technology.

The measuring instruments were situated 8 meters from the tractors exhaust pipe. The piping and instrumentation diagram of field measurements at Turku University of Applied Sciences can be found on picture 3. A heated tube had to be installed to provide accurate measurement data from the exhaust pipe. The tube was divided to a Servomex and the heated tube proceeded to a Gasmeter. CO<sub>2</sub> and O<sub>2</sub> were measured with a Servomex MiniMP 5200. CO<sub>2</sub>, CO, NO<sub>x</sub>, NH<sub>3</sub> and CH were measured with a Gasmeter DX4000 FT-IR Gas analyzer. Calcmeter software was used to collect data from the Gasmeter to Microsoft Excel. The servomex saved the measurement data automatically to an USB-stick. The piping and instrumentation diagram in field measurements can be found on picture 3.

Table 3 Measurement instruments used in field measurements

Measurement	Device
Carbon Dioxide (CO <sub>2</sub> ), Oxygen (O <sub>2</sub> )	Servomex MiniMP 5200
Carbon dioxide (CO <sub>2</sub> ), Carbon monoxide (CO), Nitrogen Oxides (NO <sub>x</sub> ), Ammonia (NH <sub>3</sub> ), Hydrocarbons (CH)	Gasmeter DX4000 FT-IR Gas analyser

## FIELD MEASUREMENTS PIPING AND INSTRUMENTATION DIAGRAM (PID)



Picture 3 Piping and instrumentation diagram in field measurements

### 2.2 Engine details

The field measurements were performed with an AGCO Power 49 AWF diesel engine. The engine was prototype model which was equipped with software for research purposes. The engine was an intercooled 4-cylinder direct injection engine with turbocharger. DOC and SCR were used for aftertreatment.

Table 4 Engine information of field measurements. (Valtra 2016)

Engine	
Engine type	49 AWF
Cylinders	4
Cylinder displacement	4,9 dm <sup>3</sup>
Software	Prototype

### 2.3 Fuel and lubrication

The field measurements were performed mostly with Neste EN 590 DFO. The fuel wasn't relevant for measurements so at the tank was mixed fuel of a different manufacturer. Engine lubrication used in the engine was Valtra Engine CR-4 10W-40. Engine lubrication information can be found on Table 5. (Kalliokoski 2016)



Table 5 Lubrication information used in field measurements. (Valtra 2016)

Lubrication information	
Viscosity class (SAE J300)	10W-40
Density @ 15 °C (ASTM D1298)	0,868 kg/dm <sup>3</sup>
Viscosity @ 40 °C (ASTM D445)	100 cSt
Viscosity @ 100 °C (ASTM D445)	14,8 cSt
Viscosity index (ASTM D2270)	154
Pour point (ASTM D97)	-42 °C
Flash point (ASTM D92)	230 °C
Total base number TBN (ASTM D2896)	10,5 mg KOH/g
Sulfated ash (ASTM D874)	1,40 %

## 2.4 Test procedure

The measurement instruments were installed in a van, which was driven on a trailer. The measuring points were installed on an exhaust pipe so it wouldn't accidentally measure ambient air. Measuring lines were attached to the measuring instruments in the van. Due to high electricity consumption, an aggregator had to be installed to the back of trailer.

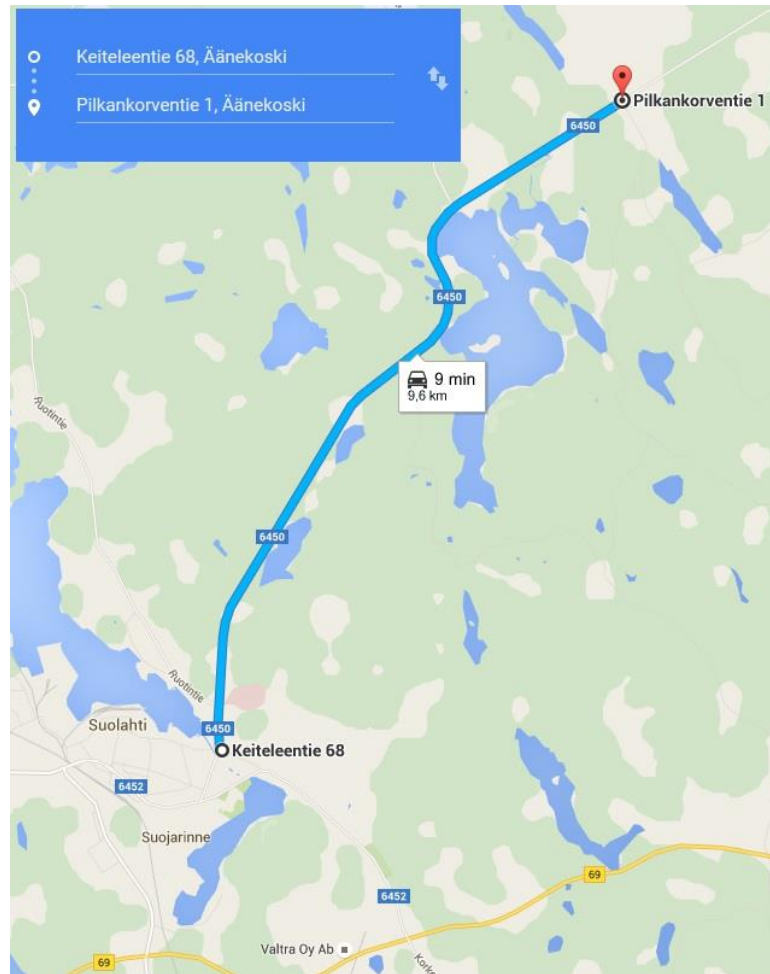


Picture 4 Van and aggregator on the trailer



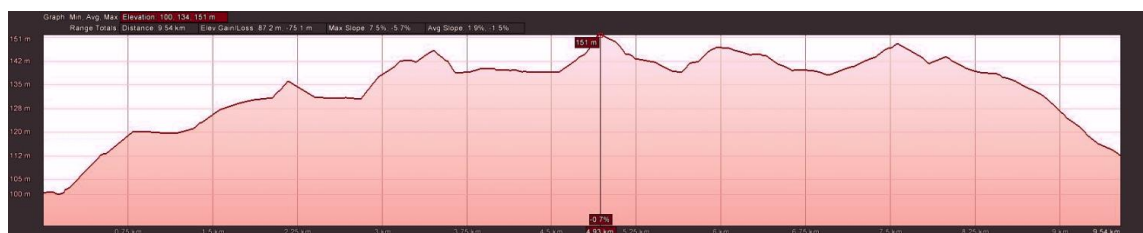
Picture 5 Measurement instruments assembled on the exhaust pipe

The field measurements were performed on three separate days. On-road measurements were performed by driving 19.2 kilometers on the road with maximum speed of 40 km/h. One cycle took approximately 30 minutes.



Picture 6 Route for on-road measurements

The on-road measurements started at Keiteleentie 68, Äänekoski, and the tractor turned back to same route at Pilkankorventie 1, Äänekoski. The route for field measurements was very diverse. The route contained little bit of urban driving and many accelerations caused by hills, crossroads and speed bumps. The route had many hills in both directions and the longest hill was at 7 kilometres from starting point. None of the measurements were identical due to many variables related to driving with traffic.



Picture 7 Height profile of the route (Google Earth, 2017)

The height profile presents the hills in the route from starting point to turning point. The starting point was at 100 metres above the ocean and highest point was at 151 metres above the ocean.

Table 6 Schedule of field measurements

Date	Information
27.6.2016	Measuring instrument assembly
28.6.2016	Measuring instrument assembly, Two on-road measurements performed
29.6.2016	7 on-road measurements performed, 8 lifting measurements performed
30.6.2016	6 on-road measurements performed, Dismantle of measuring instruments



Picture 8 On-road measurements on action



Picture 9 Weight used in lifting measurement

The lifting measurements were performed at Valtra's factory. The plan was to keep the lifts identical but a few deviations occurred. Lifting measurements were performed by lifting 1100 kilograms up and down. The weight used in the lifting measurements was attached to tractor's front loader. The procedure was to start timing and lift the weight, wait 20 seconds, lower the weight and wait until two minutes has passed from starting the time. One cycle consisted of five lifts.



## 2.5 Results

### **Former measurement campaign**

Similar measurements were conducted at 2014 by Metropolia University of Applied Sciences. Target for those measurements to examine NRD's effects to particle emissions in tractor engines in field and laboratory. The field measurements were conducted in Suolahti and the laboratory measurements were conducted at the engine laboratory at Turku University of Applied Sciences.

In the field measurements the van was on a trailer and measurement instruments collected data from air from above the van. The laboratory measurements were performed with the same cycle as in this thesis.

Results show that engine load affects the formation of particles. The traditional DFO produces more PM emissions than NRD. But the engine load affects to deviation in the formation of emissions. (Mattila, 2014)

## On-road measurements

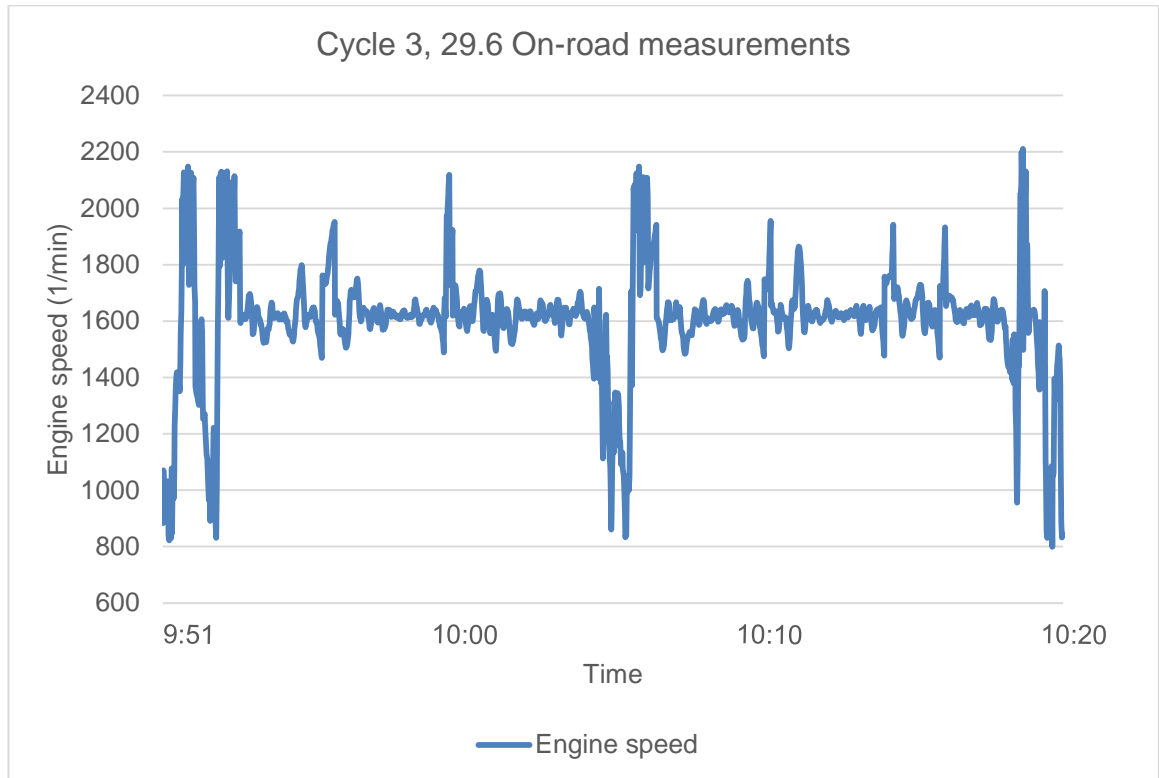


Figure 1 Engine speed in on-road measurements.

Engine speed in on-road measurements was mostly steady apart from starting and stopping the measurement, at turn points and at points when driving up or down hill. The Versu transmission is the reason for steadiness of engine speed. The transmission is a CVT (**C**ontinuously **V**ariable **T**ransmission) which has four speed ranges with five quick shifts. The transmission automatically changes shifts and ranges which provides steady engine speed and an even load to the engine.



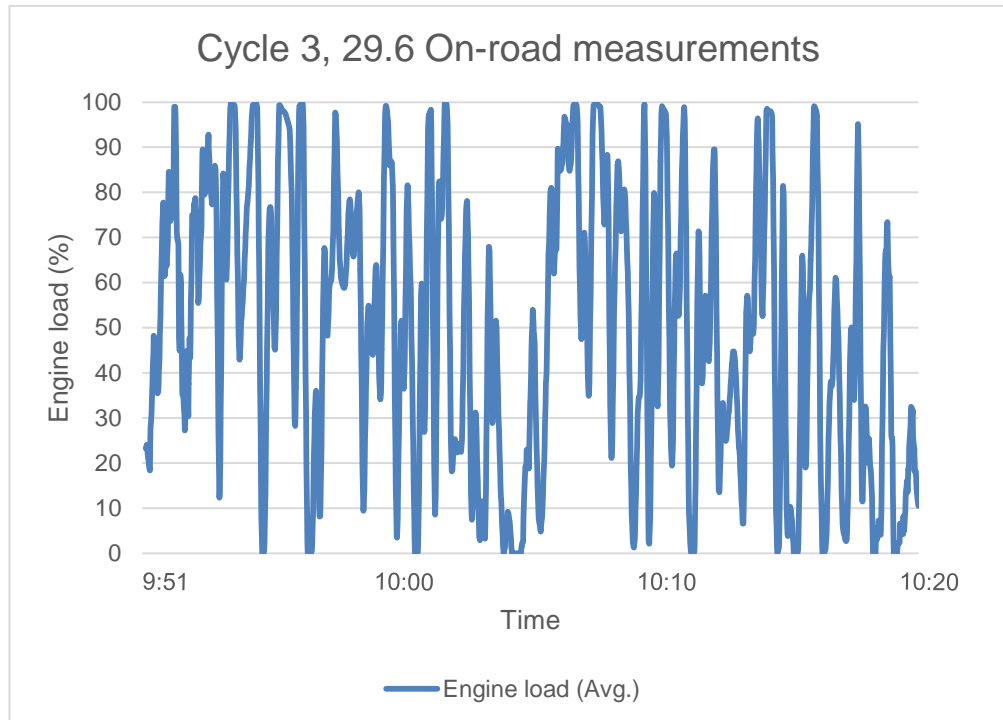


Figure 2 Engine load in on-road measurements

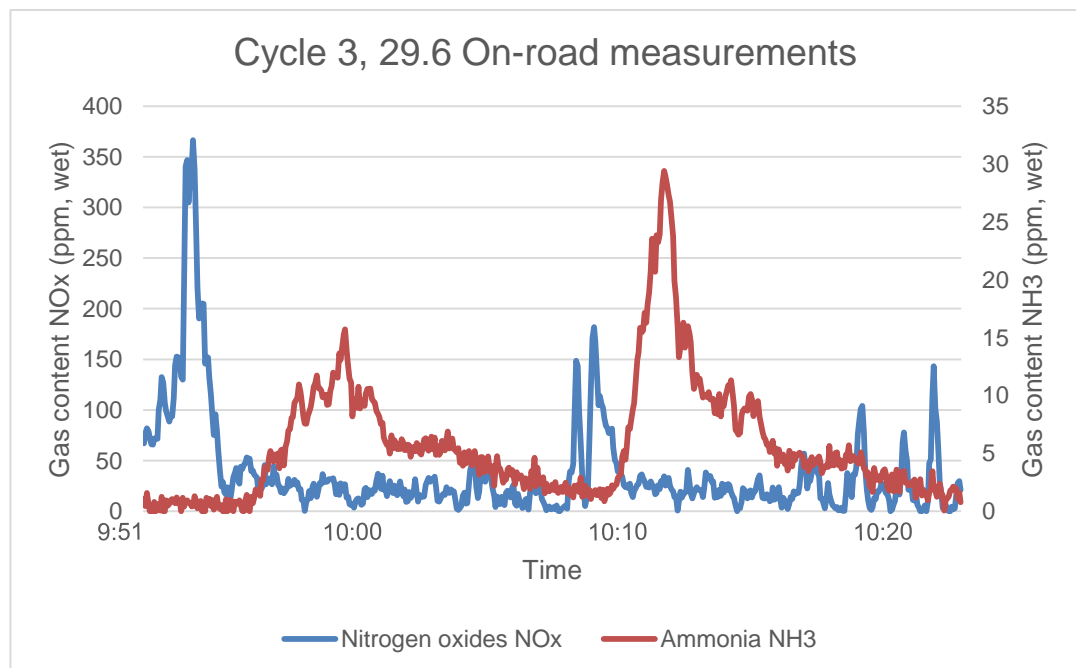


Figure 3 NO<sub>x</sub> and NH<sub>3</sub> slip measured with Gasmeter

The engine load in on-road measurements is inconsistent due to the shape of road, traffic and other variables in the measurements.

Accelerating points can be seen clearly on the two spikes of NO<sub>x</sub>. The first spike must have been very fast acceleration or the engine has been on idle for a while, which rises NO<sub>x</sub> up to 370 ppm. Spikes at the end of measurements possibly originate from stopping and accelerating at crossroads. Some NH<sub>3</sub> slip can be seen at rising the longest hill and after accelerating from the turning point.

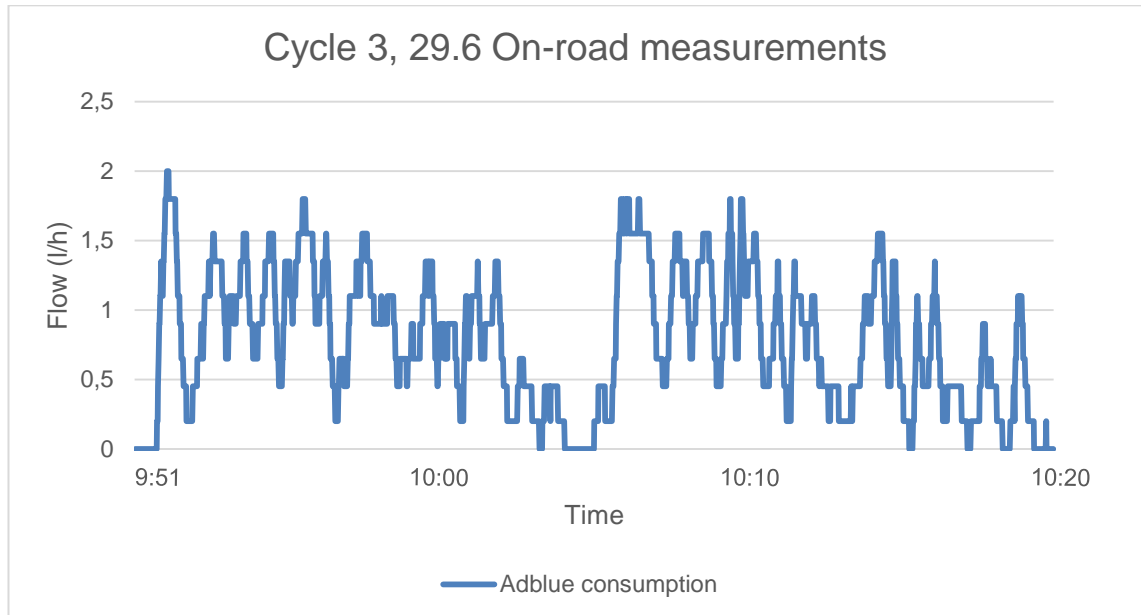


Figure 4 Adblue consumption

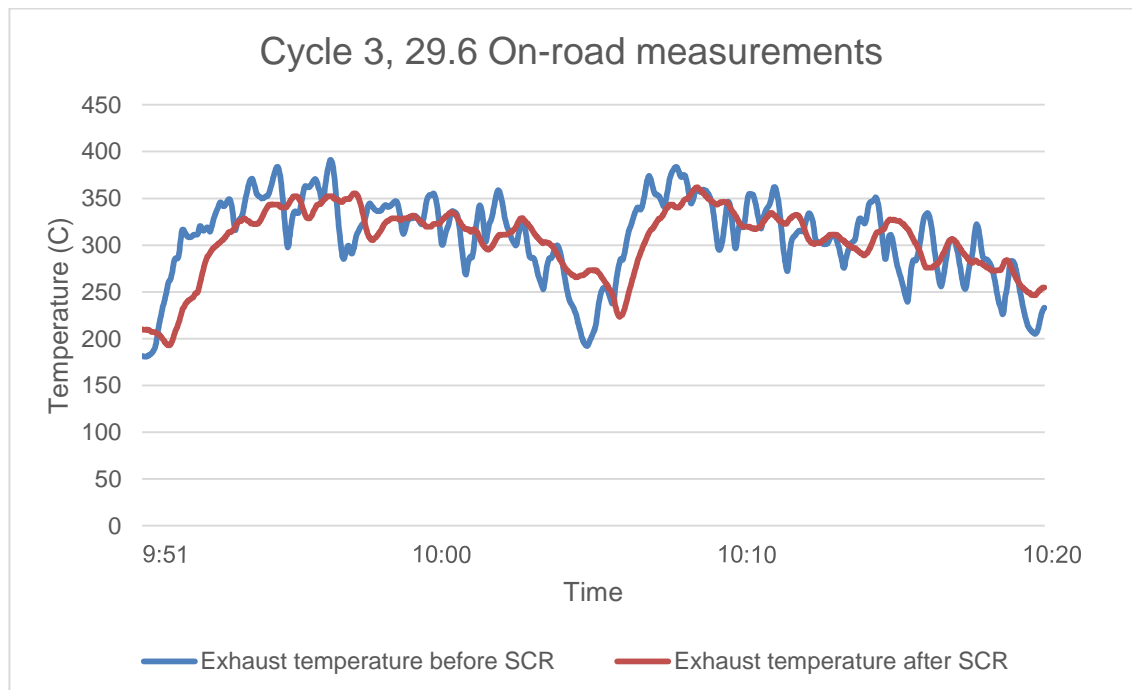


Figure 5 Exhaust gas temperature before and after SCR

The temperature before SCR (blue graph) and after SCR (red graph) reacts similarly to engine load. The NH<sub>3</sub> slip increases when exhaust gas temperature is clearly over 300 °C.

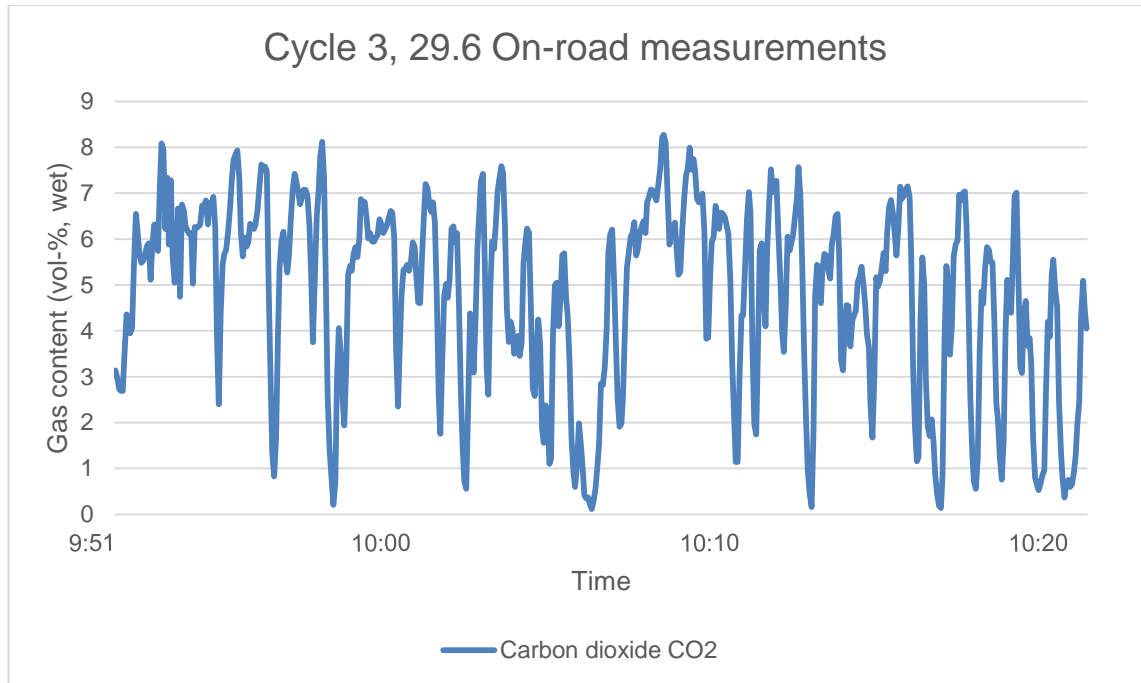


Figure 6 CO<sub>2</sub> emissions measured with Gasmeter

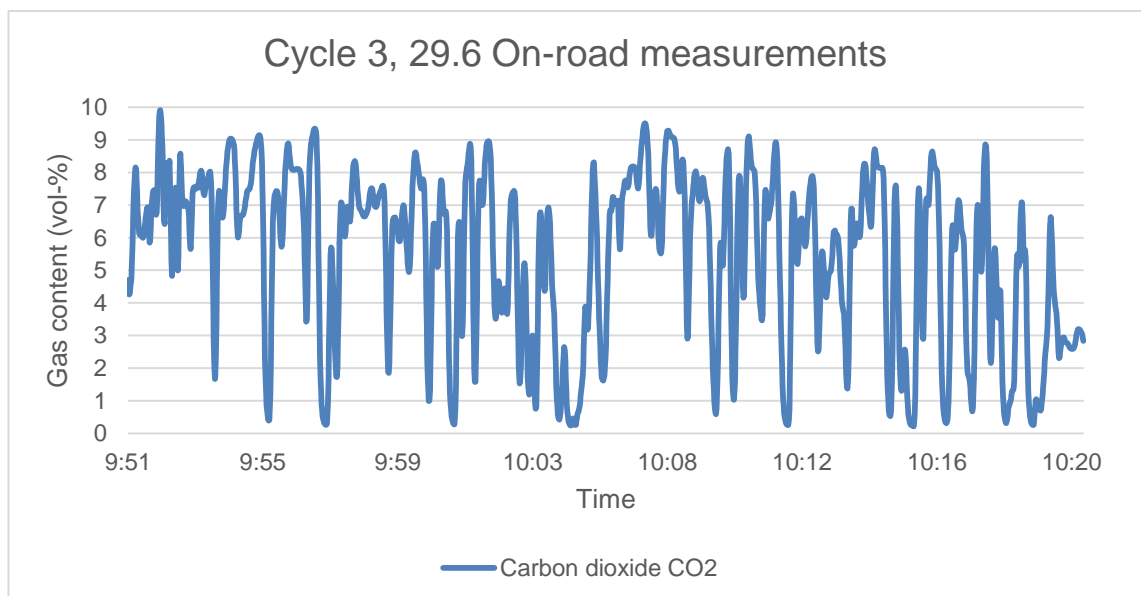


Figure 7 CO<sub>2</sub> emissions measured with Servomex

The CO<sub>2</sub> emissions measured with Gasmeter and Servomex are similar. The Servomex measures a little more accurately than the Gasmeter. This is due to the Gasmeter's lower measurement frequency. The CO<sub>2</sub> on higher engine loads rises to 7-10 % and on lighter engine load decreases to 0-4 %.

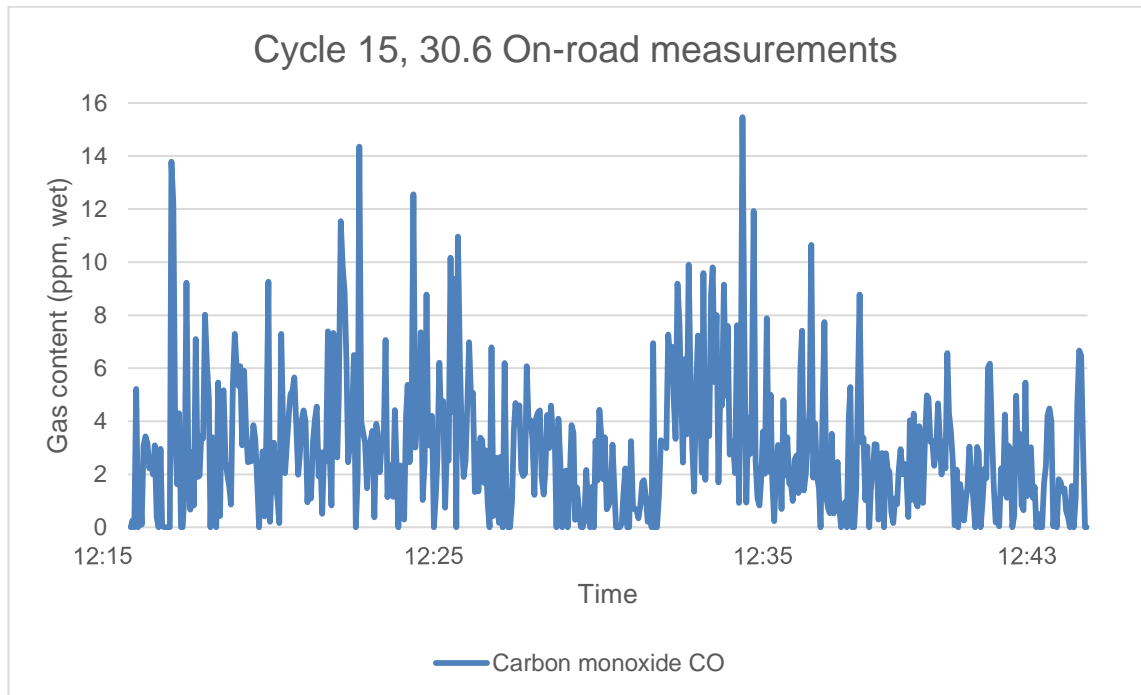


Figure 8 CO emissions measured with Gasmeter

The CO emissions are more sensitive to engine load. After the start of the measurements there were many hills etc. This causes many spikes before midpoint. It is typical that CO emissions reach higher points when rising engine load. The minimal 1 second measurement frequency with Gasmeter isn't capable to measure fast spikes.

## Lifting measurements

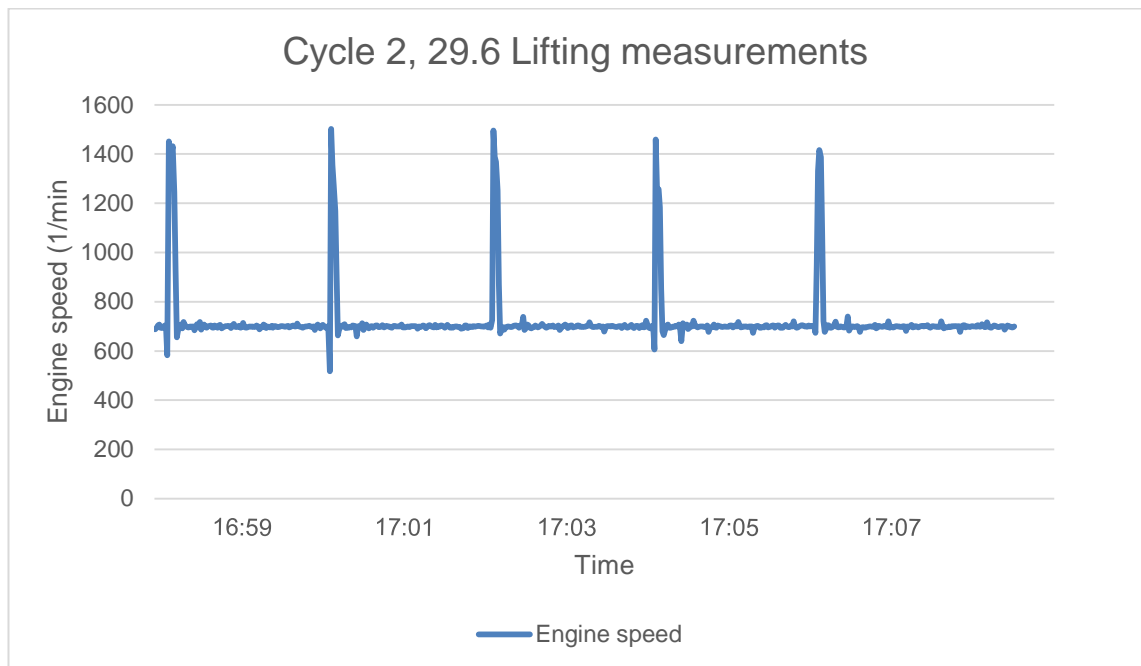


Figure 9 Engine speed in lifting measurements

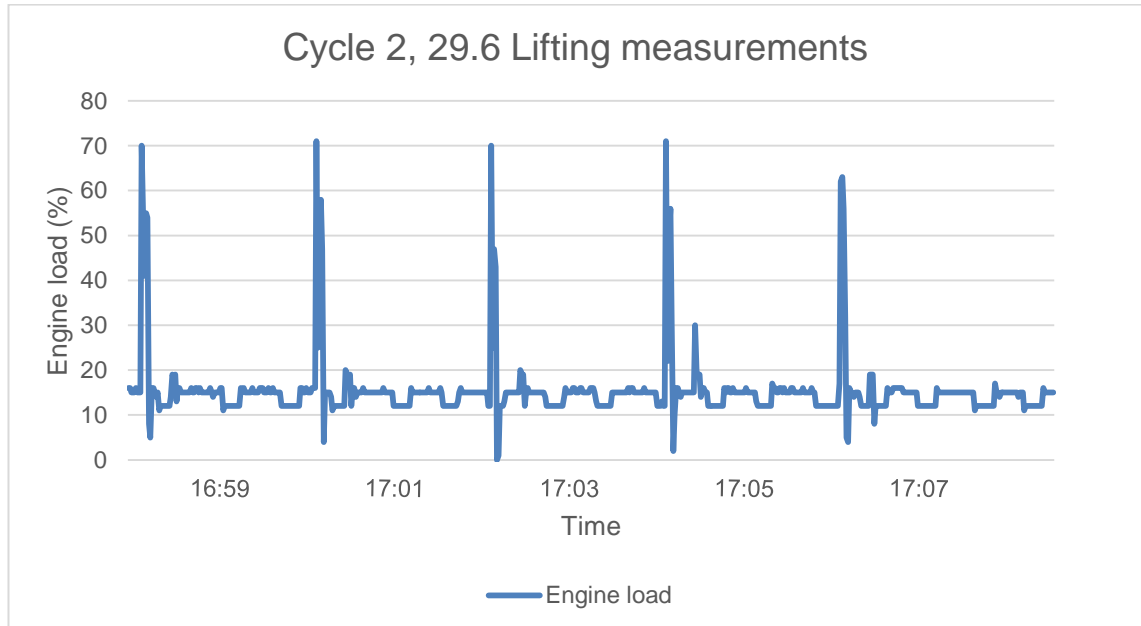


Figure 10 Engine load in lifting measurements

Engine speed and engine load behave clearly when raising and lowering the load. Variation in engine speed and engine load is due to variation of joystick movement. For

example, another lift could have been little faster than the other. The driver didn't push the gas pedal when lifting the load. The tractor has an automatic gas which reacts when the engine senses load.

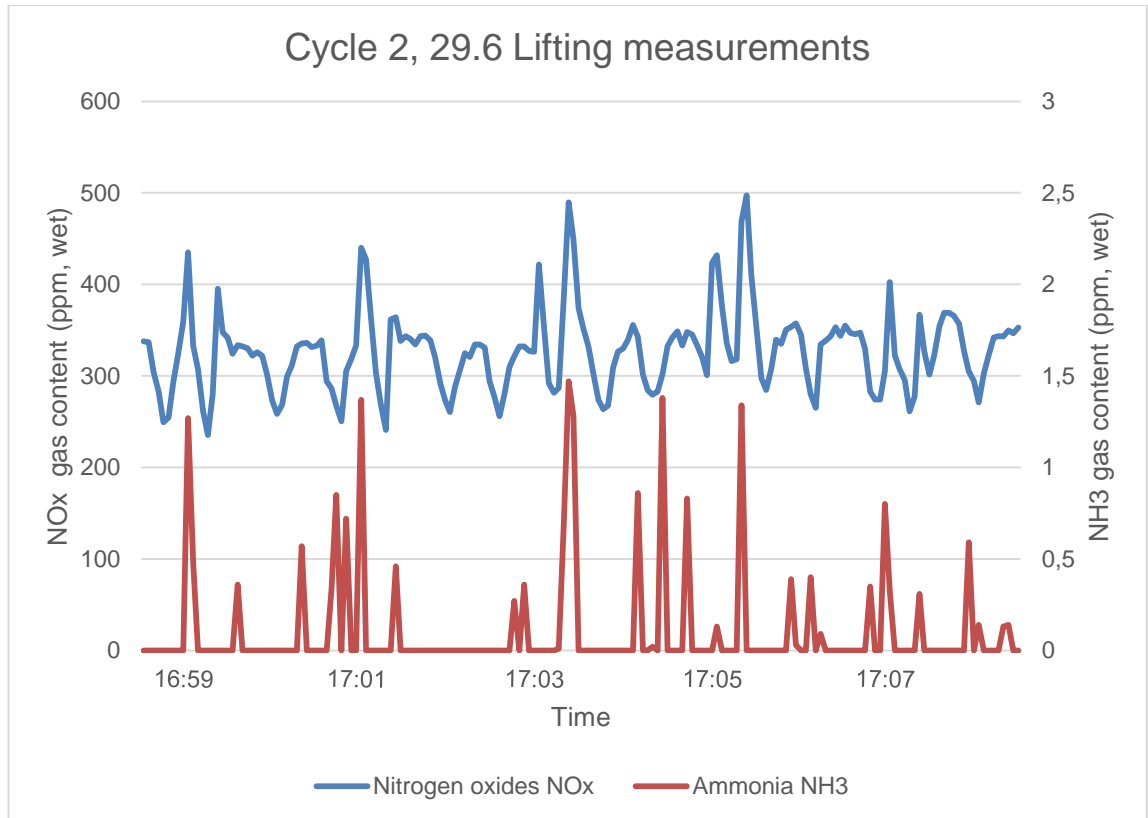


Figure 11 NO<sub>x</sub> and NH<sub>3</sub> emissions measured with Gasmeter

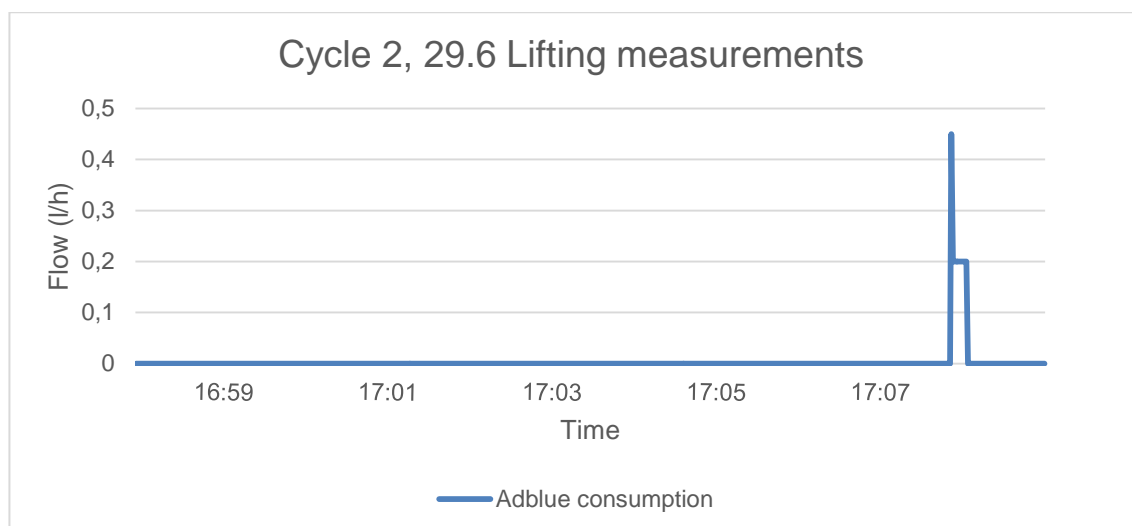


Figure 12 Adblue consumption

The first lift started at 16.59 and a clear spike on  $\text{NO}_x$  can be seen right after. After 20 seconds, a second small spike is visible. Lifting spikes vary from 400 ppm to 500 ppm. None of the lifts were exactly the same which causes the inaccuracies on the figure.  $\text{NH}_3$  slip was very minimal. On the second figure it can be seen that the slip didn't reach more than 1.5 ppm. Little spikes can be seen on the lifting points.  $\text{NH}_3$  spike can be excess urea at SCR.

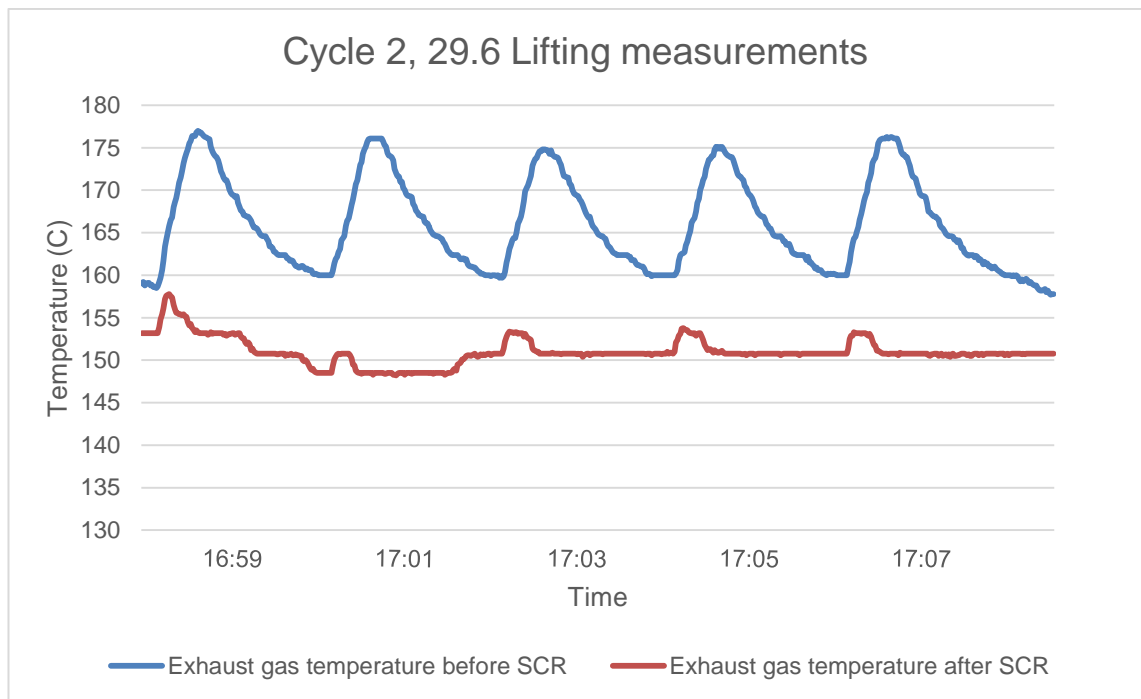
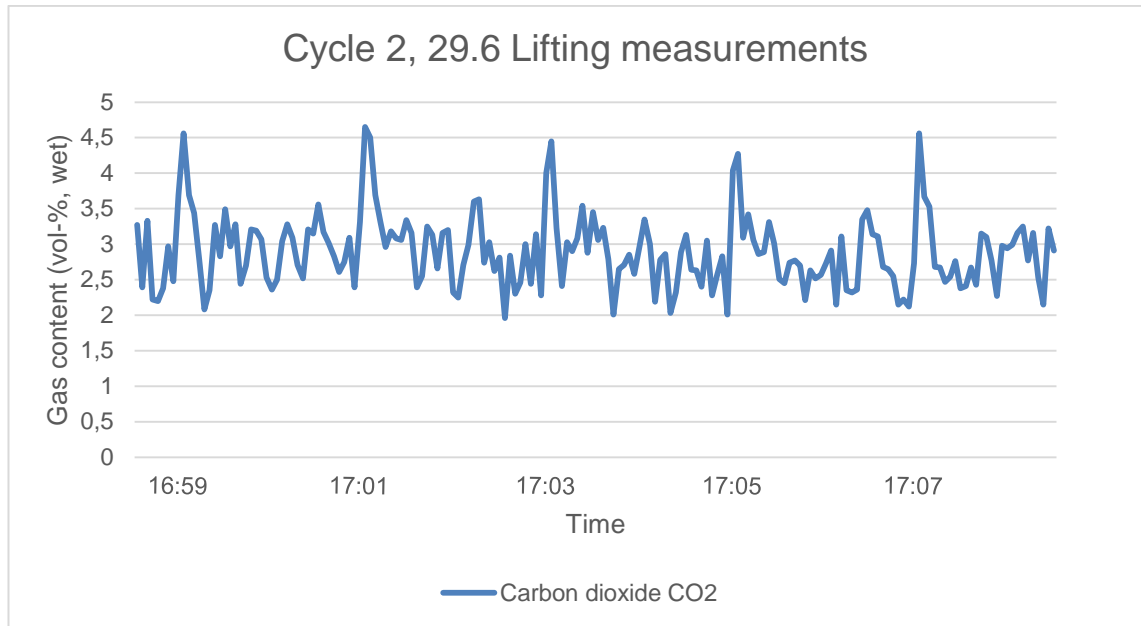
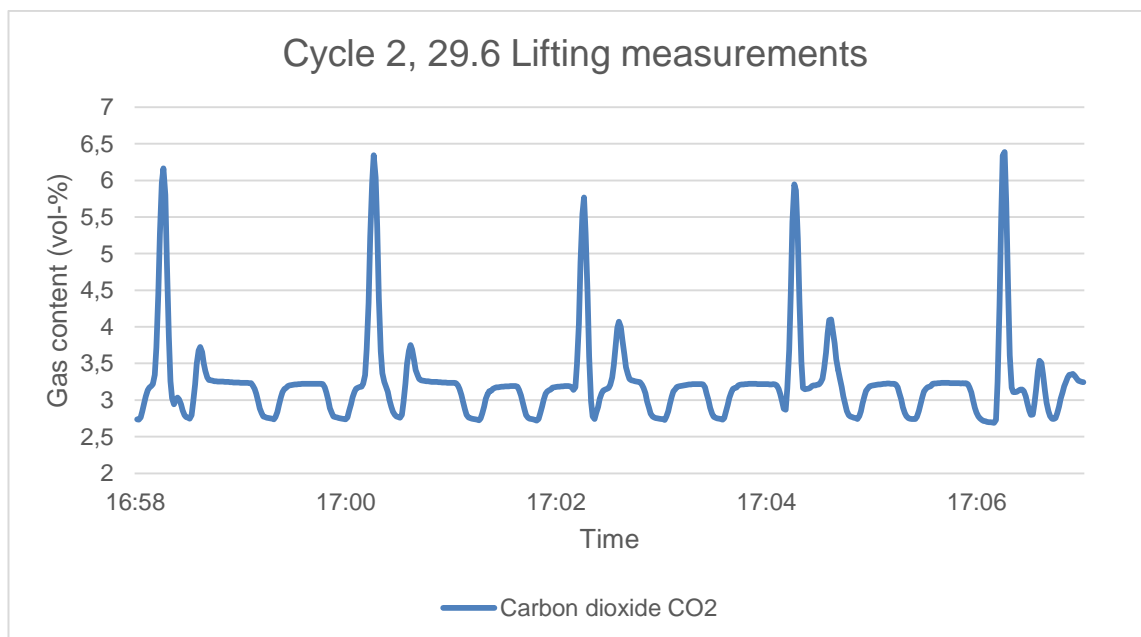


Figure 13 Exhaust gas temperature before and after SCR

Exhaust gas temperature before SCR (blue graph) doesn't rise more than 178 °C and after SCR (red graph) stays under 156 °C. This indicates that there should not be any urea-injection to SCR.

Figure 14 CO<sub>2</sub> emissions measured with GasmeterFigure 15 CO<sub>2</sub> emissions measured with Servomex

CO<sub>2</sub> measured with Gasmeter and Servomex are similar. Servomex measurement data is more linear than Gasmeter measurement data. CO<sub>2</sub> spikes in the Gasmeter data are a little lower than in the Servomex. This is the cause of the Measurement frequency. Spikes in the Gasmeter are at 4.5-5 % and in the Servomex at 5.8-6.5 %. At idle speed and no load the CO<sub>2</sub> is at 2-3.5 %.



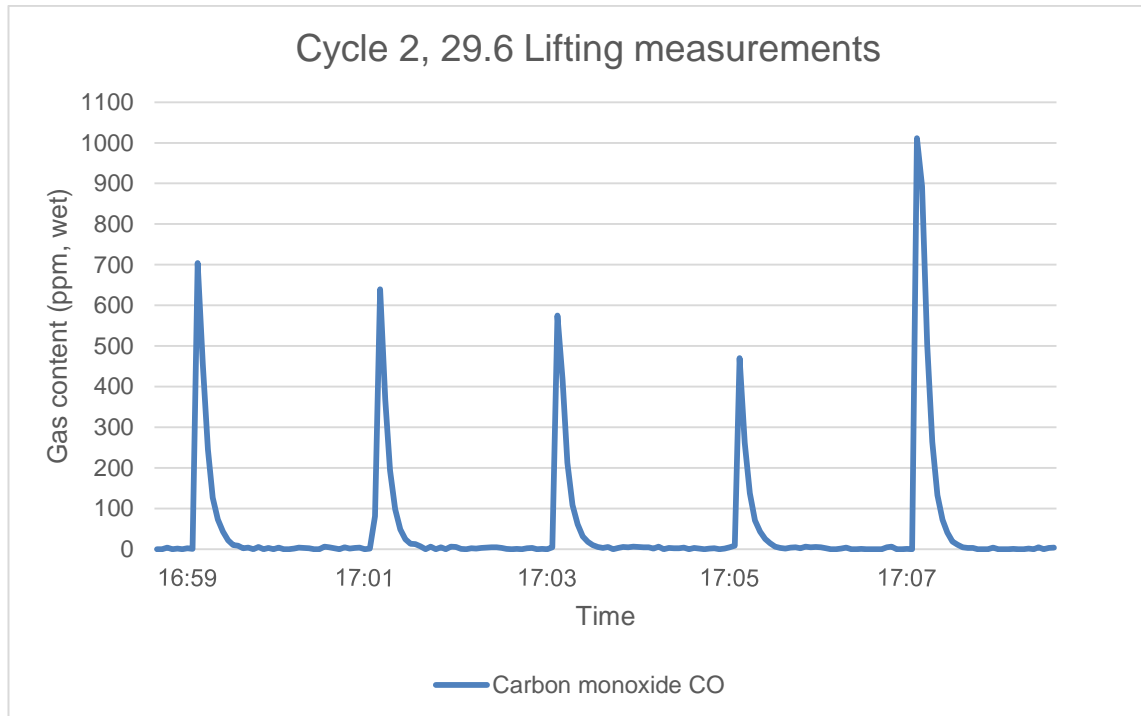


Figure 16 CO emissions measured with Gasmeter

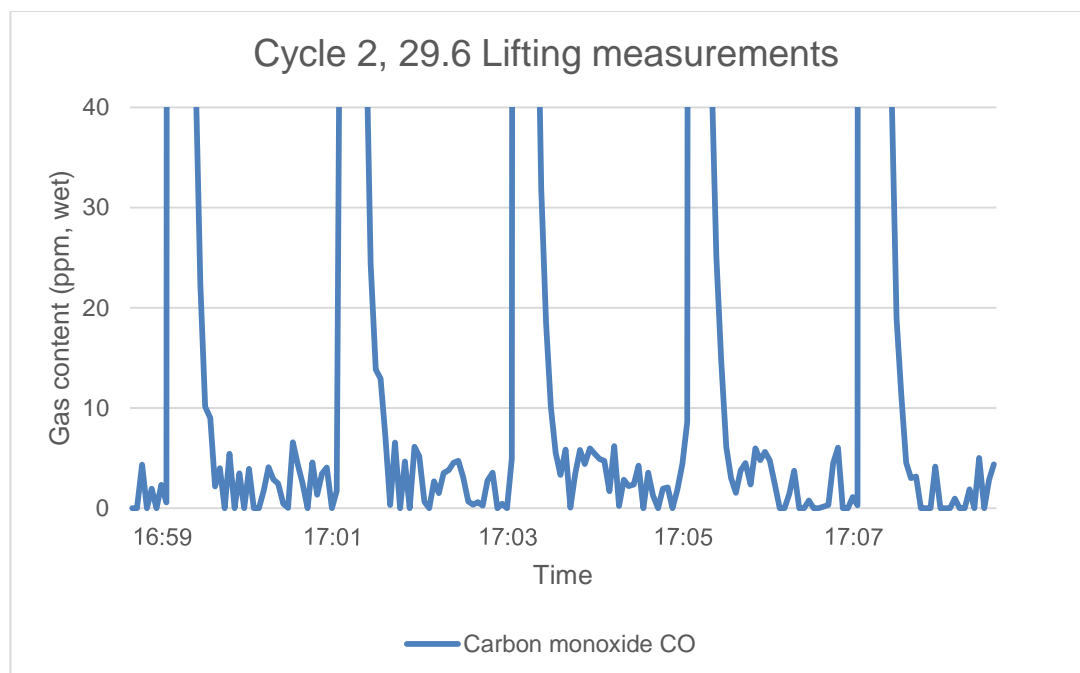


Figure 17 CO emissions measured with Gasmeter at smaller scale

The CO spikes are very apparent. Four first spikes are from 470 to 700 ppm. The last spike reaches up to 1010 ppm. This can be due to faster lift. At idle, the CO stays in steady 0-6 ppm.

### 3 LABORATORY MEASUREMENTS

This chapter presents the facilities and measurement devices used in laboratory measurements. This chapter contains also engine details and fuels and lubrication used in laboratory measurements. The test procedure for soot accumulation and passive regenerations and the schedule for the laboratory measurements are presented at the end of chapter.

#### 3.1 Facilities

Laboratory measurements were performed at the Engine laboratory at Turku University of Applied Sciences. The goal of the laboratory measurements was to get DPF to regenerate passively by filling up the DPF with soot. On passive regenerations no post injection fuel is provided. If the DPF doesn't regenerate passively, filter gets clogged gradually. The laboratory measurements were driven on two different diesel fuels, DFO and NRD and with two emission standards, Tier 4 Final and Stage 5.

The measurements were performed with an Agco Power's 44 AWF engine. The test bed is attached with National Instrument's LabVIEW based computer software, which controls the engine and collects measurement data. A Schenck W400 Dynamometer was used to control the engine load. The dynamometer can handle constant and dynamic loads and can be controlled. The temperature sensors are PT-100 type and pressure sensors are Keller Piezo based. Airflow is measured with an ABB Sensysflow FMT-700P and fuel mass flow is measured with a Micro Motions CMF025M Coriolis Mass flowmeter. Smoke is measured with an AVL 415 S, PM with a Pegasor PPS-M, NO<sub>x</sub> with an Eco Physics CLD 700EI ht and HC with a CAI HFID 300. CO, CO<sub>2</sub> and O<sub>2</sub> are measured with a Servomex Xentra 4900, CO<sub>2</sub>, CO, NO<sub>x</sub> and NH<sub>3</sub> with a Gasmeter DX4000 FT-IR Gas Analyzer. The lab measurement analysis were gathered to an Analysis lab point 1 (Before AT) and 2 (After AT.) Measurement data was transferred to Microsoft Excel. Piping and instrumentation diagram in laboratory measurements can be found in Appendix 1.

Table 7 Measurement instruments used in laboratory measurements

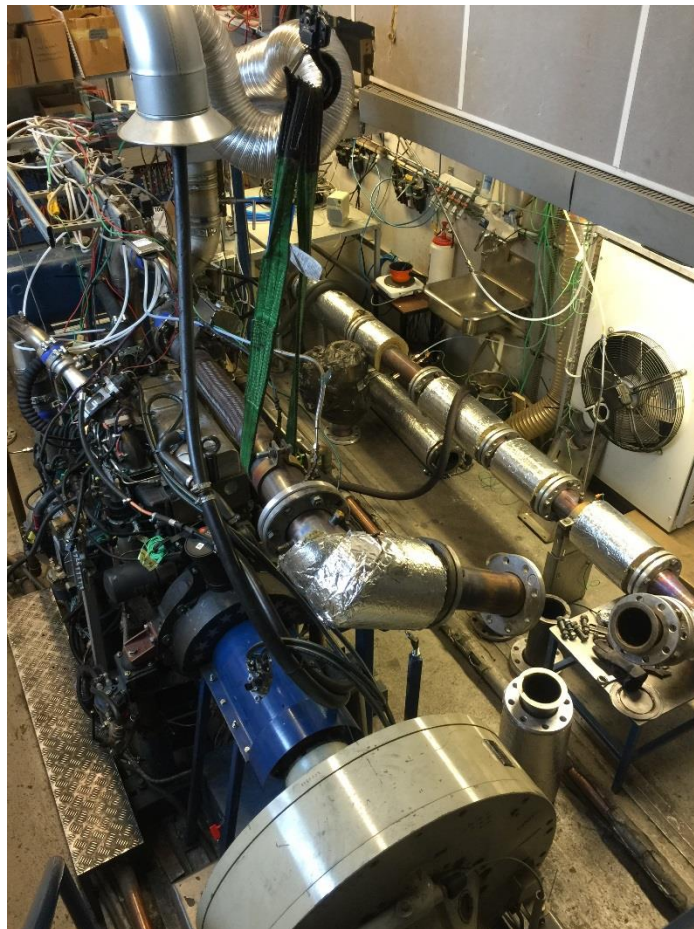
Measurement	Device
Temperature	PT-100 Type sensors
Pressure	Keller Piezo Type sensors
Airflow	ABB Sensysflow FMT-700P
Fuel	Micro Motions CMF025M Coriolis Mass flowmeter
Smoke	AVL 415 S
Particle matter (PM)	Pegasor PPS-M
Nitrogen Oxides (NO <sub>x</sub> )	Eco Physics CLD 700EI ht
Hydrocarbons (HC)	CAI HFID 300
Carbon Monoxide (CO), Carbon Dioxide (CO <sub>2</sub> ), Oxygen (O <sub>2</sub> )	Servomex Xentra 4900
Carbon dioxide (CO <sub>2</sub> ), Carbon monoxide (CO), Nitrous Oxides (NO <sub>x</sub> ), Ammonia (NH <sub>3</sub> )	Gasmet DX4000 FT-IR Gas Analyser

### 3.2 Engine details

The laboratory measurements were performed with an prototype AGCO Power 44 AWF diesel engine. The engine was an intercooled 4-cylinder direct injection engine with a turbocharger. The engine used in the laboratory measurements was driven with SET B which can be found on Appedix 1. SET B contains DOC, DPF and SCR as an aftertreatment system. The prototype engine had two prototype softwares for different emission standards.

Table 8 The prototype engine information on laboratory measurements (Valtra 2016)

Engine	
Engine type	44 AWF
Cylinders	4
Cylinder displacement	4,4 dm <sup>3</sup>
Power kW / hp @ r /min (ISO 14396)	
Maximum power	77/105/1900
Maximum power with Power boost -function	85/115/1900
Torque Nm @ / r / min	
Maximum torque	470/1500
Maximum torque with Power boost -function	510/1500



Picture 10 Engine and dynamometer used in laboratory measurements

### 3.3 Fuel and lubrication

Laboratory measurements were performed with two types of fuels, DFO and Neste renewable diesel oil. The fuel analysis of DFO and NRD can be found on Appendix 3. The fuel analysis of DFO was performed with the ENISO5165 method and NRD was performed with the ASTM D6890.

### 3.4 Test procedure

#### Soot accumulation

To fill the DPF with soot, the engine had to be driven on medium load with decreased fuel injection pressure. The engine was driven for two hours on 2100 rpm on 190 Nm torque. Common-rail pressure was decreased to 50 MPa.

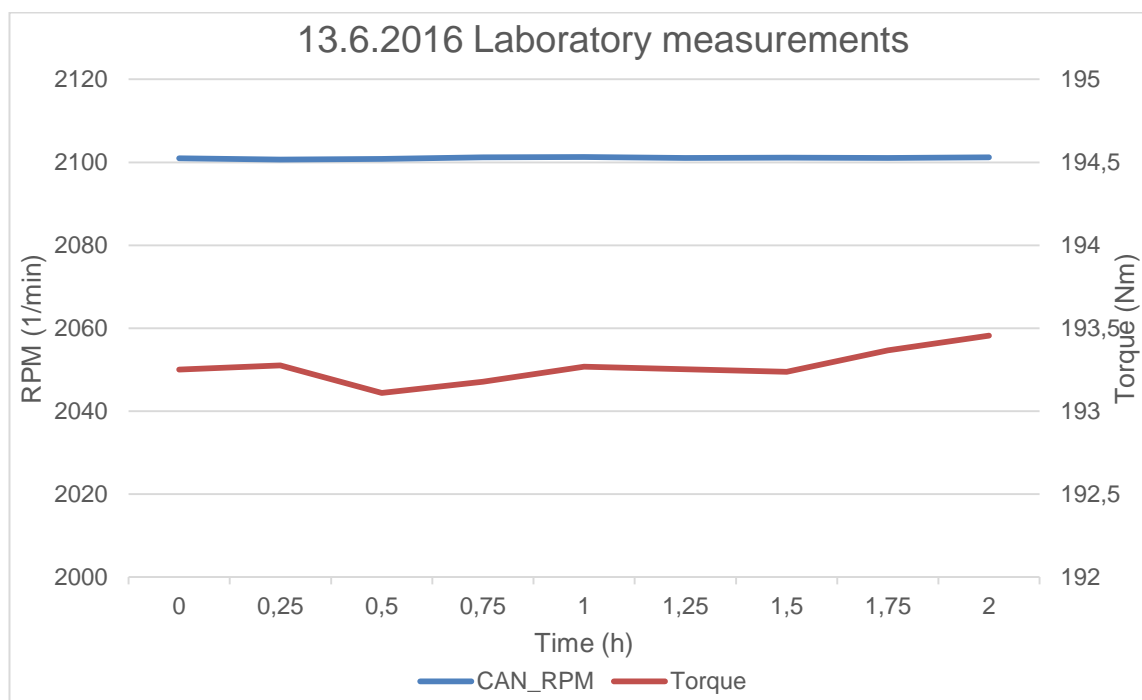


Figure 18 Engine speed and torque on soot accumulation

Soot accumulations were driven before every passive regeneration cycles. Soot accumulations were driven a total of four times.

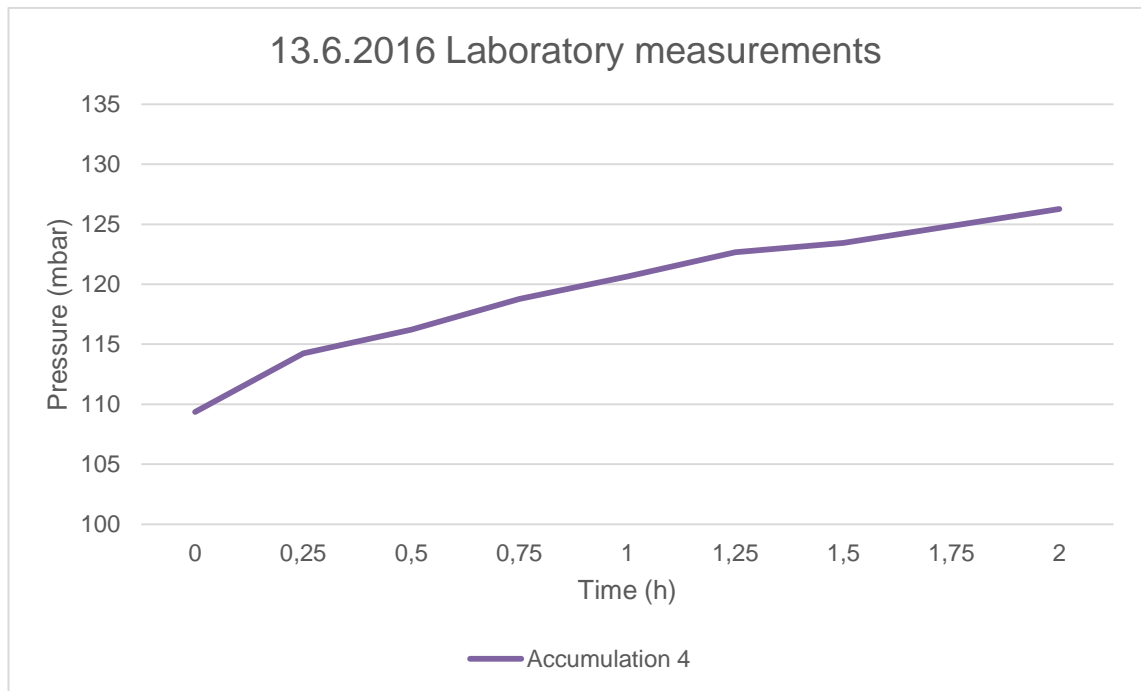


Figure 19 Backpressure increase

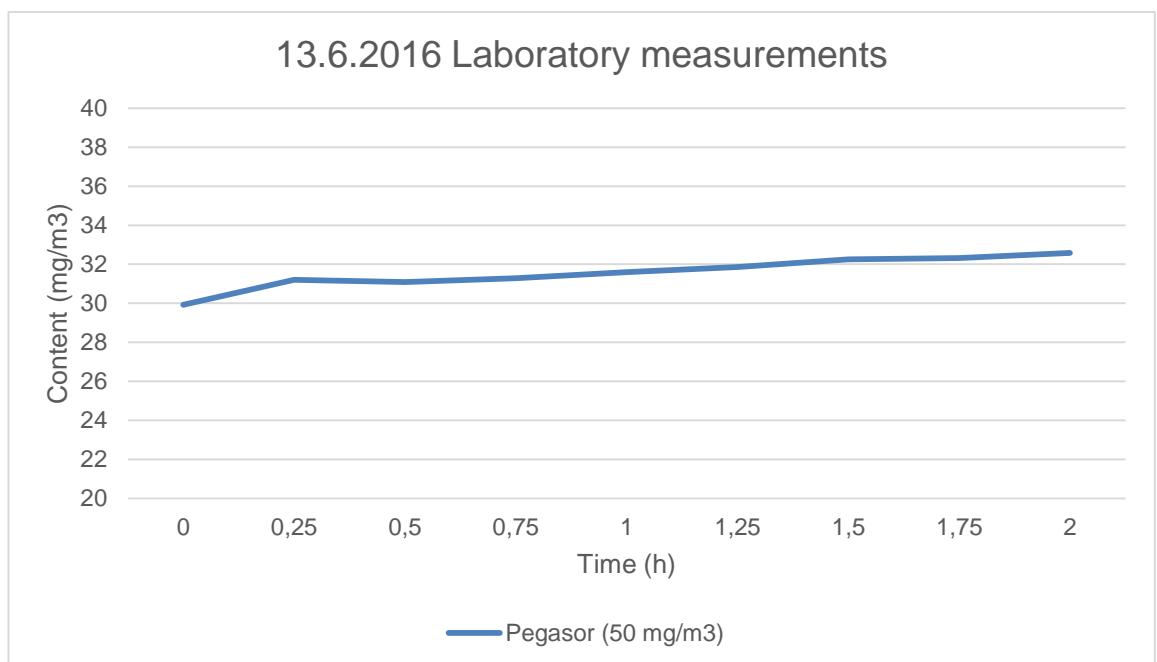


Figure 20 PM content in exhaust gas

It was possible to fill the DPF with soot. It can be seen by investing backpressure and PM content in exhaust gases. The backpressure increases clearly from 110 mbar to 126

mbar, which refers to that the exhaust pipe gradually becomes clogged. The PM content in exhaust gas increases from 30 mg/m<sup>3</sup> to 33 mg/m<sup>3</sup>.

### Passive regenerations

Passive regenerations were driven on identical cycles lasting 15 minutes. Three cycles were driven on time. Cycles were driven from 18 to 40 times. The cycle is based on loading the engine with different torque and engine speed.

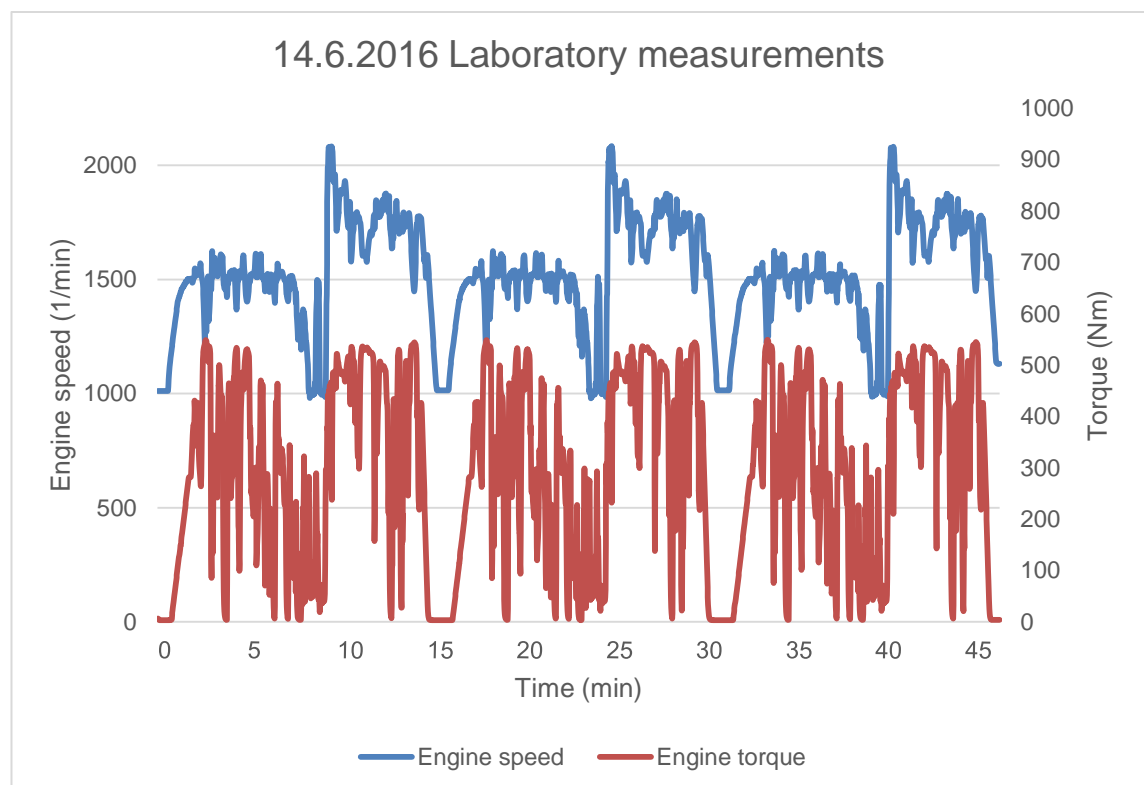


Figure 21 Engine speed and torque on three cycles

Table 9 Schedule of the laboratory measurements

Description	Date	Total cycles
Soot accumulation 1	17.5.2016	1
T4F & DFO	18–19.5.2016	40
Soot accumulation 2	31.5.2016	1
Stage5 & DFO	2-3.6.2016	33
Soot accumulation 3	6.6.2016	1
T4F & NRD	7-8.6.2016	33
Soot accumulation 4	13.6.2016	1
Stage5 & NRD	14.6.2016	18



### 3.5 Results

#### Passive regeneration

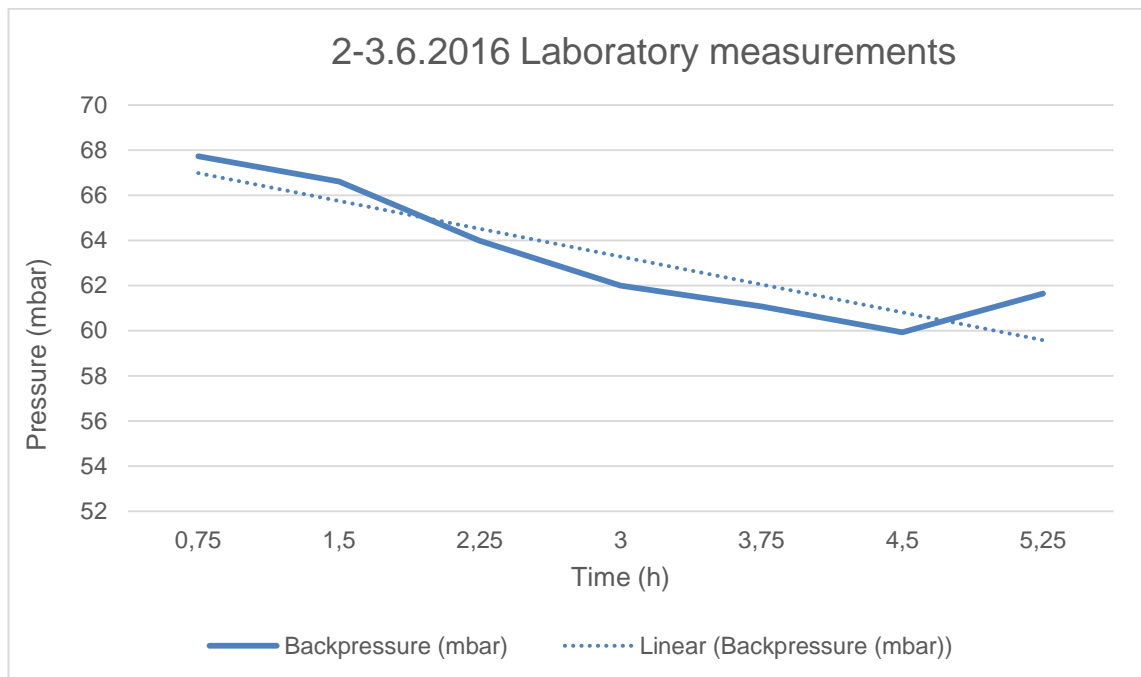


Figure 22 Stage 5 & DFO average backpressure per three cycles

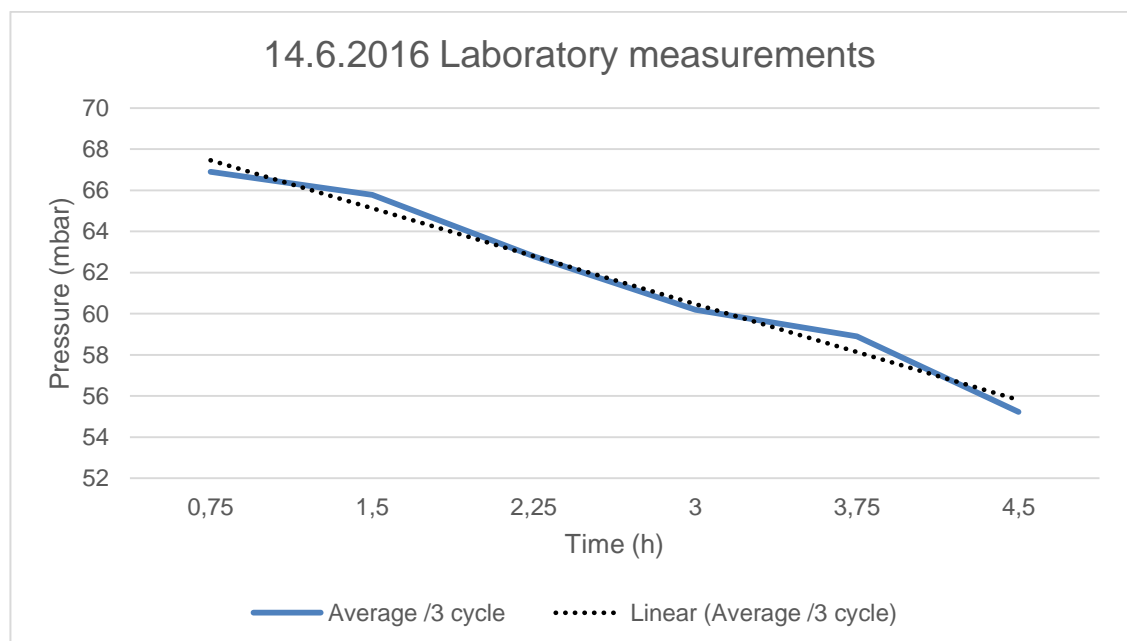


Figure 23 Figure 24 Stage 5 & NRD average backpressure per three cycles

The average backpressure on first three cycles was very similar with both DFO and NRD. It seems that backpressure decreases more with NRD than with regular DFO. With DFO, the backpressure is at the lowest point at 60 mbar when four and a half hours have been driven. Backpressure decreases to 55 mbar with NRD at the same point.

Figures of backpressure indicate that the DPF starts to regenerate almost immediately. On Stage 5, it takes 4,5 hours to regenerate the DPF.

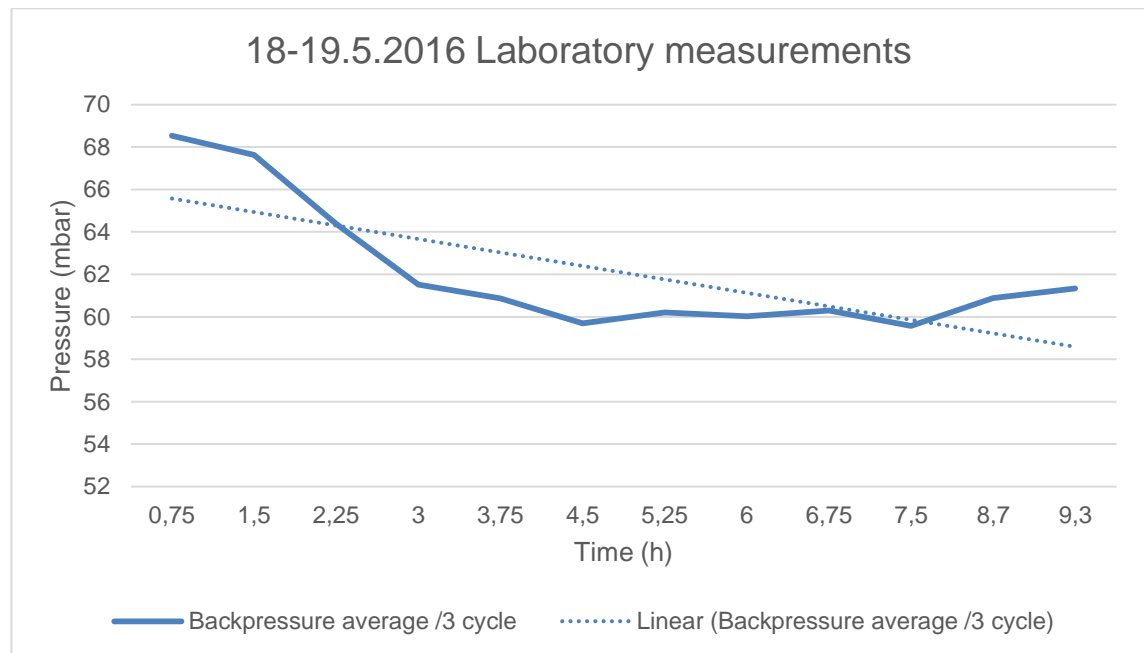


Figure 24 Figure 24 Tier 4 final & DFO average backpressure per three cycles

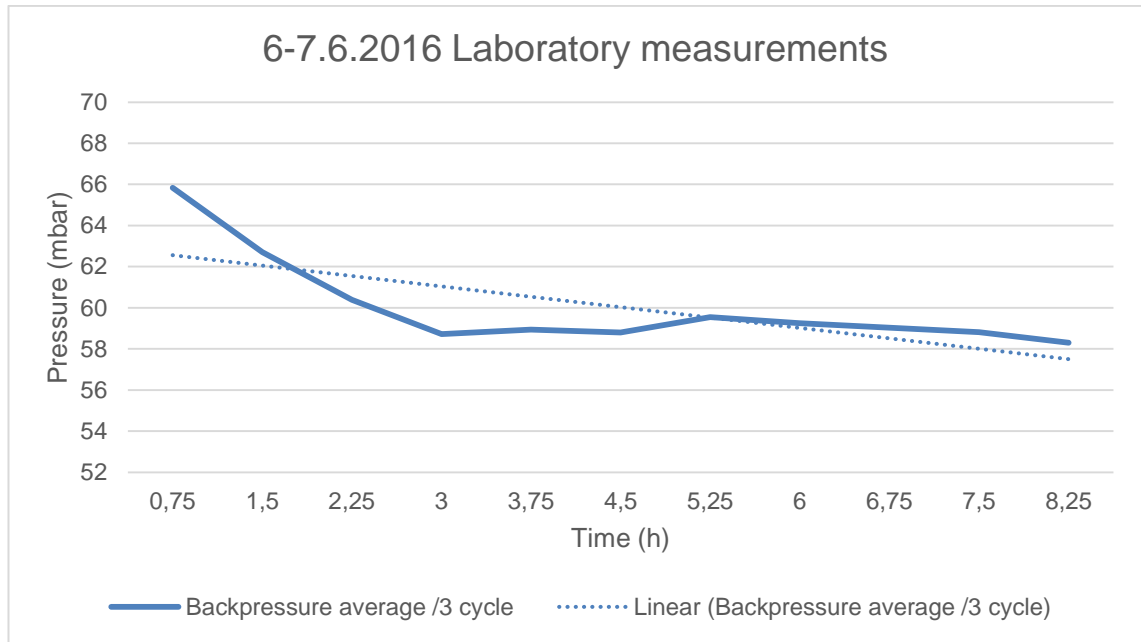


Figure 25 Figure 25 Tier 4 final & NRD average backpressure per three cycles

The average backpressure reacts in the same way as with Stage 5. Backpressure decreases more with NRD than DFO. The backpressure with DFO drops from 69 mbar to 60 mbar after four and a half hours. The backpressure with NRD drops from 66 mbar to 59 mbar in three hours. The backpressure rises a little bit in both figures which means that the DPF starts gathering soot.

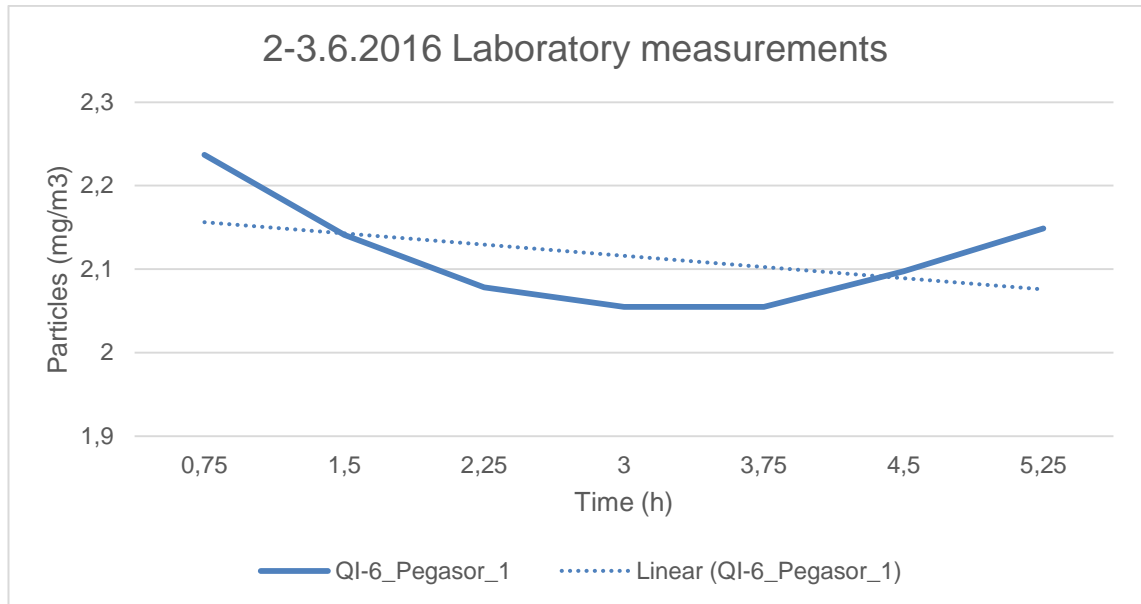


Figure 26 Stage 5 & DFO PM in exhaust gas average per three cycles

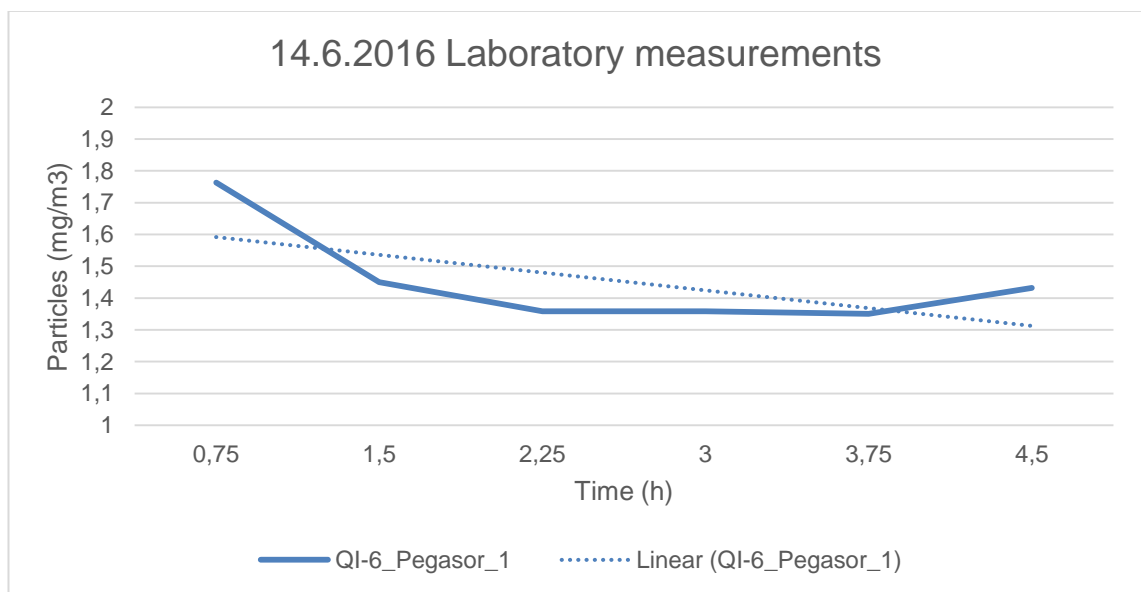


Figure 27 Stage 5 & NRD PM in exhaust gas average per three cycles

When DPF regenerates passively, PM emissions are much higher when driven on DFO. PM on DFOs cycles stay over 2 mg/m<sup>3</sup>. The PM drops only 0.18 mg/m<sup>3</sup> from 2.23 mg/m<sup>3</sup> to 2.05 mg/m<sup>3</sup>. Whilst with NRD, the PM emissions drop from 1.8 mg/m<sup>3</sup> to 1.4 mg/m<sup>3</sup>.

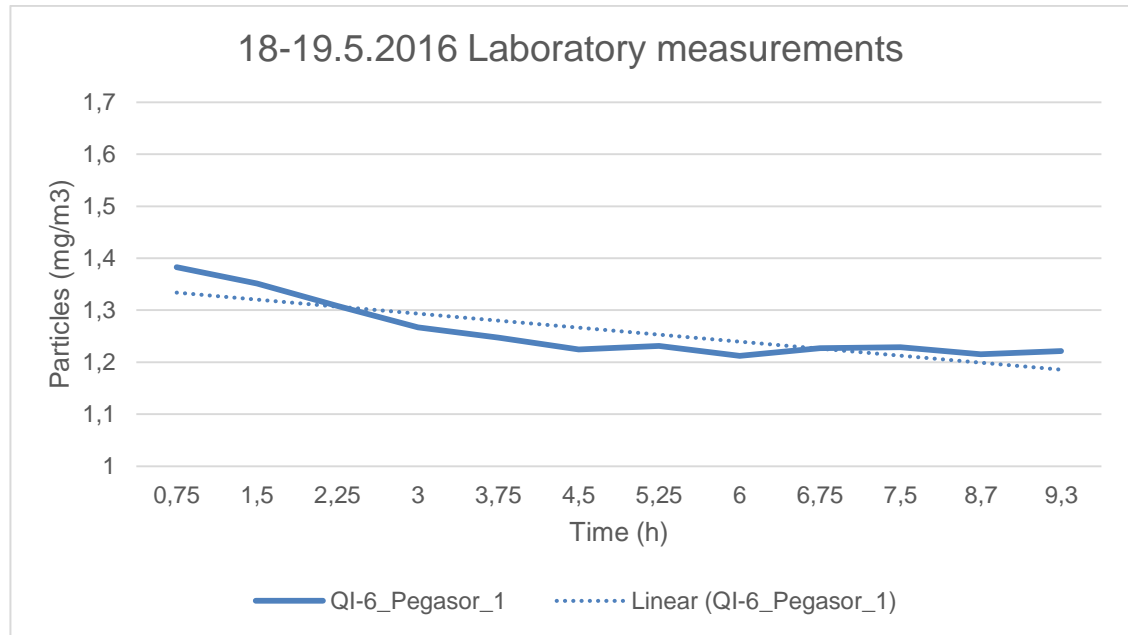


Figure 28 Tier 4 Final & DFO PM in exhaust gas average per three cycles

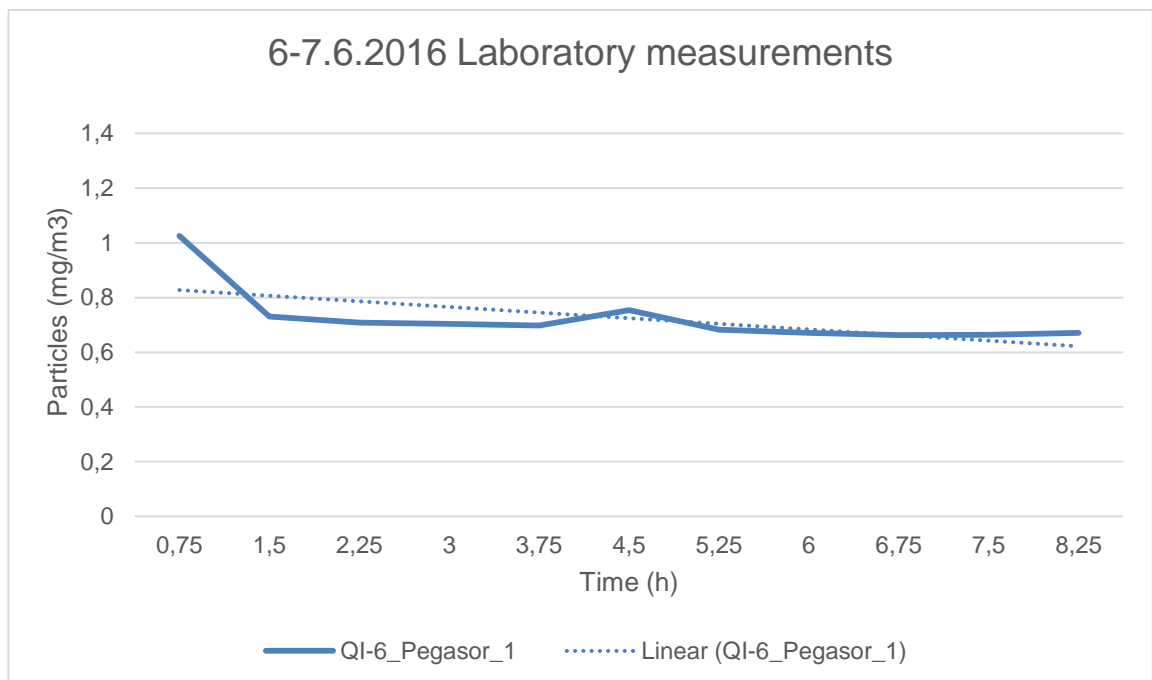


Figure 29 Tier 4 Final & NRD PM in exhaust gas average per three cycles

DPF starts to regenerate immediately in the first cycle. Regeneration happens much faster with NRD than with DFO. It takes 4,5 hours with DFO to steady the PM emissions but with NRD it takes only 1,5 hours. PM emissions are little lower when driven on NRD than on DFO.

## 4 CONCLUSIONS

### On-road measurements

NO<sub>x</sub> emissions in on-road measurements react to engine load well. The control of the SCR system was based on closed loop controlling with NO<sub>x</sub> sensors. When the engine load drops, the amount of injected urea is decreased. CO<sub>2</sub>, CO and O<sub>2</sub> react clearly to engine load and it can be predicted from the figures what has occurred.

### Lifting measurements

NO<sub>x</sub> emissions in the lifting measurements react clearly to engine load. NO<sub>x</sub> emissions are a little higher because urea is not injected as the exhaust gas temperature is too low. Excess urea in the exhaust pipe causes some NH<sub>3</sub> slips. CO<sub>2</sub>, CO and O<sub>2</sub> emissions react to the engine load as predicted.

### Laboratory measurements

In soot accumulation DPF was successfully filled with soot. This can be observed in the rise of exhaust gas backpressure and by investigating the PM graph.

On passive regenerations, the DPF was successfully regenerated without any post-injection. A clear difference can be seen between NRD and DFO. PM in exhaust gases are lower with NRD than with DFO. When using NRD the PM emissions are 31 % lower with Stage 5 and 44 % lower with Tier 4 final.

## 5 SUMMARY

This thesis is a part of HERE project that aims to identify and analyze exhaust particle emissions on engines and effects to human health. The project is funded by TEKES and many other companies.

For this study, two measurement were conducted. One in Suolahti at Valtra's factory and another in engine laboratory at Turku University of Applied Sciences. The goal for on-road measurements in Suolahti was to collect information how emissions behave on the tractors designed purpose. The goal for laboratory measurements was to get DPF regenerate passively. During the laboratory measurements comparisons are made between Stage 5 and Tier 4 final emission standards, as well as how NRD and DFO-fuel behaves during passive regeneration.

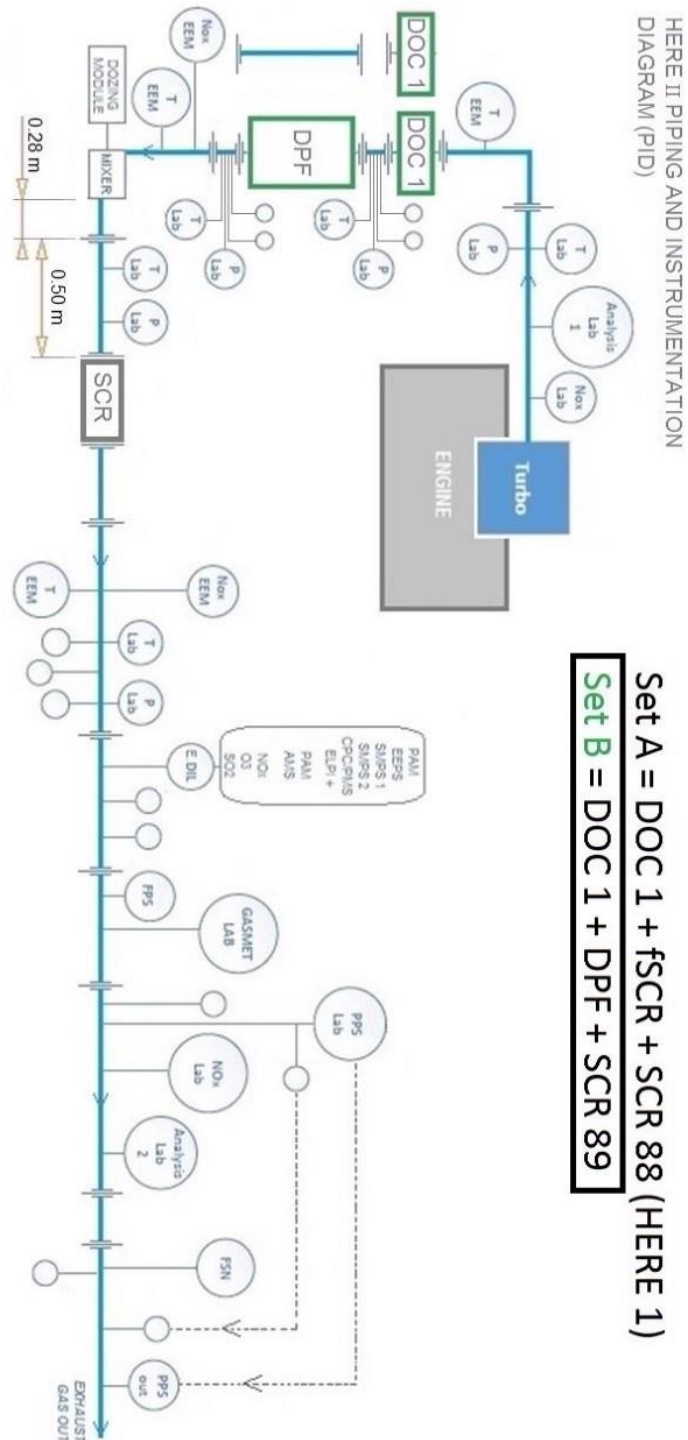
The results in on-road measurements show that emissions react to engine load with predictable manner. The results can be stated as reliable, since there are no major variations. Most of the work was spent to analysing the results due to large number of measurement results. The results in laboratory measurements show that the DPF can be regenerated passively. The regeneration affects more with NRD than with DFO. The NRD decreases PM emissions clearly than using DFO. The exhaust backpressure decreases most with Stage 5 and NRD.

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## Piping and instrumentation diagram in laboratory measurements



## Schedule on field measurements 29.6.2016

Time	Event	Info
8.10	Heated lines on 185 °C	
8.16	Servomex ja logger check	
8.29	Gasmet calibration	
9.09	Tractor started	
9.11	Servomex ja logger check	
9.15	Scan started, continuous measurement	
9.32	5 seconds syncing	
9.35	Start from Valtra	
9.46	At measuring place	
9.47	Scan stopped, Scan started	
		Note: Vacuum dryer not adjusted
9.51	Measurement started, TTY 4	
10.06	Turning point	
10.07	Continue measurement	
10.21	Measurement ended	
10.22	Scan stopped, Scan started	
10.23	Vacuum dryer adjusted	
10.24	Scan started, continuous measurement	
10.34	Measurement started, TTY 5	
10.48	Turnign point	
10.49	Continue measurement	
11.03	Measurement ended	
11.04	Scan stopped	
11.05	Scan started	
11.09	Measurement started, TTY 6 (without cs)	
11.39	Measurement ended	
11.40	Scan stopped	
11.41	Scan started	
11.42	Off to Valtra	
11.55	At Valtra	
11.58	Scan stopped	
	Dining	
13.00	Scan started	
13.01	Start from Valtra	
13.13	At measuring place	

13.18	Measurement started, TTY 0-measurement	
13.48	Measurement ended	
13.50	Scan stopped	
13.51	Scan started	
13.55	Measurement started, TTY 6 + CS	
14.24	Measurement ended	
14.26	Scan stopped	
14.27	Scan started	
14.29	Measurement started, TTY 5 repeat	
14.58	Measurement ended	
15.00	Scan stopped	
15.01	Scan started	
15.05	Measurement started, TTY	
15.35	Measurement ended	
15.36	Scan stopped	
15.40	Off to Valtra	
15.52	At Valtra	
16.17	Scan started	
16.19	Lifting test	
16.20	Lifting test	
16.32	Tractor shutted down	
16.39	Tractor started	
		PTD
		Porous
		tube
18.02	Diluter change	diluter
	Measurement over, Scan stopped,	
19.32	Continuous measurement stopped	
19.33	Gasmet flush	
19.40	Tractor shutted down	

## Schedule of lifting measurements

Lifting measurement		1100 kg on tractors front loader	
TTY 3	Time	TTY cold 1	
	1 16.46	21	18.19
	2 16.48	22	18.21
	3 16.50	23	18.23
	4 16.52	24	18.25
TTY 4	5 16.54	25	18.27
		TTY cold 2	
	6 16.58	26	18.34
	7 17.00	27	18.36
	8 17.02	28	18.38
TTY 5	9 17.04	29	18.40
	10 17.06	30	18.42
		TTY hot 1	
	11 17.18	31	19.10
	12 17.20	32	19.12
TTY 6	13 17.22	33	19.14
	14 17.24	34	19.16
	15 17.26	35	19.18
		TTY hot 2	
	16 17.32	36	19.23
	17 17.34	37	19.25
	18 17.36 slow lift	38	19.27
	19 17.38	39	19.29
	20 17.40	40	19.31

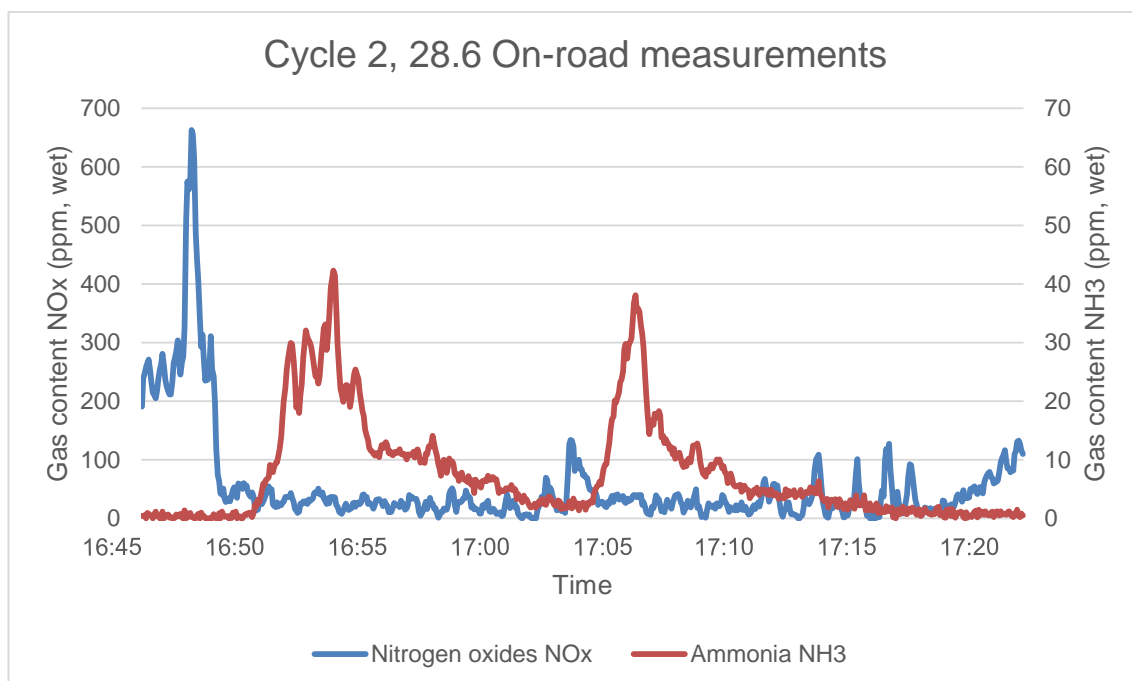
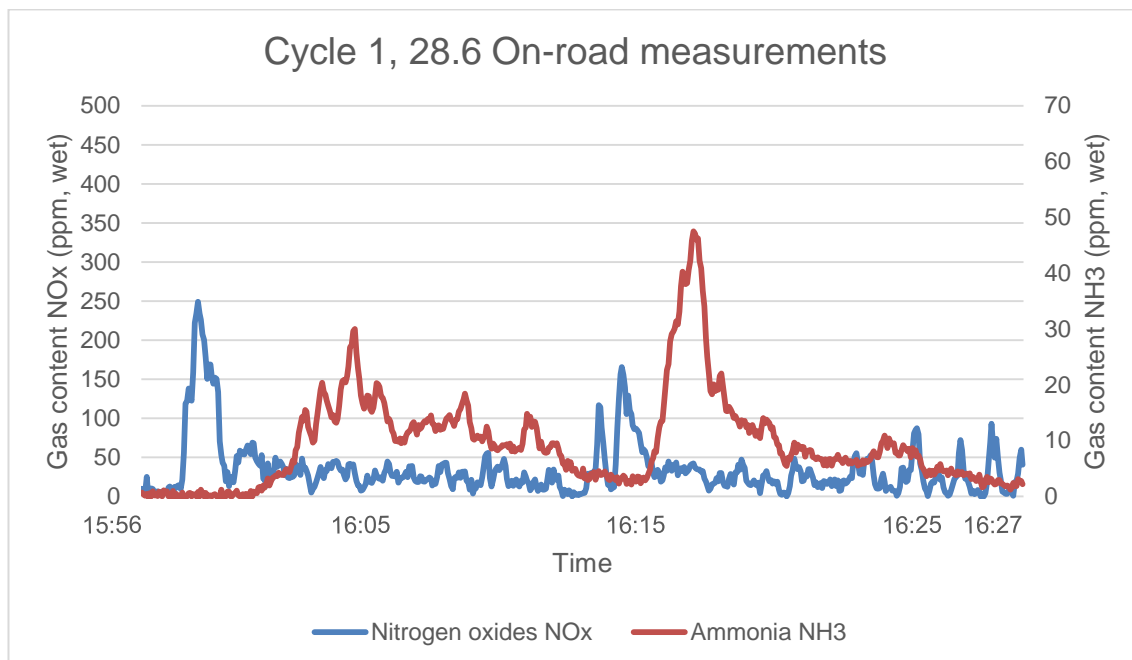
## Servomex checkups from time to time.

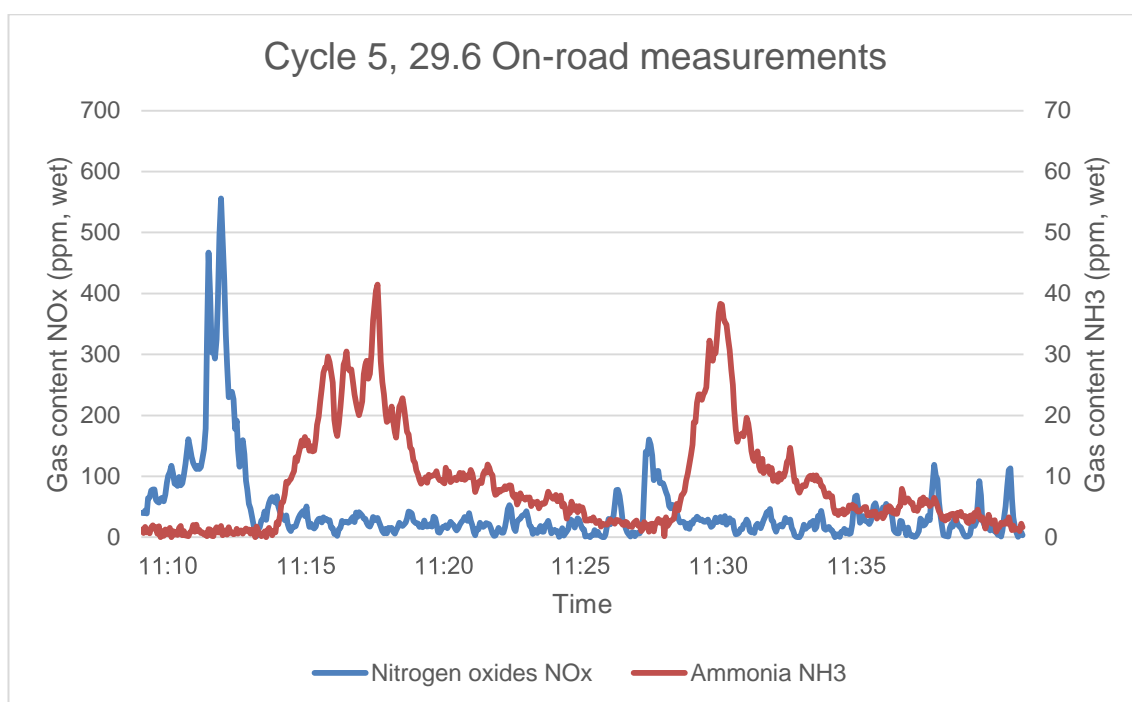
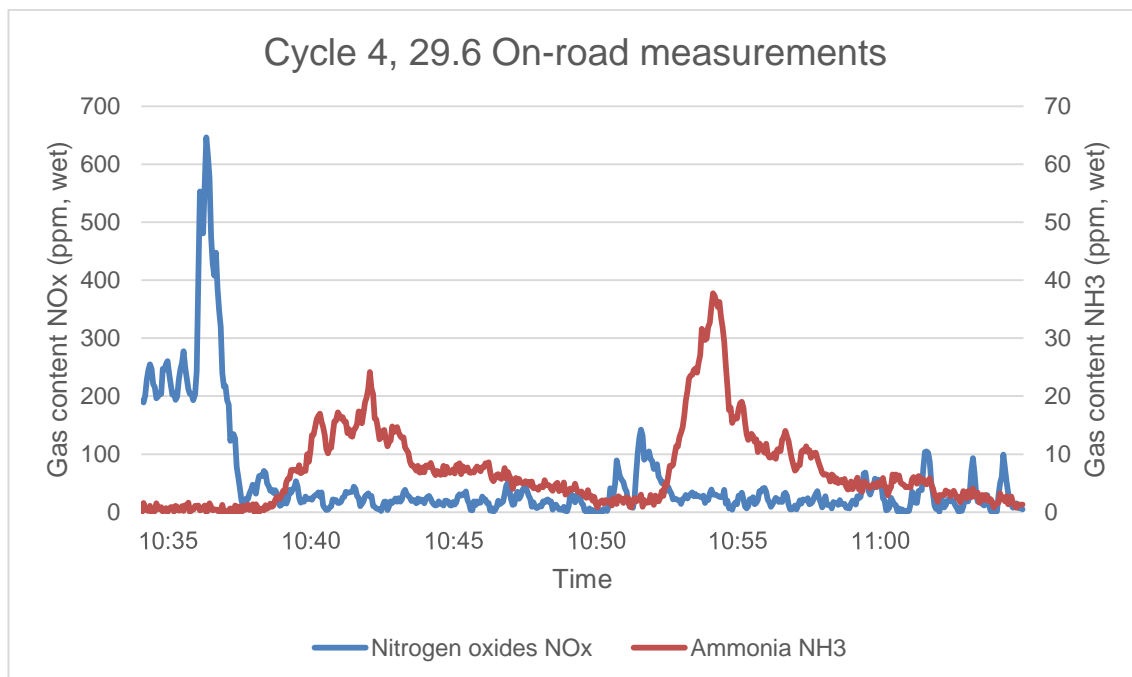
Time		Servomex (%)	Logger (mA)	Engine shutted
8.16	O2	20.4	7.624	
	CO2	0.4	4.22	
9.11		Servomex (%)	Logger (mA)	Engine on idle
	O2	15.5	6.44	
	CO2	3.7	9.56	
9.49		Servomex (%)	Logger (mA)	
	O2	16.4	6.6	
	CO2	2.88	8.5	

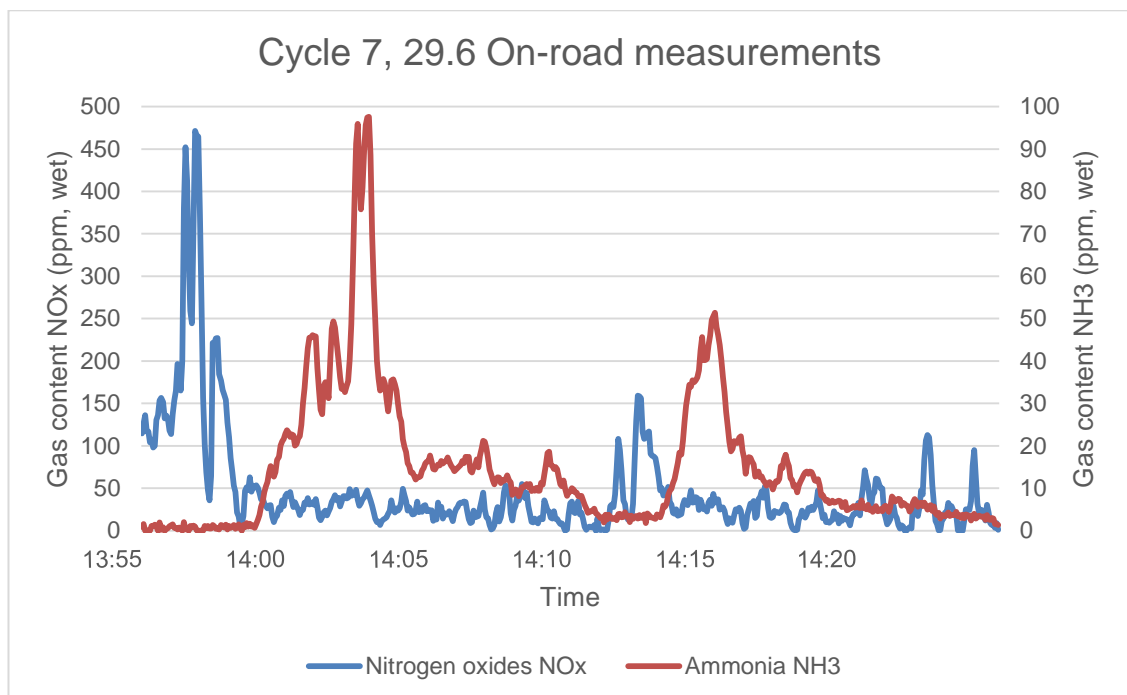
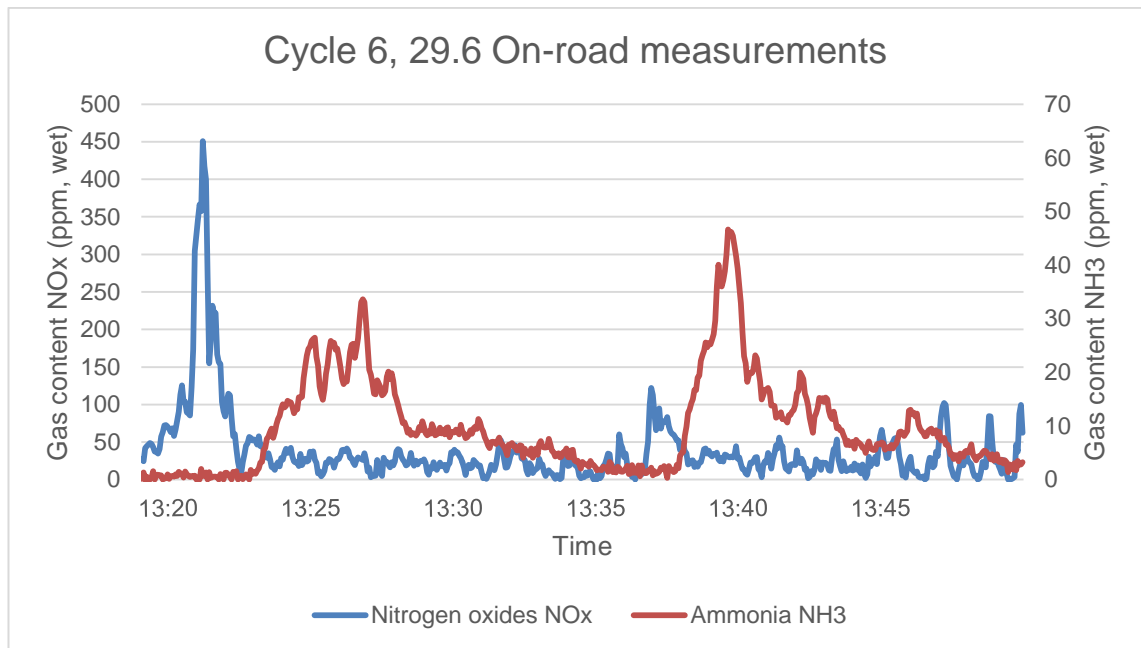
		Servomex (%)	Logger (mA)
10.22	O2	16.7	6.6
	CO2	2.91	8.25
		Servomex (%)	Logger (mA)
11.04	O2	16.4	6.7
	CO2	2.8	8.4
		Servomex (%)	Logger (mA)
11.40	O2	16.7	6.6
	CO2	3.19	9.1
		Servomex (%)	Logger (mA)
13.50	O2	16.1	6.6
	CO2	3.06	9.1
		Servomex (%)	Logger (mA)
14.26	O2	16.2	6.6
	CO2	2.7	8.2
		Servomex (%)	Logger (mA)
15.00	O2	15.7	6.5
	CO2	3.2	9.3
		Servomex (%)	Logger (mA)
15.37	O2	16.5	6.6
	CO2	2.7	8.9
		Servomex (%)	Logger (mA)
16.17	O2	15.7	6.5
	CO2	3.23	9.2

## Figures from field measurements

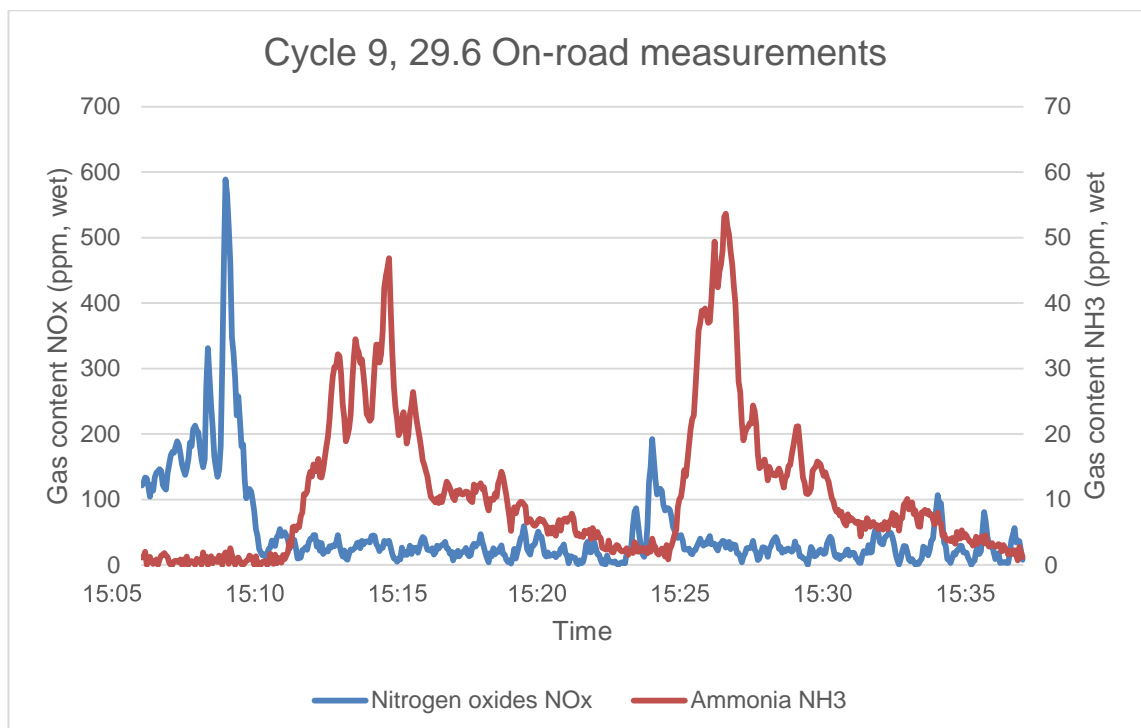
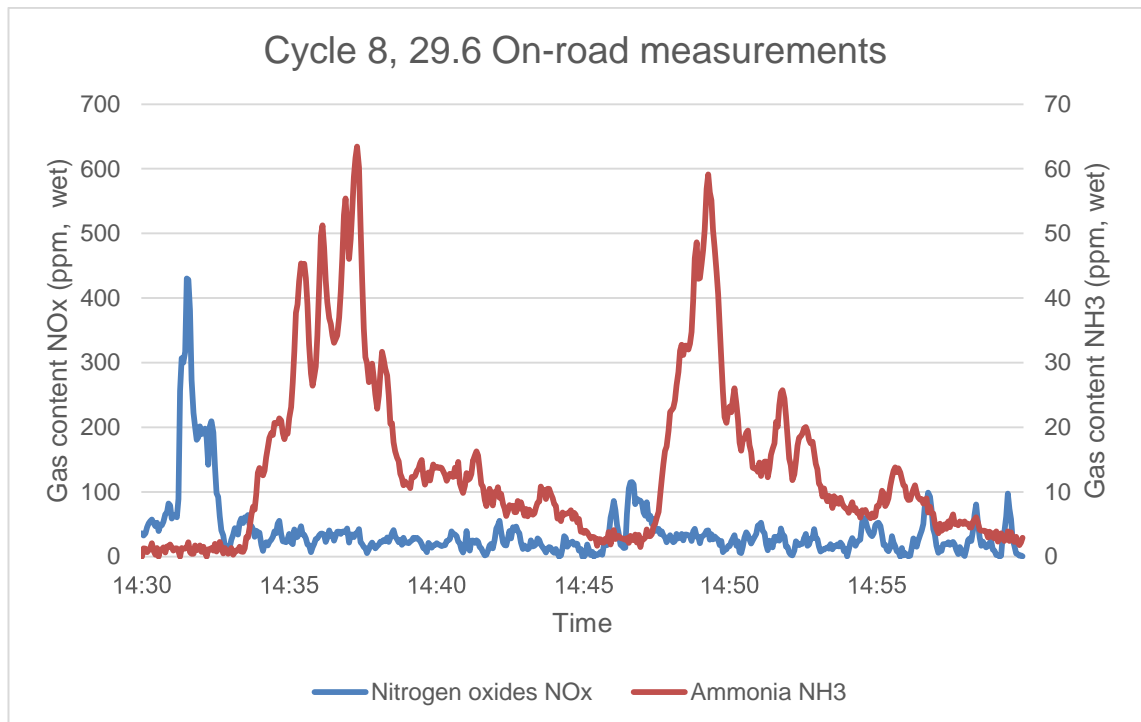
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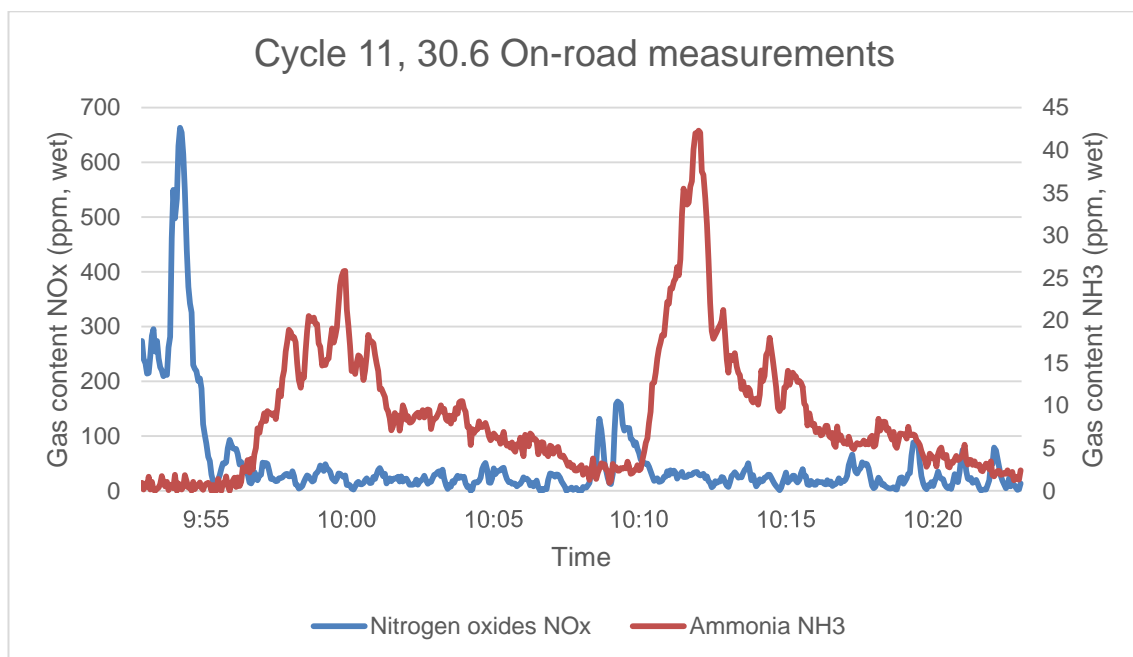
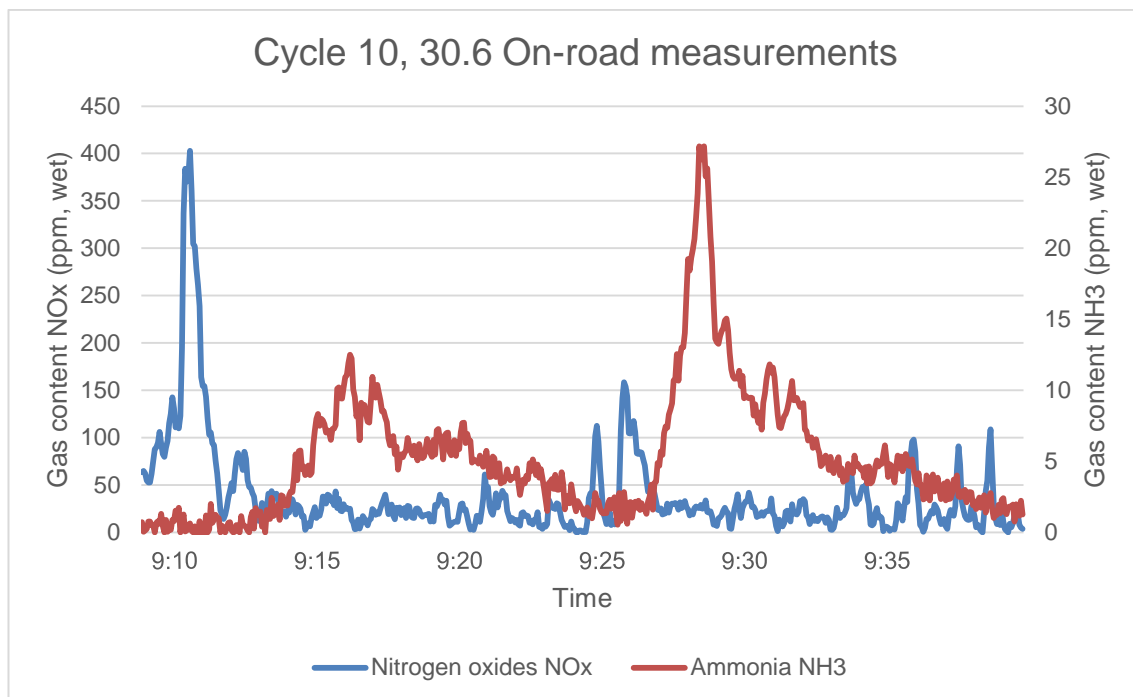


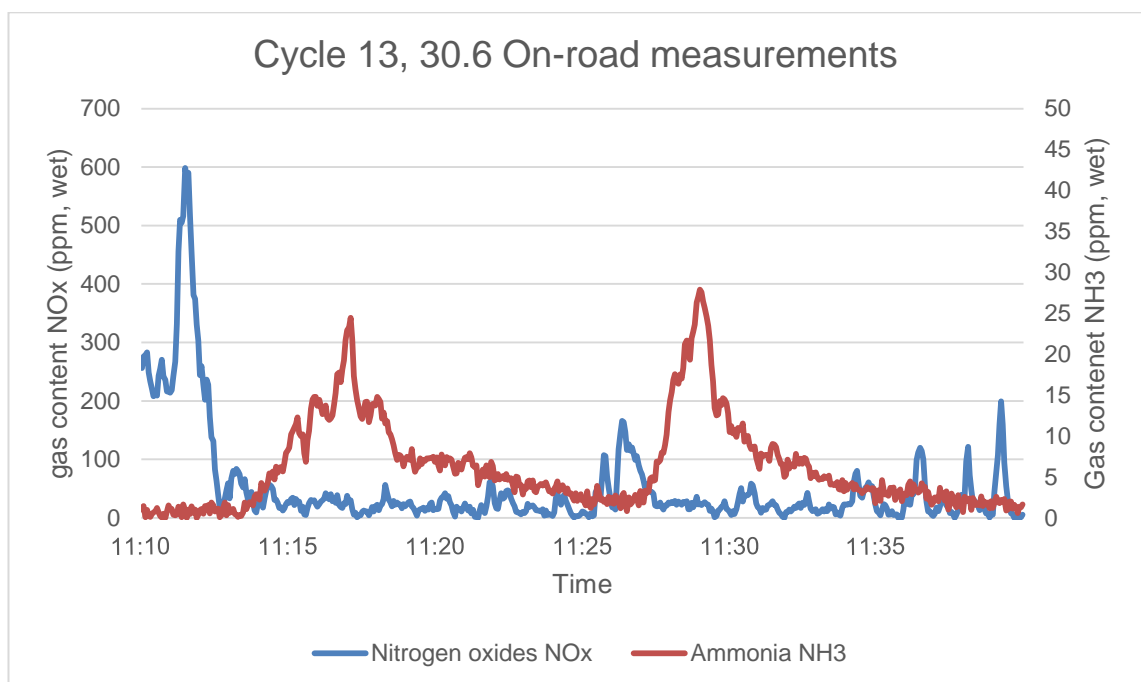
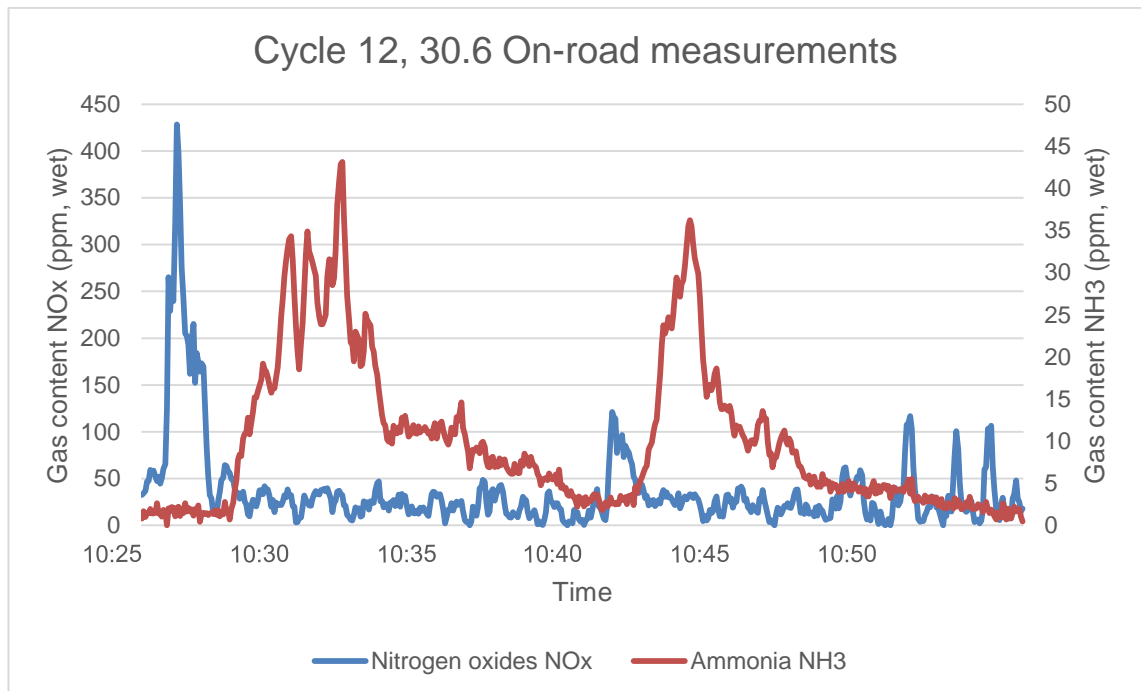


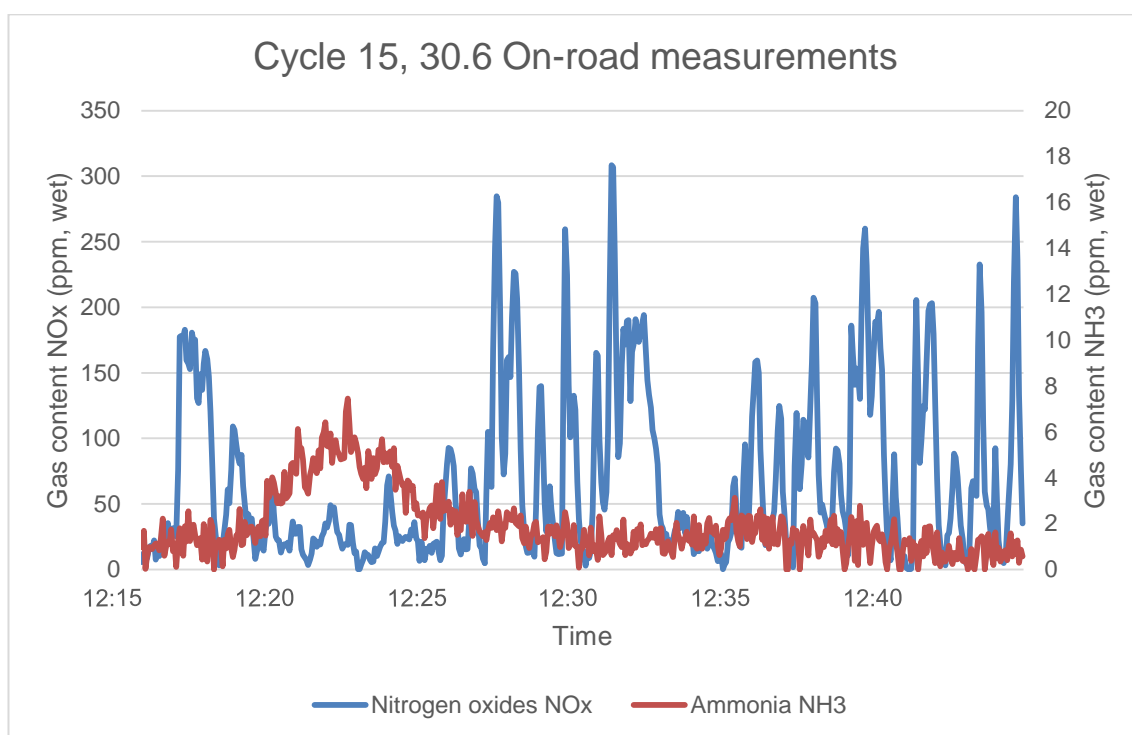
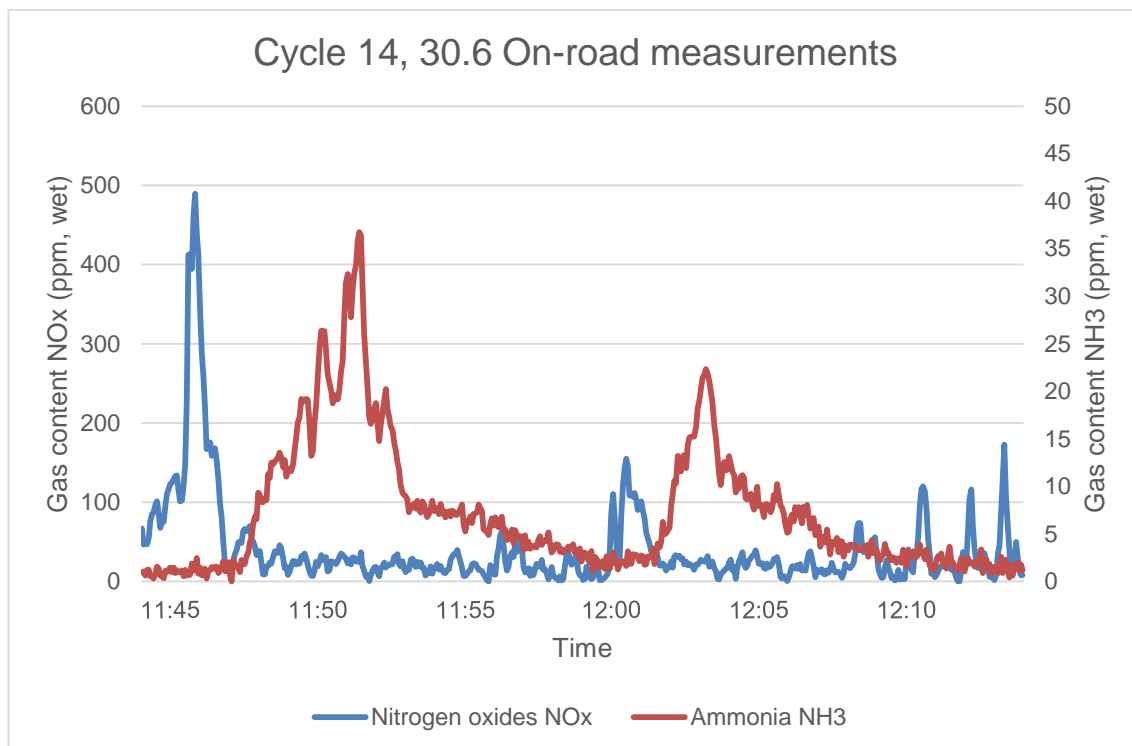




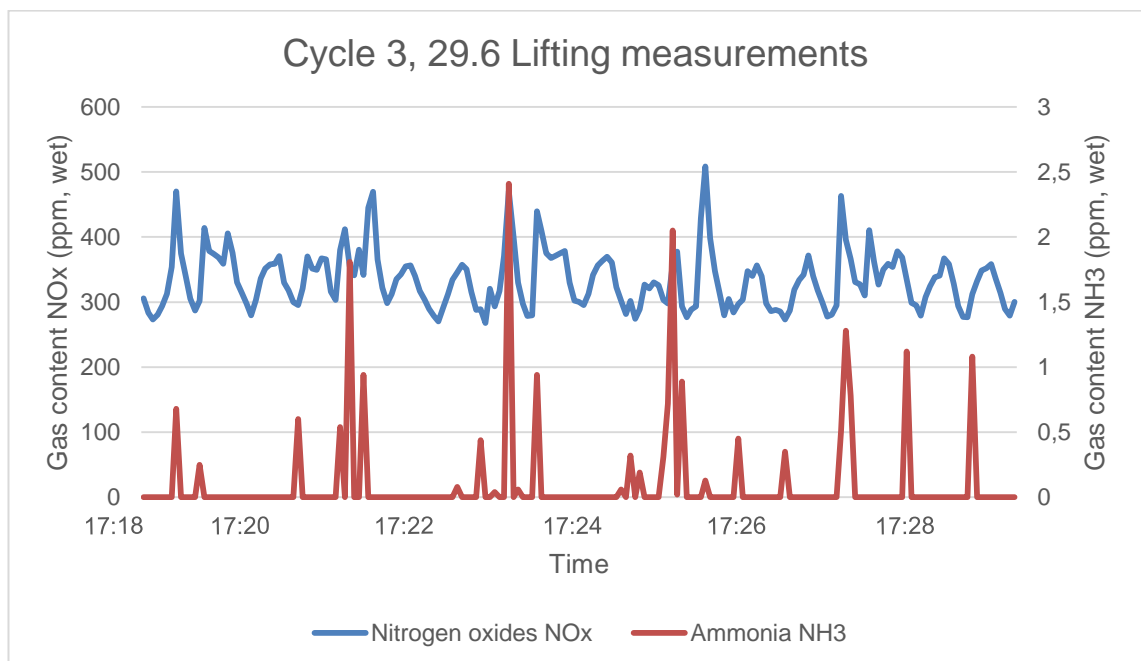
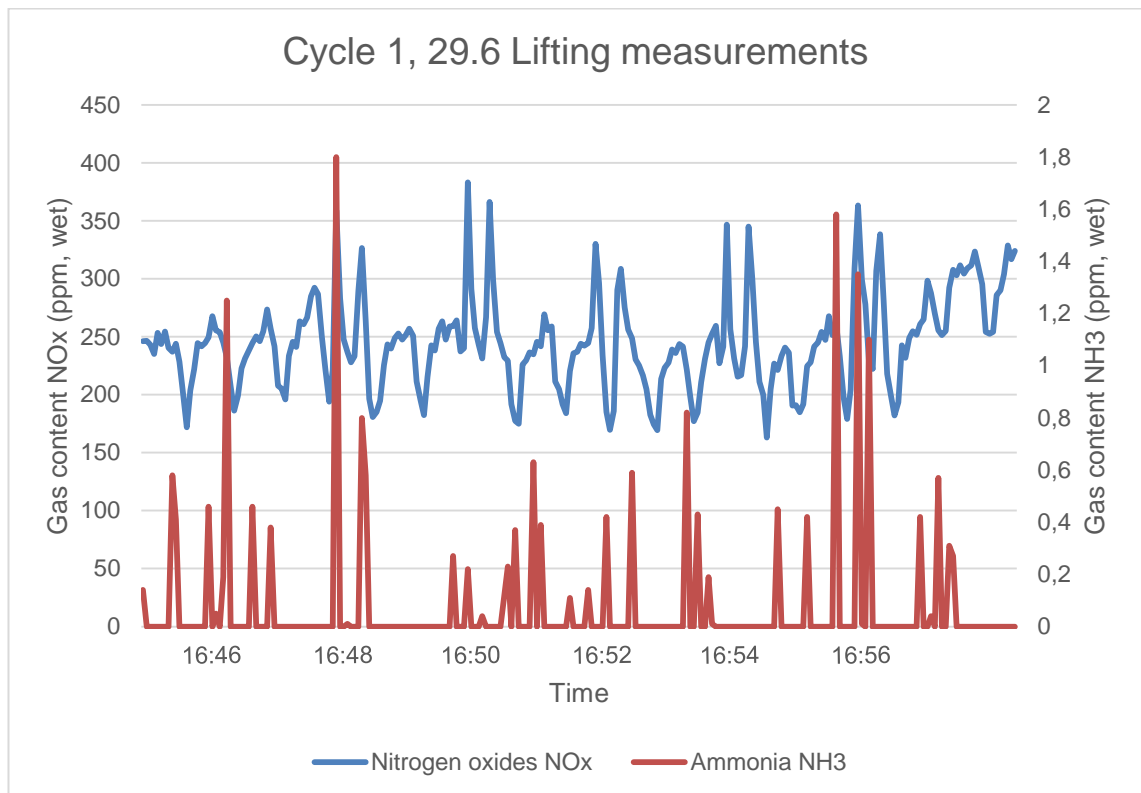


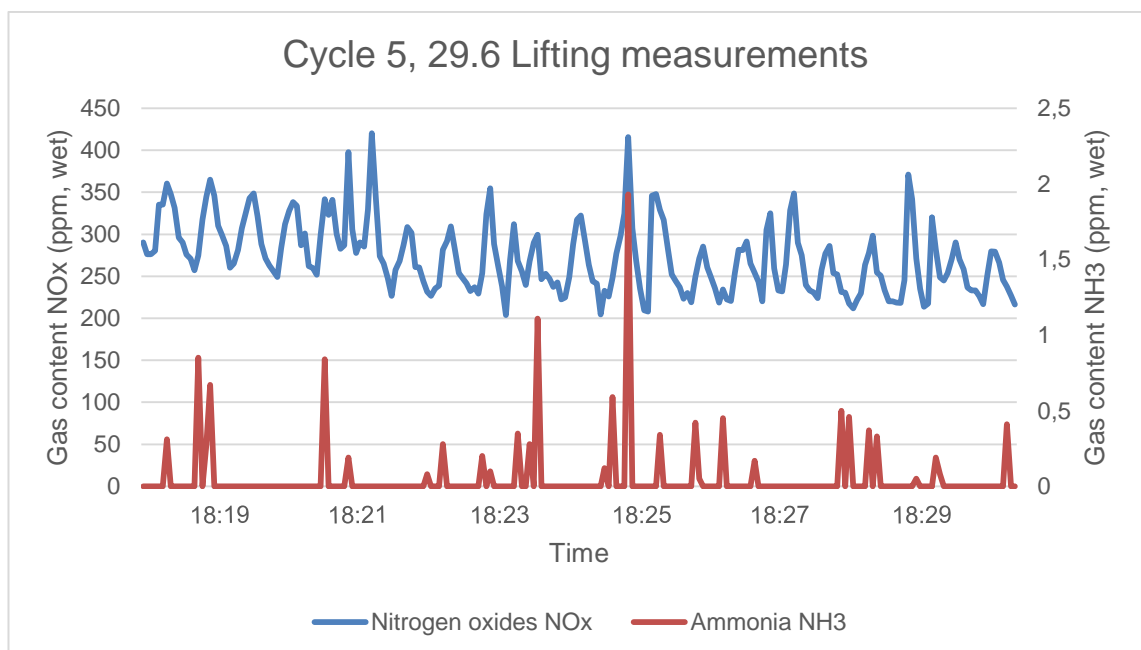
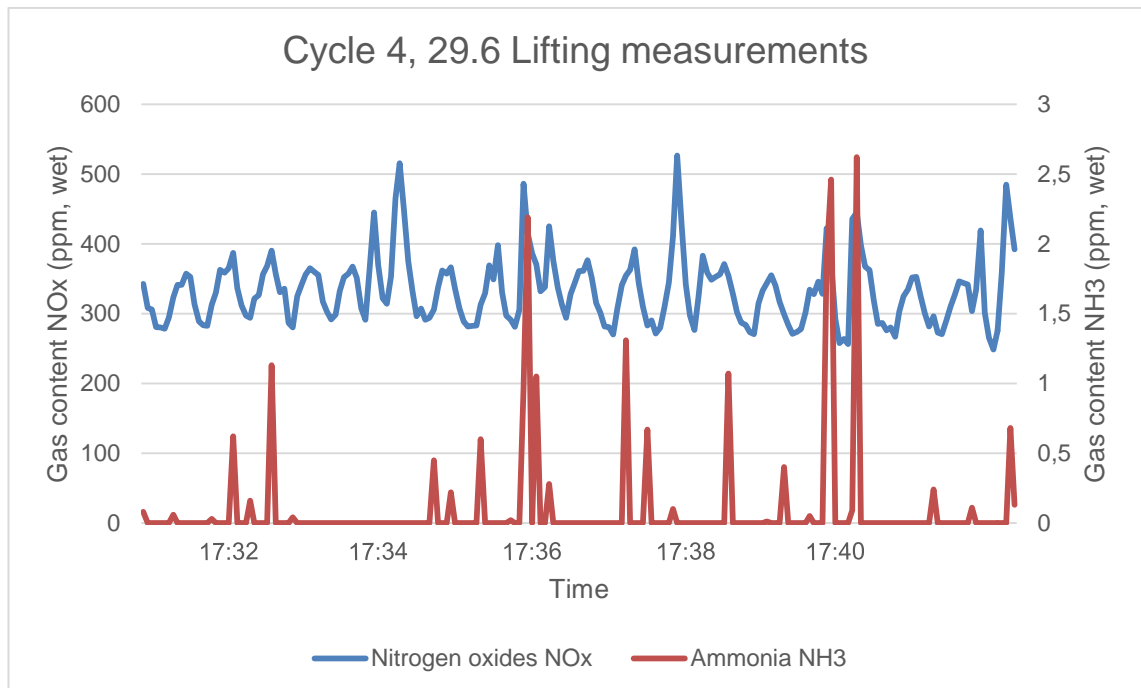


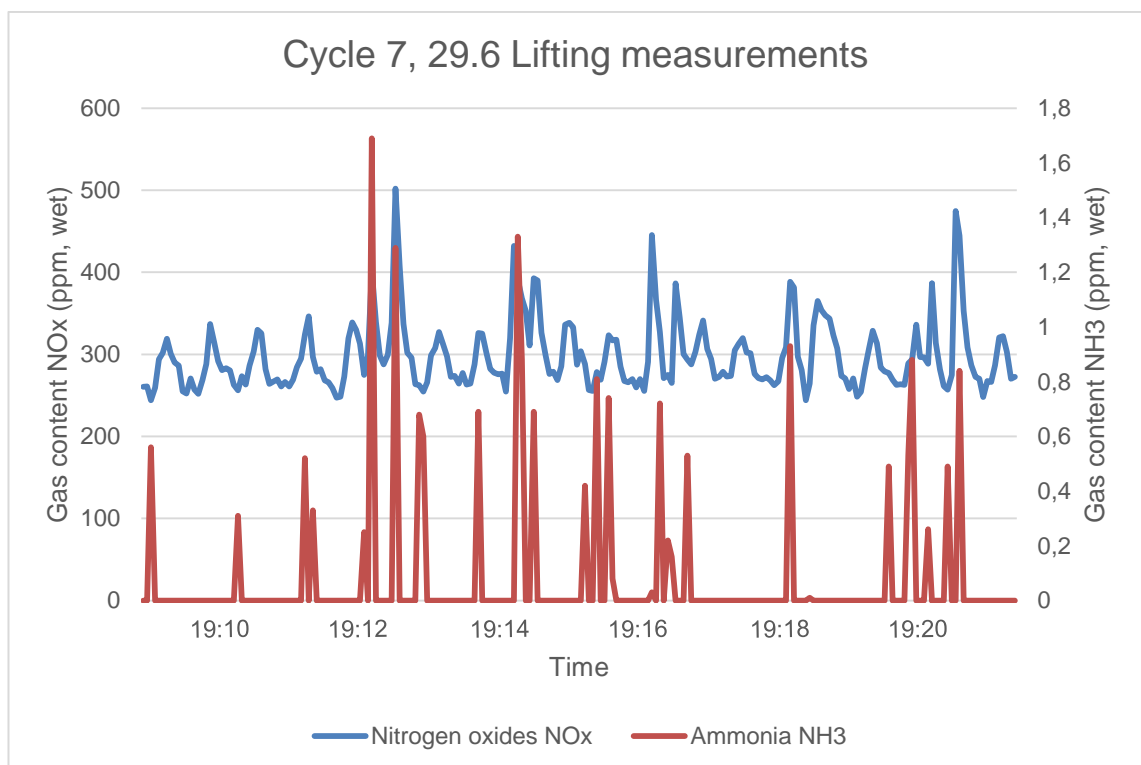
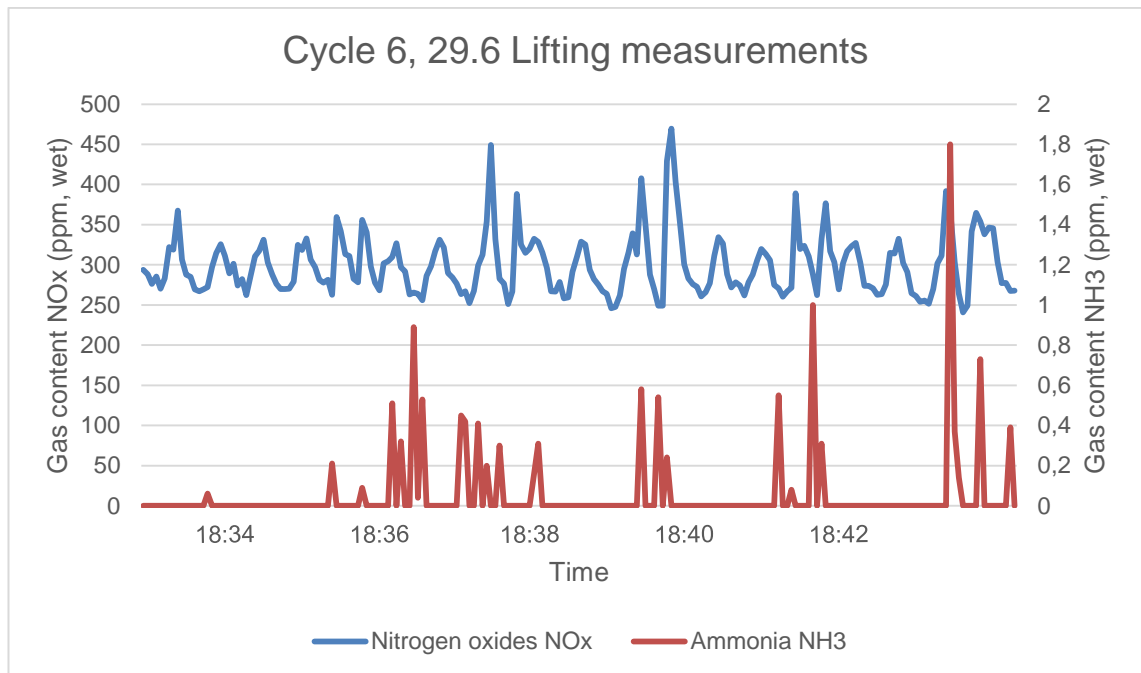


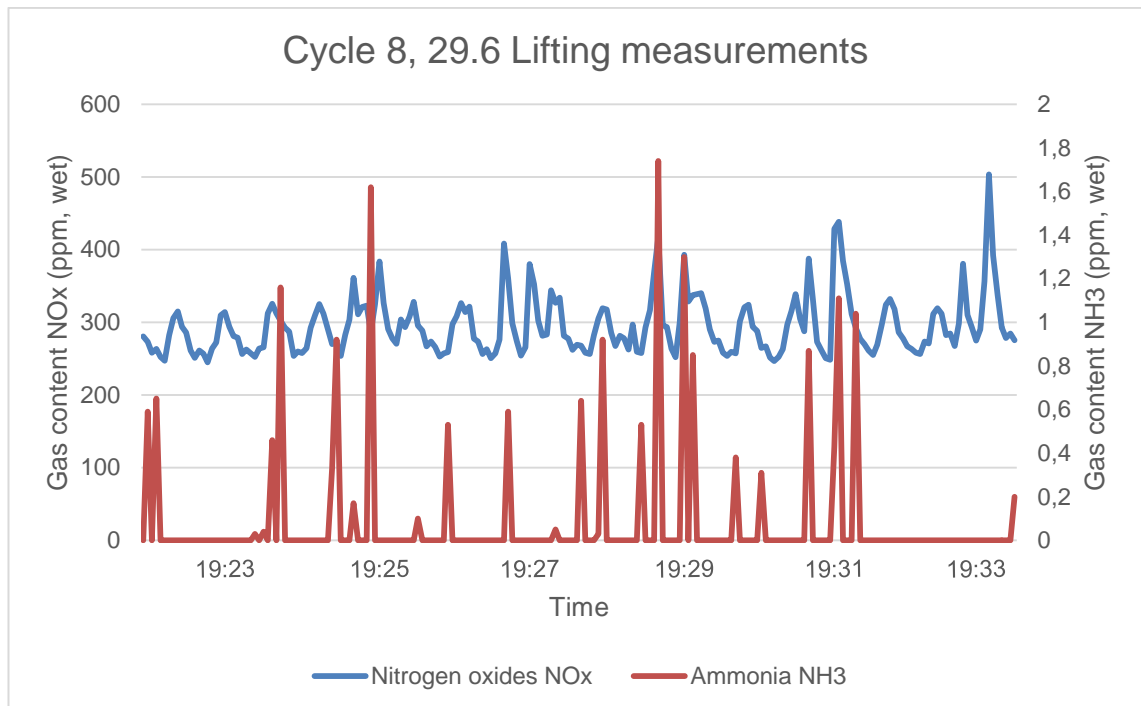


This cycle was faster than other cycles. The change of driver affected to the driving speed. The new driver drove little faster than in other cycles and the cycle 15 took 2 minutes less than others. Normal time for cycle was 30 minutes and for this cycle was 27 minutes.

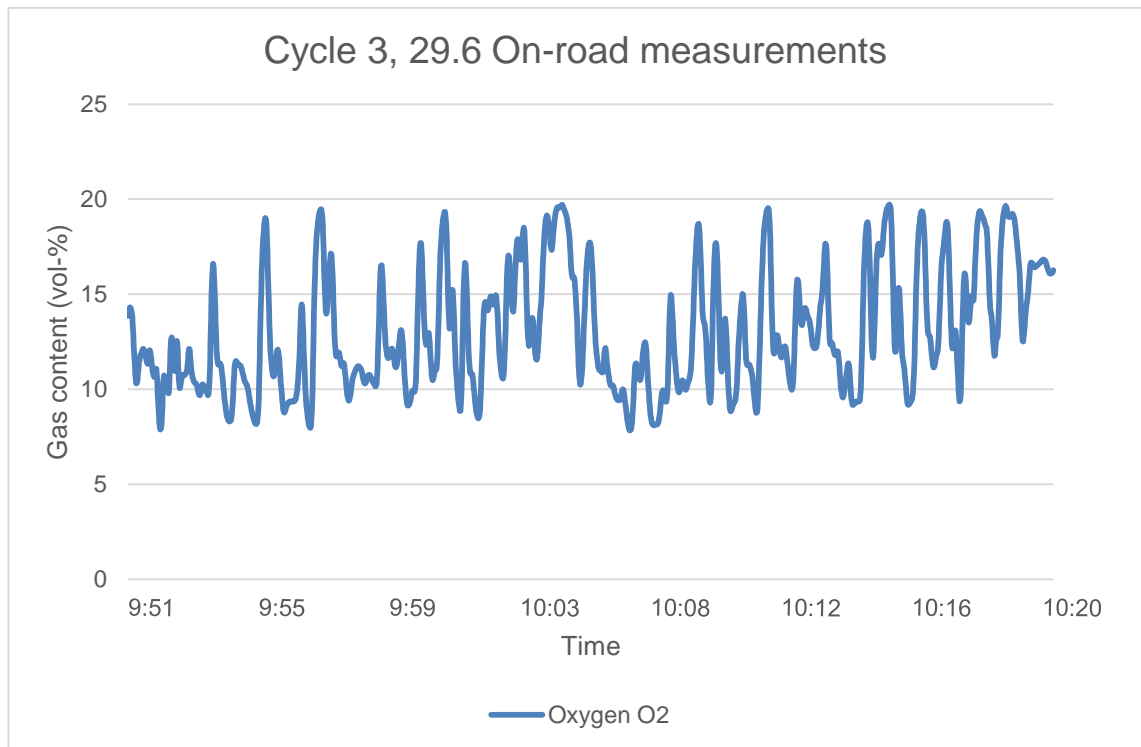
**NO<sub>x</sub> and NH<sub>3</sub> slip in lifting measurements**



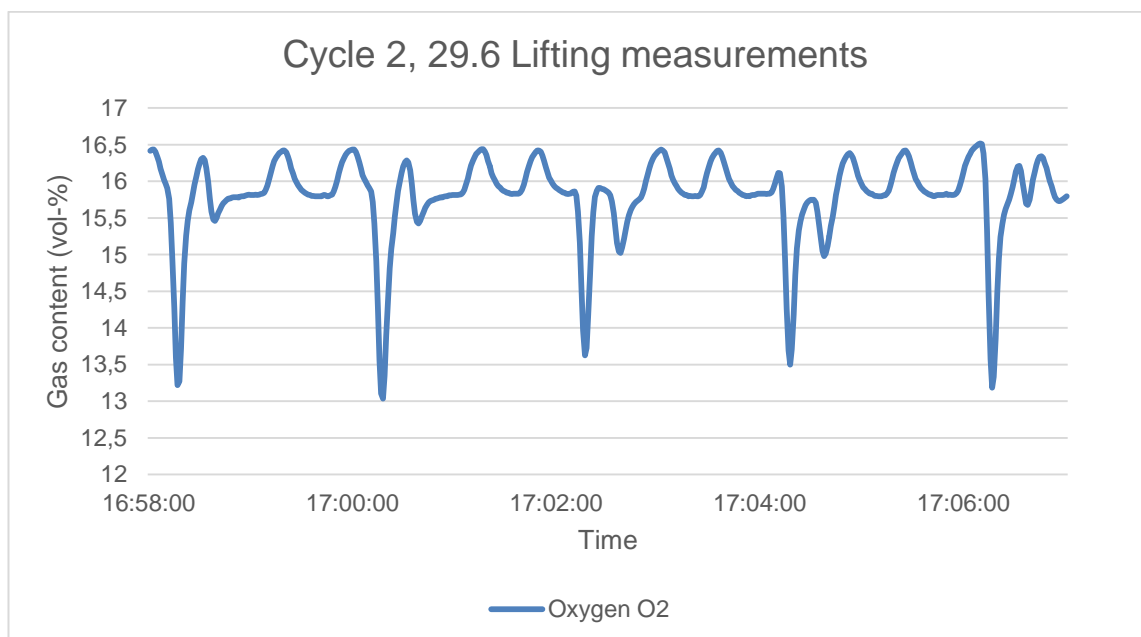








O<sub>2</sub> in exhaust gas measured with Gasmeter. When engine load is light, the O<sub>2</sub> rises to 15-20 %. On higher loads, the O<sub>2</sub> decreases to 7-10 %.



O<sub>2</sub> in exhaust gas measured with Servomex. The O<sub>2</sub> in drops exhaust gas can present the loadspikes clearly. The O<sub>2</sub> in lifting work drops to 13-13.6 % and at idle speed the O<sub>2</sub> is from 15.7 to 16.4 %.