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RESEARCH OF EXHAUST EMISSION CONTROL OF OFF-ROAD DIESEL ENGINE AND ACTIVE REGENERATION OF DIESEL PARTICULATE FILTER

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BACHELOR'S THESIS | ABSTRACT

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RESEARCH OF EXHAUST EMISSION COMTROL OF OFF-ROAD DIESEL ENGINE AND ACTIVE REGENERATION OF DIESEL PARTICULATE FILTER

This thesis is an introduction into a measurement campaign that is part of the HERE (Health Relevant and Energy Efficient Regulation of Exhaust Particle Emissions) project funded by TEKES FiDiPro programme. This study took place at Turku University of Applied Sciences and was conducted in April 2016. The purpose of the study is to examine the different emissions and particle matter found in the exhaust gas stream of a diesel engine and to find different ways to reduce them while maintaining the energy efficiency and performance of the engine. The measurements of the study were conducted in co-operation with Tampere University of Technology (TUT) and the Finnish Meteorological Institute (FMI). The measurement campaigns' goal was to test different aftertreatment system configurations and the active regeneration of diesel particulate filter and to measure their differences in emission control.

This thesis presents the results of the measurement campaign and takes a look into the different ways to reduce the emissions found in the exhaust gases. Therefore, the thesis consists of two parts: short theoretical section, which takes a look into the emissions found from a normal diesel engine's raw exhaust gas and different types of aftertreatment equipment used to reduce them, and a measurement data presentation and analysis. The test engine was run on a dynamometer and the measurements were realized with an array of different devices and documented with computer software and partly with pen and paper.

KEYWORDS:

NRD, DIESEL, ENGINE, HERE, EMISSIONS, DOC, DPF, SCR, DFO,

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RESEARCH OF EXHAUST EMISSION CONTROL OF OFF-ROAD DIESEL ENGINE AND ACTIVE REGENERATION OF DIESEL PARTICULATE FILTER

Tässä opinnäytetyössä esitellään mittauskampanja joka on osa HERE (Health Relevant and Energy Efficient Regulation of Exhaust Particle Emissions) projektia, joka on TEKES FiDiPro-ohjelman rahoittama. Tutkimus tehtiin Turun ammattikorkeakoulun tiloissa huhtikuussa 2016. Tutkimuksen tarkoitus on tutkia dieselmoottorin pakokaasussa olevia eri päästöjä ja erilaisia tapoja joilla niitä voidaan vähentää kuitenkaan heikentämättä moottorin suorituskykyä ja energiatehokkuutta. Tutkimus toteutettiin yhteistyössä Tampereen Teknillisen Yliopiston ja Ilmatieteenlaitoksen kanssa. Mittauskampanjan tavoite oli tutkia erilaisia pakokaasun jälkikäsittely järjestelmiä, dieselhiukkassuodattimen aktiivista regenerointia ja mitata niiden eroja päästöjen hallinnassa.

Opinnäytetyössä esitellään mittauskampanjan tulokset ja tehdään katsaus eri tapoihin joilla pakokaasupäästöjä voidaan vähentää. Opinnäytetyö koostuu kahdesta osasta: ensimmäisessä tutustutaan eri pakokaasupäästöihin ja erilaisiin jälkikäsittelylaitteisiin joilla niitä vähennetään, ja toisessa esitellään ja analysoidaan tutkimuksesta saatu mittaustieto. Tutkimuksen aikana moottoria ajettiin dynamometrissä, mittaukset tehtiin erinäisillä mittalaitteilla ja tulokset dokumentoitiin tietokoneella ja osittain kynällä ja paperilla.

ASIASANAT:

NRD, DIESEL, MOOTTORI, HERE, PÄÄSTÖT, DOC, DPF, SCR, MOOTTORIPOLTTOÖLJY, JÄLKIKÄSITTELY, ISO 8178 C1

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Table 3 Urea injection quantity on measurement 1 Mode 7 29

LIST OF ABBREVIATIONS (OR) SYMBOLS

AdBlue	AdBlue is a registered trademark for Aqueous Urea Solution 32 (AUS32), which is made with 32,5% urea and 67,5% de-ionized water. It is used as a diesel exhaust fluid (DEF) in selective catalytic reduction (SCR) to lower the NOX emissions from diesel engines.
AT	Aftertreatment
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DEF	Diesel Exhaust Fluid
DFO	Diesel Fuel Oil
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
EGR	Exhaust Gas Recirculation
EU	European Union
FMI	Finnish Meteorological Institute
fSCR	SCR on Filter
FSN	Filter Smoke Number
GDI	Gasoline Direct Injection
HC	Hydrocarbons
HDV	Heavy-duty Vehicles
HERE	Health Relevant and Energy Efficient Regulation of Exhaust Particle Emissions
ISO-8178-C1	International standard for exhaust emission measurement from a number of non-road engine applications
LDV	Light-duty vehicle
M1	Mode 1 2100RPM 452Nm
M7	Mode 7 1500RPM 280Nm
N_2	Nitrogen
NH_3	Ammonia
NO	Nitrogen oxide

NO_x	Nitrogen oxides
NRSC	Non-road steady cycle
NRD	Neste Renewable Diesel
O_3	Ozone
OEM	Original Equipment Manufacturer
PM	Particulate matter
SCR	Selective Catalytic Reduction
Set A	DOC 1 + DPF + SCR 89 combination
TUAS	Turku University of Applied Sciences
TUT	Tampere University of Technology
VOC	Volatile Organic Compound
Versus M1	SetB vs. DOC+SCR vs. NoAT Mode1 Measurement
Versus M7	SetB vs. DOC+SCR vs. NoAT Mode7 Measurement

1 INTRODUCTION

This thesis will introduce you to a study made in spring 2016 which was realized as part of the HERE project funded by the TEKES FiDiPro programme. Its main goals were to improve the understanding of exhaust particle emissions and to study different kinds of aftertreatment configurations to be able to more accurately propose right types of aftertreatment combinations to different types of engines. The HERE project runs from spring 2013 to spring 2017. HERE aims to reduce the exhaust article emissions without significantly impacting engine performance or energy efficiency.

Emissions found from diesel engine exhaust gases have negative effects on human health and nature. A diesel engine's exhaust gas emissions include, but are not limited to, carbon and nitrogen oxides, hydrocarbons and particle matter. Almost all exhaust gas emissions have been shown to increase the risk of either cancer or lung and airway diseases.

This is the reason why there is an ever growing need for very low emissions and different types of aftertreatment systems to push down the emissions as the emission standards tighten. There are many ways to reduce exhaust gas emissions on a diesel engine but this thesis concentrates on the effects of different types of aftertreatment and fuels. In this study the used aftertreatment systems were as follows SetB: a combination of Diesel Oxidation Catalyst (DOC), Diesel Particulate Filter (DPF) and Selective Catalytic Reduction (SCR); DOC+SCR: as the name tells this combination only uses a DOC followed by SCR. Fuels used in this study are refined by NESTE and there are two types of fuel used in the tests: diesel fuel oil (DFO) which is an equivalent to normal Diesel, and NESTE's renewable diesel, NRD, which is produced from vegetable oils yet has about the same fuel quality as synthetic diesel fuels.

2 MAIN EXHAUST GAS EMISSIONS AND POLLUTANT REDUCTION

2.1 Emissions from a diesel engine

Exhaust gases from a diesel engine contain many different pollutants and emissions which can be harmful to humans, animals and/or nature. Exhaust emissions are in part responsible for global warming and other effects on nature.

Main emissions in exhaust gases

- Carbon Dioxide (CO_2)

  This gas contributes to global warming, for example, and is one of the most significant emissions in diesel exhausts.

- Oxides of nitrogen (NO_X)

  Consisting of mainly two oxides (NO and NO_2) this gas is very toxic and also plays a role in the formation chemistry of smog.

- Unburned Hydrocarbons (HC)

  Result of incomplete combustion of diesel fuel or oil pan escape. Irritating to eyes, harmful to vegetation and some are carcinogenic.

- Carbon Monoxide (CO)

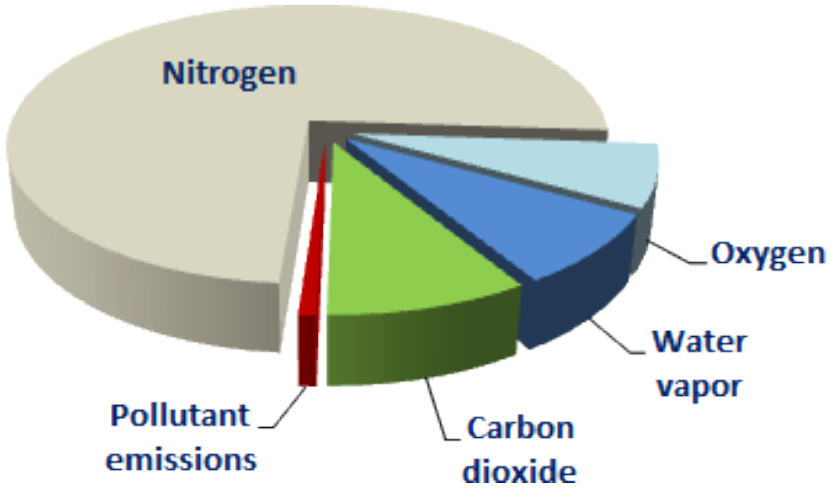
  Forming typically under low oxygen conditions and can be fatal if the concentration is high enough (only indoors).

- Smoke
  Formation can be seen from the color, white is for water vapor and unburnt fuel, blue for unburnt lubrication oil particles and black for unburnt solid carbon particles (i.e. soot).

- Particle Matter (PM)

  Is comprised of three main fractions: solid fraction including carbon and ash, soluble organic fraction including organic materials from fuel and lubricating oil and sulfate fraction which includes sulfuric acid.

(Majewski, 2012)



Picture 1: Relative concentration of pollutant emissions in diesel exhaust gas (Majewski, 2012).

The possibility of new emissions must be considered whenever additives (catalytic or not) are introduced into the fuel or lube oil and when fluids are introduced into the exhaust gas. A well-known example is urea used as a NOx reductant in SCR catalyst systems—emissions from SCR engines can include ammonia, as well as a number of products from incomplete decomposition of urea. Low quality fuels can also be another source of emissions—for instance, residual fuels used in large marine engines contain heavy metals and other compounds known for their adverse health and environmental effects. (Majewski, 2012.)

2.1.1 Distribution of particulate size

Particulate matter (PM) emission is a mixture of carbonaceous soot with other solid and liquid materials, such as condensed heavy hydrocarbons. Other terms that are sometimes used are total particulate matter (TPM) and, in case of diesel engines, diesel particulate matter (DPM). The DPM acronym is common in occupational health regulations. (Majewski, 2012.)

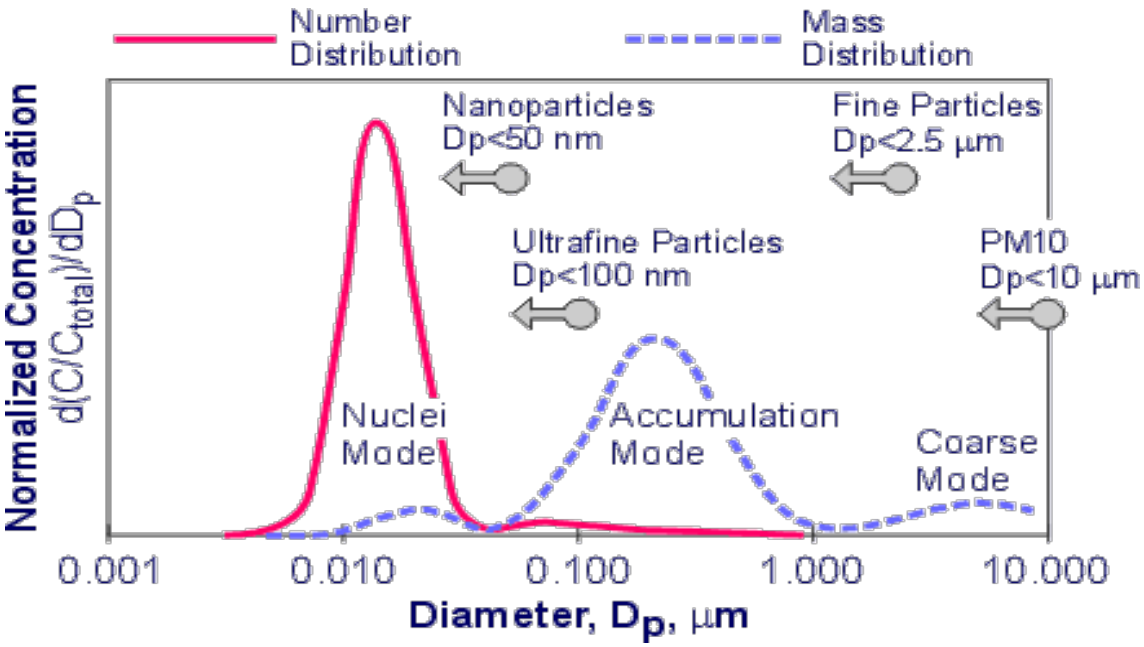


Figure 1 Distribution of diesel particulate size (Majewski, 2002).

In the European Union, solid particle number (PN, sometimes also abbreviated SPN) emission standards have been adopted for light- and heavy-duty onroad diesel vehicles and engines, as well as for gasoline vehicles with directly injected engines. Particle number emission limits must be met in addition to the PM mass based limits. While controlling essentially the same emission, the adopted PN limits have been more stringent than the corresponding mass limits to ensure that particulate filters be used in future diesel engines. (Majewski, 2012.)

2.2 Pollution reduction technologies in diesel engines

Diesel engine emissions can be controlled with three different options: engine design techniques, exhaust gas aftertreatment and diesel fuel related technologies (Majewski, 2014). This thesis concentrates mainly on the exhaust gas aftertreatment part.

Exhaust gas aftertreatment consists of many different types of catalysts and filters, these include, but are not limited to, Diesel Oxidation Catalyst (DOC), Diesel Particulate Filter (DPF) and Selective Catalytic Reduction (SCR). These are explained below with a bit deeper look into each one of them.

2.2.1 Selective catalytic reduction SCR

Selective catalytic reduction (SCR) of NOx with nitrogen containing compounds, such as ammonia or urea, has been used for many years in stationary NOx control applications. The SCR catalyst is capable of high, 90% reductions of NOx emissions. Since the middle of the first decade of the twenty-first century, SCR technology has been adapted for mobile applications of both heavy- and light-duty diesel engines. SCR catalysts are used on many heavy-duty diesel engines to comply with the Euro V (2008) emission standards, as well as on some Japanese 2005 heavy-duty engines and on most US2010 heavy-duty engines. (Majewski, 2014.) Although SCR is not the only method for reducing the NO_x emissions in light- and heavy-duty applications, it has become the main solution because of its effectiveness and the tightening of NO_x emission regulation.

2.2.2 Diesel oxidation catalyst DOC

Diesel oxidation catalyst (DOC) got its name from its ability to increase the oxidation of several diesel exhaust gas components using oxygen. Oxygen is available in large quantities in the exhaust gas stream. DOC can be used to oxidize and reduce the concentration of the following pollutants and to turn them into

harmless products: carbon monoxide (CO), hydrocarbons (HC) and organic diesel particulates (SOF). (Majewski, 2012.) Oxidation of these emissions also helps to eliminate odors associated with diesel exhaust gases.

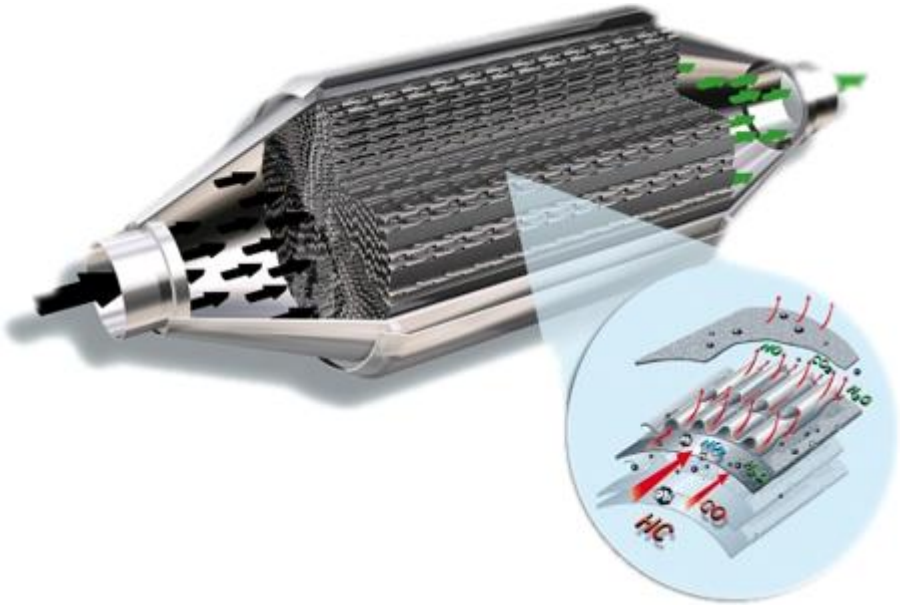
2.2.3 Diesel particulate filter DPF

Diesel particulate filters (DPF) are devices that physically capture diesel particulates to prevent their release to the atmosphere. Diesel particulate filter materials which show significant filtration efficiency (exceeding 90%) have been developed. These materials also have good mechanical and thermal durability. DPF technology has become the most effective way to reduce diesel particulate emissions, including the particle mass and number, with high efficiency. (Majewski, 2011.) As a physical filter, DPF needs to be regenerated with heat and NO_2 or O_2. Again, emission standards have helped DPF to become the main reduction method of particulate matter (PM) and after EURO VI standard, the use of DPF was basically forced on to the industry.

Picture 2 Diesel particulate filter (Majewski, 2011).

2.2.4 Combined aftertreatment systems (fSCR, POC)

There are also some combinations of the previous aftertreatment systems such as particle oxidation catalyst (POC); this system acts as a DOC/DPF hybrid oxidizing CO, HC and SOF emissions and at the same time offering higher particulate matter filtration than a normal DOC. This type of partial flow filtration is still much lower than in a full flow filter DPF, according to Addy Majewski (2014). fSCR is a combination of SCR and DPF that filtrates PM and catalytically reduces NOx Emissions, filtration of PM is lower than with DPF but better than in SCR. Normally combined aftertreatment systems are weaker than their solo counterparts but combined solutions save a lot of space in real life application where space can be of concern. Although the use of POC is decreasing because of its inability to achieve high filtration efficiencies required to reach the Stage 5 emission standards, in the same time the use of fSCR has increased because it includes a DPF.



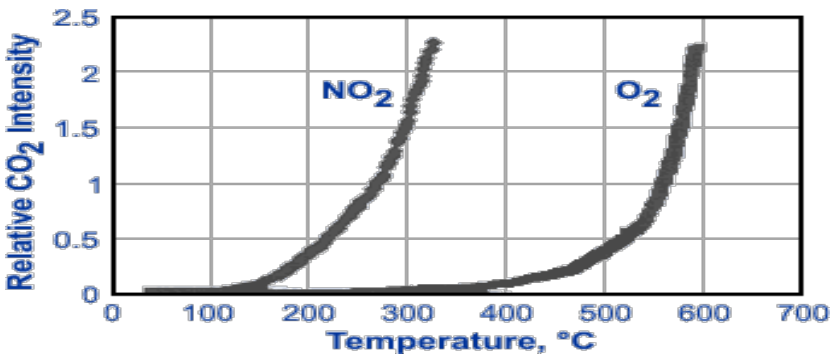
Picture 3 Particulate oxidation catalyst (Majewski, 2014)

2.3 Regeneration of DPF

Diesel particulate filter is a physical filter which needs to be cleaned in a process called regeneration. Thermal regeneration of diesel particulate filters involves the oxidation of solid particulates to gaseous products, preferably to CO2. Depending on the DPF system design and on the engine operating conditions (exhaust gas temperature), the oxidation of carbon in diesel soot can occur via reactions with oxygen or nitrogen dioxide. (Majewski, 2005.)

Regeneration can be divided into two different categories: passive and active. Passive regeneration means that the regeneration happens through the normal use of the engine and the regeneration process does not affect the engine or exhaust gas flow. Active regeneration is normally done periodically and works by increasing the exhaust gas temperature before DPF through the use of, for example, late-post injection of fuel, sprays of diesel straight to the exhaust gas flow or different types of burners in the exhaust pipe.

Oxygen is normally available in high concentrations in diesel exhaust gas, however temperatures required to achieve significant regeneration through O_2 oxidation are so high (over 550 °C) that it is mainly achievable only through an active regeneration process. Nitrogen dioxide requires lower temperatures than oxygen to achieve usable regeneration rates. Its concentration in raw exhaust gas is not high enough, therefore increasing the concentration is normally done through catalytic oxidation of NO. NO_2 soot oxidation is the main regeneration mechanism used by most of the active and passive DPF systems. (Majewski, 2014.)



Picture 4 Oxidation of PM with NO_2 and O_2 (Majewski, 2005)

3 RESEARCH FACILITIES AND PROCEDURES

The measurement campaign was conducted at the fourth test bed at Turku University of Applied Sciences using Agco Power's 44 AWF Engine as the basis of the measurements. Other participating parties were Tampere University of Technology (TUT) and Finnish Meteorological Institute (FMI). These parties conducted their own measurements and this thesis is based on the measurements made by TUAS instruments. The test bed is fitted with National Instruments' LabVIEW based computer software, which can be used to control the engine and collect the measurement data. The engine load is handled by a Schenck W400 Dynamometer. This dynamometer can handle constant and dynamic loads and these both can be controlled from the control room. Temperature sensors are PT-100 type and pressure sensors are Keller's Piezo based. Airflow and fuel amount are measured with an ABB Sensysflow FMT-700P and a Micro Motions CMF025M Coriolis mass flowmeter, respectively. Smoke is measured with an AVL 415S, particle matter (PM) with a Pegasor PPS-M, nitric oxides (NOx) with an Eco Physics' CLD 700EI ht, hydrocarbons (HC) with a CAI HFID 300 and carbon oxides and oxygen (CO,CO_2,O2) with a Servomex Xentra 4900 (see Table 1 below). All measurements were made from analysis lab points 1 (referred as "before AT" in the future) and 2 (referred as "after AT" in the future) as shown in appendix 1, "Piping and instrument diagram of the test setup". The test bed and the control room were separated to minimize any noise and smell emanating from the engine. Both rooms also had automatic ventilation systems to keep out any exhaust gases. Engine exhaust gases are conducted to outside air through a silencer. Data collected from the tests was transferred to Microsoft Excel and analyzed and presented in the form of figures and tables.

Most of the measurements were performed with two different fuels: normal diesel fuel oil (DFO) and Neste's NRD, which is a renewable diesel fuel produced from vegetable oils and waste animal fats. Although not a pure BTL type of fuel, NRD's fuel quality is equal to that of BTL and GTL fuels.

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
Nitric Oxides (NO_X)	Eco Physics CLD 700EI ht
Hydrocarbons (HC)	CAI HFID 300
Carbon Monoxide (CO), Carbon Dioxide (CO_2), Oxygen (O_2)	Servomex Xentra 4900

Table 1 Measurement devices used

Measurements used a set of aftertreatment hardware with measurement points before and after the hardware. Reference measurements were taken without any aftertreatment but any changes in exhaust pipe backpressure were adjusted to the same level as with the aftertreatment system on.

Picture 5 Engine and test bed, exhaust pipe without aftertreatment (Matias Bastman, 2016)

Measurement	Used aftertreatment setup
Meas 1 DFO M1	SetB (DOC+DPF+SCR)
Meas 1 DFO M7	SetB (DOC+DPF+SCR)
Meas 1 NRD M1	SetB (DOC+DPF+SCR)
Meas 1 NRD M7	SetB (DOC+DPF+SCR)
DOC+SCR DFO M1	DOC+SCR
DOC+SCR DFO M7	DOC+SCR
DOC+SCR NRD M1	DOC+SCR
DOC+SCR NRD M7	DOC+SCR

Table 2 Different aftertreatment systems used in measurements.

Table 2 above shows the different aftertreatment configurations used during the measurement campaign. Specifications of the different aftertreatment devices used are displayed in Appendix 4: Aftertreatment information. The locations of the different devices are also displayed in Appendix 1: Piping and instrument diagram of the test setup.

4 PRESENTATION OF THE RESULTS

4.1 Setup and preliminary measurements

The setup of the engine and test bed were done in March 2016 before the start of the measurement campaign. These included testing of the engine and finding the maximum torque in 2100RPM and 1500RPM. This information was then used to determine the different points used in ISO 8178 testing. In addition, different types of aftertreatment devices were fitted to the exhaust piping and pipes of same size were made to replace the devices when they were not used.

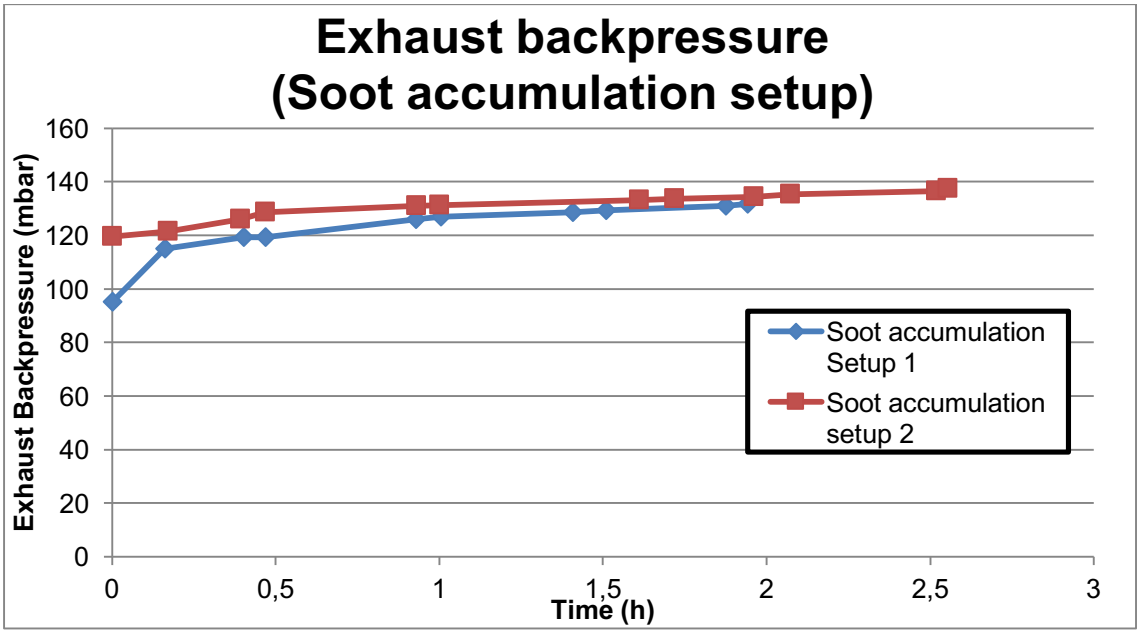


Figure 2 Development of exhaust backpressure in soot accumulation setup (2100RPM, 191 Nm)

This figure shows the required time of soot accumulation to be used in regeneration measurements. These soot accumulation setup runs were done before the start of the intense measurement phase which is why they are presented here as part of the preliminary tests. Two hours of soot accumulation was chosen because it produced enough soot buildup to increase the exhaust backpressure remarkably. Soot accumulation tests were done with special engine calibration to accelerate the soot buildup and using DFO as fuel.

4.2 Reference

Reference measurements were conducted using ISO 8178 C1 Standard loadpoints. Both displayed points were measured twice, once after a stabilization period and once after 15 to 20 minutes. The second NRD Mode7 measurement was made 30 minutes after the first one. Mode1 (M1) loadpoint is 2100RPM and 100% engine load (452Nm) and Mode7 (M7) is 1500RPM and 50% load (280Nm). These loadpoints are also always used when referring to M1 and M7 in the future. All tests included in the intense measurement campaign are listed in appendix 2: Measurement test table. Also included are the different measurement devices used by TUT and FMI, displayed by date and measurement test.

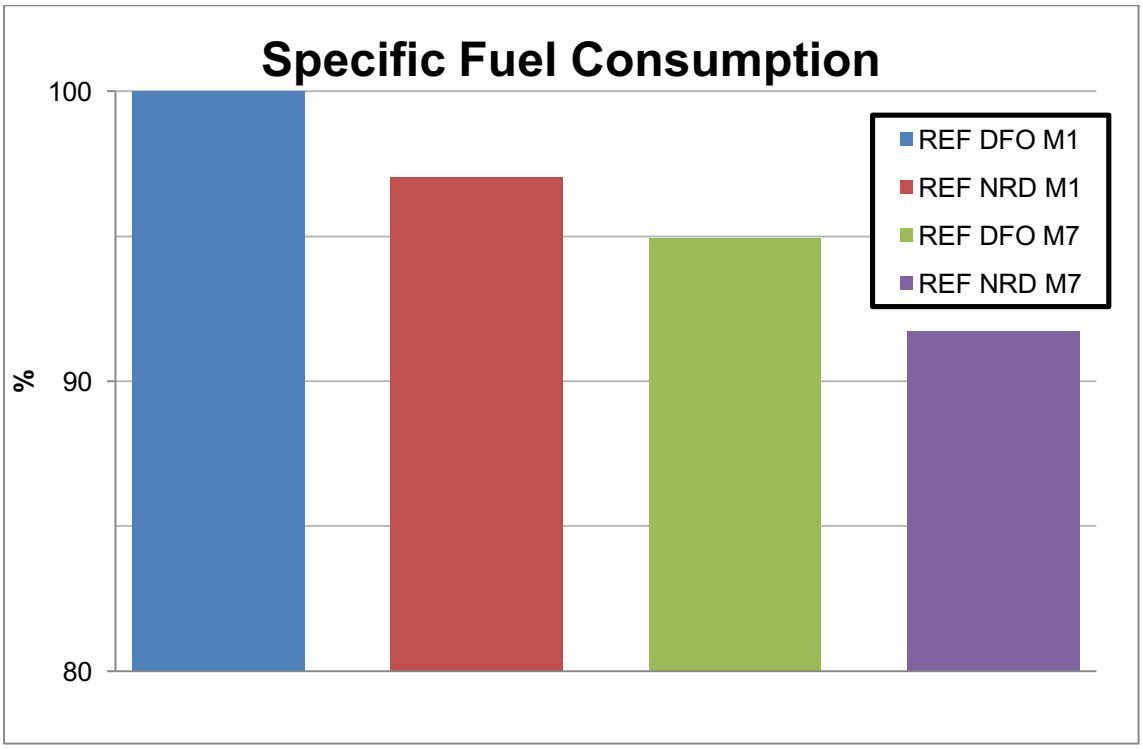


Figure 3 SFC in reference measurements (NRD vs. DFO)

Comparing the pure SFC of these two fuels is difficult due to the differences in their properties, so although their consumptions are different from each other, so are their properties.

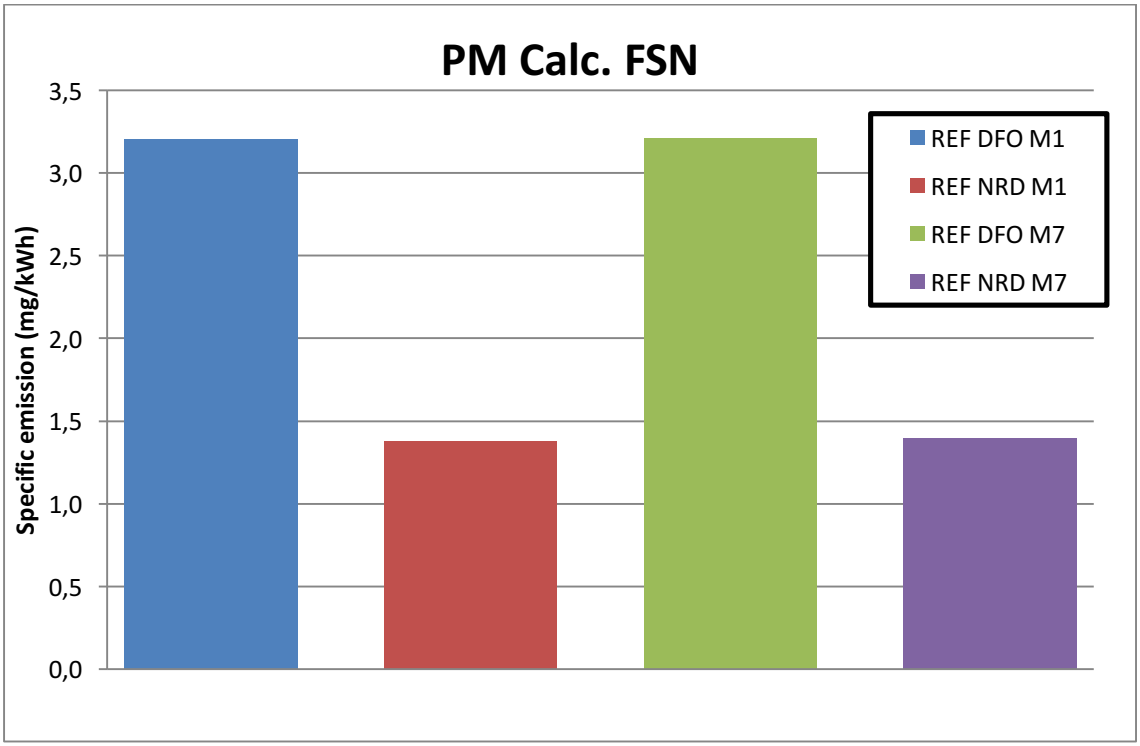


Figure 4 PM emissions in reference measurement (NRD vs. DFO)

Particle matter emissions are more than double when comparing the NRD to DFO. Particle matter is calculated from filter smoke number, using the following formula extracted from the result calculation datasheets.

$$SPM = \frac{\frac{565 * \ln\left(\frac{10}{10 - 0{,}8 * FSN}\right)^{1{,}206}}{1000} * k_p * \dot{m}_e}{\frac{1{,}293}{P}}.$$

Where SPM = specific particle matter

FSN = filter smoke number

P = engine power

k_p = particle correction

m_e = exhaust mass flow

Following figure displays particle matter emissions based on the measurements made with Pegasor PPS-M device.

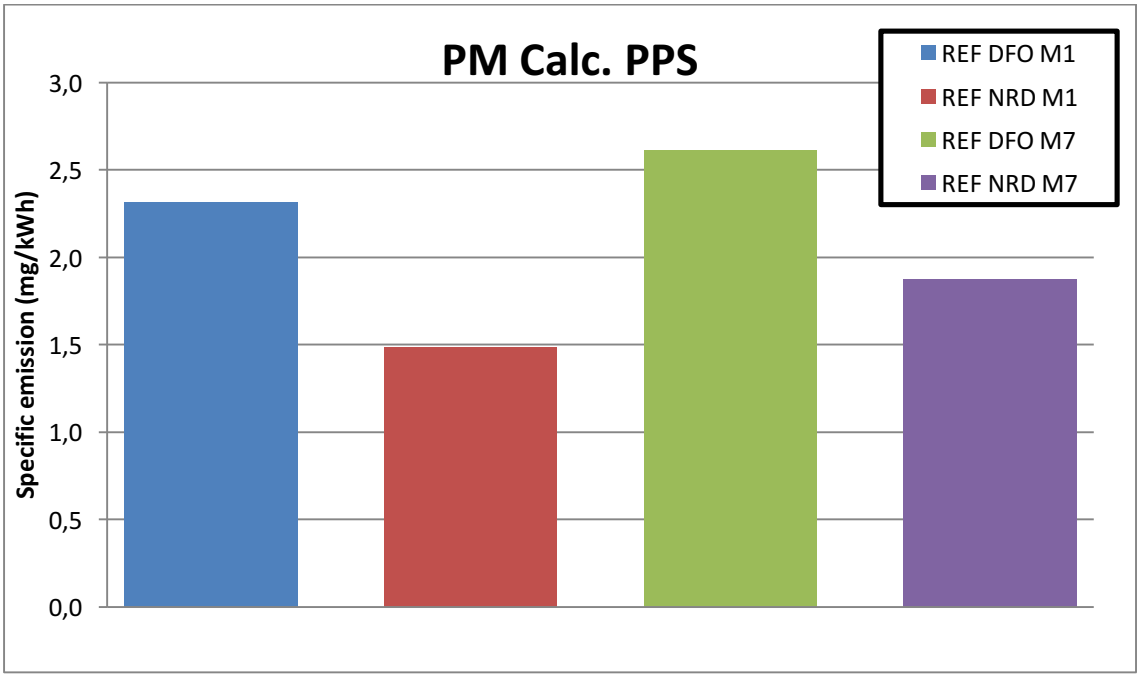


Figure 5 PM emissions in reference measurement using PPS (NRD vs. DFO)

Although it displays measurements much in line with FSN they deviate a bit from each other and a decision was made to use only data based on FSN measurements. Particle matter using PPS was calculated using the following formula

$$SPM_{PEG} = \frac{m_e * 1000}{\rho_e} * \frac{PEG * P}{1000}$$

Where SPM = specific particle matter

PEG = Pegasor 50 measurement

P = engine power

ρ_e= particle correction

m_e = exhaust mass flow

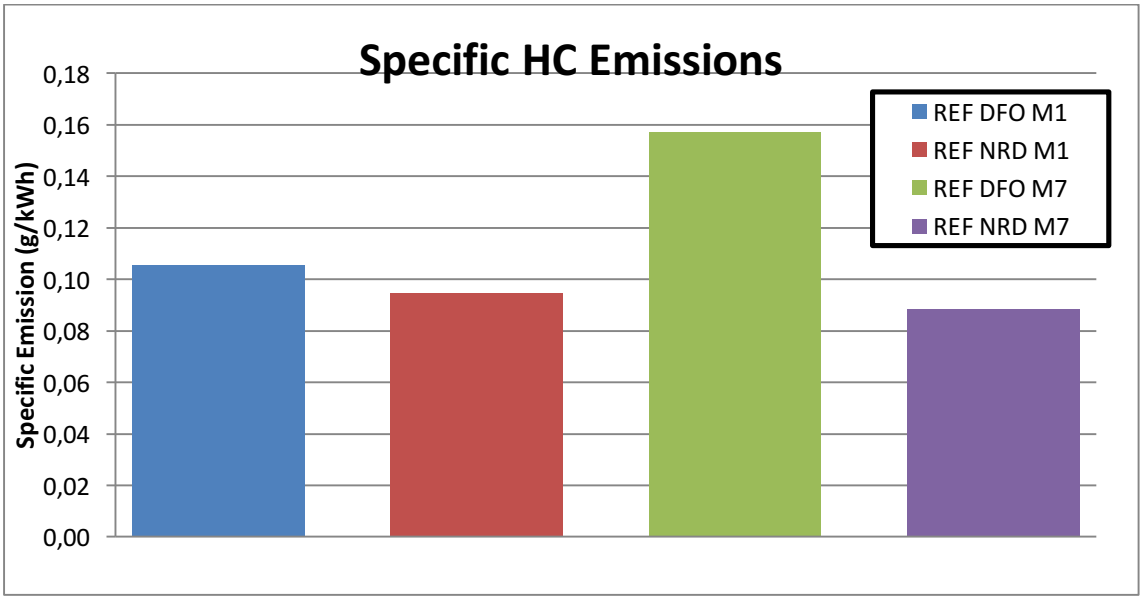


Figure 6 HC emissions, reference measurement (NRD vs. DFO)

Hydrocarbon emissions are rather equal except for the Mode7 DFO emissions, which rise to almost double to that of NRD.

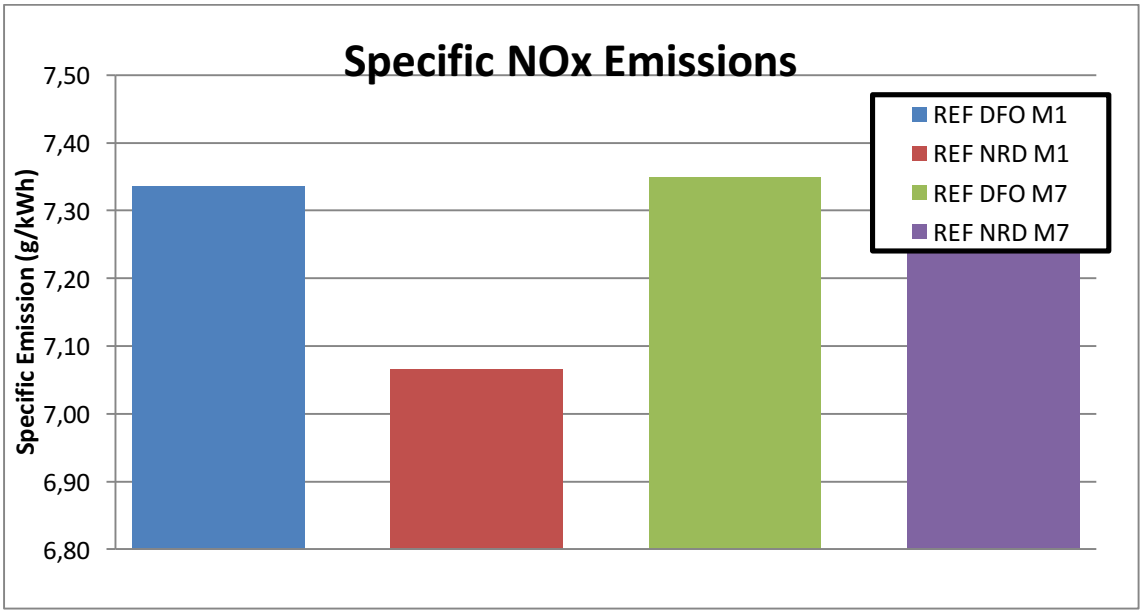


Figure 7 NO_x emissions, reference measurement (NRD vs. DFO)

Nitric oxide emissions are almost equal with both fuels and both measurement points. Nitric oxide emissions are combined from nitric monoxide and nitric dioxide emissions.

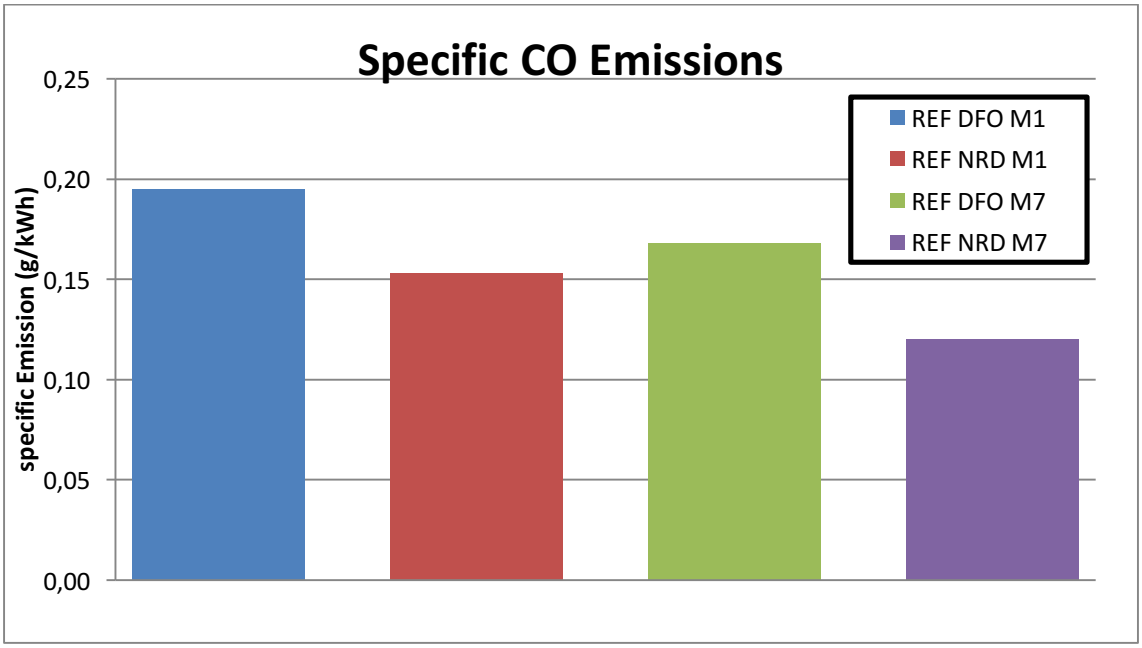


Figure 8 CO emissions, reference measurement (NRD vs. DFO)

Carbon monoxide emissions follow the same style as the NO_X emissions, although differences between NRD and DFO are a bit larger.

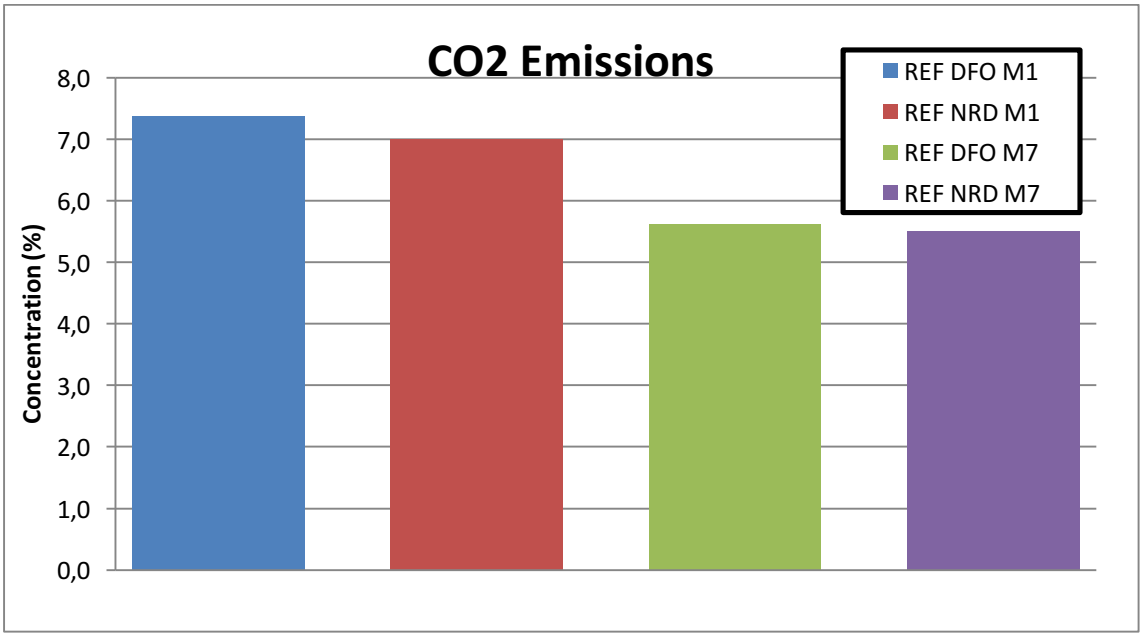


Figure 9 CO_2 emissions, reference measurement (NRD vs. DFO)

Carbon dioxide emissions decrease as other emissions increase and that is the reason why only Mode7 NRD shows a slight decrease here.

4.3 ISO 8178 related measurements

4.3.1 Measurement 1

Following measurements were made during the first few days of the intensive measurement campaign and are based on the ISO 8178 C1 Modes 1 and 7. Aftertreatment setup was the so-called SetB (see Table 2 for included AT devices). See Appendix 2 for more info on measurement devices used by TUT and FMI. Appendix 3 displays alpharatios for all measurements including SCR. Appendix 4 has more information on the used aftertreatment devices.

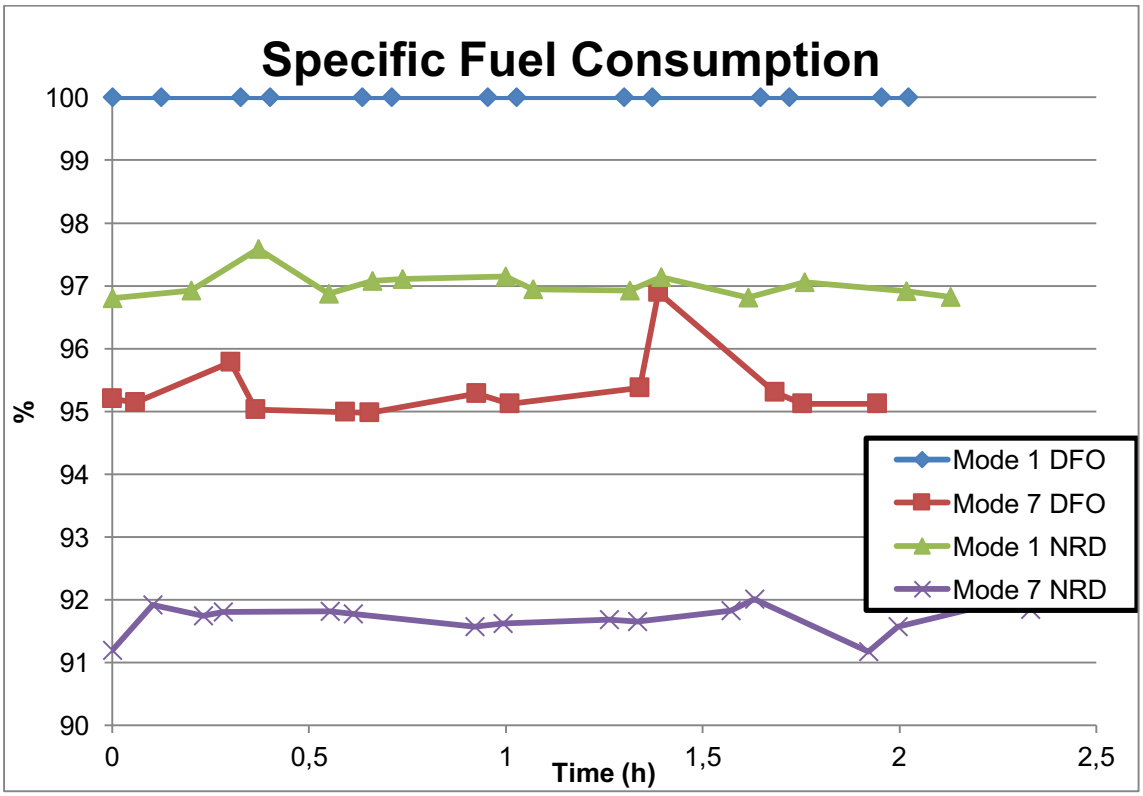


Figure 10 SFC in measurement 1 (NRD vs. DFO)

Specific Fuel Consumption on measurement 1 mainly follows the same direction as in the reference measurements. Again, direct comparison is difficult between the fuels.

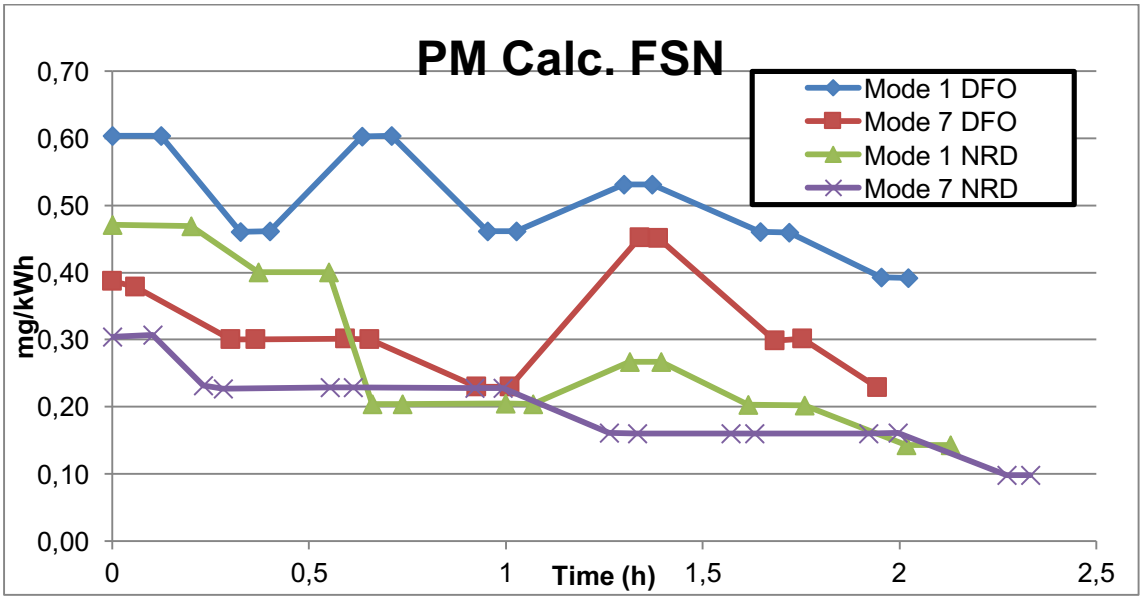


Figure 11 PM calculated from FSN, measurement 1 (NRD vs. DFO)

Particle matter emissions from NRD are about half of the emissions from DFO. The direction of these results is the same as those from the reference measurement.

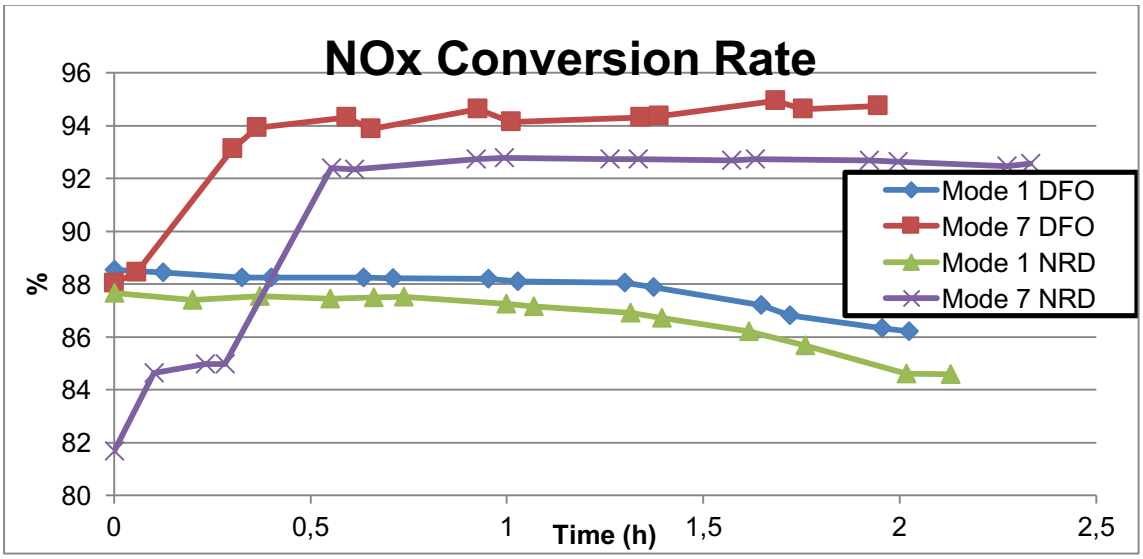


Figure 12 NO_x conversion rate, measurement 1 (NRD vs. DFO)

This figure demonstrates the NO_X conversion rate of the SCR process. Alpharatio values and an explanation for the rising conversion rate are given on the next page.

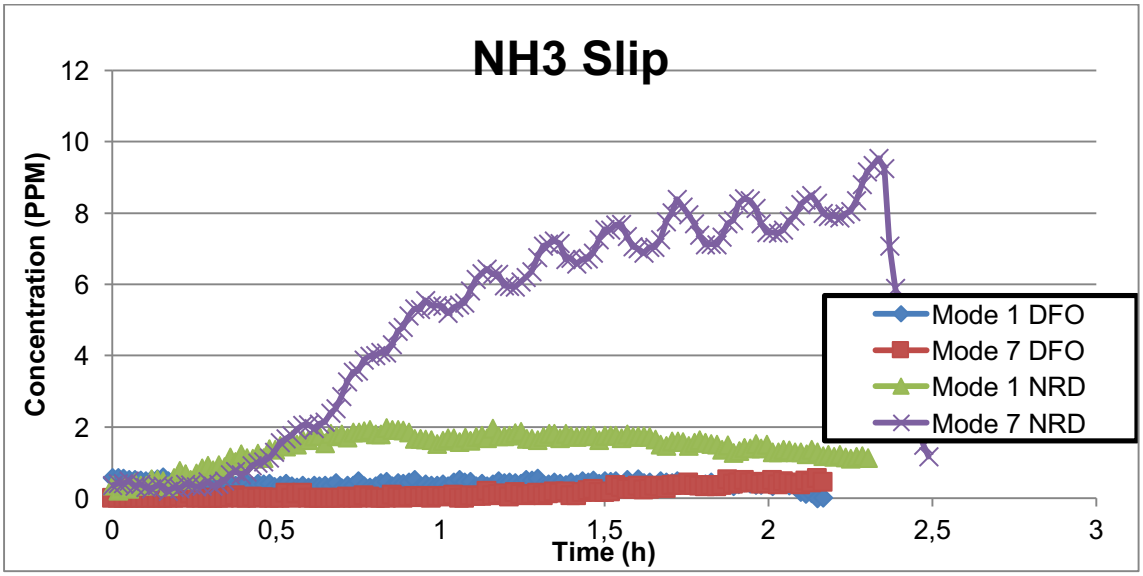


Figure 13 NH_3 slip after AT, measurement 1 (NRD vs. DFO)

Displayed here are the ammonia slips from the SCR. Ammonia slip needs to be kept below 10ppm due to limitations set for this study. Urea dosage is controlled with the so-called alpha ratio, smaller alpha means lower dosage when comparing to measured NO_x emissions before AT. In this test, the Mode 1 alpharatio for both fuel types was 0.95 and alpha for Mode 7 was 1.1.

It can be seen that the Mode 7 alpha is a bit high for NRD because its ammonia slip almost exceeds the 10ppm threshold, although with DFO the slip is only a fraction of the limit. This can also be due to temperatures in SCR as seen in figure 14. The mode 1 alpharatio is very suitable for both fuels and even the highest peak slip is below 2ppm.

As can be seen from Figure 11, there is a rise in NO_X conversion rate with both Mode7 runs. This increase is not a product of alpharatio adjustments, although urea injection quantity increased a bit during the DFO Mode7 run. The alpharatio was not adjusted from the set value in any part of the measurement.

Table 3 Urea injection quantity on measurement 1 Mode 7

Measurement	1	2	3	4	5	6	7	8
DFO M7 Urea Quantity (g/h)	630	710	712	710	695	690	665	
NRD M7 Urea Quantity (g/h)	754	737	730	730	732	720	630	719

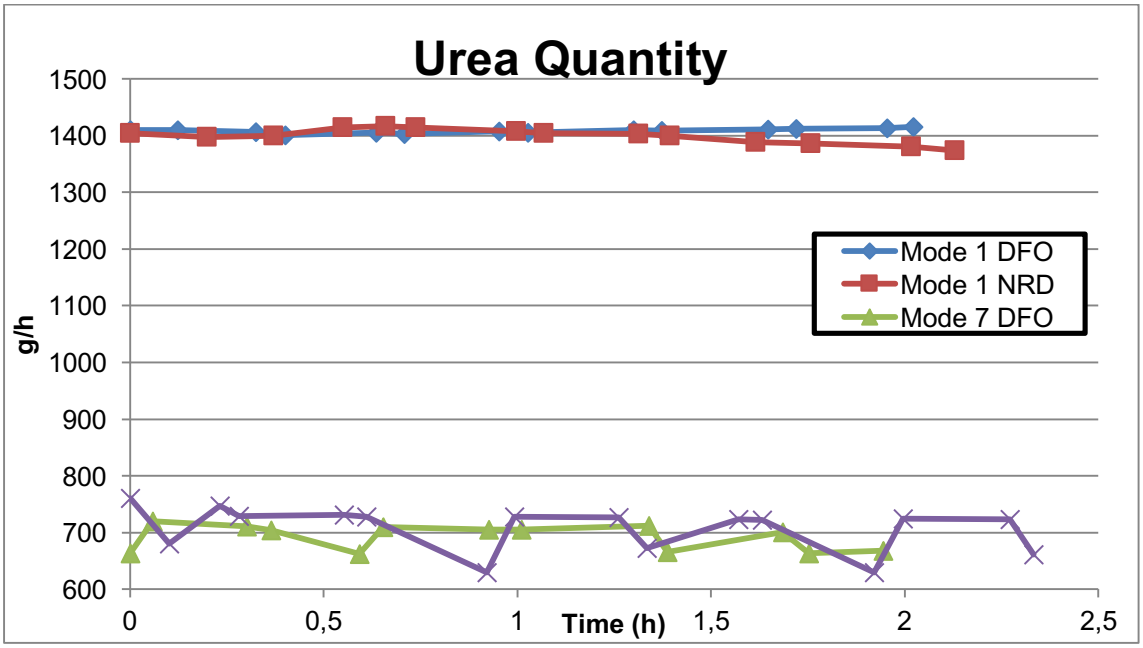


Figure 14 Urea injection quantity, measurement 1 (NRD vs. DFO)

Shown here is the urea injection quantity figure which shows a steady injection in M1 but in M7, the quantity varies by almost 10%. Reasons for this variance are not known. One possible reason for this is that the used engine parameters are "sailing" between two set points.

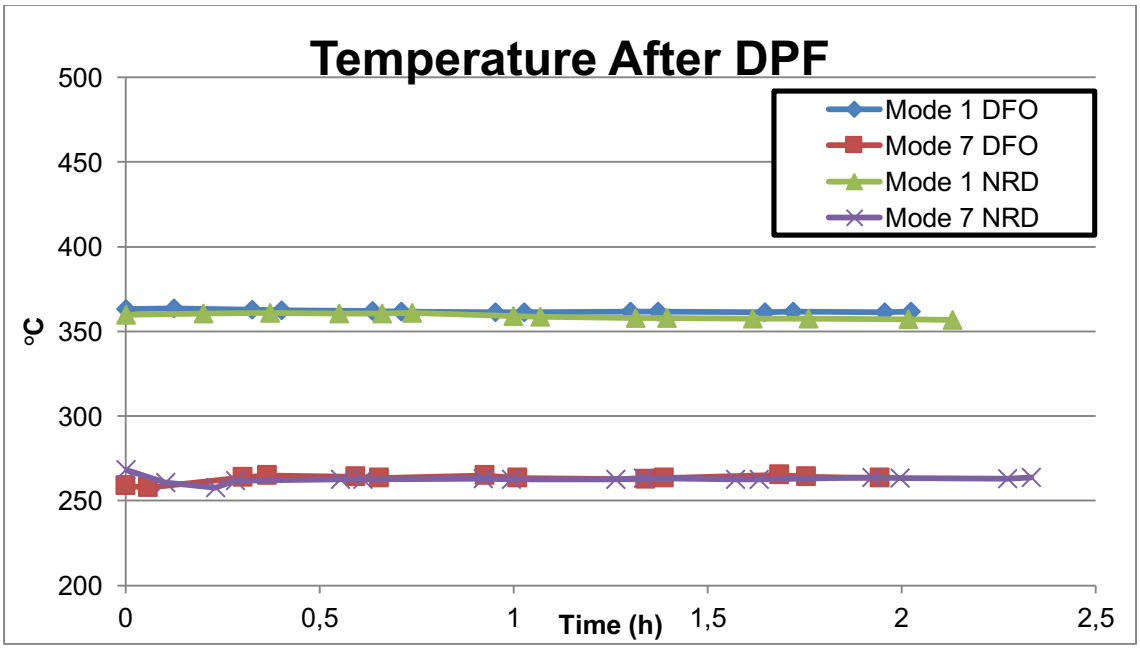


Figure 15 Exhaust gas temp after DPF, measurement 1(NRD vs. DFO)

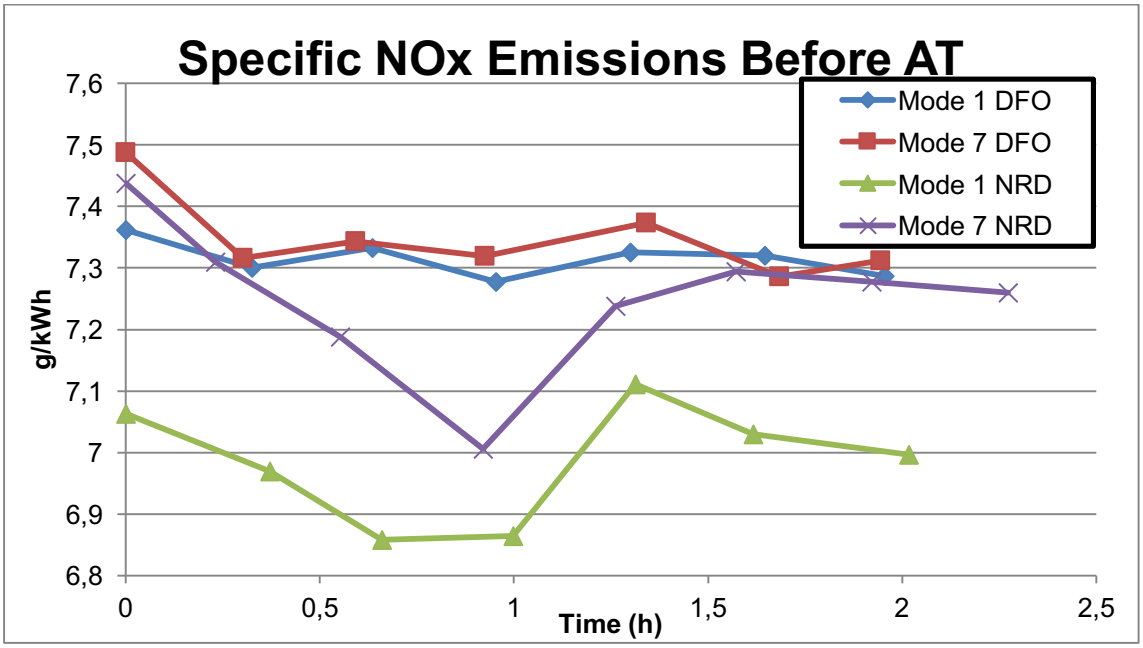


Figure 16 Specific NO_X before AT, measurement 1 (NRD vs. DFO)

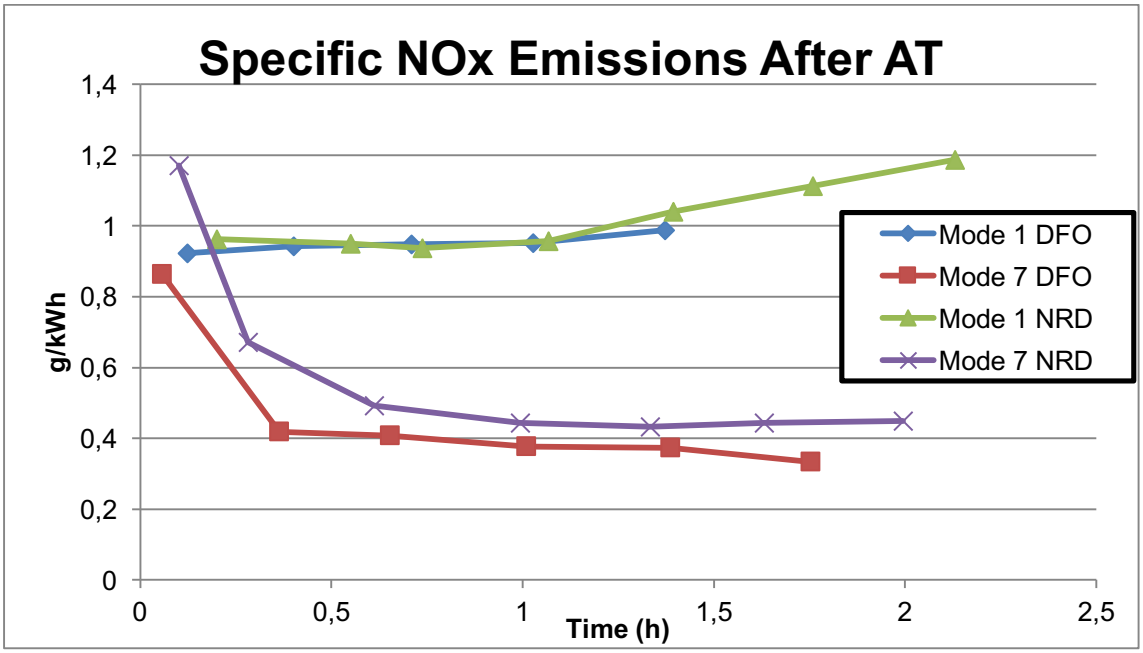


Figure 17 Specific NO_X after AT, measurement 1 (NRD vs. DFO)

Displayed here are nitric oxide emissions both before and after the aftertreatment system. Although there are some differences between the fuels before AT, they are evened out after the SCR process.

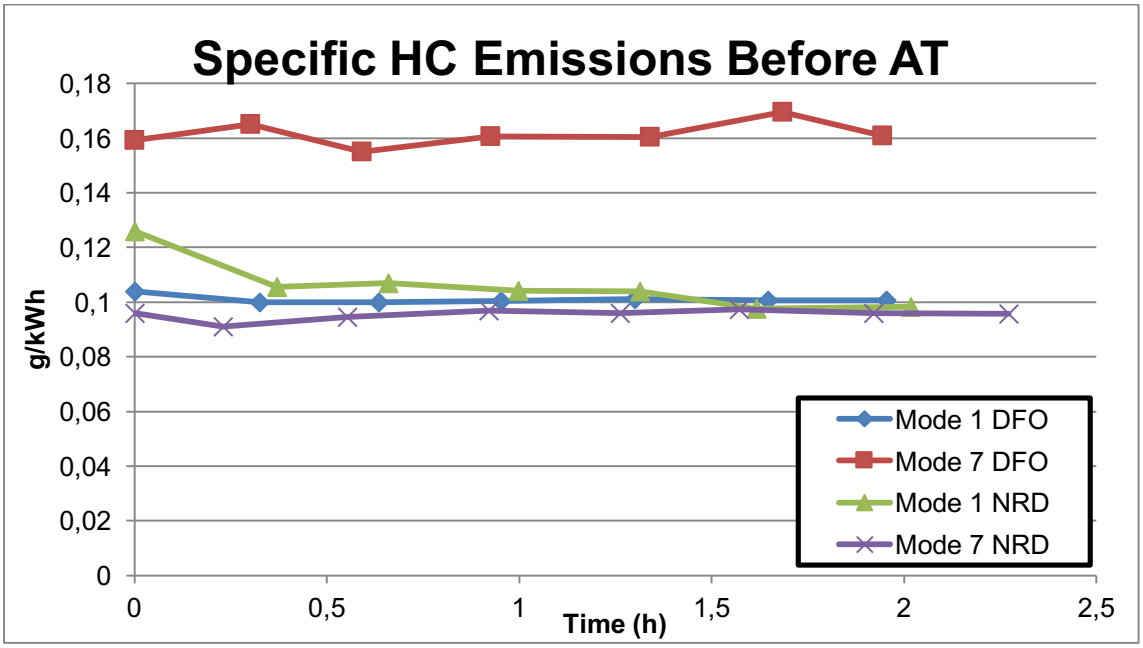


Figure 18 HC emissions before AT, measurement 1 (NRD vs. DFO)

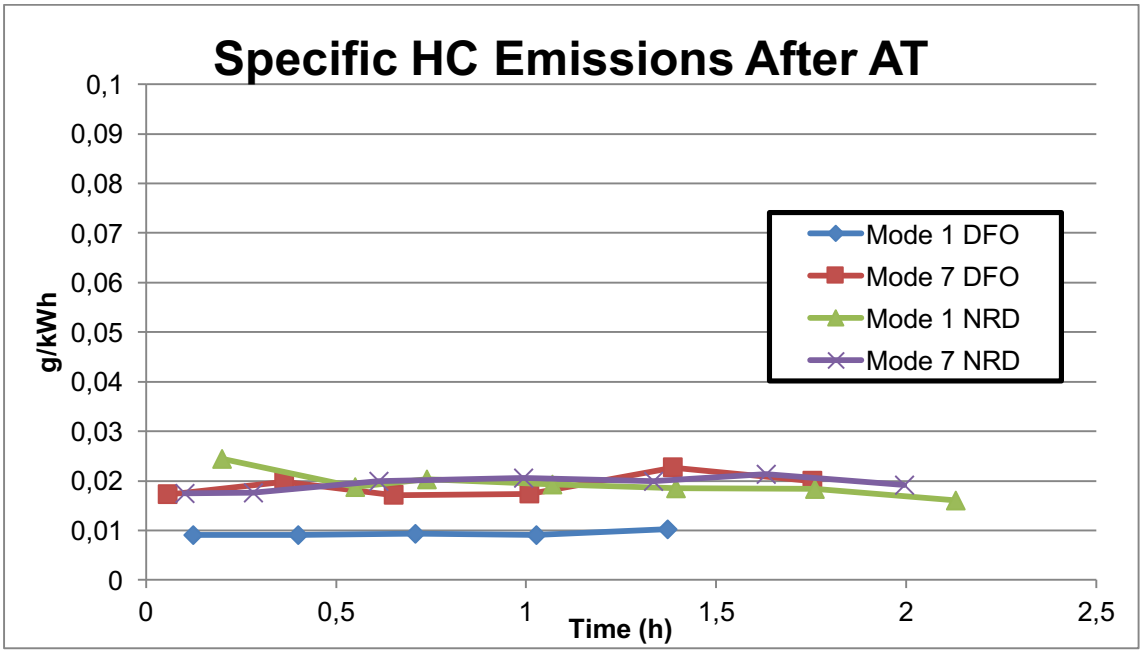


Figure 19 HC emissions after AT, measurement 1 (NRD vs. DFO)

These two figures demonstrate the importance of DOC aftertreatment of hydrocarbon emissions. Emissions are reduced by 90% or more. There is not much difference in emissions between the two fuel types, although before AT DFO mode7 is a bit higher than the other measurements.

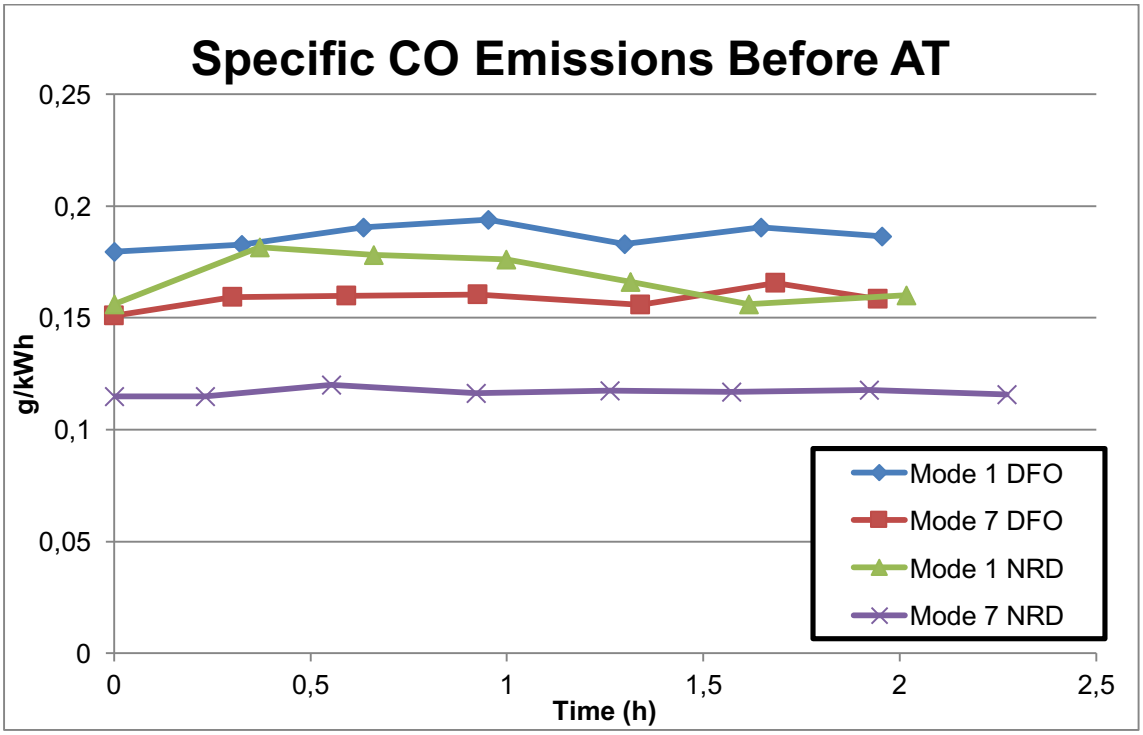


Figure 20 CO emission before AT, measurement 1 (NRD vs. DFO)

Differences here are very small between the fuels. Emissions after DOC are reduced to zero because of the oxidizing catalysts and therefor the figure for CO emissions after DOC is not displayed. This also means that the DOC works as it should.

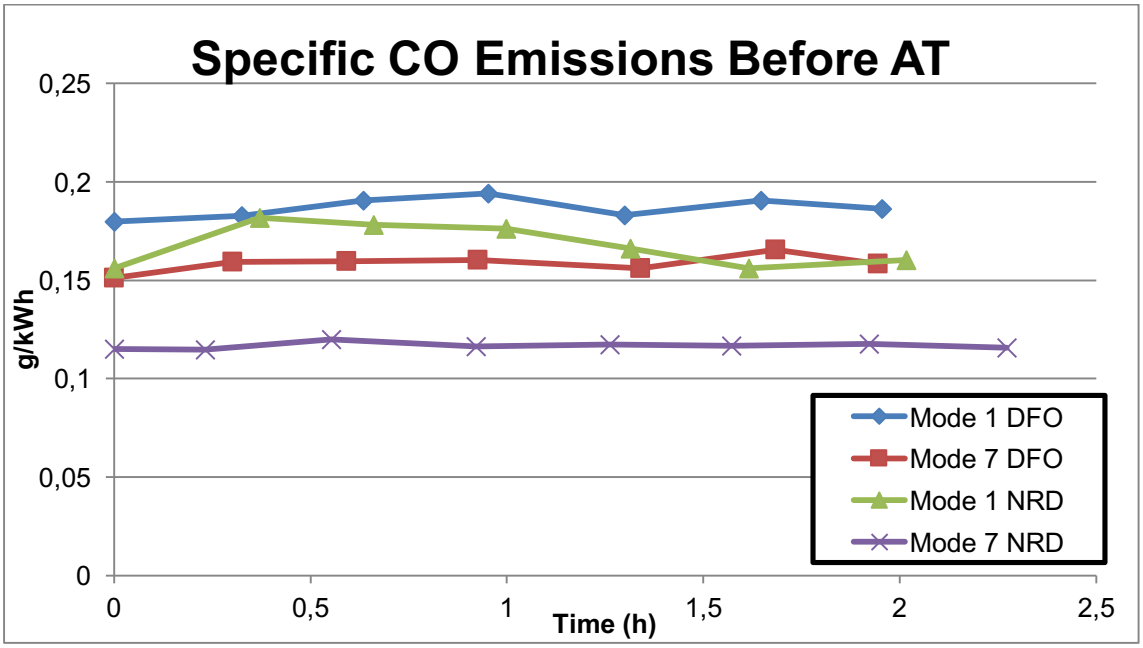


Figure 21 O_2 emission before AT, measurement 1 (NRD vs. DFO)

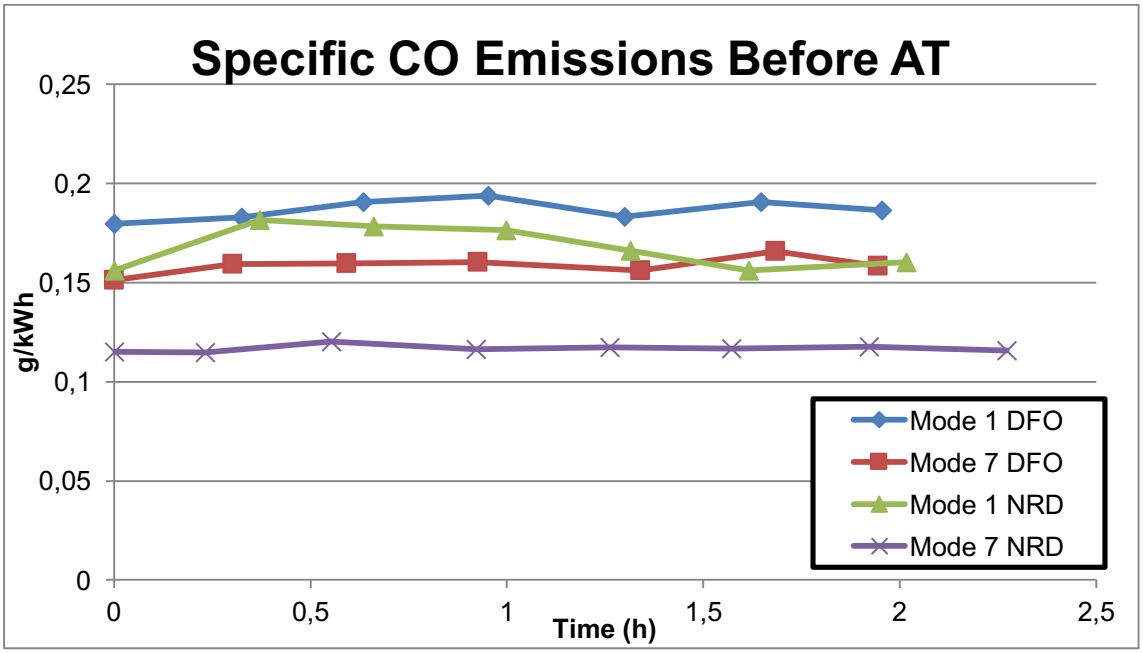


Figure 22 CO_2 emission before AT, measurement 1 (NRD vs. DFO)

Carbon dioxide and oxygen emissions are displayed above, measured from the raw exhaust. Carbon dioxide and oxygen emissions for following ISO 8178 tests are not presented but are included in the appendixes.

SetB vs. DOC+SCR vs. NoAT (ISO 8178 C1 Mode1)

These figures demonstrate the differences between two fuel and three aftertreatment types. ISO 8178 C1 Mode1 is displayed first. Measurement data is gathered from previous measurements and stacked together. This is to show the differences more easily. These measurements are referred to as Versus M1 in the future. See Appendix 2 for more info on the devices used by TUT and FMI.

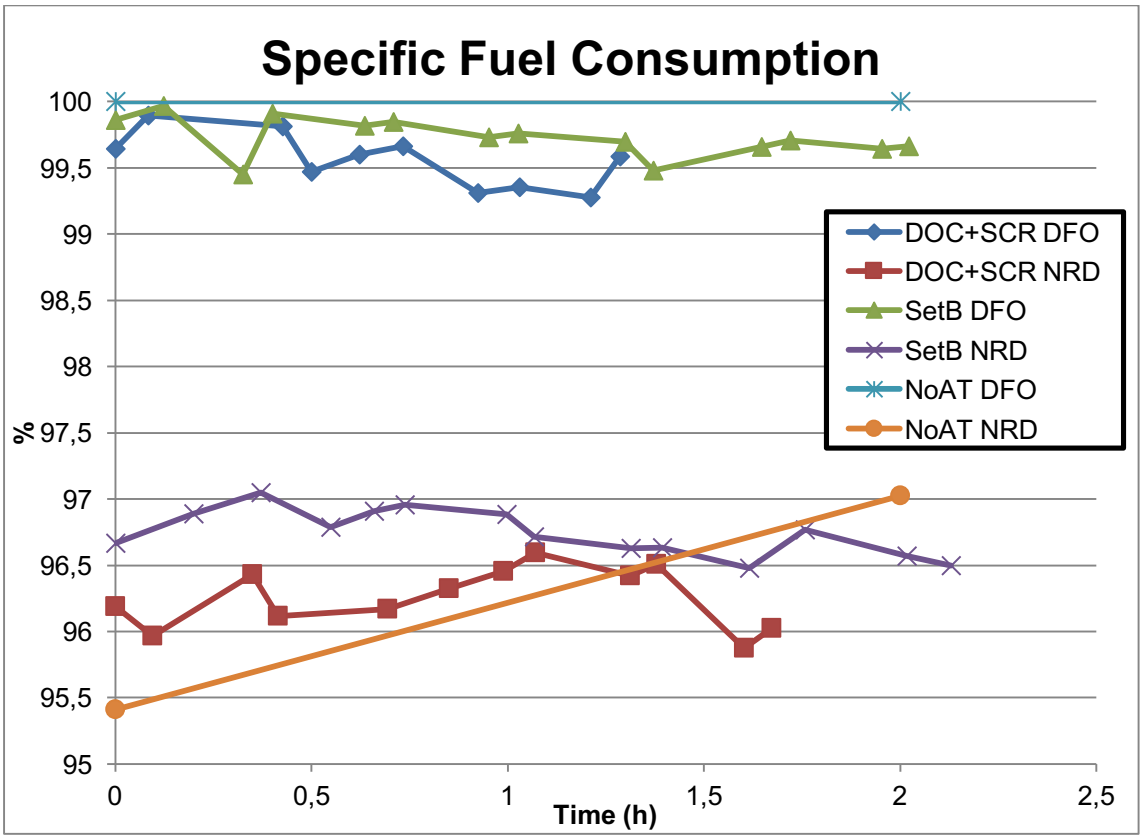


Figure 23 SFC in Versus M1

Different aftertreatment configurations seem to have only a small effect on the specific fuel consumption between each other. However, with NRD the differences here are a bit wider than with DFO.

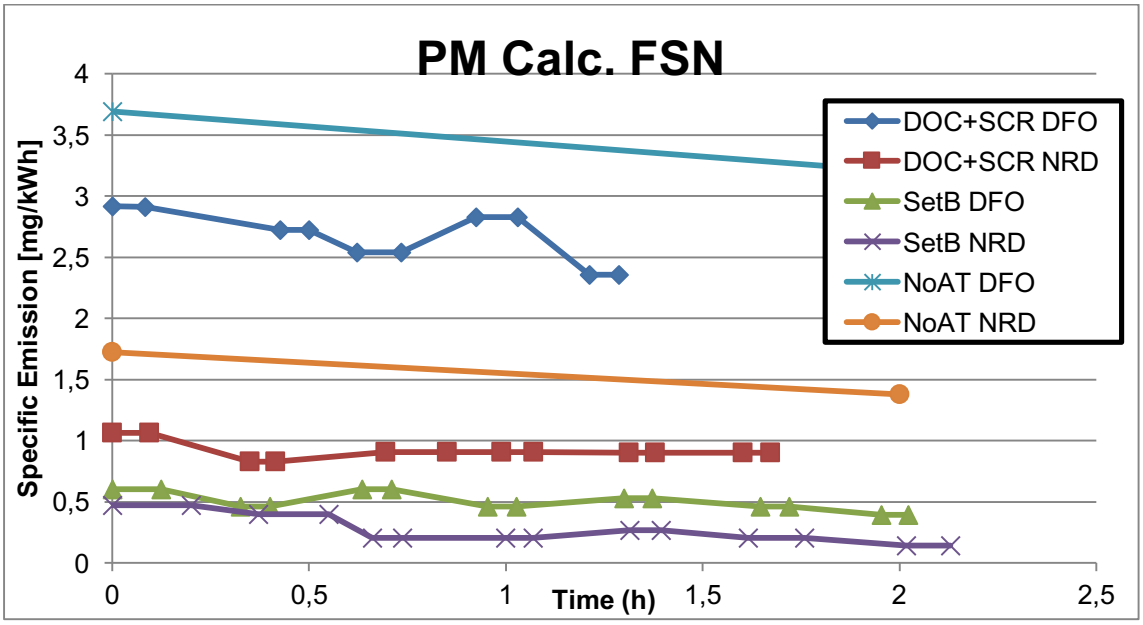


Figure 24 PM emissions in Versus M1

Here you can see how much DPF aftertreatment lowers the particle emissions from the engine when compared to NoAT and DOC+SCR configurations.

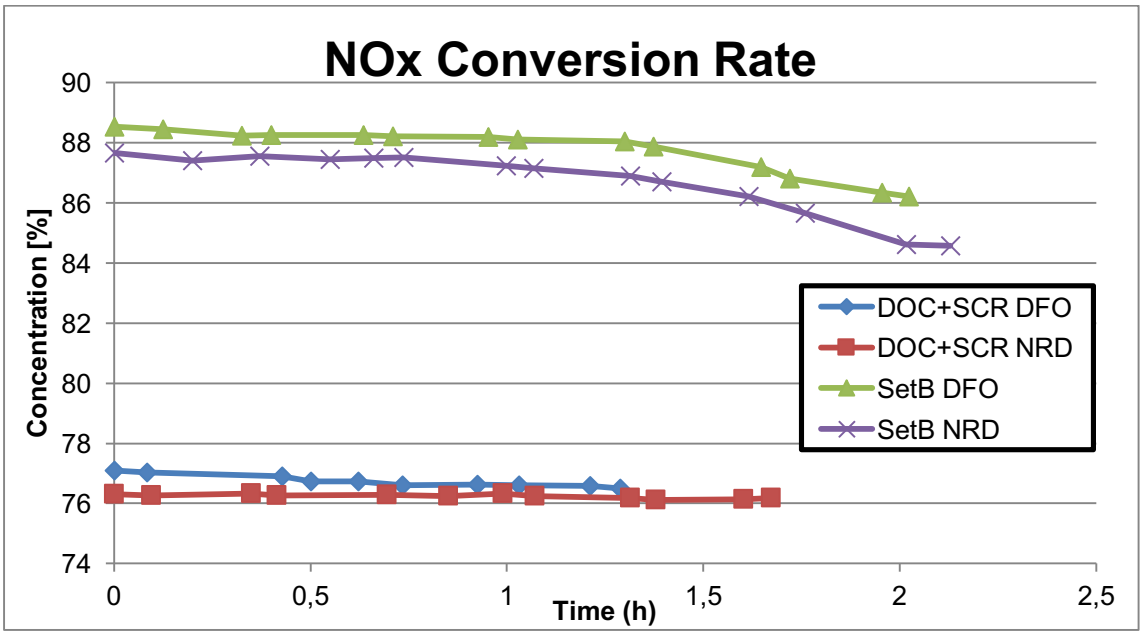


Figure 25 NO_x conversion in Versus M1

SetB has a greater conversion rate because there was more urea injected into the system with SetB (see Figure 26).

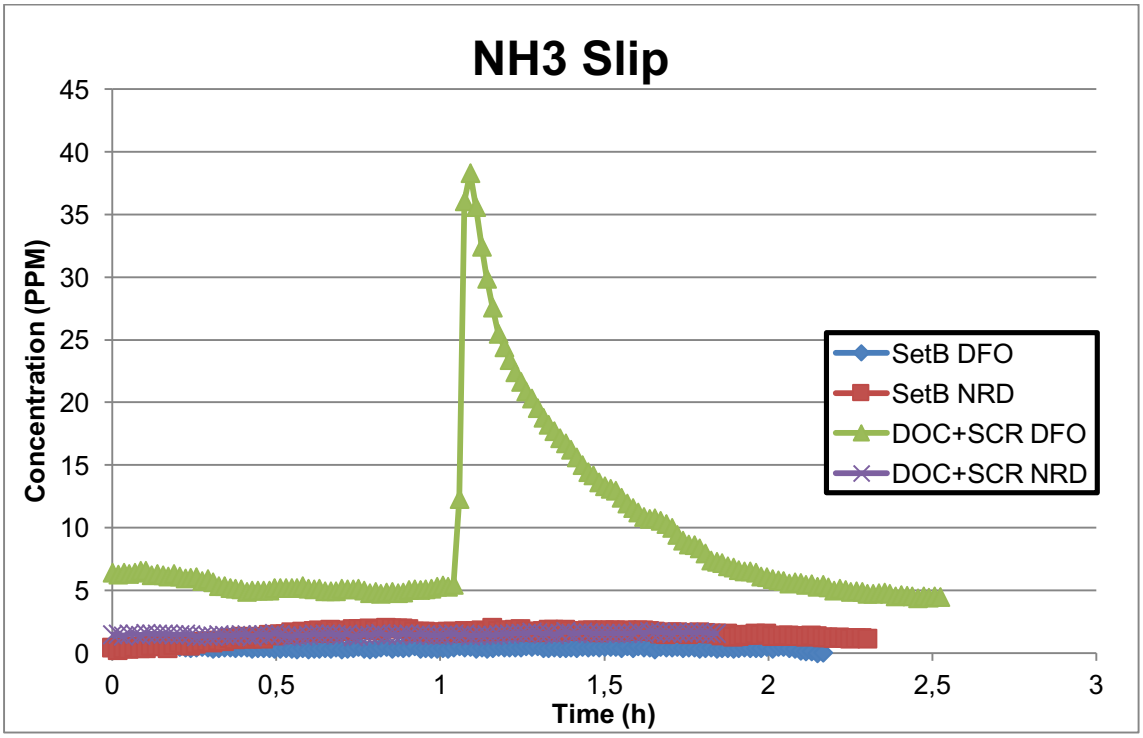


Figure 26 NH_3 Slip after AT in Versus M1

Shown here is the ammonia slip for both the SetB and DOC+SCR aftertreatment configurations. The alpha ratio for DOC+SCR is 0.8 and for SetB, the alpha is 0.95. Both alphas are suitable for both fuels although the DOC+SCR alpha yields a bit higher ammonia slip compared to SetB with DFO. There is also an ammonia slip spike with DOC+SCR DFO, which tops at 45ppm and after the spike gradually decreases to the normal value. No explanation can be found as to what was the culprit behind this ammonia slip spike. One possible reason for this is that SCR, which have been used for a while, have began to deactivate a bit and therefore the slip has risen.

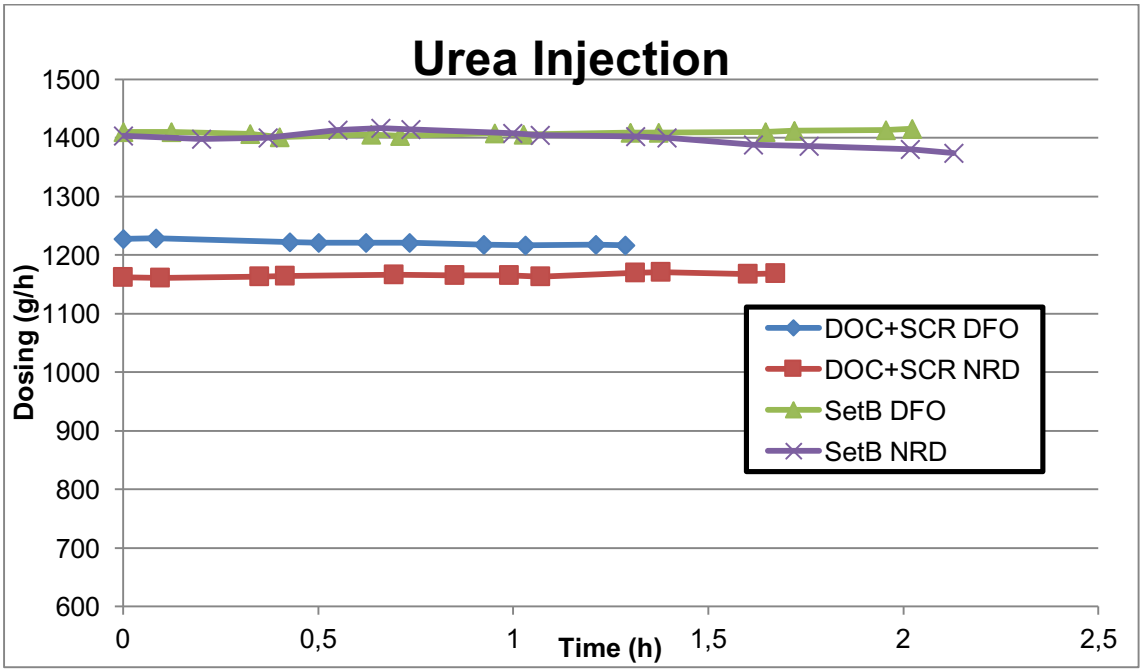


Figure 27 Urea injection quantity in Versus M1

Figure 26 displays a very steady injection quantity and there is nothing to suggest that injection quantity variance was a culprit for the DOC+SCR ammonia slip spike seen in Figure 25. Also there are no noticeable differences in temperatures seen in Figure 27.

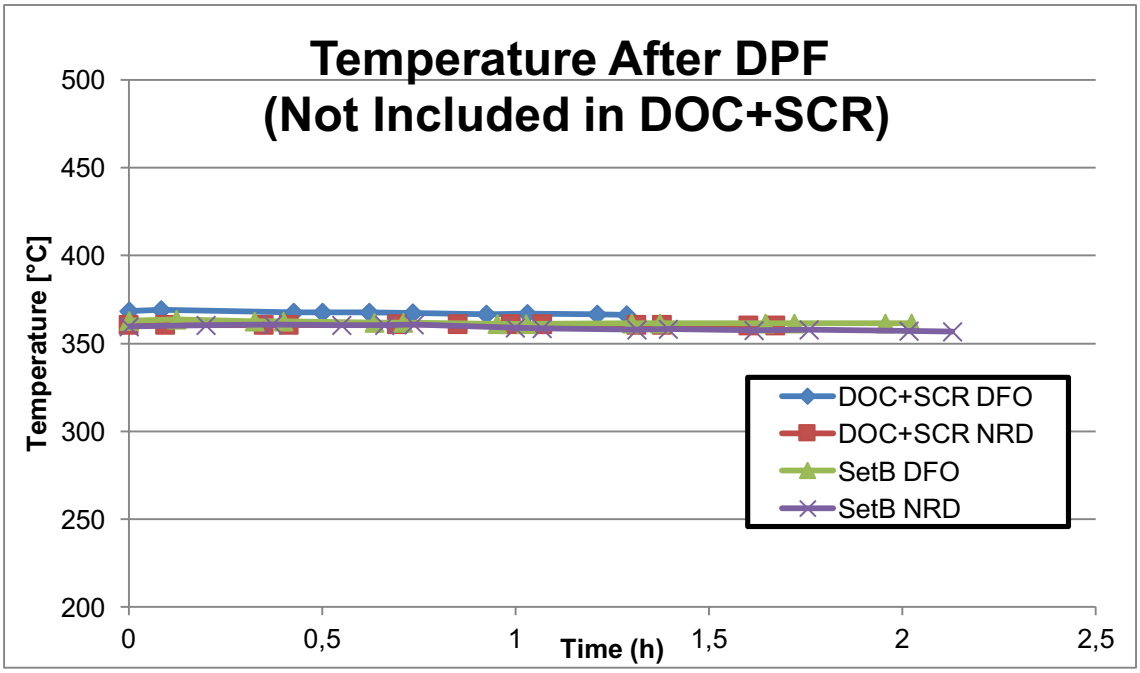


Figure 28 Exhaust gas temp after DPF in Versus M1

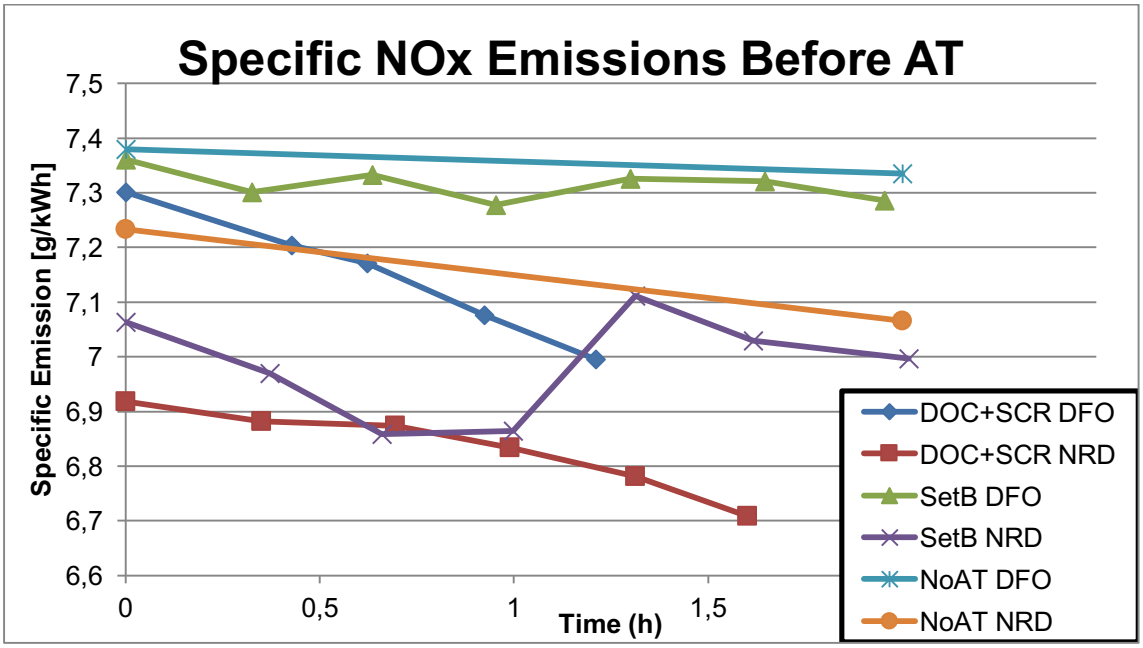


Figure 29 NO_X emissions before AT in Versus M1

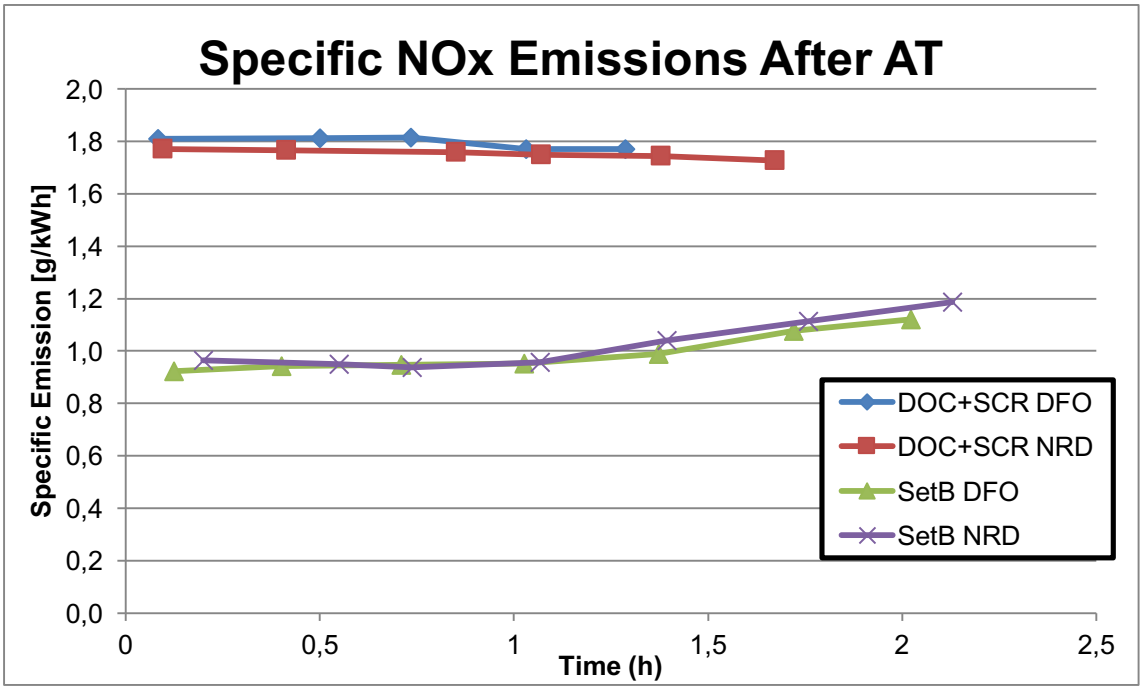


Figure 30 NO_X emissions after AT in Versus M1

Shown here is the result of the lowered NO_x conversion rate. Even though emissions before AT are within a small range, after AT emissions are very different when comparing the DOC+SCR to SetB configurations.

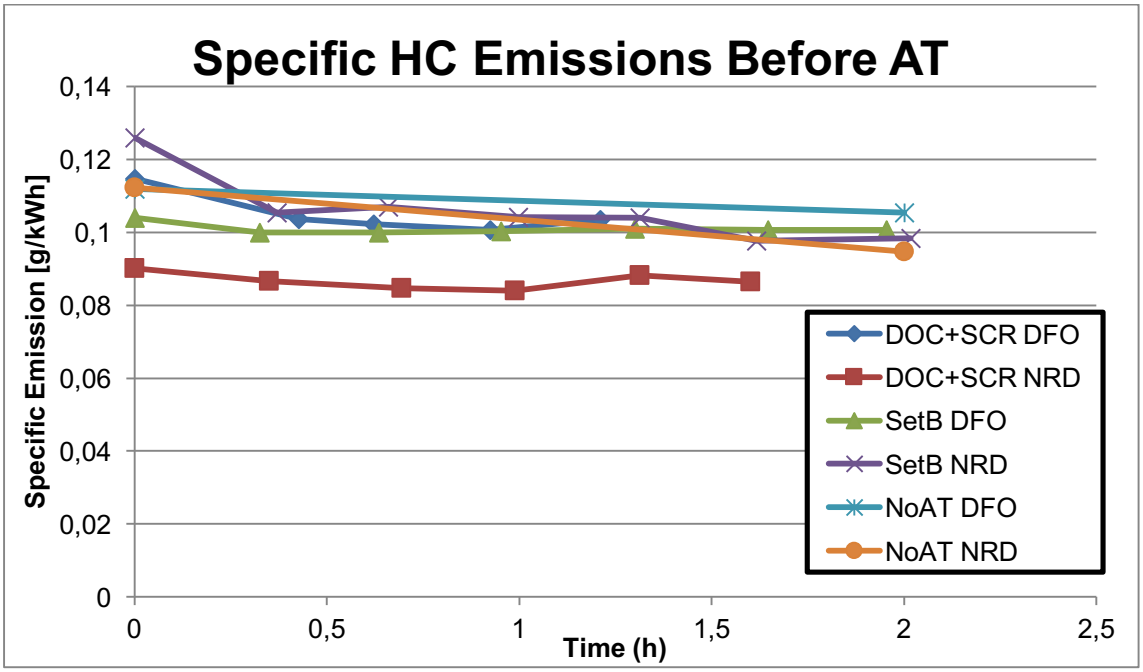


Figure 31 HC emissions before AT in Versus M1

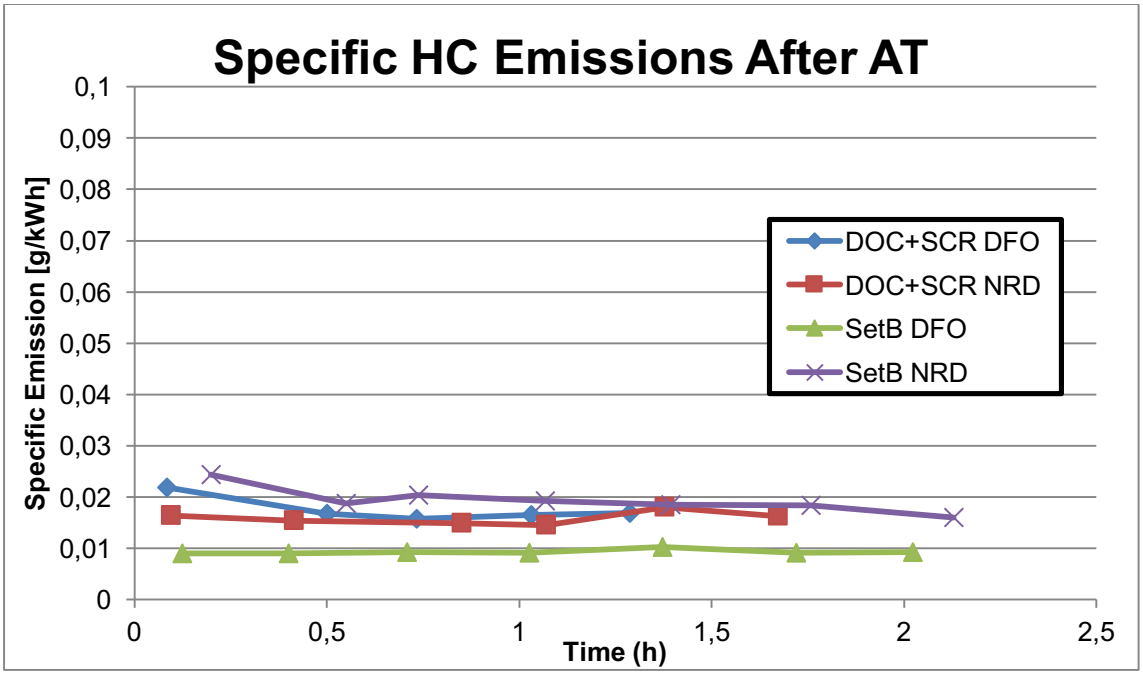


Figure 32 HC emissions after AT in Versus M1

HC emissions vary only very slightly and DOC aftertreatment lowers the emissions to about 10% of the initial level. NoAT emissions before AT are on the same level as the other AT configurations.

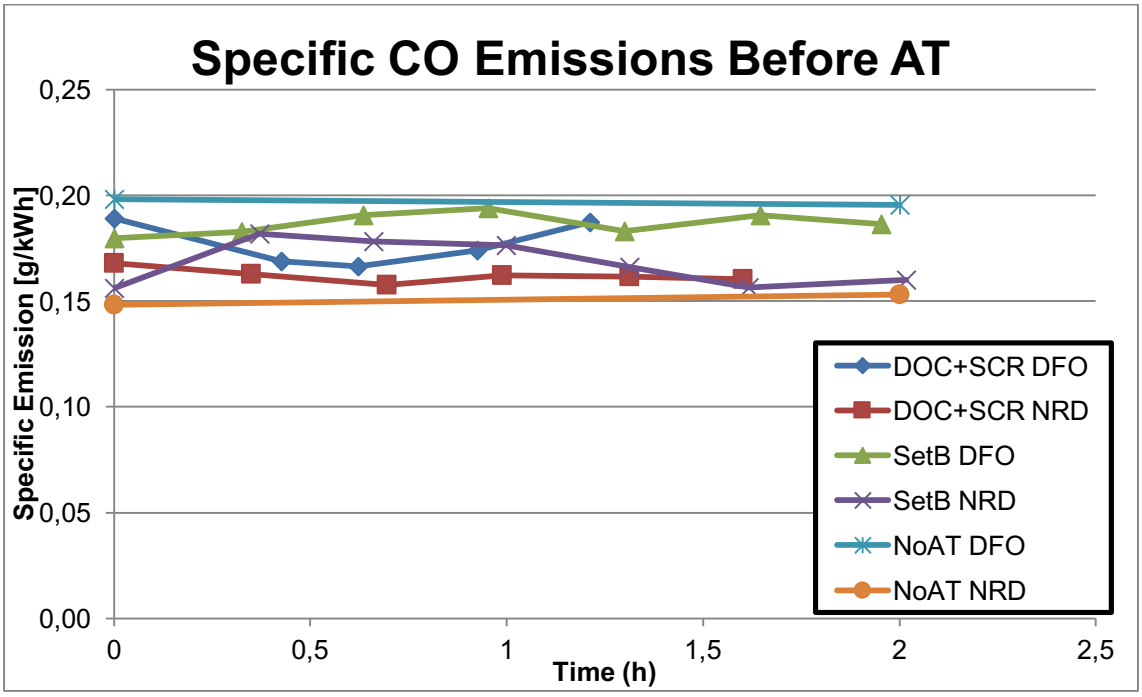


Figure 33 CO emissions before AT in Versus M1

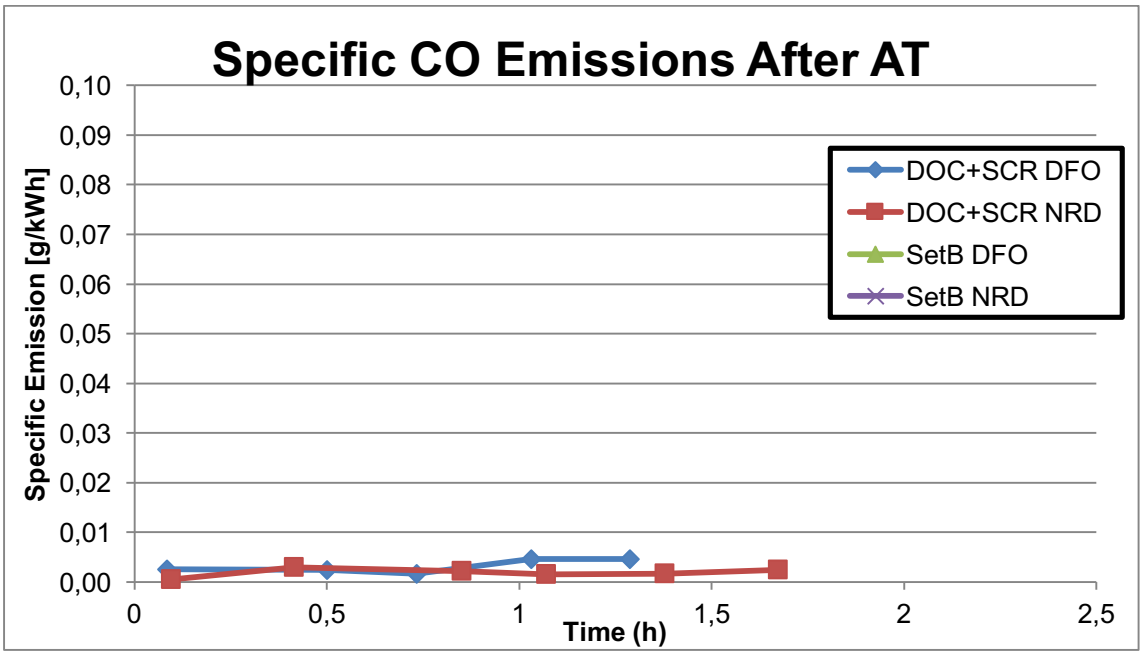


Figure 34 CO emissions after AT in Versus M1

CO emissions are reduced to basically zero after the exhaust gases are passed through the DOC oxidizer and are very well lined before AT.

4.3.2 SetB vs. DOC+SCR vs. NoAT (ISO 8178 C1 Mode7)

This measurement concentrates on the ISO 8178 C1 Mode7 loadpoint and figures are comprised of SetB, DOC+SCR and NoAT results stacked together. The measurement is done to ease the reading of the results. These measurements are referred to as Versus M7 in the future.

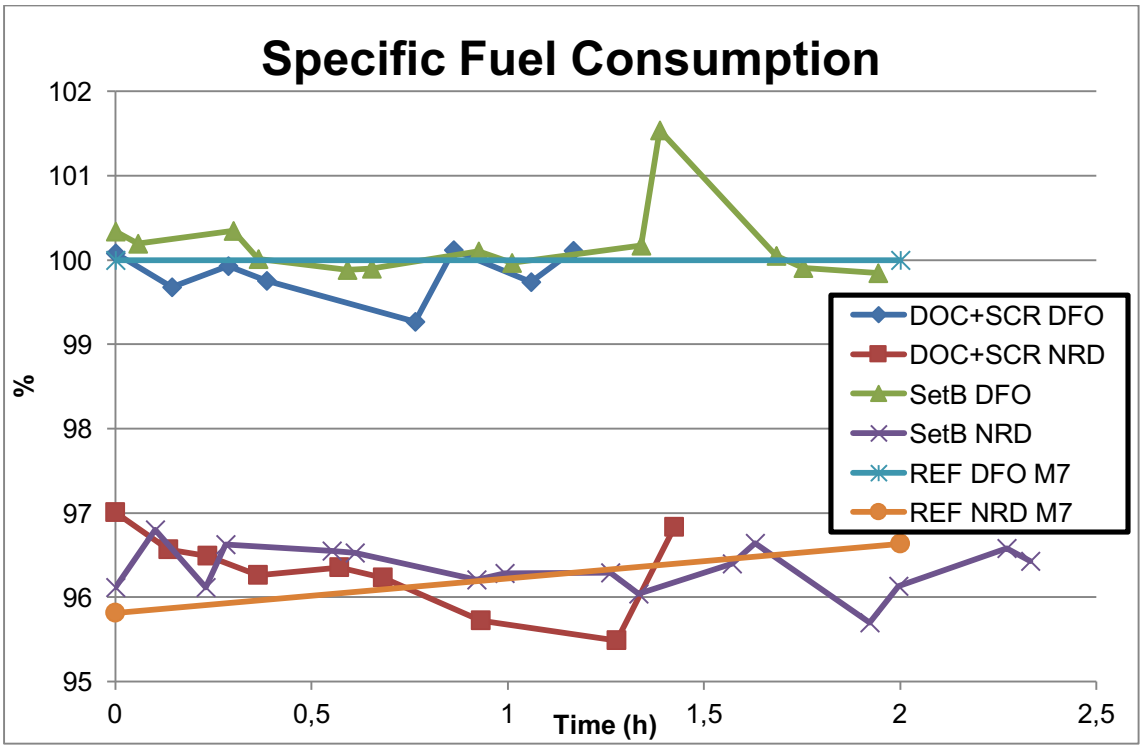


Figure 35 SFC in Versus M7

Specific fuel consumption follows mainly the same style as in the previous measurements. In addition, it seems that the aftertreatment configuration doesn't affect the SFC much in Mode7 either.

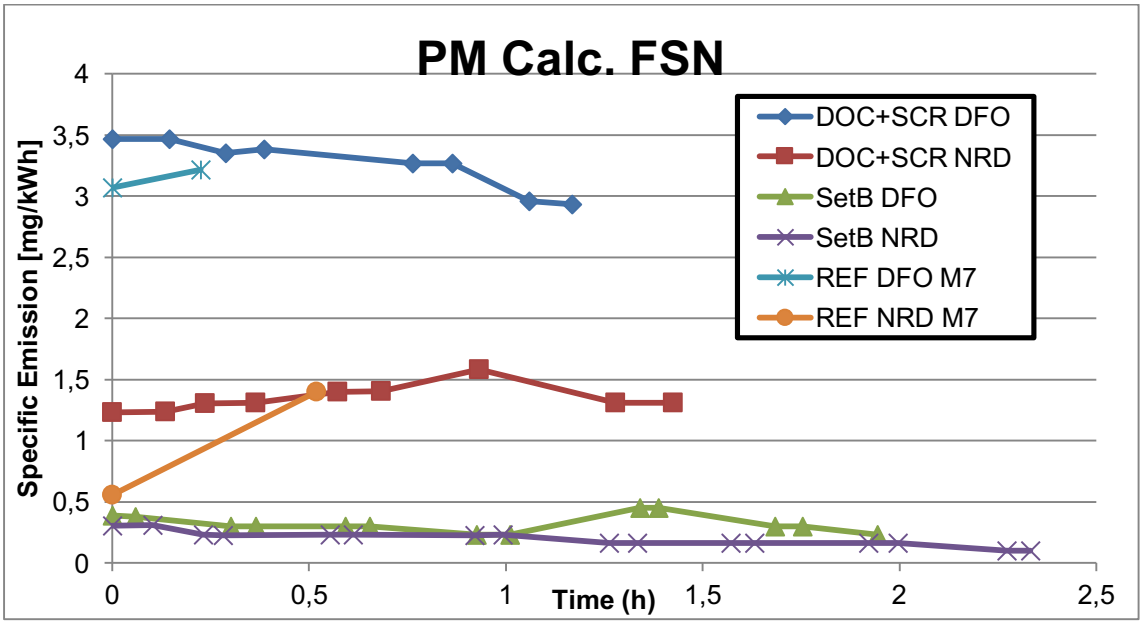


Figure 36 PM emissions in Versus M7

Again, particle matter emissions are greatly reduced in the configuration with the DPF as displayed in the figure.

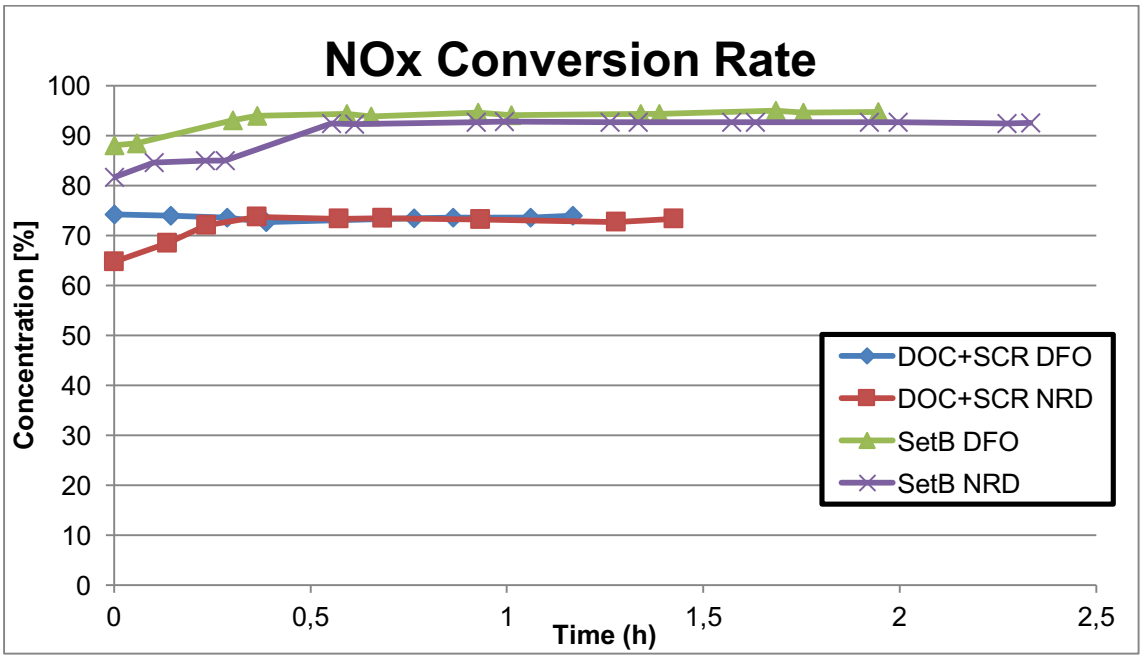


Figure 37 NO_X conversion in Versus M7

Again, NO_X conversion rate seems to be affected by the lack of DPF and efficiency is down almost 20% compared to SetB aftertreatment configuration.

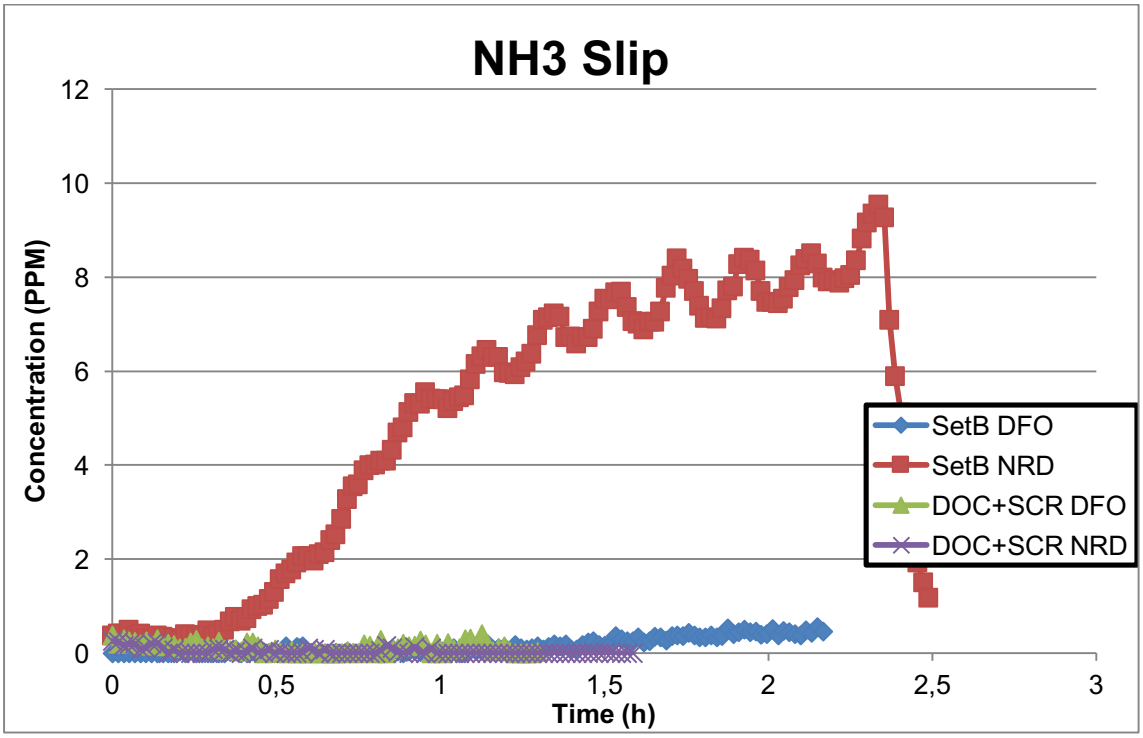


Figure 38 NH_3 Slip After AT in Versus M7

Here you can see the Mode 7 ammonia slip for both SetB and DOC+SCR after-treatment configurations with NRD and DFO fuels. Alpha ratio for DOC+SCR is 0.8 and SetB alpha is 1.1.

Ammonia slips for both DOC+SCR tests are very low with peak slip at about 0.5ppm. Same applies to the SetB DFO test, with only the SetB NRD showing a higher NH_3 slip when compared to others. This is the same result as in measurement 1 (NRD vs. DFO) so it is not a surprise.

Again Figure 37 shows the same rise in NO_X conversion rate as in measurement 1. Because the results for SetB are the same, the explanation from page 26 can be applied here. Alpha ratio was not adjusted from the set value in any part of the measurement.

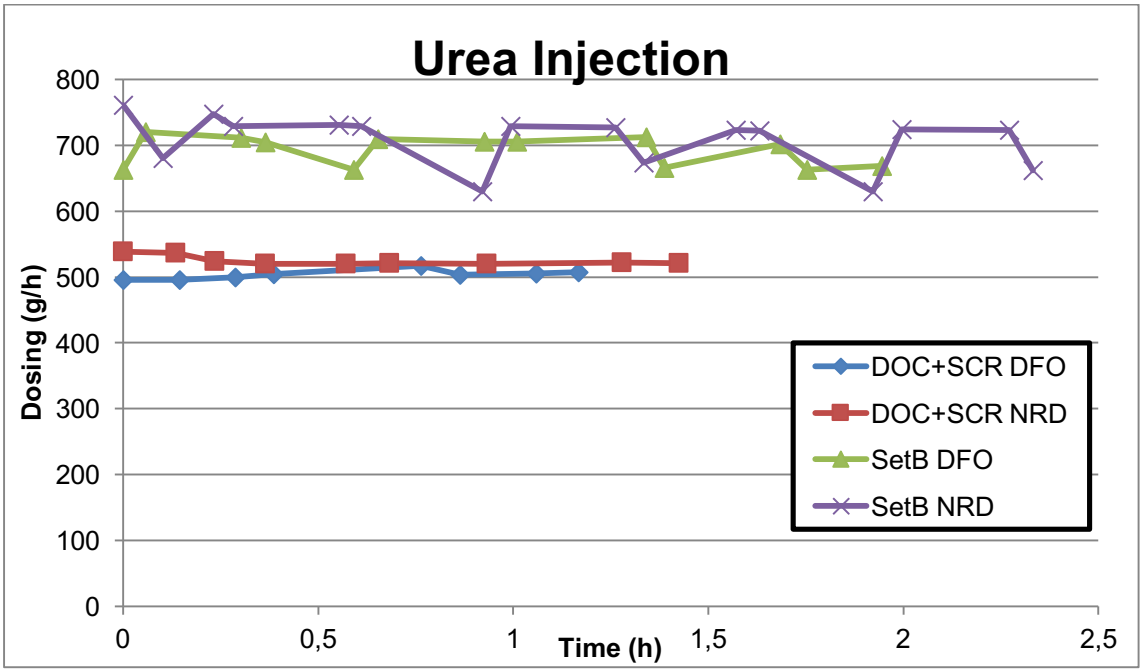


Figure 39 Urea injection quantity in Versus M7

These figures show that there is something wrong with the injection quantity in SetB M7. On the other hand, DOC+SCR injection looks steady and temperatures are in line with SetB as shown in Figure 39.

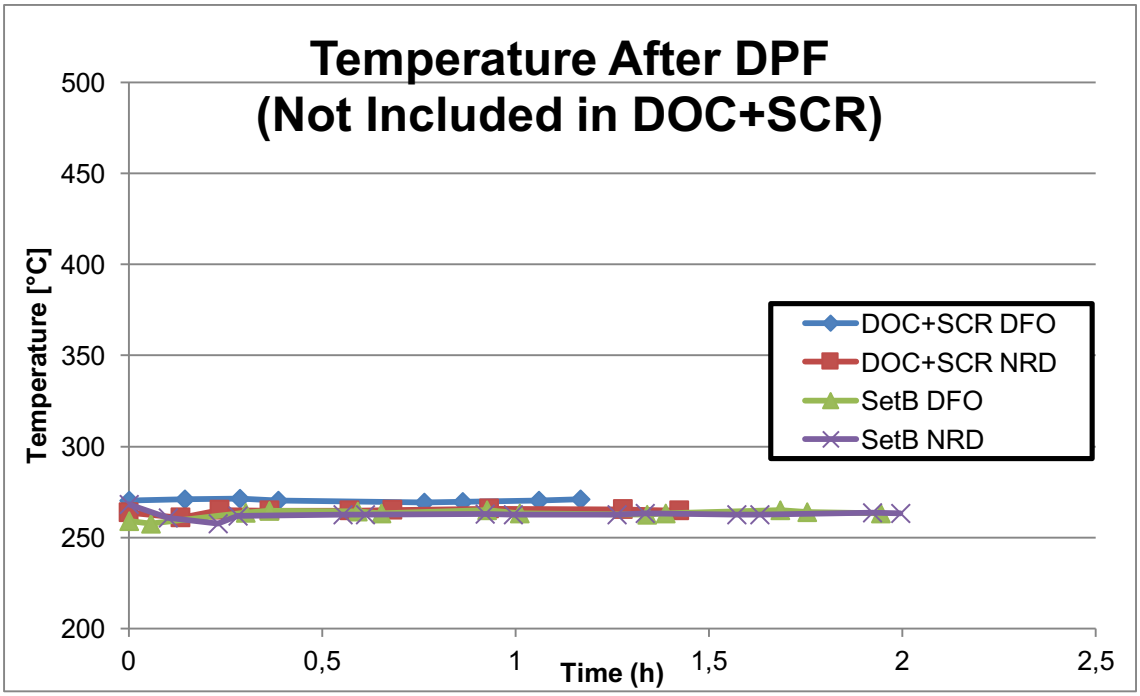


Figure 40 Exhaust gas temp in Versus M7

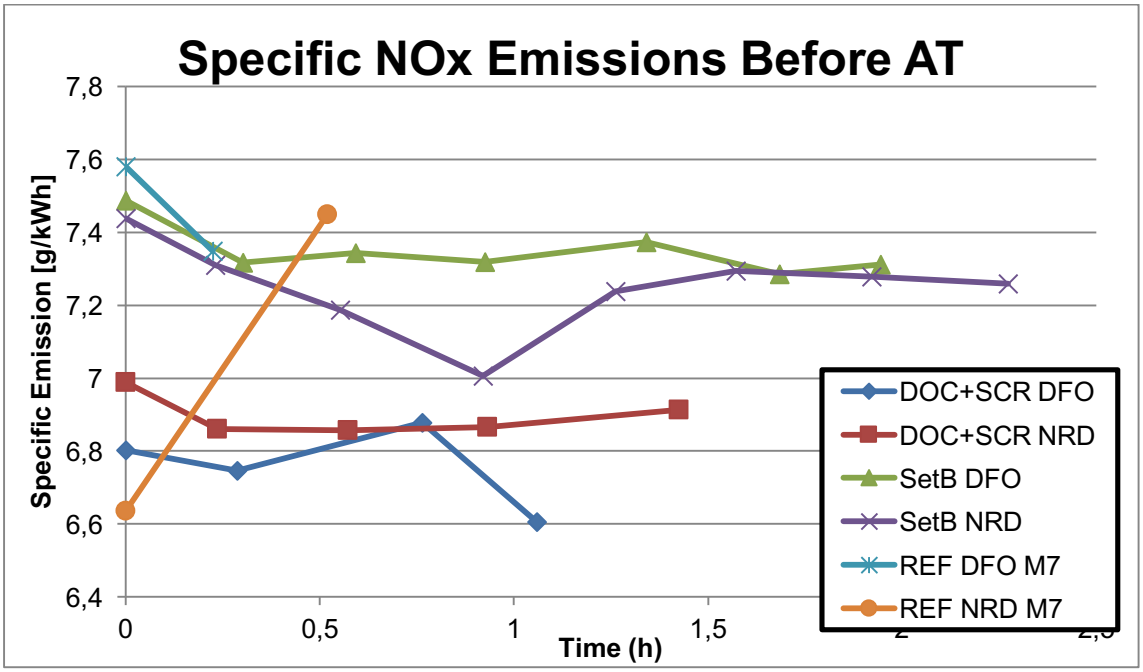


Figure 41 NO_X emissions before AT in Versus M7

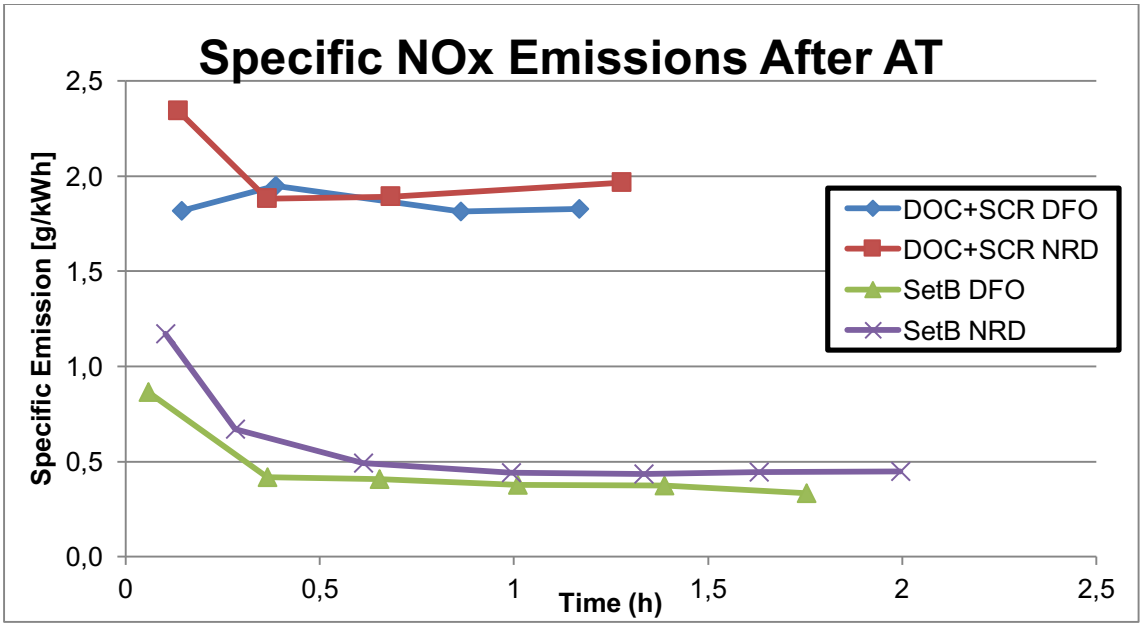


Figure 42 NO_X emissions after AT in Versus M7

NO_X emissions are again greatly reduced after passing the SCR treatment. However, the difference in NO_x conversion rate affects the reducing process and the overall emissions are higher in DOC+SCR configuration, even though its emissions were a bit lower before AT when compared to SetB configuration.

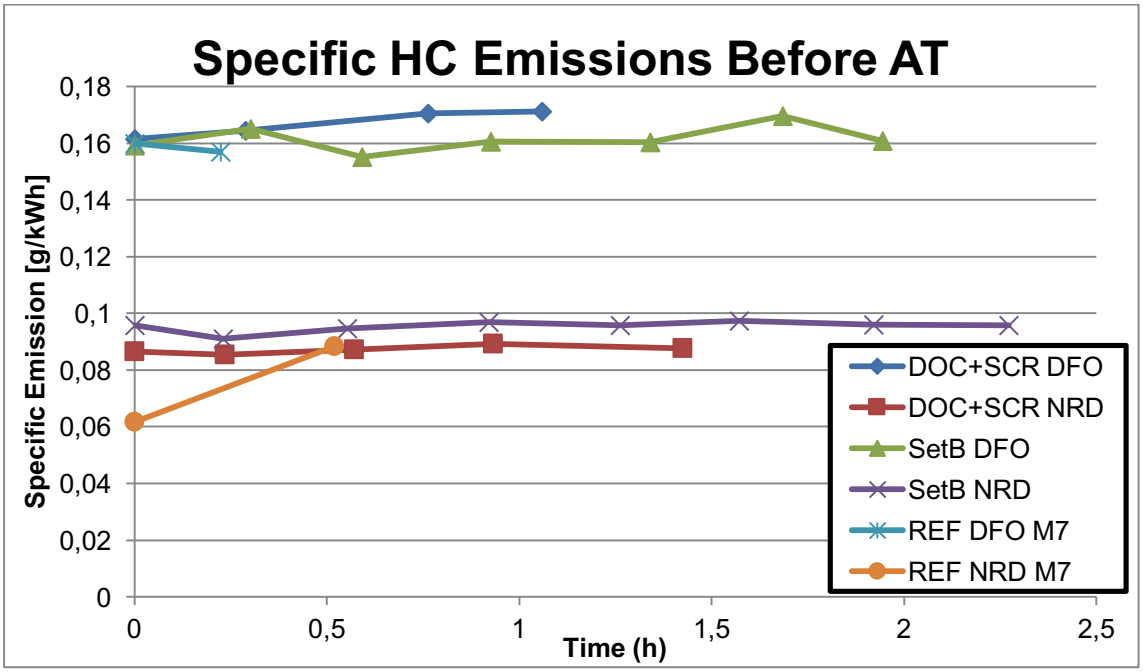


Figure 43 HC emissions before AT in Versus M7

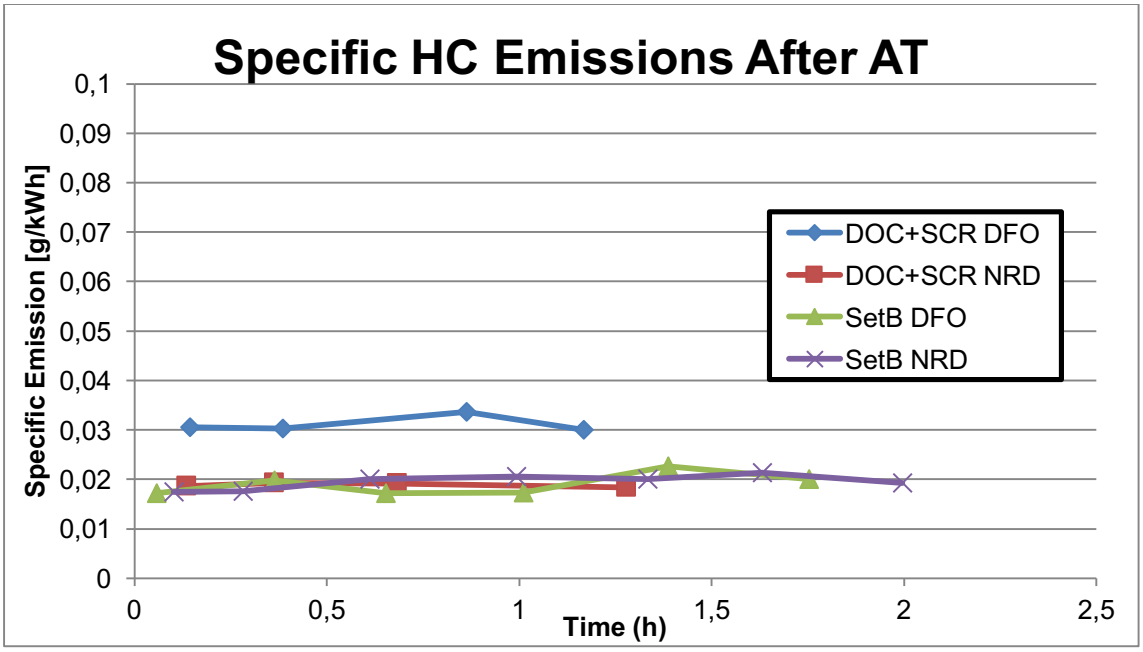


Figure 44 HC emissions after AT in Versus M7

Hydrocarbon emissions before AT range much more widely in M7 testing when compared to M1. In addition, the type of fuel affects the HC emissions greatly. After AT emissions are again reduced to 10% of the raw exhaust gas emissions.

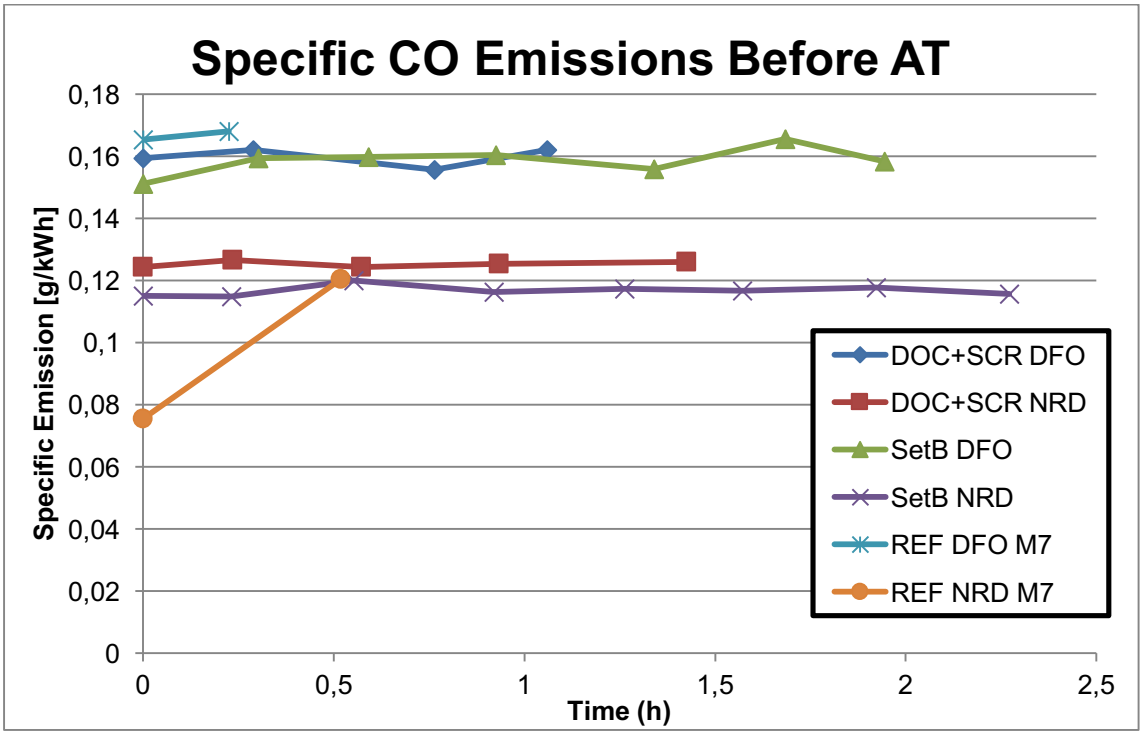


Figure 45 CO emissions before AT in Versus M7

Carbon monoxide emissions follow the same pattern as the M1 measurement. Before AT, emissions of the same fuel type are well lined and the differences between the fuels are not very big.

4.4 Active regeneration

Active regeneration testing and measurement were done as part of the measurement campaign. Measurements were done during a three-day period that included three soot accumulation runs and six regeneration runs. These six regenerations were divided into two different types: two runs for O_2-Regeneration and four runs for NO_2-Regeneration. The first two NO_2 regenerations failed to produce consistent measurement data due to incompatible testing procedure. Shown here are only the latter two of the four NO_2-regenerations.

These tests were done using DFO and engine parameters were altered so that the fuel injection included a late post-injection feeding fuel into the exhaust gas flow, increasing the after DOC temperatures to desired levels for O_2 and NO_2-regenerations. Soot accumulation was done using the data gathered from the soot accumulation setup run done before the start of the measurement campaign and using special engine calibration to boost the buildup. Soot accumulations were done with 2100RPM engine speed and 190Nm engine load and O_2-regenerations with 1500RPM engine speed and 295Nm engine load.

4.4.1 O_2-regeneration (temperature after DOC >500 C°)

Active regeneration with oxygen was conducted on the third day of the active regeneration testing. To succeed in the regeneration, the temperature after DOC must exceed 500 C° so that the oxygen is included in the regeneration process. Lower than 500 C° results in only NO_2 based regeneration, which was the target on NO_2-regeneration. Temperatures were handled by tuning the engine load. Measurements were taken from the same points on the exhaust pipe as in the other tests. See Appendix 1 for more info on the instrument diagram.

O_2-regeneration 1 is done before the soot accumulation to reset the DPF so that previous tests do not affect the soot accumulation and regeneration results. Therefore, the real results are from the O_2-regeneration 2. See Appendix 2 for more info on the devices used by TUT and FMI.

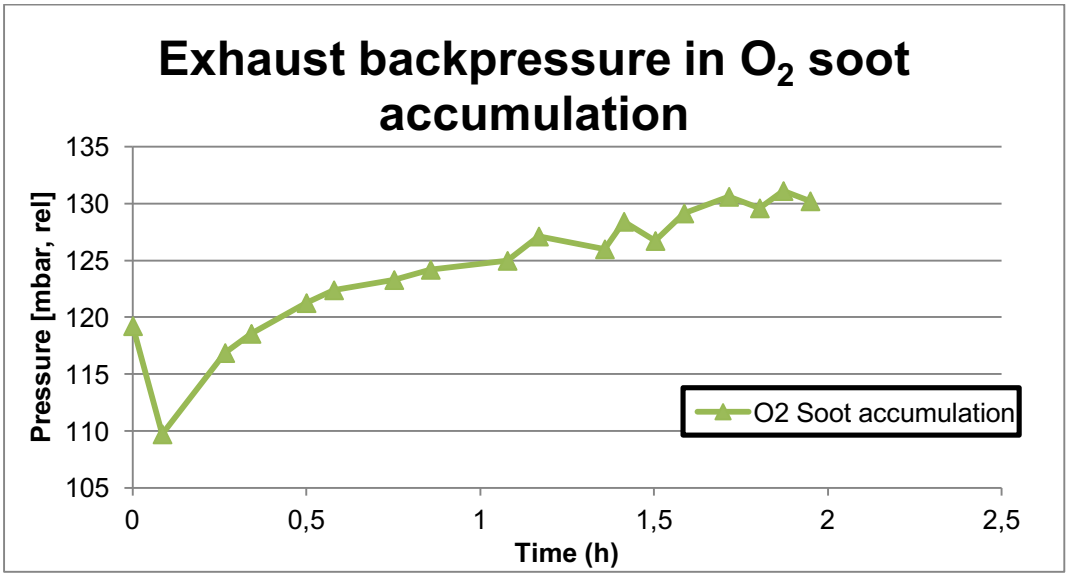


Figure 46 Exhaust Backpressure in O_2 Soot accumulation

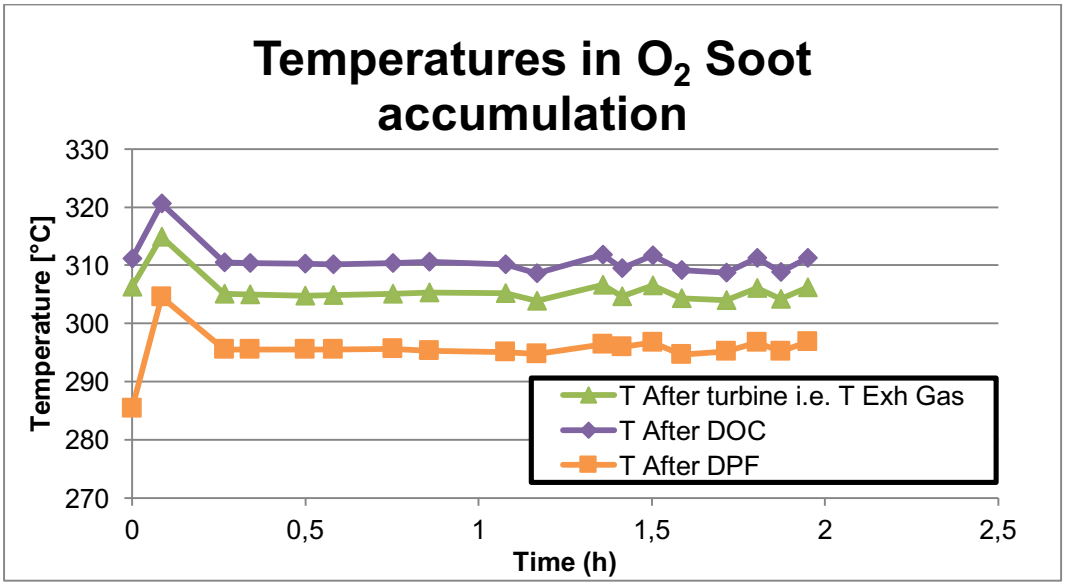


Figure 47 Temperatures in O_2 soot accumulation

Shown here are the temperatures and backpressure from the soot accumulation run. The backpressure figure shows clearly that the DPF is beginning to restrict the exhaust gas flow and the backpressure is increased by almost 30% after about two hours of soot accumulation. Temperatures on the soot accumulation stay fairly even over the two-hour accumulation period.

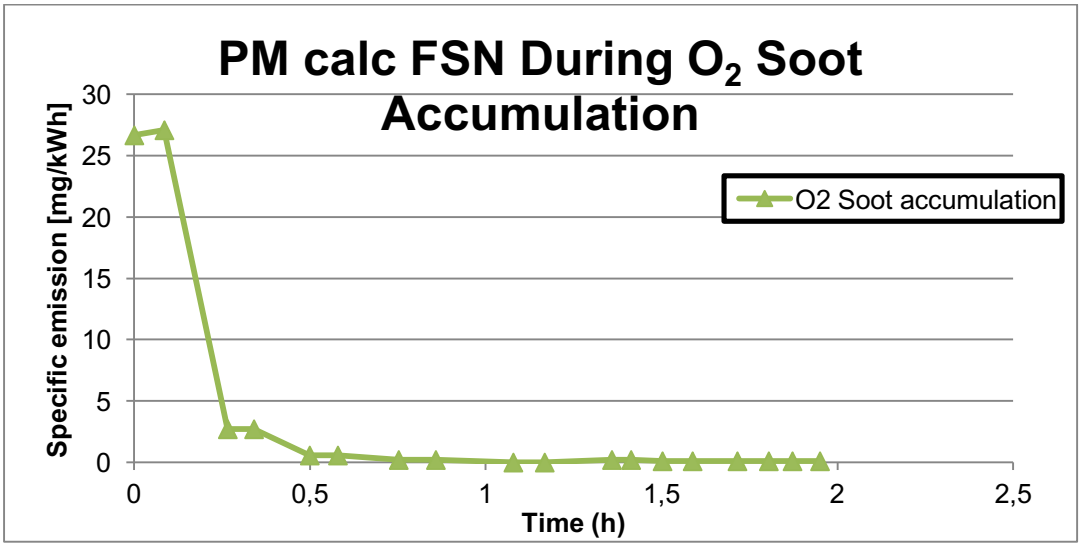


Figure 48 PM emissions in O_2 soot accumulation

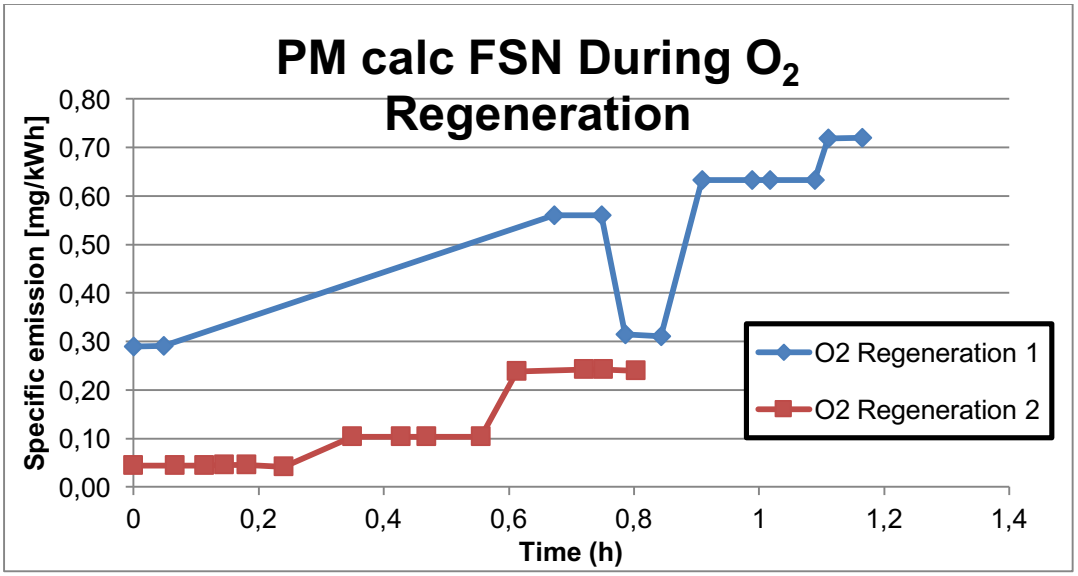


Figure 49 PM emissions in O_2 regenerations

Particle matter emissions during the soot accumulation are reduced to basically zero as can be expected because the soot and other particles are filtered by the DPF. During regeneration, the particle emissions are increased slightly over time. Though polluting, the emissions released during the regeneration are only a fraction of those filtered by the DPF.

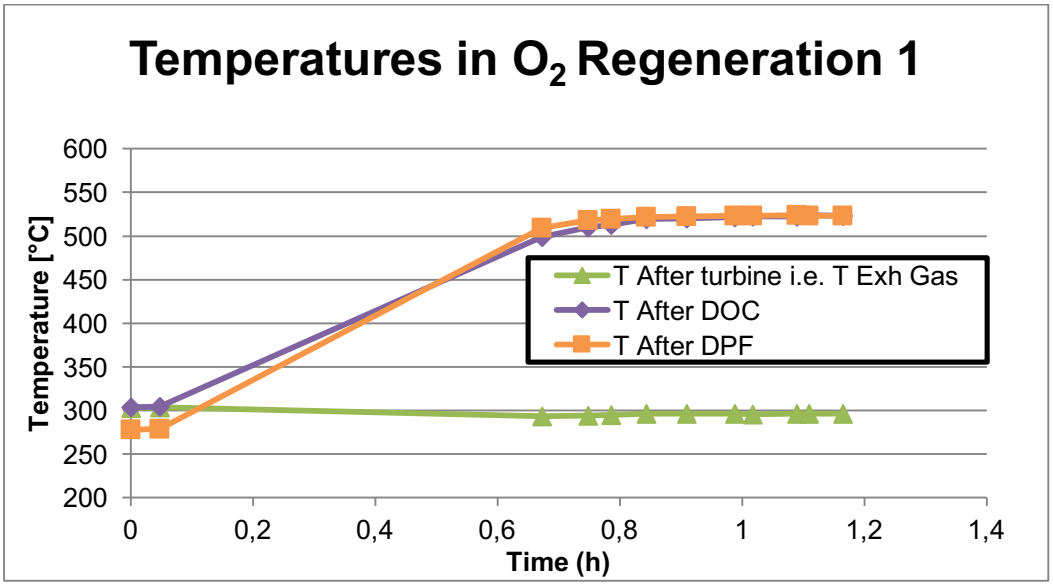


Figure 50 Temperatures in O_2 regeneration 1

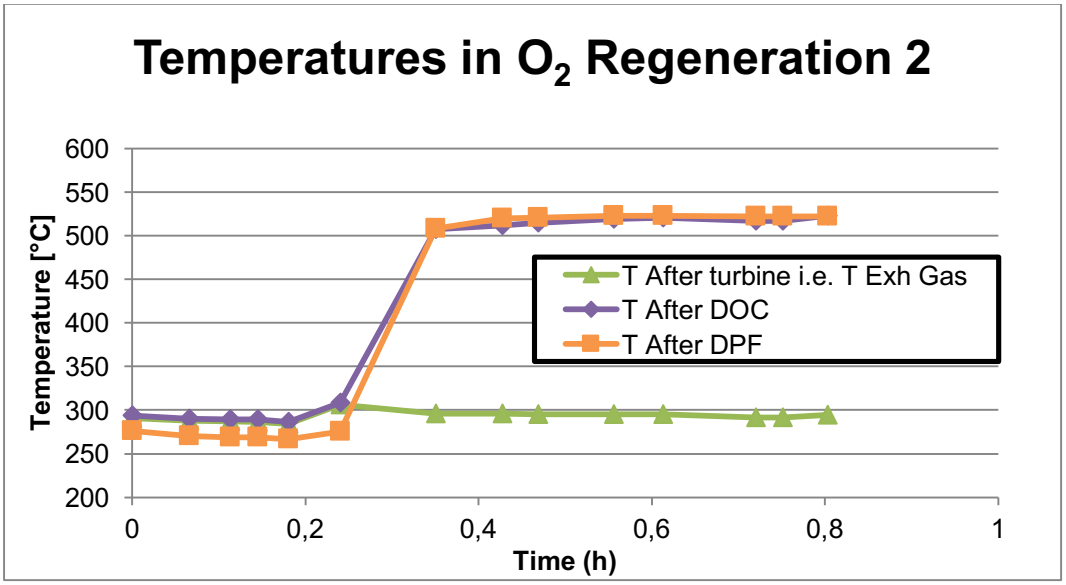


Figure 51 Temperatures in O_2 regeneration 2

Temperatures during the regenerations are very well lined with each other and the desired temperature of 500 C° is achieved and maintained for about 30 minutes in both regeneration runs. These figures also demonstrate the effect of the late post injection of fuel, which raises the temperature of the exhaust gases in the DOC by oxidation.

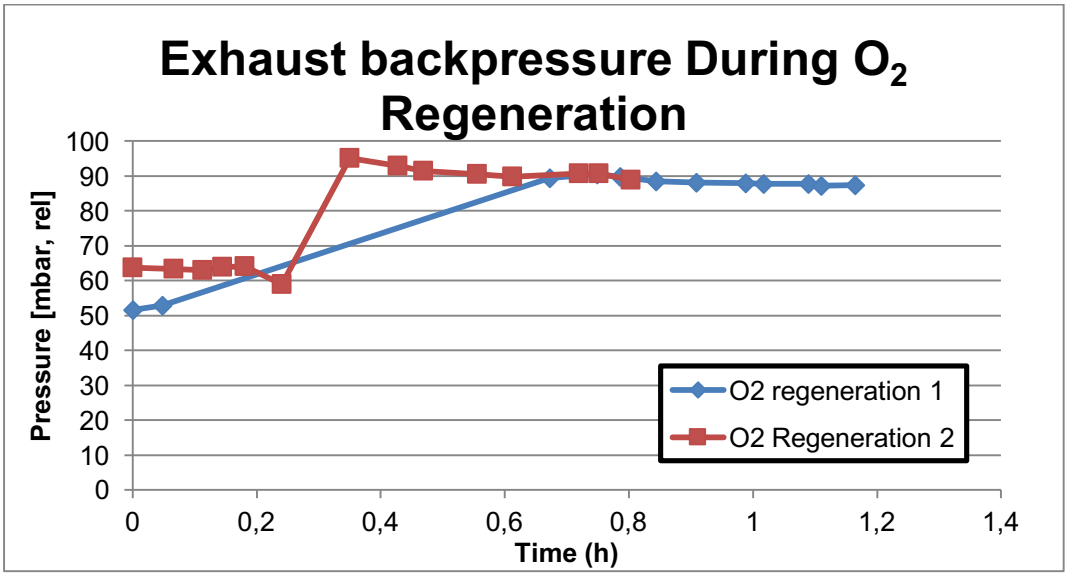


Figure 52 Exhaust backpressure in O_2 regenerations

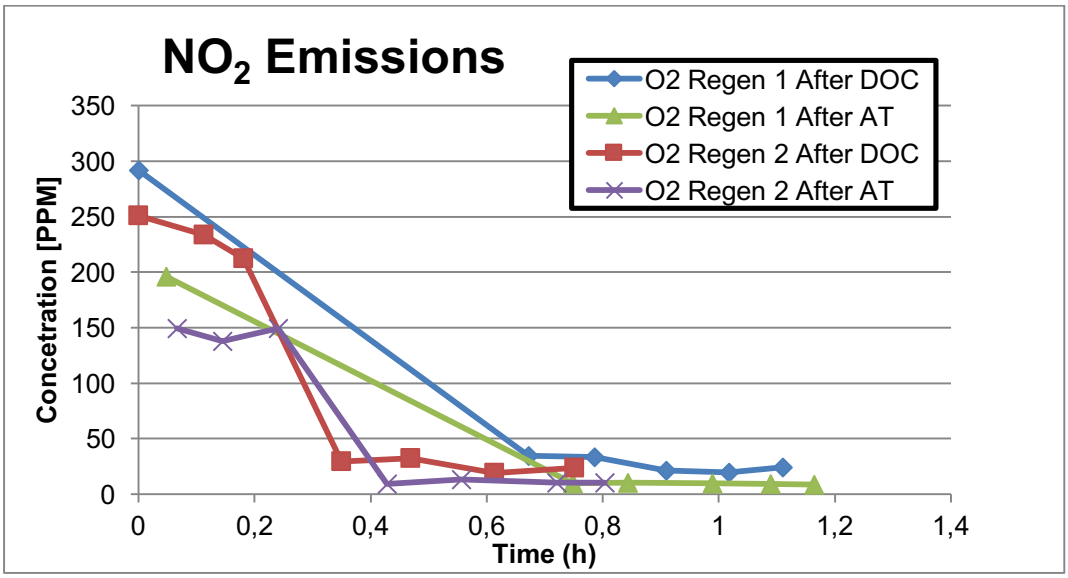


Figure 53 NO_2 emissions in O_2 regenerations

In Figure 48, the exhaust backpressure from the regenerations can be observed and you can notice a small decrease in the backpressure. In both regenerations the rise in backpressure is explained through the start of late post injection. Nitric dioxide emissions are measured so that regeneration through NO_2 oxidation can also be taken into account. It also seems that the start of LPI and the rise in temperature affects the NO_2 production greatly.

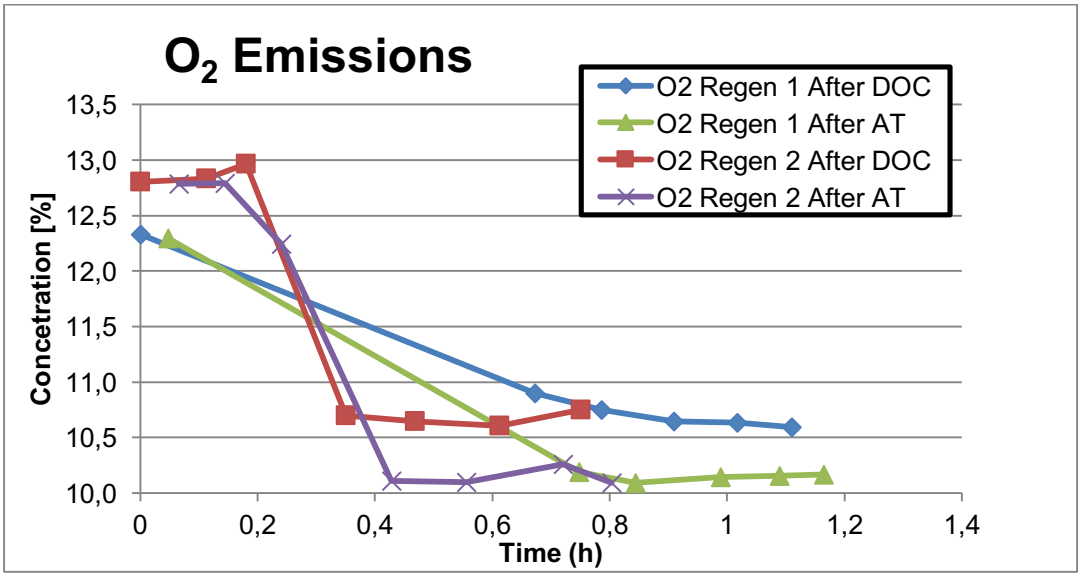


Figure 54 O_2 emissions in O_2 regenerations

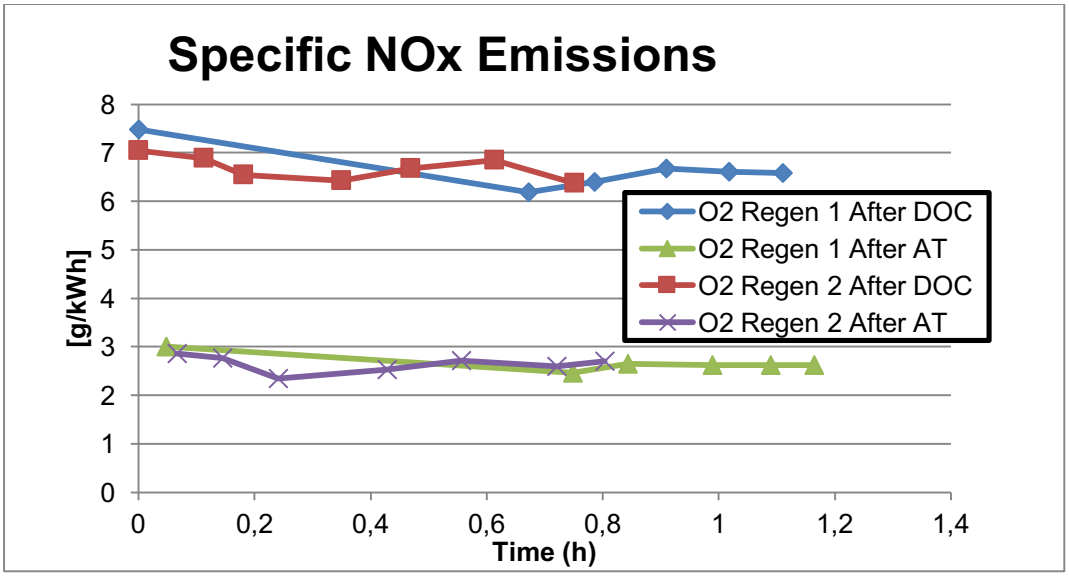


Figure 55 NO_X emissions in O_2 regenerations

Shown here are the oxygen and nitric oxide emissions. Oxygen emissions show a notable decrease in concentration after AT when comparing to after DOC. This also serves as a good indication of the regeneration process having started inside the DPF, oxidizing soot into CO and CO_2.

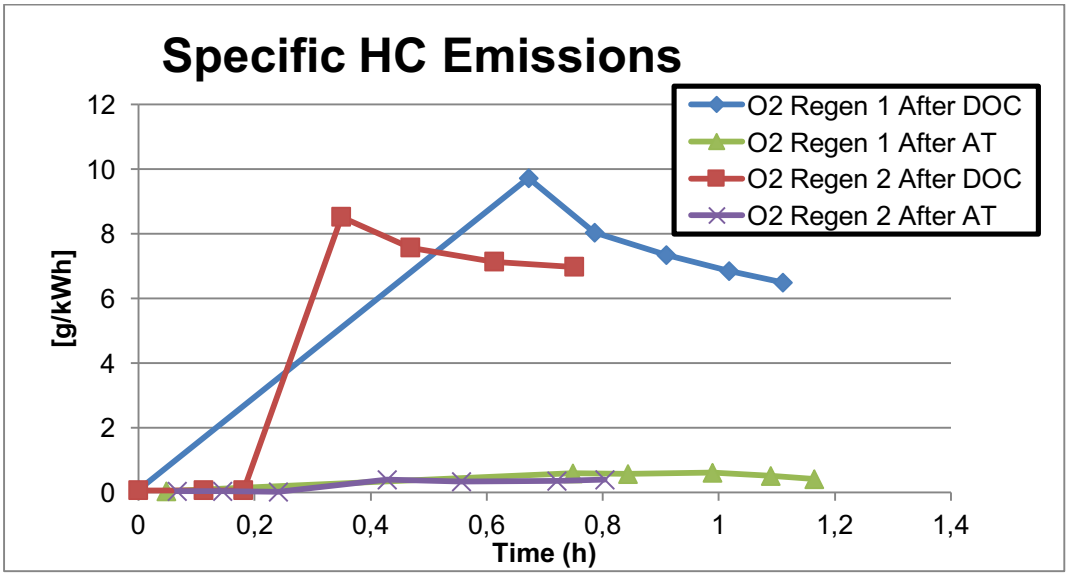


Figure 56 HC emissions in O_2 regenerations

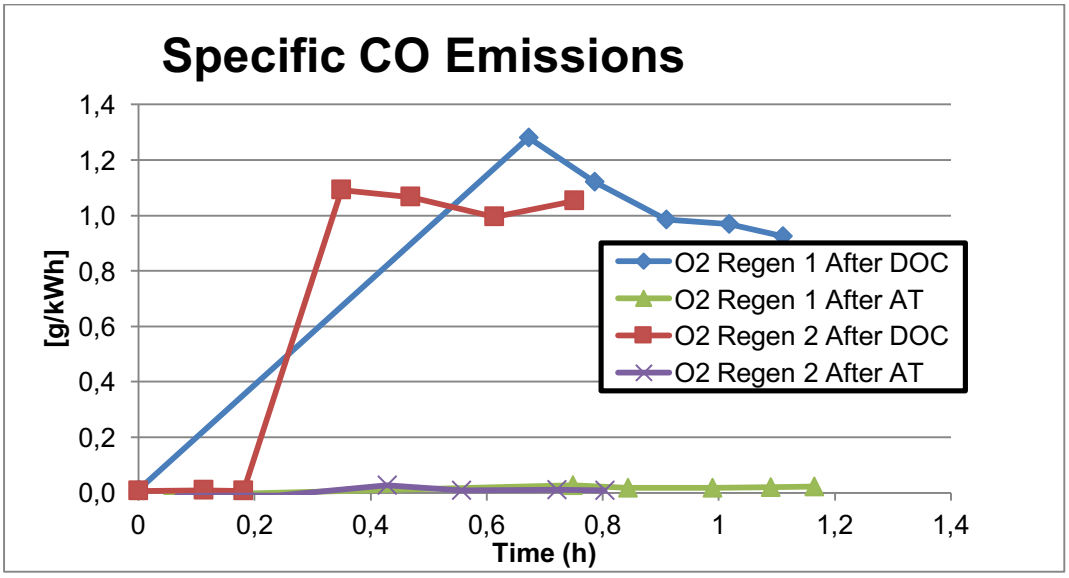


Figure 57 CO emissions in O_2 regenerations

Emissions of hydrocarbons and carbon oxide are increased significantly in the regeneration, but this was to be expected as the late post injection adds unburnt fuel to the exhaust flow and the regeneration process produces carbon oxides as a product.

4.4.2 NO_2-regeneration (temperature after DOC 400 C°<T<500 C°)

NO_2-regeneration testing was conducted on the second day of the active regeneration testing. Testing was done using the same engine speed (1500RPM) and engine load (295Nm) as in the O_2-regeneration testing. Late-post injection was altered to achieve the temperature desired. Regeneration and soot accumulation was done using DFO.

Regeneration through the use of NO_2 emission requires a lower temperature (400 C°<T<500 C°) than the O_2-regeneration but has other negative sides when compared to O_2. NO_2 emissions normally found on the exhaust gas flow are not sufficient to be used in the DPF regeneration process and therefore its concentration must be increased by using a NO_2 catalyst before the DPF.

NO_2-regeneration should show a decrease in NO_2 concentrations after DPF, also the oxygen concentration will be lower due to introduction of more CO and CO_2 to the exhaust flow through the regeneration process. As in the O_2-regeneration, NO_2 regeneration 1 was used to ensure that the DPF was reset to a comparable state before the soot accumulation so that the results would not be affected by previous tests and soot accumulations. Again, the measurements were taken from the same points as in the other tests. See Appendix 1 for info on the instrument diagram and Appendix 2 for more info on devices used by TUT and FMI.

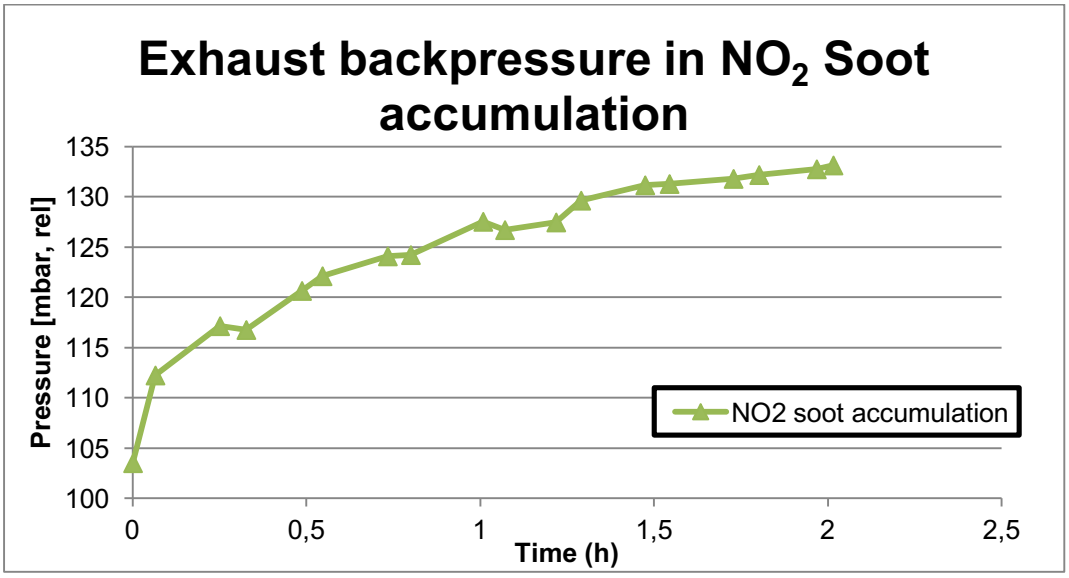


Figure 58 Exhaust backpressure in NO_2 soot accumulation

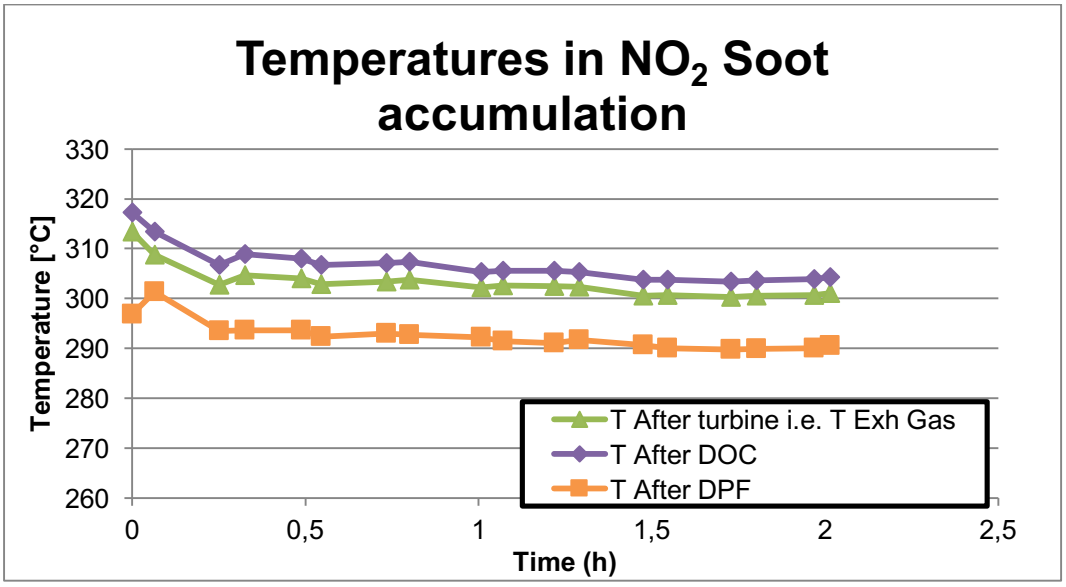


Figure 59 Temperatures in NO_2 soot accumulation

NO_2 soot accumulation follows the same pattern as the O_2 soot accumulation. Temperatures are fairly even throughout the accumulation period and are consistent with those of O_2 soot accumulation. Exhaust backpressure is again building up fairly evenly across the accumulation and in the end it is almost 30% higher than in the beginning. This is a significant rise and clearly demonstrates the need of regeneration in the DPF.

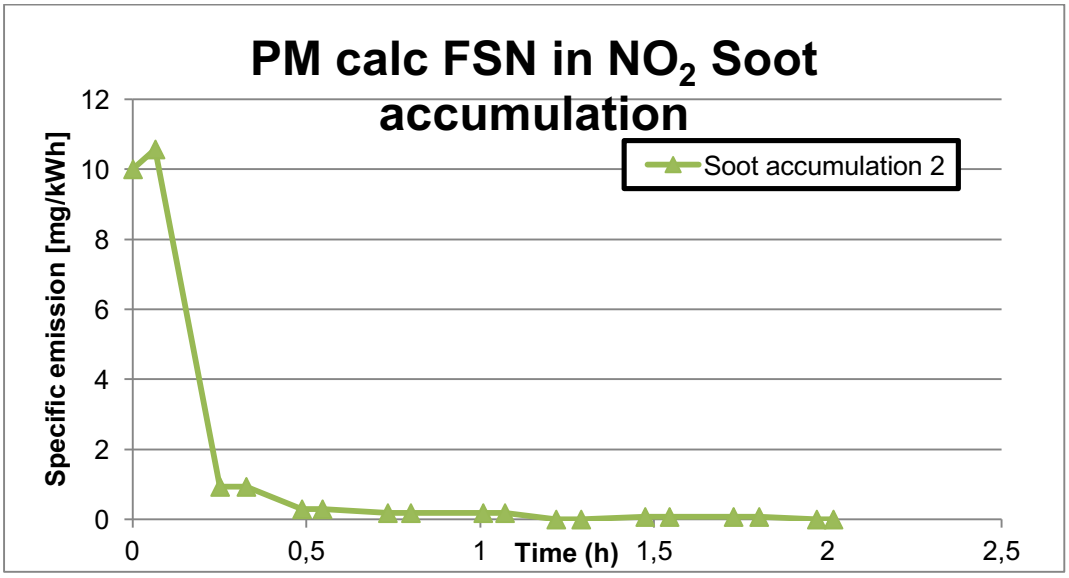


Figure 60 PM emissions in NO_2 soot accumulation

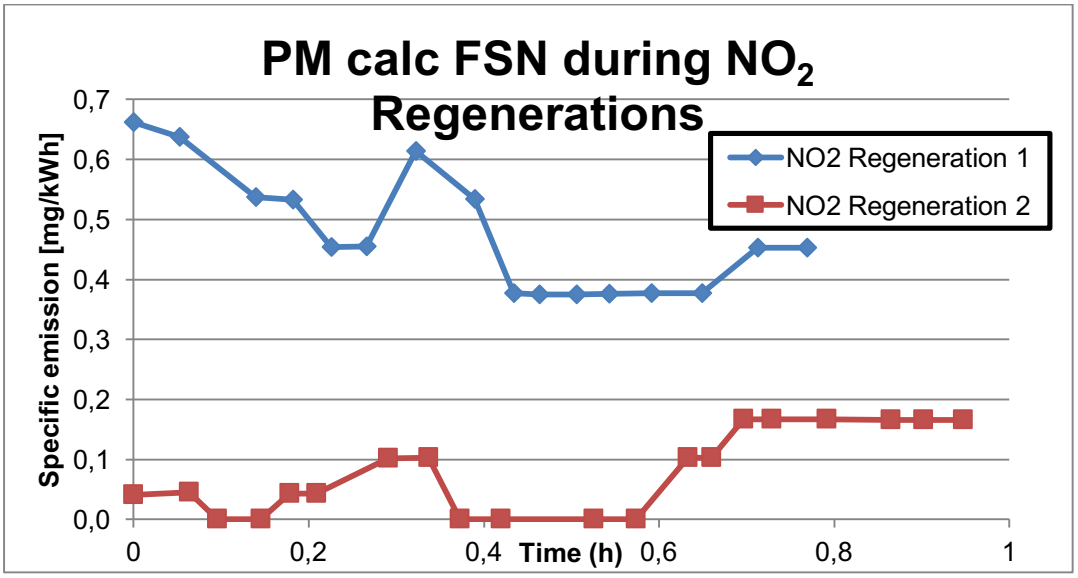


Figure 61 PM emissions in NO_2 regenerations

Particle matter emissions are in line with both O_2 soot accumulation and regeneration.

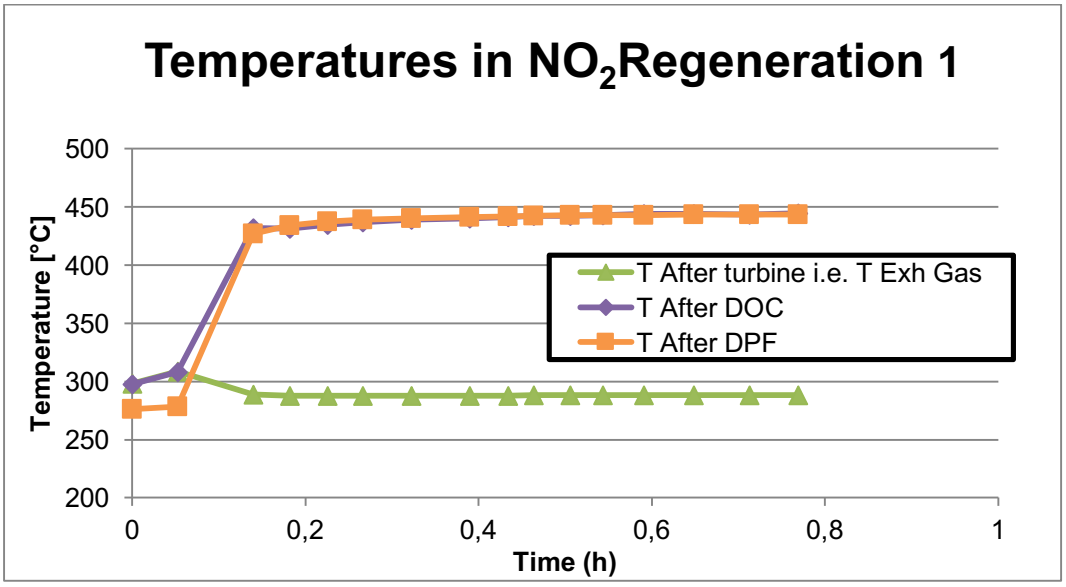


Figure 62 Temperatures in NO_2 regeneration 1

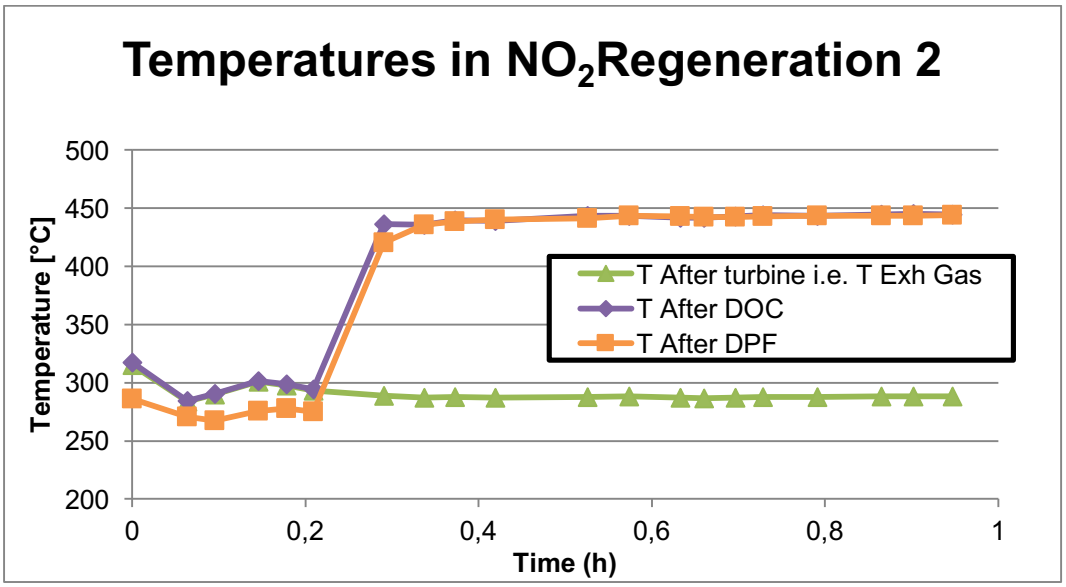


Figure 63 Temperatures in NO_2 regeneration 2

Temperatures in both of the regenerations are right in the middle of the target zone and they are maintained for over 30 minutes. Again it can be seen that the late-post injection of fuel raises the temperatures of the exhaust flow only after DOC.

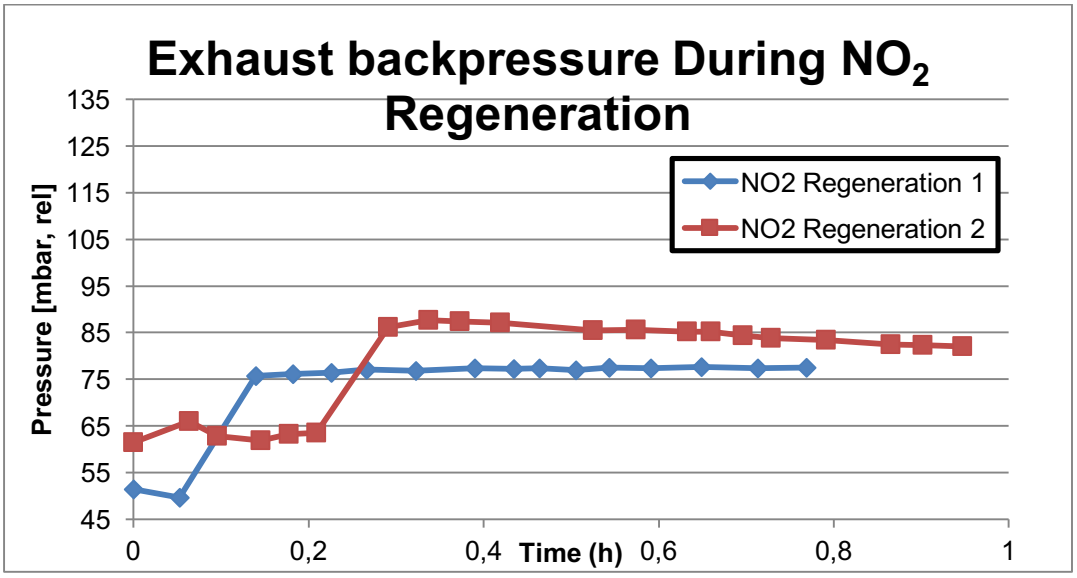


Figure 64 Exhaust backpressure in regenerations

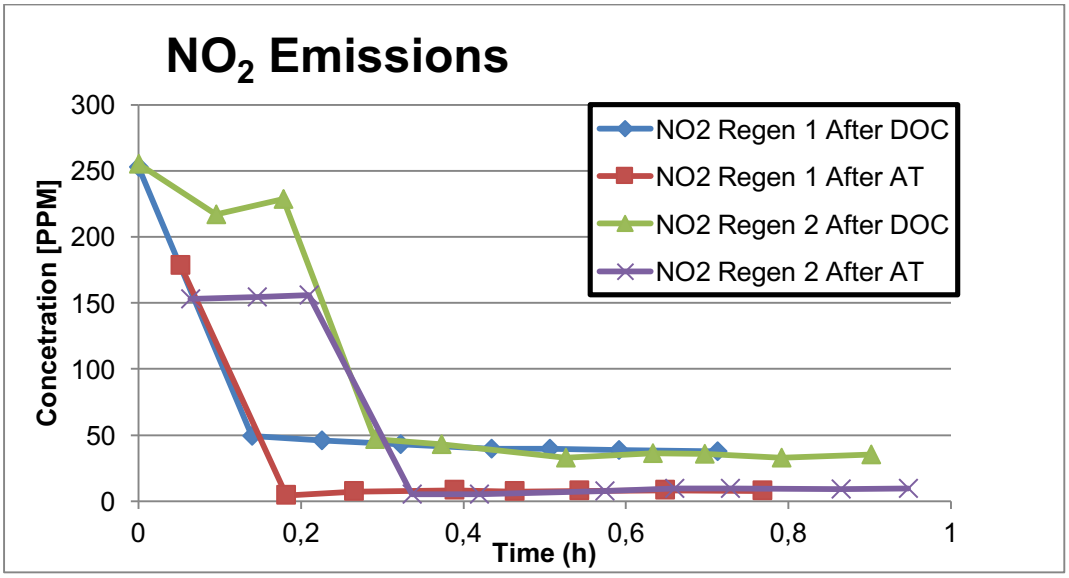


Figure 65 NO_2 emissions in NO_2 regenerations

Shown here are the exhaust backpressure of both of the regenerations and there is a noticeable decrease in the regeneration 2 backpressure. Regeneration 1 does not show any decrease because it was done after the first set of O_2-regenerations. Again, the increase in the backpressure can be explained with the start of LPI. Nitric dioxide emissions also show a noticeable decrease in concentration further confirming that the regeneration is happening.

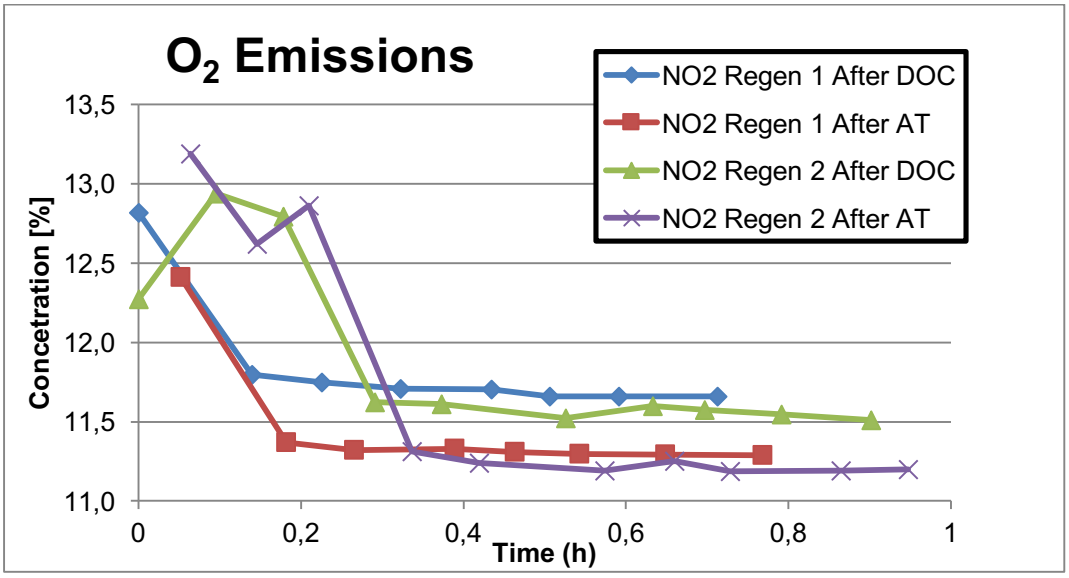


Figure 66 O_2 emissions in NO_2 regenerations

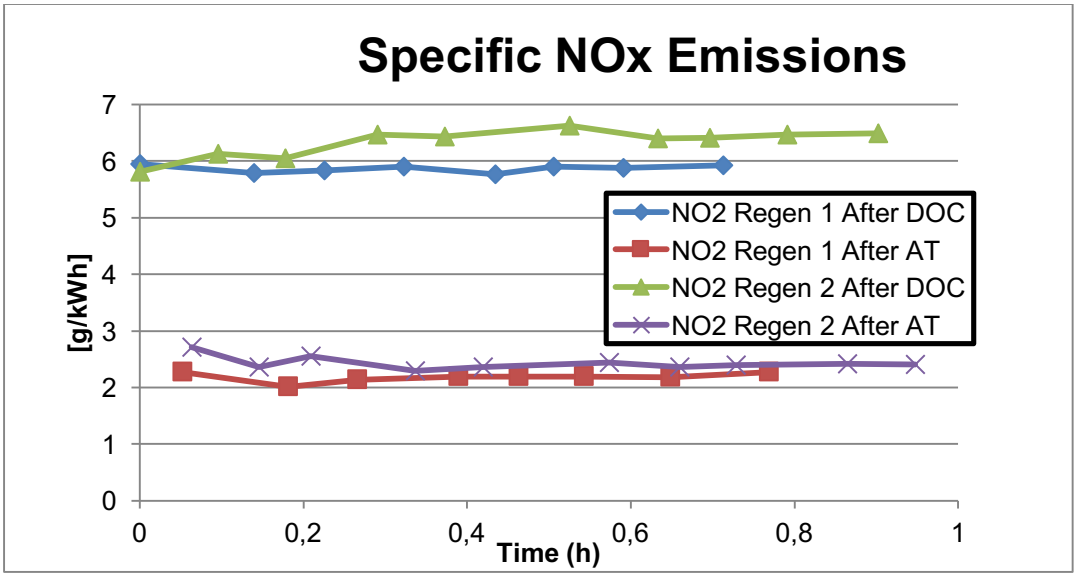


Figure 67 NO_X emissions in NO_2 regenerations

Oxygen emissions decrease as predicted due to increased carbon monoxide and carbon dioxide emissions. Though it is not as significant as in the O_2-regeneration where the concentration evened out at about 10% concentration. Nitric oxide emissions are in line with O_2-regenerations.

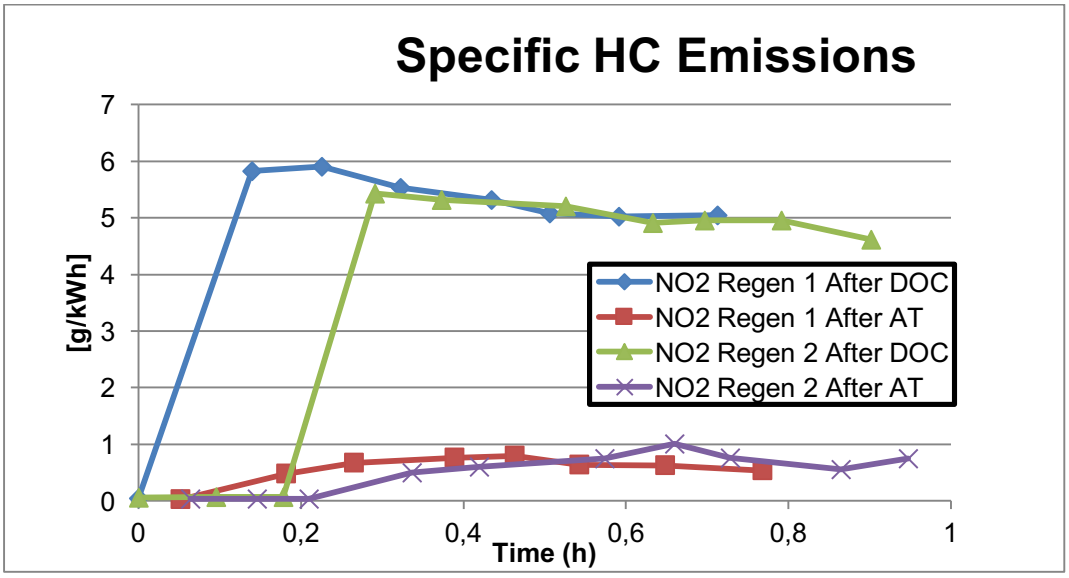


Figure 68 HC emissions in NO_2 regenerations

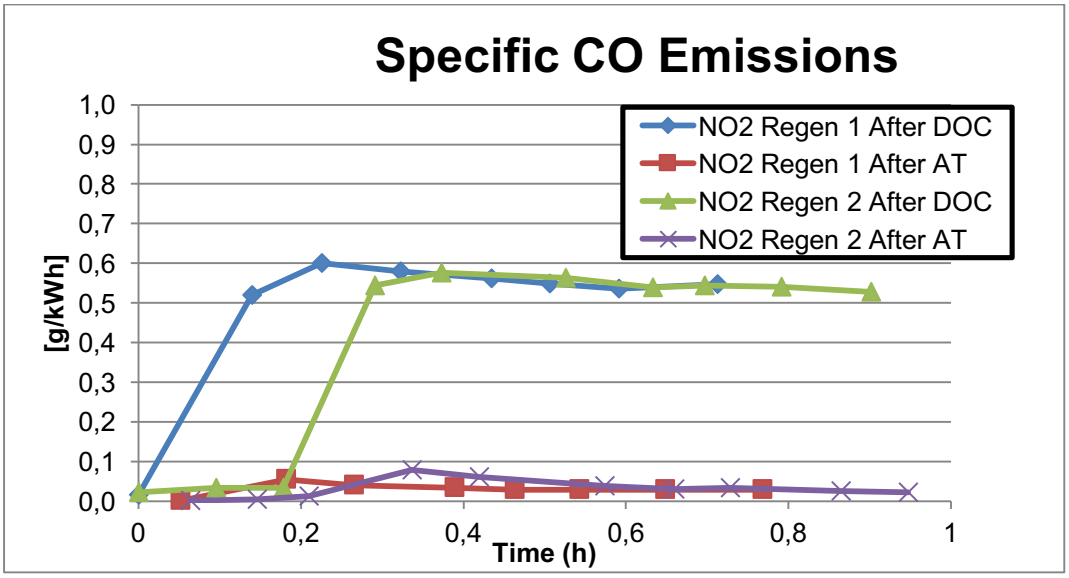


Figure 69 CO emissions in NO_2 regenerations

Hydrocarbon and carbon monoxide emissions are increased after the start of the regeneration and are again the products of late-post injection of fuel and the oxidization in the DPF.

5 SUMMARY

This measurement campaign was part of the HERE Project funded by the TEKES FiDiPro Programme and its aim was to understand exhaust particle emissions and ways to reduce them to be able to help propose right kind of aftertreatment systems for different types of diesel engines, and at the same time try not to significantly lower the energy efficiency and performance of the engine or even improve it. The project also intends to provide more information and knowledge to legislators, hence possibly having an effect on emissions legislation.

This study has concentrated on the regeneration of diesel particulate filter, emission reduction of two different aftertreatment systems: SetB (DOC, DPF and SCR) and DOC+SCR and the differences between normal diesel fuel oil and Neste's NRD. This study and the intensive measurement campaign are based on the findings of the first part of this project, conducted in spring 2015. That study can be accessed in the form of a thesis written by Georgios Rolis, named "Experimental study of an off-road engine with respect to gaseous and particulate emissions over different exhaust aftertreatment configurations". For example, SetB name for one of the aftertreatment configurations carried over from the first part of the project and the same loadpoints of the ISO 8178 C1 test were used to measure the emissions during the test runs.

This thesis is made up of two parts: short theoretical section, which takes a look at the emissions found from a normal diesel engine's raw exhaust gas and different types of aftertreatment equipment used to reduce them, and a measurement data presentation and analysis. Data is first presented in form of figures and any significant abnormalities are explained. This also includes a small comparison of the results between the different fuels and aftertreatment systems. After that there is a short discussion section before the conclusion of the thesis.

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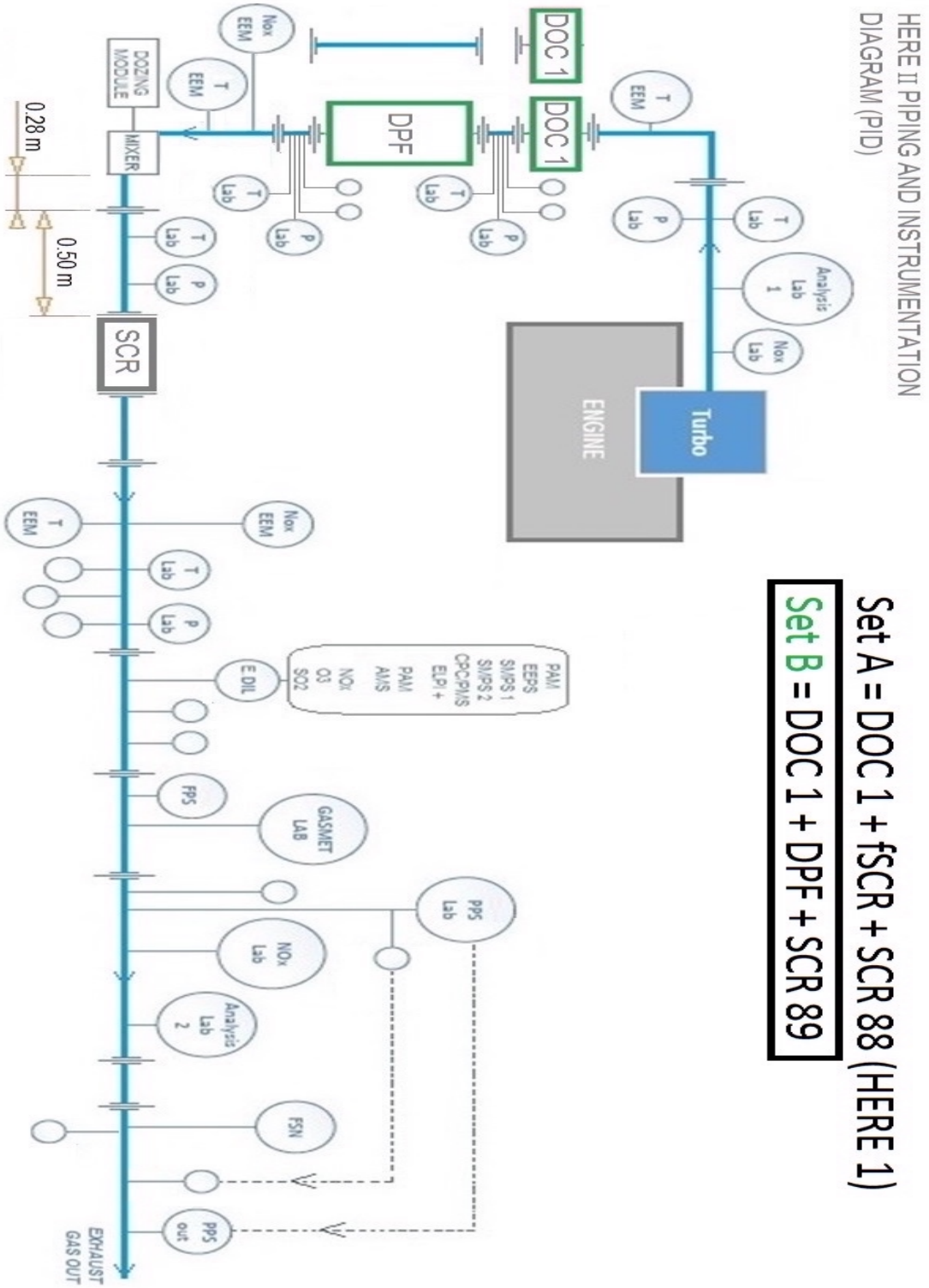
Georgios Rolis, experimental study of an off-road engine with respect to gaseous and particulate emissions over different exhaust aftertreatment configurations, 26.10.2016, 2015

Turku University of Applied Sciences, http://www.turkuamk.fi/fi/tutkimus-kehitys-ja-innovaatiot/hae-projekteja/here/, 27.10.2016, 2015

Appendix 1: Piping and Instrument diagram of the test setup



Appendix 2: Measurement test table

Date	6.4.	7.4.	8.4.	12.4.	13.4.	14.4.	15.4.	18.4.	19.4.
Measurement test	Reference DFO	Reference NRD	Meas1 SetB DFO	Regeneration O2 (failed)	Regeneration NO2	Regeneration O2	Meas1 SetB NRD	DOC+SCR DFO	DOC+SCR NRD
Parties included	TUT, FMI	TUT, FMI	TUT, FMI	TUT, FMI	TUT, FMI	TUT, FMI	TUT, FMI	TUT, FMI	TUT, FMI
eELPI	x	x	x	x	x	x	x	x	
EEPS	x	x	x	x	x	x	x	x	
SMPS	x2	x2	x2	x2	x2	x2	x2	x2	
CPC/PSM	x	x	x	x	x	x	x	x	
ELPI+	x	x	x	x	x	x	x	x	
PAM	x2	x2	x2	x2	x2	x2	x2	x2	
AMS	x	x	x	x	x	x	x	x	
PM-Collection									
Nox-analysator (+NH4)	x	x	x	x	x	x	x	x	
O3-analysator	x	x	x	x	x	x	x	x	
SO2-Analysator									
CO+CO2 -analy-sator	x	x	x	x	x	x	x	x	

Appendix 3: Alpharatio Table

Measurement	Used aftertreatment setup	Used alpharatio
Meas 1 DFO M1	SetB	0,95
Meas 1 DFO M7	SetB	1,1
Meas 1 NRD M1	SetB	0,95
Meas 1 NRD M7	SetB	1,1
DOC+SCR DFO M1	DOC+SCR	0,8
DOC+SCR DFO M7	DOC+SCR	0,8
DOC+SCR NRD M1	DOC+SCR	0,8
DOC+SCR NRD M7	DOC+SCR	0,8

Table of the used Alpharatio values during each measurement and Aftertreatment setup

Appendix 4: Fuel Oil Analysis

NESTE

Tulostiedoite
TS-16-004255

7.12.2016

Asiakas

Panu Aho
Turun Ammattikorkeakoulu Oy Sepänkatu 1 20700 Turku

Aihe

Moottoripolttoöljynäytteet

Näytteet

	Nimike	Kohde	Näytteenottopaikka	Näytteenottoaika	Näytetunnus
1.	MUU	Tutk.näyte ulk (Ana)		11.11.2016	04005884
	DFO 033 / Turun amk:n moottoripolttoöljynäyte, näyte saapunut 11.11.2016, HERE				
2.	MUU	Tutk.näyte ulk (Ana)		11.11.2016	04005885
	DFO 034 / Turun amk:n moottoripolttoöljynäyte, näyte saapunut 11.11.2016, HERE				
3.	MUU	Tutk.näyte ulk (Ana)		11.11.2016	04005886
	DFO 035 / Turun amk:n moottoripolttoöljynäyte, näyte saapunut 11.11.2016, HERE				
4.	MUU	Tutk.näyte ulk (Ana)		11.11.2016	04005887
	DFO 036 / Turun amk:n moottoripolttoöljynäyte, näyte saapunut 11.11.2016, HERE				
5.	MUU	Tutk.näyte ulk (Ana)		11.11.2016	04005888
	NEXBTL / Turun amk:n moottoripolttoöljynäyte, näyte saapunut 11.11.2016, HERE				

Tulokset

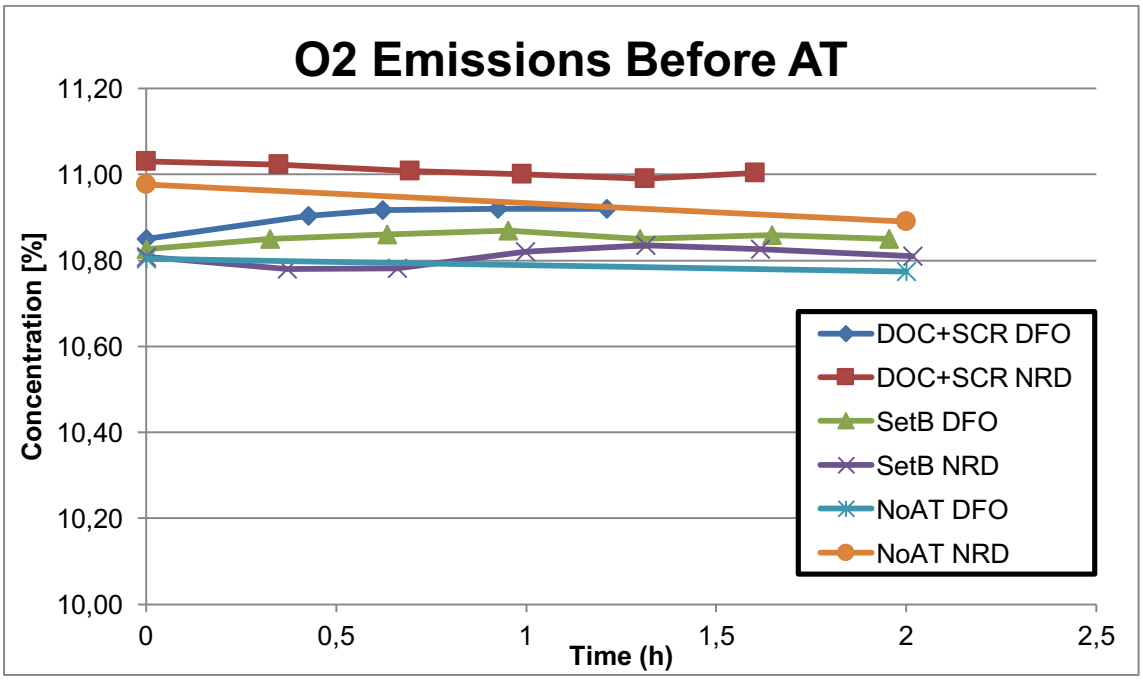
Ominaisuus	Menetelmä	Yksikkö	Näyte 1.	Näyte 2.	Näyte 3.	Näyte 4.	Näyte 5.
Tiheys 15°C	ENISO12185	kg/m3	841,7	842,3	842,4	841,4	780,0
Tuhka 775°C öljytuotteista	ENISO6245	wt-%	0,001	0,001	<0,001	<0,001	<0,001
Setaaniluku moottorilla	ENISO5165		52,4	52,5	52,6	52,5	
Monoaromaatit	EN12916	wt-%	25,1	26,2	26,4	25,1	0,3
Diaromaatit	EN12916	wt-%	3,2	4,2	4,3	4,7	<0,1
Tri+ aromaatit	EN12916	wt-%	0,34	0,52	0,50	0,58	<0,02
Polyaromaatit	EN12916	wt-%	3,5	4,8	4,8	5,3	<0,1
Aromaatit	EN12916	wt-%	28,6	30,9	31,2	30,4	0,3
Lämpöarvo kalorimetrinen	ASTMD4809	MJ/kg	45,662	45,693	45,779	45,826	47,250
Teh. lämpöarvo (vety määritetty)	ASTMD4809	MJ/kg	42,833	42,881	42,954	43,344	44,033
Kokonaistyppi, öljytuotteet	ASTMD4629	mg/l	21	20	21	16	0,7
Hiili, C, öljytuotteista	ASTMD5291	wt-%	86,1	86,0	86,2	79,1	84,8
Vety, H, öljytuotteista	ASTMD5291	wt-%	13,3	13,3	13,3	11,7	15,2
Setaaniluku IQT-analysaattorilla	ASTMD6890						77,0
Näytteen vastaanotto ja hävitys	LISÄTYÖ		ok	ok	ok	ok	ok
Rikki, (XRF)	NM380	mg/kg	7,0	10,0	9,0	10,0	11,0

Elektroninen hyväksyntä

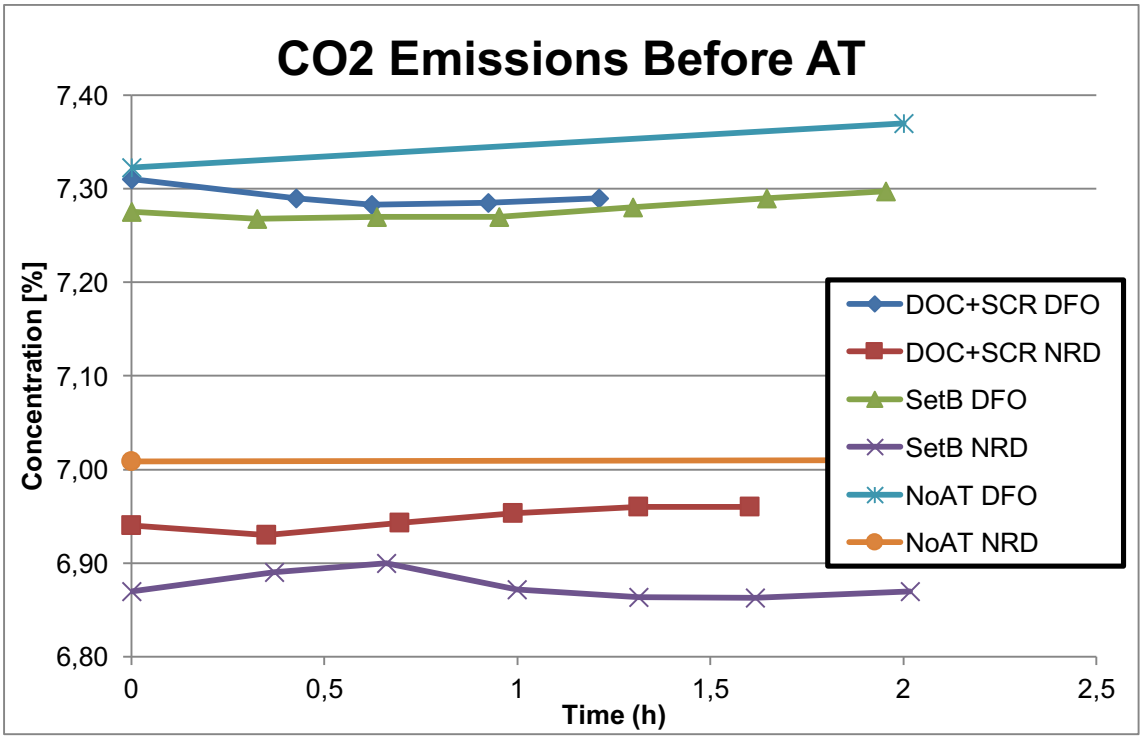
Laatija

Mari Pesonen
Laboratorioesimies
mari.pesonen@neste.com

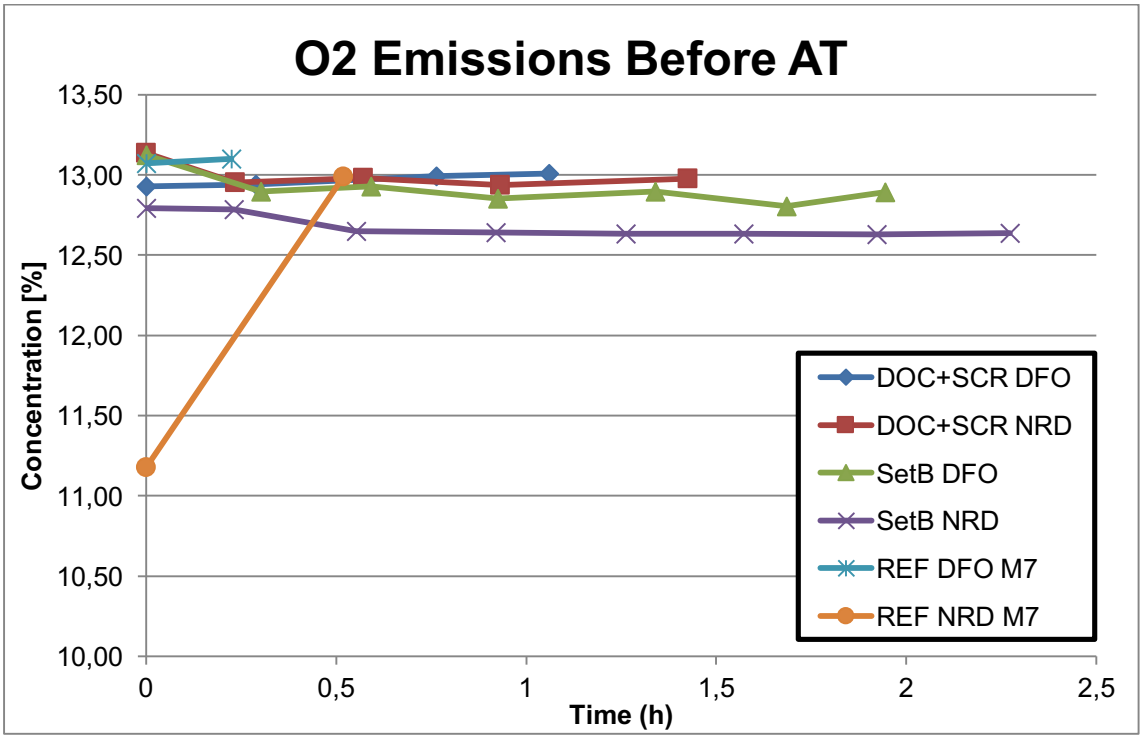
Appendix 5: CO_2 and O_2 emissions of ISO 8178 Tests



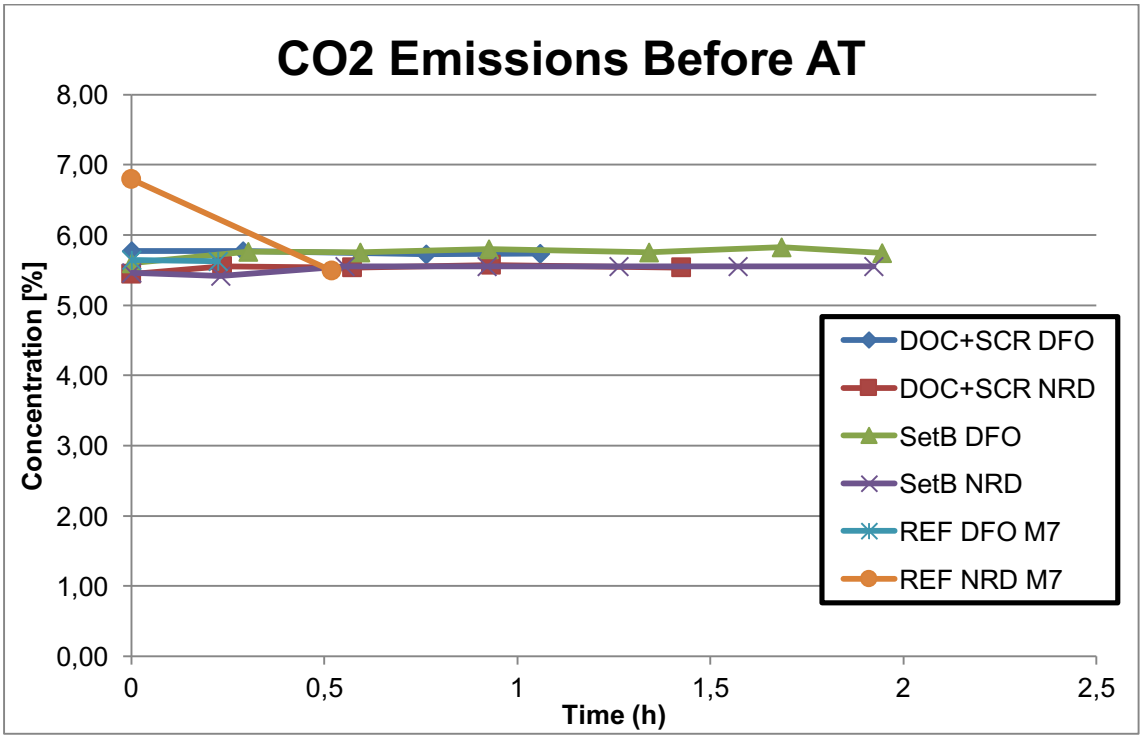
O_2 Emissions of Versus M1 Test



CO_2 Emissions of Versus M1 Test



O_2 Emissions of Versus M7 Test



CO_2 Emissions of Versus M7 Test