Green Deal validation

Measurement report - Jan de Nul - vessel 2

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Summary

The government and the maritime sector signed a Green Deal in 2019 to make maritime shipping, inland shipping and ports more sustainable. One aspect of the Dutch Green Deal, is a program for validation of the effects of sustainable maritime solutions. TNO conducted a measurement campaign under the validation program to validate the proper operation and emission claims on a diesel particulate filter (DPF) from emigreen.

Validation measurements were performed on the engines of an 'Ultra Low Emission vessel' (ULEv). On this vessel, a DPF was fitted on top of the TIER III certified engines with OEM selective catalytic reduction (SCR) system. Where the primary goal of this study is to evaluate the claim of Emigreen with respect to the ULEv particle emission limits, also performance of the SCR system with respect to the ULEv NO_x limit value is evaluated. In addition, possible degradation of the system is evaluated with comparison to previous measurements and MGO and HVO fuel is used to evaluate the effectiveness of the aftertreatment system with different fuels.

Validation of both aftertreatment systems is succesful if particle emissions (particle number and particle mass) remain below the applicable limit values in weighted cycle results, and if nitrogen oxides (NO_x) emissions are reduced to levels below the applicable limit. Note that possible adverse side effects from the emission aftertreatment systems on other emission components should be weighted against NO_x and particle matter emission reductions as well.

In total, two engines were measured with in-stack emission instruments. The first engine was measured while operating on low sulphur maritime gas oil (MGO), the second engine was measured on hydrotreated vegetable oil (HVO). For both engines, emission evaluations are performed on the E2 and D2 emission cycles specified in the NO_x technical code 2008 (IMO, 2009).

From the measurements, the following conclusions can be drawn:

Particle number emissions over the E2 and D2 cycles measured between 3.5×10^{10} to 4.4×10^{10} #/kWh and between 5.8×10^{10} to 6.2×10^{10} #/kWh respectively. Particle mass emissions over the E2 and D2 cycles measured between 2 to 4 mg/kWh and between 3 to 5 mg/kWh respectively. There is no increase of particulate emissions measured compared to its operation at comissioning of the vessel which happened in 2020. This indicates that there was no deterioration of the DPF. The measurements therefore show that the Emigreen DPF system performs well and emissions are well below the ULEv limit values of 1.0×10^{12} #/kWh and 15 mg/kWh respectively. A combination of regular active regenerations and periodic external cleaning ensures these filters remain in proper working order.

The NO_x emissions over the E2 and D2 cycles measured between 0.4 to 0.5 g/kWh and between 0.5 to 1.0 g/kWh respectively. Therefore, NO_x emissions are reduced well below the ULEv limit value of 1.8 g/kWh. It should however be noted that significant NH_3 slip up to 27 mg/Nm^3 is observed during the measurements, pointing to likely over injection of AdBlue in the SCR, or reduced catalyst efficiency.

The measurements give only a short term indication of the actual emissions. Therefore, a temporary issue related to urea crystalisation and release in the exhaust stack is also possible.

The observed NH_3 slip shows that correct functioning of the SCR system is not a given. While the tested systems were equiped with an OEM engine monitoring system, potential amonia slip issues were not detected by this system. Further diagnostics and emissions monitoring can aid in signaling potential issues leading to high NO_x or NH_3 emissions. In contrast to ULEv ships, inland shipping vessels fullfilling the Stage V requirements are required to install a NO_x control diagnostics (NCD) system for the purpose of NO_x emission monitoring (European Commission, 2017). The addition of NH_3 monitoring capabilities to such a system in combination with a regulatory NH_3 limit could aid in ensuring good funcitoning SCR systems.

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1 Introduction

1.1 Background

The Dutch Green Deal maritime validation projects offer manufacturers of sustainability solutions in the maritime industry a possibility to get their sustainability claims validated. One of the parties making use of this deal is Emigreen with their diesel particulate filter (DPF) systems. Emigreen produces selective catalytic reduction (SCR) and DPF systems for application in marine diesel engines. Under the Green Deal, Emigreen submitted a claim with respect to their DPF systems.

As DPF systems affect the local particulate emissions from the stack of vessels, validation of the DPF technology requires measurement of the tank-to-propellor (TTP) particulate emissions. Ships currently equipped with this technology offer a good opportunity to measure emissions from the stack and compare them to the acting regulatory and voluntary limits.

This report describes the measurements aboard a trailing suction hopper dredger from Jan de Nul. The vessel is equipped with three main diesel generators with OEM SCR systems and Emigreen DPF systems and was made available by Jan de Nul for this measurement campaign.

1.2 ULEv vessel notation

Maritime ship pollution rules under the International Maritime Organization (IMO) are contained in the MARPOL convention. As of January 2016, the strictest norm on new build marine vessels under MARPOL is described with IMO Tier III. The Tier III regulation prescribes a stricter engine speed dependant NO_x emission limit on the weighted cycle emissions of the ship's engines compared to previous regulations (see Figure 1.1). The NO_x limit value for TIER III engines is given as $NO_{x,lim}\left[\frac{g}{kWh}\right] = 9 \cdot n^{-0.2}$ for engines running at speeds between 130 and 2000 rotations per minute (RPM). Here n is the engine speed expressed in RPM.

Current aftertreatment systems allow for pollutant emission reductions below the posed NO_x limit values in IMO Tier III. To offer a pathway for vessel owners/operators to prove they exceed existing MARPOL requirements, Bureau Veritas (BV) developed the 'Ultra-Low Emission Vessels' (ULEv) notation by adopting the European Commission's Stage V policy limit values of IWP engines for the maritime industry.[1] These limit values are listed in Table 1.1.

[1] Ultra-Low Emission Vessels | Marine & Offshore (bureauveritas.com)

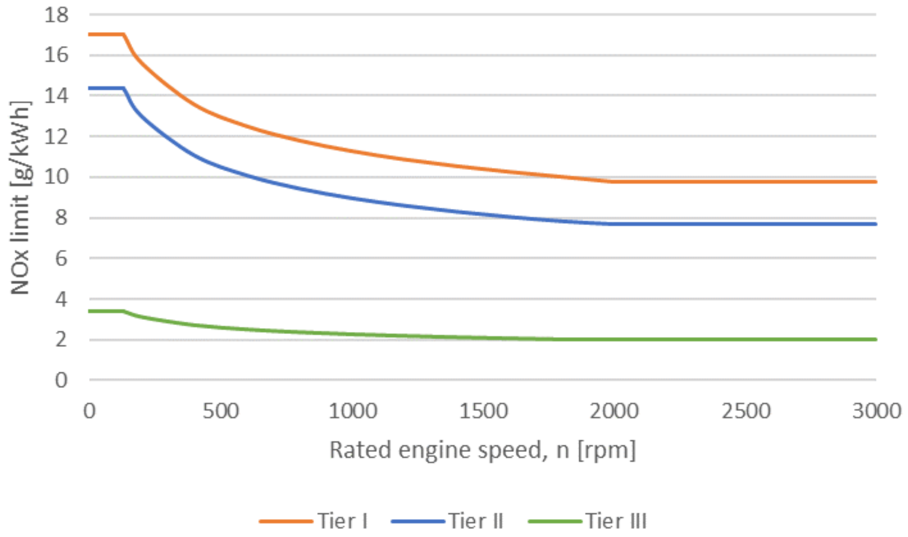

Figure 1.1: IMO Tier III emission requirements compared to IMO Tier I and II (Vermeulen, Verbeek, & Dinther, 2023).

Table 1.1: Stage V emission limit values applicable for ULEv notation (Ecopoint Inc., 2021).

Net Power [kW]	CO [g/kWh]	HC [g/kWh]	NO_x [g/kWh]	PM [g/kWh]	PN [1/kWh]
≥ 300	3.50	0.19	1.80	0.015	$1x10^{12}$

1.3 Objectives

The objective of the measurements carried out onboard the vessel is twofold. The measured vessel is equipped with both SCR and DPF systems. As such, next to particulate emissions related to the DPF system, also NO_x emissions related to the SCR system can be evaluated.

The objectives of the onboard measurements are:

- Onboard validation of the SCR and DPF emission control systems in service against ULEv limit values. At least NO_x and particle matter (PM) and particle number (PN) emissions are to be measured. Evaluation of emissions is performed on representative engine load conditions.
- Evaluation of possible degradation of the NO_x control system. Emission measurement results are compared to commissioning measurement results on the same ship from the same measurement company.

Both the real world NO_x and particulate emissions measured aboard the vessel are compared to the emission limits posed by the ULEv notation (see Section 1.2). Validation of the Emigreen DPF claim is successful if particulate emissions are shown to remain well below the ULEv PN and PM limits. The NO_x emission check is successful if measured emissions are shown to remain below both IMO Tier III and ULEv limit values and the SCR system is shown to operate without adverse effects on the in-stack emissions.

1.4 Approach

To determine the real world pollutant emissions from the stack of the ULEv vessel, the CO_2, CO, NO_x, PM, PN, NH_3 and HC emission concentrations where measured together with several engine parameters on a set of representative load points. Emissions are evaluated based on an onboard implementation of the guidelines in the NO_x technical code 2008 (IMO, 2008).

2 Methods

2.1 Onboard measurements

Measurements onboard the ship are performed at berth at various load points. In total two of the three main generator engines of the ship are measured on a single fuel type. On each engine, a single measurement is performed while DPF regeneration is in progress. This measurement serves as an indication of possible elevated emissions during the regeneration cycle.

2.1.1 Load points

The load points to run the measurements at are defined by the official marine engine test cycle. One additional load point is used to capture the routine usage of the vessel's engines. This additional load point is repeated while DPF regeneration is active to compare emissions during normal operation and during regeneration cycles.

The measured vessel uses a diesel-electric architecture. As such, the main generators onboard the ship supply power for both the main propulsion systems and utility consumers. For main propulsion engines which run at a constant speed with a controllable pitch propeller, the official test cycle as described in the NO_x technical code 2008 is the E2 cycle. Similarly, for constant speed auxiliary engines, the NO_x technical code prescribes the use of the D2 cycle. Both cycle definitions are shown below in Table 2.1 and Table 2.2 respectively, and should be used in evaluation of the relevant emissions. As all load points in the E2 cycle are included in the D2 cycle, the latter is leading during the measurement campaign.

Table 2.1: E2 test cycle definition.

Speed	100%	100%	100%	100%
Power	100%	75%	50%	25%
Weighting Factor	0.2	0.5	0.15	0.15

Table 2.2: D2 test cycle definition.

Speed	100%	100%	100%	100%	100%
Power	100%	75%	50%	25%	10%
Weighting Factor	0.05	0.25	0.3	0.3	0.1

All noted load points are attainable during measurements along the kay with activation of a combination of the dredge pump, jet pump, bow thruster and main thrusters. While 100% engine power is sometimes viable while moored to the dock, it is preferable to measure this load point during operation to prevent the risk of damaging harbour infrastructure. Where the 10% load point is not measured, an alternative cycle weighting for the D2 cycle is used according to the weighting rules in the NO_x technical code 2008 as **shown in** Table 2.3.

Table 2.3: Alternative D2 test cycle definition.

Speed	100%	100%	100%	100%	100%
Power	100%	75%	50%	25%	10%
Weighting Factor	0.06	0.28	0.33	0.33	0

Engine load is determined based on the electrical generator power output during this measurement campaign. Conversion between the generator output power and true mechanical output power of the diesel engines onboard the vessel is documented by the engine manufacturer. The conversion of electrical to mechanical power is shown in Table 3.3 of Section 3.1.1.

2.1.2 Emission components

The emissions components measured aboard the vessel are listed in Table 2.4. Note that measured CO_2 concentrations are mainly used to enable calculation of fuel and energy specific emission values.

Table 2.4: Measured emission components.

Emission component	Abbreviation	Measured unit
Carbon dioxide	CO_2	%vol.
Carbon monoxide	CO	ppm
Oxygen	O_2	%vol.
Nitrous oxides	NO_x	ppm
Ammonia	NH_3	Mg/Nm^3
Hydrocarbons	HC	ppm
Particulate number	PN	$\#/cm^3$
Particulate mass	PM	g/cm^3

2.2 Analysis of test results

2.2.1 Onboard measurement procedure

Calculation of engine emissions in g/kWh requires emission mass flows and engine power to be measured. To calculate emission mass flow, exhaust mass flow is needed, which can be based on fuel flow and a carbon balance calculation. This is prescribed in the IMO MARPOL onboard measurement procedure described in Section 2.1 of IMO MARPOL and MEPC 177(58) (IMO, 2008). This onboard test procedure is however still quite complex. On ships, in general not all required parameters are available. On some larger ships, engine or propellor shaft torque and/or fuel consumption are sometimes measured, but also there is often uncertainty about the calibration. Moreover, engines are often grouped for the fuel consumption and power measurement. On top of this, during dynamic, continuous monitoring, there is uncertainty about averaging of signals and the time alignment between signals.

Because of the difficulty to obtain exact engine power and fuel (or exhaust) flow on board of ships, TNO developed alternative calculation methods based on the carbon balance method which are described among others in SCIPPER D1.6 (Weisheit, et al., 2020), PROMINENT D5.8 (Verbeek, et al., 2017), (Verbeek, Procedure voor het meten van uitlaatgasemissies aan boord van binnenvaartschepen, 2001). This alternative calculation method is used for the analysis of the onboard measurements described in this report. A detailed explanation of this alternative calculation method can be found in Appendix B.

The accuracy of the onboard measurement procedure was investigated in (Verbeek, Meetprotocol voor emissielabel binnenvaart, 2020). For Stage V emission levels, the total possible measurement deviation is ±20%.

2.2.2 Alternative calculation methods

To enable checking of calculated results, alternative calculation methods can be used. In this measurement campaign, two different alternative calculation methods are used to verify results. Verification of results using alternative calculation methods are included in Appendix C.

The alternative calculation methods which are deployed here are:

- Calculated total exhaust gas flow: Emission results are obtained by multiplying measured concentrations with the calculated total flow in the exhaust stack and the mechanical output power of the engine. Flow is calculated based on the speed density method with engine geometric properties and intake air properties. Engine power is determined from the generator power and mechanical power map from engine performance data.
- Measured total flow: Similar to the calculation method above, but with measured flow values using a pitot tube. This method is carried out by Eurofins.

2.2.3 Evaluation of SCR performance degradation

Selective catalytic reduction (SCR) NO_x emission reduction technology is well known in the automotive sector. The SCR systems for maritime vessels function similarly to those found in diesel road vehicles, however the SCR systems in ships are much larger in size to account for the larger exhaust gas volume flows.

High NO_x emissions of engines equipped with an SCR aftertreatment system occur mainly due to one of the following reasons:

- Low SCR temperature
- Defective SCR elements: Poisoning of the SCR catalyst can occur due to metal additives in the engine oil, but also sulphur in the fuel can cause reduction of catalyst efficiency at low and medium engine load. The engine oil additives contain elements like phosphor, Zink, Calcium and also sulphur. They can build up in or on the catalyst porous structure (wash coat) effectively reducing the usable catalyst surface area.
- Faulty Diesel Exhaust Fluid (DEF) injection due to a bad NO_x sensor or faulty DEF controller.

SCR performance degradation can be indicated by comparing NO_x emission measurement results between commissioning of the vessel in 2019 and current measurements.

Measurements are carried out in the same measurement setup by the same measurement team to enable one-to-one comparison of the measurement results (see Section 3.2.1). Significant deviations in energy specific NO_x emissions on the various load points could indicate potential issues related to the points above.

3 Equipment and data

3.1 Vessel specification

Measurements discussed in this report are performed onboard a trailing suction hopper dredger owned and operated by Jan De Nul Group[2]. The ship was newly constructed in 2019 and is mainly used for dredging tasks in Europe. The main properties of the vessel are listed in Table 3.1.

Table 3.1: Relevant properties of the vessel.

IMO number	*******[3]
Build year	2019
Hopper capacity	******[3]
Length	******[3]
Breadth	******[3]
Draught (loaded)	******[3]
Main generators	3 x MAN 8L27/38 (2640kW at 750RPM)
Total installed diesel power	7700 kW
Main engine IMO emission standard	Tier III and ULEv (Stage V)

3.1.1 Engine properties

The vessel is designed around a diesel-electric architecture. Power demand is met with three MAN Diesel 8L27/38 diesel generator sets. The engines are operated at a constant speed of 750 RPM and can deliver a maximum electrical power of 2640 kW. In normal use only two of the three generators are running. The third generator is available as a backup in case of failures or planned maintenance activities. Switching between different generator sets can achieved with a seamless power transition. Running engines can both be operated in symmetrical or asymmetrical loading configurations.

Efficiency of the MAN 8L27/38 engines is documented by the engine manufacturer. The specific fuel consumption (SFC) at the relevant operating points is shown in Table 3.2. Note these values show the amount of fuel used per kWh mechanical energy. Conversion between mechanical power and electrical power of the generator sets is shown **in** Table 3.3.

Table 3.2: MAN 8L27/38 specific fuel consumption.

Power setting [%]	Mechanical Power [kW]	SFC [g/kWh]
10%	264	312.7
25%	660	233.9

[2] Homepage | Jan De Nul
[3] Information removed for confidentiality reasons.

Power setting [%]	Mechanical Power [kW]	SFC [g/kWh]
50%	1320	201.9
75%	1980	197.2
100%	2640	200.3

Table 3.3: Electrical and mechanical power output mapping of the MAN 8K27/38 2640kW generator set.

Generator power [%]	Generator power [kW]	Engine power [kW]	Engine power [%]
10%	264 kW	269 kW	10.2%
25%	660 kW	666 kW	25.2%
50%	1320 kW	1328 kW	50.3%
75%	1980 kW	1991 kW	75.4%
100%	2640 kW	2649 kW	100%

The serial numbers of the engines onboard the vessel at the time of the measurement are given in Table 3.4.

Table 3.4: Engine serial numbers onboard the vessel.

Engine name	Serial number	Type	Measured?
Engine 1	P-28051-02-11	MAN 8L27/38	Yes
Engine 2	P-28051-02-12	MAN 8L27/38	Yes
Engine 3	P-28051-02-13	MAN 8L27/38	No

3.1.2 Exhaust stack architecture

Each diesel generator is equipped with an OEM SCR and EMIGREEN DPF aftertreatment systems. Due to Tier III certification of the MAN 8L27/38 engine in combination with the SCR, the DPF is installed downstream of the SCR system. A schematic representation of the exhaust stack architecture, which is the same for all main engines, is shown in Figure 3.1. Each engine has its own exhaust stack coming out of the stack tower at a 45 degree angle. In each stack, a total of 4 NO_x sensors are installed. Next to Multronic sensor data from two sensors per stack, also sensor data from two OEM NO_x sensors per stack is available in the vessel logger system. Note that DPF bypass valves are installed in the exhaust stack to bypass the DPF when heavy fuels are used.

It should be noted that the regeneration burner adds a permanent flow of fresh air to the exhaust flow due to cooling requirements on the burner elements. The volume flow of fresh air from the regeneration burner can be determined from the air pump drive frequency and DPF backpressure with data from the DPF manufacturer. DPF air flow specifications per engine load point are shown in 0 and are used where needed in the calculation of emission results. The airflow from the DPF blower affects concentration measurements of the analyser and Multronic sensor 2 positions but does not influence measurements at the Multronic sensor 1 position.

Comparisons of measurements between sensor 1 and sensor 2 are therefore not possible without correcting the measured values. Comparisons between Multronic sensor 1 and analyser measurements are possible without corrections.

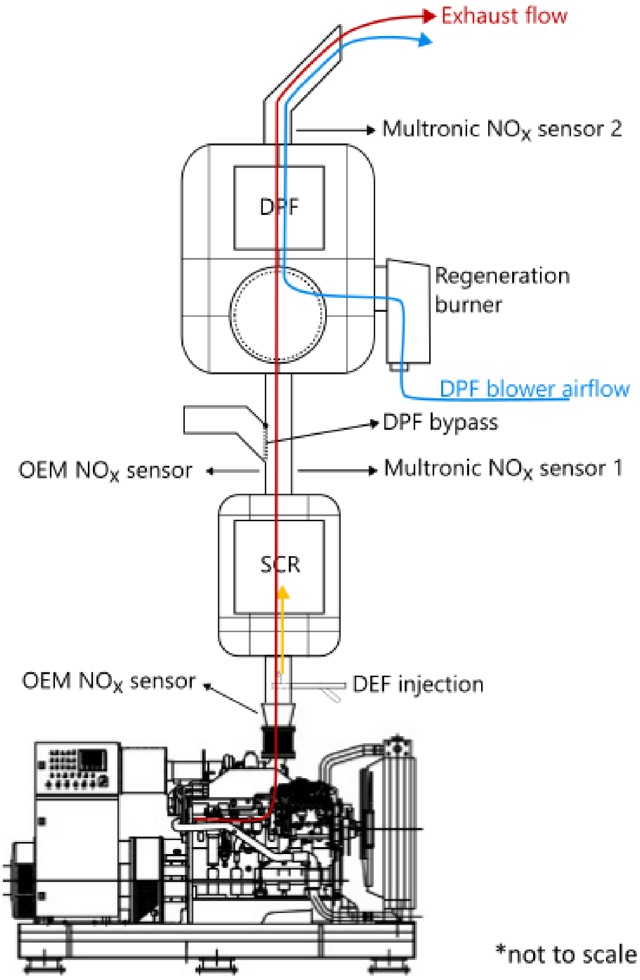

Figure 3.1: Schematic representation of the exhaust stack architecture onboard the vessel.

The SCR system is controlled by the OEM software of the engine manufacturer. The operator can switch the operating mode of the SCR system between reduced and normal operation. During the measurements described in this report, the normal operation is used to comply with IMO Tier III and the limits applicable for the ULEv notation which are the same as the limit values for Stage V (see Section 1.2). The reduced mode can be used to comply with the standard IMO Tier II regulation outside NO_x Emission Control Areas (ECA). During all testing, the normal SCR mode was used to measure the emissions under the ULEv notation.

The SCR elements onboard the vessel are replaced every two years. At the time of testing, all SCR elements were replaced within a few month before the measurement campaign. DPF filter elements of all engines are regenerated periodically and are manually cleaned in situ or in a pressurised air cleaning station approximately every 6 months.

3.1.3 Required ship and engine data

To perform the required processing on the measurement data, additional data from the ship and engine during the measurement period is required. The vessel is equipped with a digital alarm system connected to the majority of sensors on-board the ship. All required signals are therefore available in a digital logfile from the alarm system. The required signals and the location to obtain these signals are shown in Table 3.5. The required parameters in the alarm system are logged at a 3 second interval during the measurement period.

Table 3.5: Required signals onboard the measured ship.

Signal	Unit	Location	Comment
Engine speed	min-1	Alarm system	
Electrical power	kW	Alarm system	Generator power
Fuel flow	l/h	Alarm system	Power ratio of total fuel flow
Charge air temperature	°C	Alarm system	After cooler
Fuel temperature	°C	Alarm system	
Charge air pressure	kPa	Alarm system	
EGT	°C	Alarm system	
Cooling water temperature	°C	Alarm system	
Oil temperature	°C	Alarm system	
HT in & out	°C	Alarm system	
LT in & out	°C	Alarm system	
SCR temperature in	°C	Alarm system	
SCR temperature out	°C	Alarm system	
Urea mass flow	kg/h	Alarm system	
DPF blower pressure	mBar	Alarm system	
DPF backpressure	mBar	Alarm system	
DPF temperature in	°C	Alarm system	
DPF temperature out	°C	Alarm system	
DPF blower frequency	Hz	Alarm system	
Ambient temperature	°C	Alarm system	
Ambient humidity	% RH	Alarm system	
Ambient pressure	hPa	Alarm system	

3.2 Measurement resources

3.2.1 Eurofins

Eurofins Belgium is an accredited measurement lab with experience in maritime engine emission measurements. At vessel commissioning in 2020, Eurofins was involved with the first onboard measurement campaign onboard the vessel. Results of this measurement campaign are documented in (Goderis, 2020).

Eurofins is contracted by TNO to perform the required emission measurements onboard the vessel as discussed in this report. As measurements are repeated with respect to the measurement methods used at commissioning, measurement results can be compared to estimate degradation effects.

3.2.2 Multronic

Multronic emission systems is a company in Belgium with nearly 40 years of experience in the automotive industry. They design, manufacture and supply diesel engine emission aftertreatment systems for OEM and retrofit use. The company also offers monitoring solutions in the form of dataloggers with telemetry options.

Onboard the vessel, Multronic provides an independent monitoring system of NO_x emissions which can be used by Jan De Nul to provide real-time emission values of the ship to their clients. Data from the Multronic NO_x sensor is used as a secondary NO_x measurement source during the measurements detailed in this report. No adjustments to the existing logging system had to be done for this purpose.

3.2.3 Instruments

Measurements onboard the vessel are performed with the instruments listed in Table 3.6. Measurement and information sources onboard the vessel are listed in Table 3.7
.

Table 3.6: Measurement equipment used onboard the vessel.

Instrument	Parameters	Comment
Horiba PG 350E	O_2,CO,CO_2,NO_x	Dry concentration measurements.
JUM - FID	THC	Wet concentration measurement.
Gravimetric filter setup	PM	Gravimetric filter measurement according to ISO 8178-1.
TSI Nanoparticle emission Tester Model 3795	PN	CPC based particle number measurement.
H_2SO_4 sampling bath	NH_3	Absorption in H2SO4-solution and analysis by IC.

Table 3.7: Information sources onboard the vessel.

Information sources	Parameters	Comment
Multronic NO_x sensors[4]	NO_x [ppm]	NO_x concentrations above the DPF for all engines.
JDN alarm system	All ship, engine and aftertreatment parameters required for emission calculations and monitoring.	

3.3 Measurement setup

Measurements are performed in stack using the various instruments listed in Section 3.2.3. Concentrations of O_2, CO, CO_2, NO_x and HC are measured continuously trough two separate probes in pre-fabricated sample points in the exhaust stack during each full measurement day. For the dry measurement of O_2, CO, CO_2 and NO_x the sampled gas is run through a dryer first. HC concentrations are measured wet.

PM measurements run continuously for each separate load point, it should be noted that dilution flow to the filter is controlled continuously to maintain a constant filter temperature. PN concentrations are only sampled intermittently during each load point test by inserting the NPET probe periodically in the exhaust flow. Non continuous sampling is used to prevent pollution of the measurement device in case of high PN emissions.
NH_3 sampling is performed by continuously drawing a small exhaust sample stream with a controlled flow volume trough an H_2SO_4 bath for each load point. NH_3 content is later analysed in the lab.

Each load point measurement runs for 30 minutes[5]. In between load points similar stabilisation times are maintained to allow engine temperatures and emissions to stabilise.

3.3.1 Measurement location

Measurements are performed at the end of the exhaust stack of each engine at the top of the exhaust stack tower (see Figure 3.2). Exhaust stacks onboard the vessel are equipped with several sampling bungs just above the roof level of the stack tower. Measurements are performed through these openings as shown in Figure 3.3. The used sampling bungs are situated at least 5 diameters above the DPF system, note however that the distance to the exhaust bend in the stack after the sampling bungs is limited.

Four sensors are available in each exhaust stack. As introduced in paragraph 3.1.2, the sensor 2 position is used in this study to ensure sensor results can be directly compared to in stack analyser measurements. The location of the Multronic NO_x sensor 2 of a single engine is shown in Figure 3.1.

[4] Note NO_x sensors are not manufactured by Multronic but connected to the Multronic logging system.
[5] Unless specifically stated otherwise.

Figure 3.2: Global measurement location (exhaust stack)

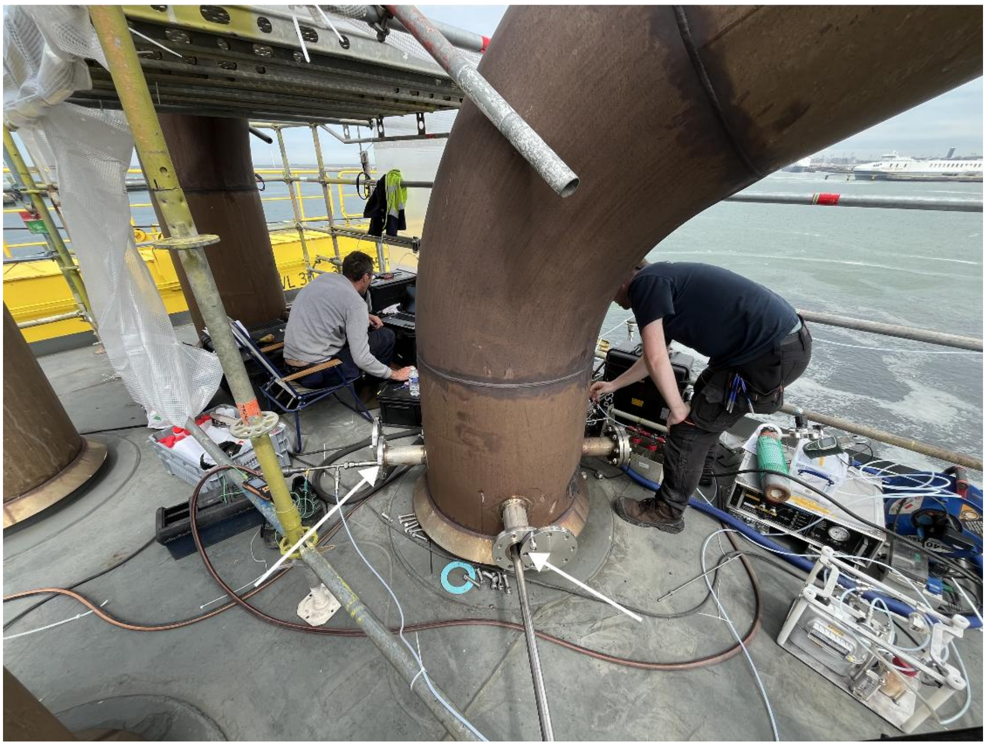

Figure 3.3: Sampling holes in the exhaust stack.

3.4 Fuel specifications

Measurements are performed on 10ppm MGO fuel and HVO fuel on engine 1 and engine 2 respectively. Different fuels are used to check the proper operation of aftertreatment systems on both fuels. As different engines are used for each fuel, no conclusion on the absolute performance differences between both fuels can be drawn. The main properties of the fuel used are shown in Table 3.8. The full fuel analysis specification are shown in Appendix E.1.

Table 3.8: Test fuel properties

Property	MGO Value	HVO Value	Unit
Fuel type	MGO 10ppm	HVO	-
Density @ 15°C	827.4	784.3	kg/m^3
Viscosity @ 40°C	2.85	3.14	mm^2/s
Sulphur	<0.03	-	%m/m
Sulphur (Low Level)	12	<10	mg/kg
Water	<0.01	<0.01	%V/V
FAME content	1	<0.1	%V/V
Cetane Index	58	93	-
Net Specific Energy	43.01	43.49	MJ/kg

3.5 Measurement planning

Planning of the measurement campaign had to change significantly due to weather conditions during the planned measurement period. The original planning is shown for reference next to the actual revised planning during the measurements.

3.5.1 Original planning

Measurements onboard the vessel are planned in three days starting on a bunker day of the vessel. An overview of the test planning is given in Table 3.9. Note that the vessel will operate in between measurements according to its running contract.

Table 3.9: Vessel measurement planning.

Date	19/12/2023	15/05/2024	16/05/2024	17/05/2024
Location	Zeebrugge (BE)	Vlissingen (NL)	Zeebrugge (BE)	Zeebrugge (BE)
Measurements	Initial ship visit TNO	Bunker day and onboard preparation for emission testing.	Emission measurements on engine 1 with MGO fuel spec: 10%, 25%, 50%, 75%, 85%, 100%, 85% (regeneration) load points	Emission measurements on engine 2 with HVO fuel spec: 10%, 25%, 50%, 75%, 85%, 100%, 85% (regeneration) load points

3.5.2 Revised planning

At time of the experiment, significant changes to the planning were needed due to several unforeseen conditions. The required changes to the planning are outlined below, and the resulting revised planning is presented below in Table 3.11.

The original planning was followed up till the installation of emission measurement equipment on the exhaust stack of the vessel on 15/05/2024. However, due to heavy rainfall in the morning of the first measurement day, and water damages to an electrical sampling line of one of the instruments, the first measurement day had to be cancelled.

To ensure the measurement program could fit in a single day, the original measurement program was simplified:

- Engine load points 10% and 85% are removed from the program.
  - The 85% load point is not required in applicable cycle calculations.
  - The 10% load point is difficult to attain under normal conditions and is therefore less relevant to this vessel.
  - The regeneration measurement is shifted to the 75% load point.
- The shifted regeneration measurement is shortened as this measurement is not required for cycle calculations. To allow shorter measurement times, PM and NH_3 measurements are excluded for this step.
  - While PM is a relevant indicator for a faulty DPF, PM filter measurements require significantly longer continuous measurement durations compared to an instantaneous PN measurement. To decrease measurement time on this measurement, PN is therefore the only particle emission indicator.
  - NH_3 emissions are not expected to be influenced significantly by DPF regeneration, therefore the added value of this measurement in this step is limited.
- Stabilisation times are decreased for PM measurements.
  - Particle emissions are expected to be relatively stable over various operating conditions of the engine due to the presence of a DPF. Stabilisation of the engine is therefore less critical. Measurement time with a PM filter is however important to ensure proper loading of the filter.
  - Stabilisation of engine operating conditions for gaseous measurements is critical as NO_x and HC formation is heavily influenced by temperatures in the combustion chamber. Decreased measurement time is however not critical as only 10 minutes of stable data is required for calculation purposes.
  - To decrease overall measurement time to 40 minutes per load point, the measurement timeline shown in Table 3.10 is used.

Table 3.10: Revised measurement timeline per load point.

Emission component	Time [min]				
	0'	10'	20'	30'	40'
Particulates	Stabilization	Start measurement			End measurement
Gaseous	Stabilization		Start measurement		End measurement

Table 3.11: Revised measurement planning

Date	17/05/2024 - Zeebrugge (BE)
06:00 – 08:30 CEST	Installation of equipment (continuation), instrument calibration and stabilisation of engine 1 (MGO) to 25% engine load.
08:30 – 11:30 CEST	Measurements on engine 1 (MGO): 25%, 50%, 100%, 75%, 75% + regeneration load point
11:30 – 13:30 CEST	Switch to HVO fuel (2 hours flushing time needed), stabilisation of engine 2 to 25% engine load.
13:30 – 16:30 CEST	Measurements on engine 2 (HVO): 25%, 50%, 100%, 75%, 75% + regeneration load point
16:30 – 18:00 CEST	Run-out and removal of equipment.

4 Results and discussion

4.1 Measurement observations

Measurements onboard the vessel were performed in the harbour of Zeebrugge in between dredging cycles. The vessel was only moored to the kay on the installation and bunkering day. During measurements, the vessel was kept approximately stationary with minimal manoeuvring at the entrance of the harbour.

On the first measurement day, bad weather conditions caused an electrical malfunction in one of the heated lines of the measurement equipment. As such, the first measurement day was cancelled and the second measurement day was reorganised according to the revised planning shown in paragraph 3.5.2.

On the second measurement day, weather conditions were good overall, with little to no precipitation and mild wind. Re-installation of instruments and the different measurements on the second measurement day were performed without further incidents or anomalies.

To achieve the different engine loads, several onboard power consumers were used. Depending on the required engine load, a combination of the dredge pump, jet pump, bow thruster and main thruster pods were used. At higher load demands, a secondary engine was started as backup. Stable load points were achieved using these methods during the measurements.

4.2 NO_x emissions

4.2.1 NO_x concentrations

NO_x emissions along with relevant gaseous emission from the tailpipe are measured using several instruments listed in 3.2.3. In addition, NO_x concentration in the tailpipe is also measured by Multronic sensors. Concentration values from sensor 2 can be directly compared to analyser results due to its similar sampling location as the analyser measurement. Sensor 1 is expected to show slightly higher concentration values due to the lack of dilution flow from the DPF blower at its sampling location. Measured NO_x concentration values on the different load points are shown in Table 4.1 and Table 4.2 along with the previously measured NO_x concentrations at the commissioning tests in 2020. Note the differences in dry and wet measurements for the Eurofins and Multronic measurements. Wet/dry correction factors based on the conditions during the measurements are shown in 0.

The majority of measured load points show significant deviations between the average measured concentrations of the Eurofins instrument and Multronic sensor 2. Furthermore, measurements between Multronic sensor 1 and sensor 2 also show large deviations above the expected deviation due to the different measurement locations. Deviations between both Multronic sensors are most likely due to non-uniform composition of the exhaust gas at the measurement location of sensor 1. Depending on the exhaust flowrate (load point) this results in over or under representation of the actual emissions.

Deviations in the measurements between the Eurofins instrument and Multronic sensor 2 are likely explained in part by the occurrence of NH_3 slip up to 27 mg/Nm^3 during the measurements. The occurrence of NH_3 slip is further detailed in Section 4.2.2. It is important to note that the used Multronic NO_x sensors are almost 1-to-1 cross sensitive to NH_3 (ammonia) up to 300 ppm while the Eurofins NO_x analyser used during the measurements has no cross sensitivity to NH_3. Cross sensitivity in NO_x sensors is not necessarily a bad property as NH_3 emission indicates a problem with the SCR system. Moreover both NH_3 and NO_x cause acidification and eutrophication and have adverse health effects (Wichink Kruit, Hoogerbrugge, de Vries, & van Pul, 2018). Cross sensitivity of the NO_x sensor indirectly ensures NH_3 slip is partially captured in the emission results. An example of the time dependant NO_x emission behaviour for 75% load on engine 1 is shown in Figure 4.1. Emission behaviour of different load points and the other measured engine are shown in Appendix D.

Table 4.1: NO_x RAW measurement results per load point – engine 1.

Avg. NO_x measurements – engine 1	Eurofins 2024 [ppm] (dry)	Multronic sensor 1 [ppm] (wet)	Multronic sensor 2 [ppm] (wet)	Eurofins 2020 [ppm] (dry)
25% load	41	88	75	6
50% load	45	96	115	25
75% load	34	49	59	36
75% load (regeneration)	35	48	62	-
100% load	18	50	61	37

Table 4.2: NO_x RAW measurement results per load point – engine 2.

Avg. NO_x measurements – engine 2	Eurofins 2024 [ppm] (dry)	Multronic sensor 1 [ppm] (wet)	Multronic sensor 2 [ppm] (wet)	Eurofins 2020[6] [ppm] (dry)
10% load	368	386	380	-
25% load	53	134	65	3
50% load	114	214	124	5
75% load	38	79	57	40
75% load (regeneration)	40	77	61	-
100% load	24	47	46	20

[6] Measurements based on EN590 10 ppm fuel.

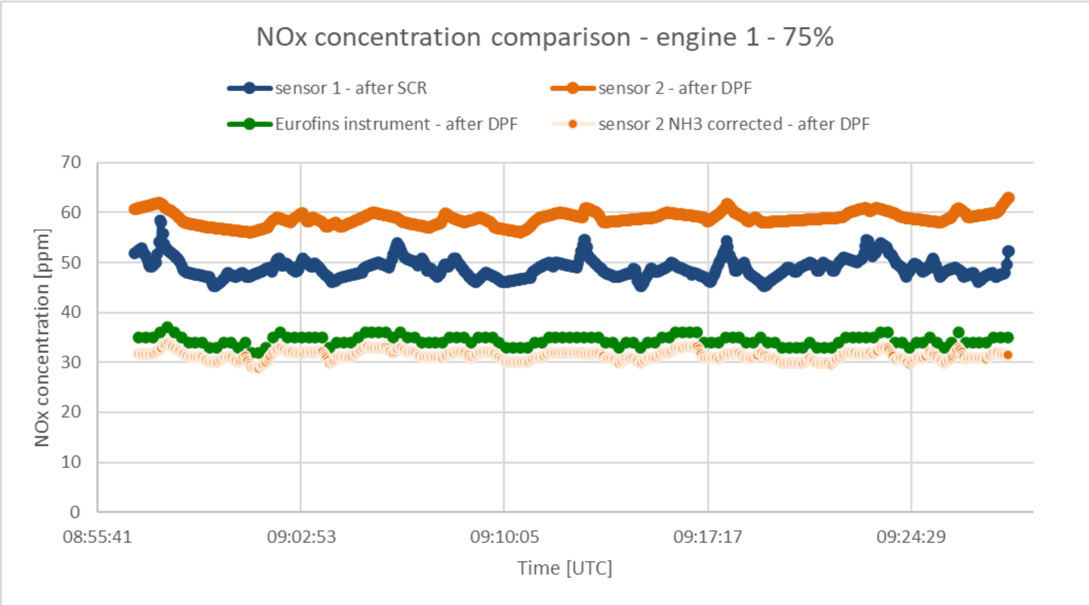

Figure 4.1: NO_x concentration measurements on engine 1 - 75% load. RAW sensor results are shown for sensor 1 (after SCR) and sensor 2 (after DPF). The RAW measured values of the certified instrument operated by Eurofins are shown as well and are measured at the same location as sensor 2. A corrected reading of sensor 2 (after DPF) is displayed based on the method explained in Section 4.2.2.

4.2.2 NH_3 slip

NH_3 slip from the SCR can for example be caused by DEF over-injection or a bad urea spray pattern. Measurements on NH_3 concentration in the exhaust are performed using a H_2SO_4 sampling technique. This measurement technique results in the average NH_3 emissions in mg/Nm³ [7] for each load point. To verify the NH_3 slip assumption, the measured average NH_3 emissions are mapped to time based concentrations based on the delta between Eurofins instrument and Multronic sensor 1 measurements of the NO_x concentration. Note that, while there is no applicable Stage V limit on NH_3 slip, other regulations requiring SCR installations impose a limit on emitted NH_3 concentrations to control slip. For Euro VI heavy duty vehicles, this limit is defined at 10ppm averaged over the WHTC engine test cycle.

Average NH_3 concentrations in ppm are calculated from:

$$C_{NH_3,avg}\,[ppm] = \frac{NH_{3,SpecificDensity}\left[\frac{mg}{Nm^3}\right] \cdot V_{m,air}\left[\frac{l}{mol}\right]}{M_{NH_3}\left[\frac{g}{mol}\right]}$$

Average concentrations for both engines on all tested load points are shown in Table 4.3.

Table 4.3: Calculated average NH_3 concentrations per load point.

Avg. NH_3 [ppm]	10%	25%	50%	75%	75% regen	100%
Engine 1	-	0.7	0.6	27.4	-	32.7
Engine 2	3.4	34.8	35.8	23.8	-	23.7

[7] Normalised cubic metre referring to 273.15K and 1013hPa.

Mapping the NH_3 concentrations is done according to:

$$C_{NH_3,y}[ppm] = C_{NH_3,avg}[ppm] \cdot n_{tot} \cdot \frac{\Delta_{NO_x,y}\ [ppm]}{\sum_{n=1}^{n_{tot}} \Delta_{NO_x,n}\ [ppm]}$$

The NO_x concentration delta is determined as $\Delta_{NO_x,y} = C_{NO_x,multronic} - C_{NO_x,eurofins}$. It should be noted only positive delta values are used in these calculations. The NO_x signal of sensor 2 corrected for NH_3 cross sensitivity with $NO_{x,corrected}[ppm] = NO_x[ppm] - C_{NH_3}[ppm]$ is shown next to the NO_x measurements by Eurofins of engine 1 in Figure 4.1.

While the estimated NH_3 correction of sensor 1 does not give a perfectly matching result to the results with the Eurofins analyser, this analysis gives good confidence that observed deviations are largely caused by NH_3 slip in the exhaust gas. With average NH_3 levels between 1 and 36 ppm depending on the engine and load point, the Stage-V regulatory limit value is crossed on multiple measurements.

4.2.3 Work specific NO_x emissions

NO_x emissions are regulated in regulation 13 of MARPOL Annex VI based on the work specific NO_x emissions. These emissions can be calculated based on the on-board measurements according to the procedure discussed in Section 2.2.1. The calculated work specific NO_x emissions are shown in Figure 4.2. Note that the shown emission values are corrected for temperature and humidity with a humidity correction factor. The applied humidity correction factors can be found in 0. NH_3 correction of sensor data is not applied in the shown results. Where applicable, results are corrected for the added airflow in the DPF (see Section 3.1.2).

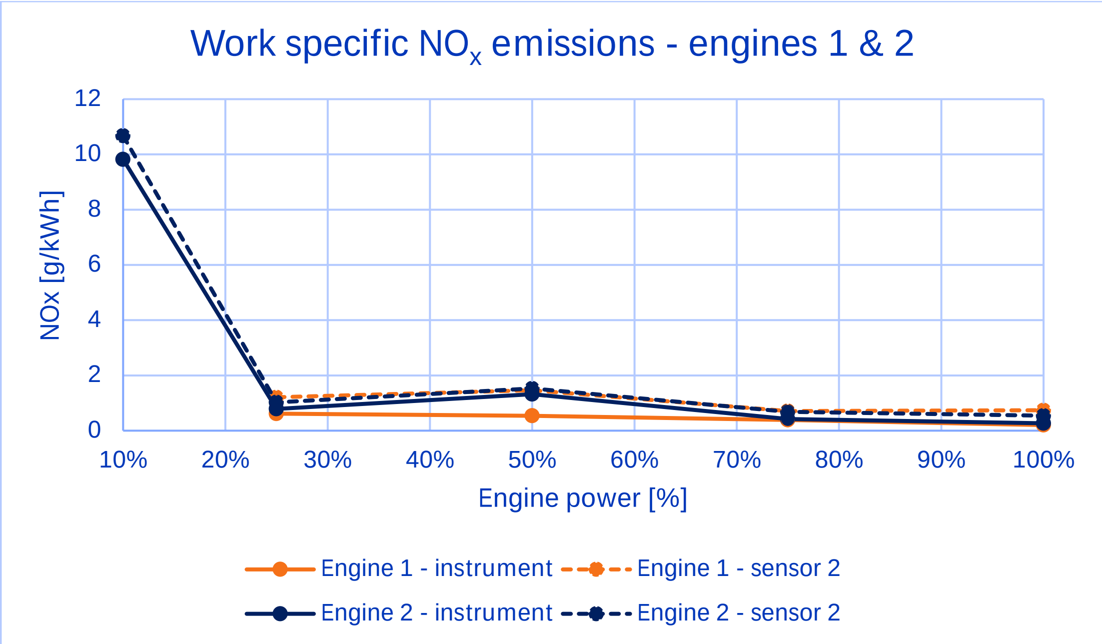

Figure 4.2: Work specific NO_x emissions for engines 1 and 2. Lines between measurement points are added for visual clarity but do not correspond to actual measured data. Emission values are corrected with a humidity correction factor and where applicable for the added airflow from the DPF. No NH_3 correction is applied to the sensor results.

Load point measurements are weighted and summed according to the NO_x technical code 2008 with the weighting factors as shown in Section 2.1.1. Note that the 10% load point is omitted in the measurements on engine 1. For engine 1, an alternative weighting is applied for the D2 cycle as explained in Section 2.1.1. The weighted work specific NO_x emission results for the E2 and D2 cycle are shown with and without a humidity correction applied in Table 4.4 and Table 4.5
Table 4.5.

Table 4.4: E2 cycle NO_x instrument and sensor based results.

E2 cycle NO_x emission results	Instrument (Eurofins) based		Sensor (Multronic) based		NO_x Tier III limit value	NO_x Stage V limit value
	NO_x	NO_x – humidity corrected	NO_x	NO_x – humidity corrected		
	[g/kWh]					
Engine 1	0.37	0.36	0.85	0.82	2.39 [8]	1.80
Engine 2	0.51	0.49	0.77	0.75		

Table 4.5: D2 cycle NO_x instrument and sensor based results.

D2 cycle NO_x emission results	Instrument based		Sensor based		NO_x Tier III limit value	NO_x Stage V limit value
	NO_x	NO_x -humidity corrected	NO_x	NO_x – humidity corrected		
	[g/kWh]					
Engine 1	0.47	0.45	1.07	1.03	2.39 [8]	1.80
Engine 2	0.97	0.95	1.23	1.20		

Weighted work specific NO_x emissions of both instrument based and sensor based measurements remain below the applicable IMO Tier III limit value and the Stage V limit value needed for the ULEv notation. The sensor based emission factor is higher compared to the emission factor derived from the instrument readings. This mismatch is explained in part by NH_3 cross sensitivity in Section 4.2.2. From the available data, no conclusion can be drawn on which value can be considered a more accurate representation of the actual emitted emissions. Due to the significant presence of NH_3 in the exhaust gas and a lack of dynamic detail on these emissions, sensor performance is not classified further in this study.

4.3 Particulate emissions

Particulate emissions are evaluated to check the proper functioning of the Diesel Particulate Filter (DPF). Emissions are evaluated on two indicators: particle number emissions and particle mass emissions. Both of these indicators have limit values under Stage V regulation as shown in Section 2.2.3. Note that the presented measurement results are only valid with the DPF bypass in the exhaust stack in the closed position.

[8] Based on a IMO Tier III constant speed engine operating at 750 RPM.

4.3.1 Particle number emissions

Particle number (PN) concentrations are measured as particles per volume in the exhaust flow. The measured concentrations of both engines on the various load points are shown in Table 4.6.

Table 4.6: PN measurement results per load point – engine 1 & 2.

Avg. PN measurements	Engine 1 (MGO)		Engine 2 (HVO)	
	Eurofins 2024 [#/cm³] (dry)	**Eurofins 2020 [#/cm³] (dry)**	**Eurofins 2024 [#/cm³] (dry)**	**Eurofins 2020[9] [#/cm³] (dry)**
10% load	-	-	21.00E+03	-
25% load	11.40E+03	35.00E+03	12.10E+03	50.00E+03
50% load	12.30E+03	25.00E+03	16.80E+03	58.00E+03
75% load	7.43E+03	32.00E+03	3.51E+03	37.00E+03
100% load	5.11E+03	35.00E+03	5.46E+03	80.00E+03
75% load (regeneration)	7.53E+03	-	16.10E+03	-

The observed PN concentration values are very low. Even during regeneration events, the PN concentration remains low with no significant different emissions compared to the same load point measurement without regeneration. In comparison to the measurement results from the commissioning test, the measured concentrations are somewhat lower (less than one order of magnitude). A small increase in filtering efficiency of the DPF is expected due to formation of a soot layer on the DPF elements over time.

PN cycle emission results are calculated according to the method described in Section 2.2.1, the resulting values are shown in Table 4.7. In line with the low measured PN concentrations, the cycle results show emission values well below the Stage V or ULEv regulatory limit value. The low PN emission results serve as one indicator for proper operation of the DPF system. No significant difference in effectiveness between EN590 (Engine 1) and HVO (Engine 2) of the DPF can be observed.

Table 4.7: Cycle PN emission results.

Cycle PN emission results	E2	D2	PN Tier III limit value	PN Stage V limit value
	[#/kWh]			
Engine 1	4.4E+10	5.8E+10	-	1.0E+12
Engine 2	3.5E+10	6.2E+10		

4.3.2 Particle mass emissions

Particle mass (PM) emissions are measured as total mass captured on a filter exposed to a regulated sample flow of exhaust gas. The filter mass measurements and their respective total sample volume are included in Appendix A.1.1 and A.2.1. The mass results per normalised air volume are shown in Table 4.8.

[9] Measurements based on EN590 10 ppm fuel.

Table 4.8: PM measurement results per load point - engine 1 & 2.

PM measurements	Engine 1 (MGO)		Engine 2 (HVO)	
	Eurofins 2024 [mg/Nm³] (dry)	**Eurofins 2020 [mg/Nm³] (dry)**	**Eurofins 2024 [mg/Nm³] (dry)**	**Eurofins 2020 [mg/Nm³] (dry)**
10% load	-	-	<0.36[10]	-
25% load	0.50	<0.19[10]	0.75	0.42
50% load	0.59	0.20	0.90	0.44
75% load	<0.41[10]	0.41	0.68	<0.20[10]
100% load	<0.35[10]	<0.19[10]	0.73	0.63

In contrast to the PN measurements, the PM measurements come in somewhat higher compared to the measurements during commissioning. In combination with the lower PN concentrations found, this might indicate emissions of larger particles. Filters were visually clean after the measurements (see Appendix A.1.1 and A.2.1), as such, composition of the emitted particulate matter can be assumed to be mainly made up of semi volatile particles such as hydrocarbons and sulphates plus adsorbed water. In addition, the results on engine 2 show slightly higher PM emissions compared to engine 1. Differences in measured mass are however very low and fall within the measurement uncertainty for low filter loading measurements.

PM cycle emission results are calculated according to the method described in Section 2.2.1, the resulting values are shown in Table 4.9. Cycle results show emission values well below the Stage V limit which applies for the ULEv notation. Low PM emission results serve as a second indicator for proper operation of the DPF system.

Table 4.9: Cycle PM emission results.

Cycle PM emission results	E2	D2	PM Tier III limit value	PM Stage V limit value
	[mg/kWh]			
Engine 1	2	3	-	15
Engine 2	4	5		

4.4 Other emissions

4.4.1 CO emissions

Carbon monoxide (CO)-emissions signifies partial combustion. The measured CO concentrations of both engines are listed in Table 4.10. The CO cycle emission results are calculated according to the method described in Section 2.2.1, the resulting values are shown in Table 4.11.

[10] Filter loading below detection limit, the shown maximum value is used in calculated results when applicable.

Table 4.10: CO measurement results per load point - engine 1 & 2.

CO measurements	Engine 1 (MGO)		Engine 2 (HVO)	
	Eurofins 2024 [ppm] (dry)	**Eurofins 2020 [ppm] (dry)**	**Eurofins 2024 [ppm] (dry)**	**Eurofins 2020 [ppm] (dry)**
10% load		-	241	-
25% load	170	9	212	10
50% load	90	12	135	15
75% load	87	15	97	15
75% load (regeneration)	82	-	92	-
100% load	92	9	109	12

Table 4.11: Cycle CO emission results.

Cycle CO emission results	E2	D2	CO Tier III limit value	CO Stage V limit value
	[g/kWh]			
Engine 1	0.6	0.8	-	3.5
Engine 2	0.8	1.1		

CO emissions are found to be below the Stage V limit value applicable for the ULEv notation. CO emissions however seem to have increased significantly since the initial measurement in 2020. The differences in CO emissions between engine 1 and engine 2 are most likely due to the differences in combustion properties between MGO and HVO.

4.4.2 HC-emissions

Hydro carbon (HC) -emissions signify the emission of unburned fuels to the environment. Especially with the use of a standalone burner for the DPF regeneration, elevated HC-emissions can occur. The measured propane equivalent HC concentrations are shown in Table 4.12.

A small difference is observed between measurements with and without DPF regeneration active where regeneration lowers the emitted HC-concentrations.

Table 4.12: HC-measurement results per load point.

Avg. HC measurements	Engine 1 (MGO)		Engine 2 (HVO)	
	Eurofins 2024 [ppm] (wet, propane equivalent)	Eurofins 2020 [ppm] (wet, propane equivalent)	Eurofins 2024 [ppm] (wet, propane equivalent)	Eurofins 2020 [ppm] (wet, propane equivalent)
10% load	-	-	4	-
25% load	3	0	3	1

50% load	3	0	2	2
75% load	4	0	3	3
75% load (regeneration)	3	-	2	-
100% load	5	0	4	2

HC-cycle emission results are calculated according to the method described in Section 2.2.1, the resulting values are shown in Table 4.13. Cycle emission results fall well below the Stage V limit value which applies for the ULEv notation.

Table 4.13: Cycle HC emission results.

Cycle HC-emission results	E2	D2	HC Tier III limit value	HC Stage V limit value
	[mg/kWh]			
Engine 1	15	13	-	190
Engine 2	12	11		

5 Conclusions

A measurement programme was conducted to determine the real world emissions performance of the maritime exhaust gas aftertreatment systems onboard a suction hopper dredger which has the ULEv notation, running on both low sulphur MGO and HVO biofuel. Both the SCR and DPF systems onboard this ship were evaluated with in-stack measurements and references of the on-board sensor monitoring system.

Both emission aftertreatment systems were evaluated for general performance and possible degradation effects, but also to their absolute emission levels in relation to the ULEv notation of the vessel. This ULEv notation incorporates the emission limits from the Stage V regulation for inland vessels on seagoing vessels.

From the measurement results and analysis, the following general conclusions can be drawn:

- During the measurement campaign, all cycle weighted pollutant emissions of NO_x and Particulate Matter are found to be well below the emission limits for IWP engines of Stage V regulation applicable for the ULEv notation. This is the case for both E2 (sailing) and D2 (auxiliary use) cycles and for operation on both MGO and HVO fuel.
  - NO_x emissions on both measured engines remain between 0.4 to 0.5 g/kWh and between 0.5 to 1.0 g/kWh for the E2 and D2 cycles respectively. Below the Stage V limit value of 1.8 g/kWh.
  - PN emissions on both measured engines remain between 3.5×10^{10} to 4.4×10^{10} #/kWh and 5.8×10^{10} to 6.2×10^{10} #/kWh for the E2 and D2 cycles respectively. Below the Stage V limit value of 10×10^{12} #/kWh.
  - PM emission on both measured engines remain between 2 to 4 mg/kWh and between 3 to 5 mg/kWh for the E2 and D2 cycles respectively. Below the Stage V limit value of 15 mg/kWh
- These results are only valid while the DPF bypass onboard the ship is in the closed position.

From the measurement results and analysis, the following conclusions can be drawn on the DPF operation:

- The DPF system is found to work well. Particle number emissions from the stack are reduced to background level concentrations under all conditions. Active regeneration of the DPF shows no increase in emitted particle numbers.
- Both on MGO and HVO, the DPF system reduces particle emissions well below the limit values which apply for the ULEv notation (at IWP engine Stage V level).
- Changes in particle number and particle mass emissions between the measurements at commissioning of the vessel and the measurements discussed in this report are insignificant. No deterioration of the DPF system is found. It should be noted that, in addition to automatic regeneration, DPF elements are manually cleaned with pressurised air in a specialised enclosure when ash loading increases.

- While observed differences between the measurements in this report and the measurements at commissioning of the vessel are small, the slight decrease in emitted particle number concentrations may in part be explained by the formation of a soot layer on the DPF elements, increasing the filtration efficiency.

From the measurement results and analysis, the following conclusions can be drawn regarding the SCR operation:

- During the measurement campaign, the SCR system is found to reduce NO_x emissions to levels well below the applicable limit value for the voluntary ULEv label (Stage V IWP) on both MGO and HVO. Significant NH_3 slip up to 27 mg/Nm^3 from the SCR system is observed, however.
- NH_3 slip can be the result of reduced catalyst efficiency, faulty DEF injection control or DEF over-injection. Measurements should be considered a spot check, therefore the observed emissions can also be due to a temporary problem relating to urea crystal formation and release in the exhaust stack or a systematic problem in the dosing control.
- NH_3 emissions are not limited under the Stage V inland shipping regulation, however, similar as for NO_x emissions, NH_3 emissions have a large potential for acidification upon deposition in the environment. NH_3 emissions therefore counteract reductions in NO_x emissions.
- In contrast to engines for vessels with an ULEv notation, engines for the propulsion of inland waterway vessels fulfilling the Stage V requirements are required to have a NO_x control diagnostics (NCD) system onboard to monitor the proper operation of the NO_x control system. Such a system, or equivalent monitoring system with NH_3 measurement capabilities could prevent unnoticed high NO_x or NH_3 emissions to guarantee proper SCR operation.

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Appendix A
Emission measurement results

A.1 Engine 1: P-28051-02-11

Table A.1: Emission measurement results – engine 1

Load point	25%	50%	75%	100%	75%
TIME start [UTC]	06:38	07:22	08:57	08:10	09:54
TIME stop [UTC]	07:08	07:52	09:27	08:40	10:09
Duration [min]	30	30	30	30	15
Engine speed [RPM]	750	750	750	750	750
Electrical load [kW]	623.46	1248.40	1873.17	2373.66	1870.27
Mechanical power [kW]	660	1320	1980	2112	2640
Ambient T [degC]	23.0	23.6	24.9	25.0	25.1
Ambient P [hPa]	1008	1008	1009	1008	1009
Relative humidity [%]	51.1	49.0	46.9	45.5	43.8
Manifold T [degC]	37.58	39.47	44.54	44.54	42.15
Manifold rel P [hPa]	469.98	1217.89	2111.93	2865.68	2099.55
SCR T inlet [degC]	325.2	331.0	324.1	325.8	326.5
SCR T outlet [degC]	321.5	331.7	332.4	333.8	333.6
DPF T inlet [degC]	309.5	320.3	323.7	324.3	443.8
DPF T outlet [degC]	304.4	314.8	320.5	321.2	383.5
Exhaust P [hPa]	1008.4	1007.4	1008.2	1007.1	1007.7
Exhaust T [degC]	308.5	320.0	325.5	326.8	386.0
Flow [Nm^3/h], dry	4810	8129	11293	14337	8858
Flow [Nm^3/h], wet	5116	8687	12096	15369	9515
Urea mass flow [kg/h]	11.6	23.0	29.9	36.64	30.11
DPF backpressure [mbar]	14.82	23.34	35.25	43.26	39.75
DPF blower pressure [mbar]	22.95	35.77	45.84	70.20	69.85
DPF blower flow [m^3/h]	248	278	264	435	445
DPF regeneration active?	no	no	no	no	yes
HT in/out [degC]	75/77	75/77	75/78	77/81	75/78
LT CW Temp [degC]	36	36	36	36	36
Fuel T [degC]	34	34	34	34	34
Oil T [degC]	69	70	73	73	73

Fuel use [kg/min]	2.60	4.24	6.00	7.70	6.57
Dry to wet factor	0.94	0.94	0.93	0.93	0.93
Humidity correction factor	0.96	0.96	0.97	0.98	0.97
O_2 [V%], dry	14.39	13.76	13.53	13.26	13.02
CO_2 [V%], dry	5.02	5.52	5.73	5.86	6.13
CO [ppm], dry	169.66	90.22	87.25	92.23	81.53
NO_x – instr. [ppm], dry	40.70	45.41	34.43	17.85	34.69
NO_x – sensor 2 [ppm], wet	75.01	115.21	58.77	61.09	61.46
HC [ppm propane eq.], wet	2.83	2.93	3.83	5.23	2.83
PM [mg/Nm^3], dry	0.5	0.59	0.41	0.35	0
PN [#/cm^3], dry	1.14E+04	1.23E+04	7.43E+03	5.11E+03	7.53E+03
NH_3 [mg/Nm^3], dry	0.55	0.45	20.84	24.83	-
CO [g/kWh][11]	1.62	0.68	0.62	0.65	0.54
NO_x – instr [g/kWh][12,11]	0.62	0.54	0.39	0.20	0.37
NO_x – sensor 2 [g/kWh][11]	1.21	1.46	0.71	0.74	0.70
HC [mg/kWh][11]	13.37	10.93	13.46	18.25	9.34
PM [mg/kWh][11]	3.82	3.54	2.32	1.96	-
PN [#/kWh][11]	8.71E+10	7.38E+10	4.2E+10	2.87E+10	3.98E+10

[11] Referenced to mechanical power
[12] Humidity corrected value

A.1.1 PM filters

Engine 1 - 25%

Engine 1 - 50 %

Engine 1 - 75%

Engine 1 - 100 %

Table

A.2: PM measurement specifications – engine 1

Load steps	25%	50%	75%	100%	75% regen
PM filter mass [mg]	0.1	0.1	<0.1[13]	<0.1[13]	-
Volume Flue gas [Nm³]	0.208	0.1687	0.2469	0.2820	-
Dilution Air Volume [Nm³]	0.5090	0.5250	0.5250	0.5160	-
Total volume [Nm³]	0.7108	0.6937	0.7719	0.7980	-
Dilution	3.5	4.1	3.1	2.8	-
Tmax Filter [°C]	37.8	41.0	33.4	41.0	-

A.2 Engine 2: P-28051-02-12

Table A.3: Emission measurement results - engine 2

Load point	10%	25%	50%	75%	100%	75%
TIME start [UTC]	15:28	11:47	12:36	14:08	13:24	14:57
TIME stop [UTC]	15:58	12:17	13:06	14:38	13:54	15:12
Duration [min]	30	30	30	30	30	15
Engine speed [RPM]	750	750	750	750	750	750
Electrical load [kW]	250.33	625.23	1248.04	1876.44	2374.78	1876.11
Mechanical power [kW]	264	660	1320	1980	2112	2640
Ambient T [degC]	25.6	28.2	26.3	26.2	26.4	25.9
Ambient P [hPa]	1009	1009	1009	1009	1009	1009
Relative humidity [%]	43.2	37.9	41.5	41.6	40.3	43.1
Manifold T [degC]	36.95	37.97	39.71	42.13	44.72	41.95
Manifold rel P [hPa]	158.85	436.79	1178.11	2092.26	2834.43	2087.38
SCR T inlet [degC]	286.6	342.7	346.7	335.7	339.3	336.9
SCR T outlet [degC]	284.7	323.0	331.8	331.7	336.0	331.4
DPF T inlet [degC]	309.8	333.3	331.1	328.8	332.5	438.6
DPF T outlet [degC]	334.6	341.0	329.9	328.6	332.0	383.8
Exhaust P [hPa]	1010.1	1009.3	1009.1	1008.4	1007.1	1008.6

[13] Filter loading below detection limit

Exhaust T [degC]	328.0	336.3	335.5	334.5	338.0	393.5
Flow [Nm^3/h], dry	5080	5950	9165	13930	16481	14025
Flow [Nm^3/h], wet	5339	6331	9794	14901	17654	15061
Urea mass flow [kg/h]	0	10.9	18.0	27.1	32.1	27.1
DPF backpressure [mbar]	7.4	11.5	20.4	31.2	40.2	36.5
DPF blower pressure [mbar]	21.58	24.75	33.08	47.79	61.18	71.14
DPF blower flow [m^3/h]	250	245	234	158	443	445
DPF regeneration active?	No	No	No	No	No	Yes
HT in/out [degC]	63/65	73/75	76/79	75/78	79/83	75/78
LT CW Temp [degC]	36	36	36	36	36	36
Fuel T [degC]	35	35	35	35	35	35
Oil T [degC]	68	69	70	73	74	73
Fuel use [kg/min]	1.57	2.58	4.20	5.95	7.70	6.54
Dry to wet factor	2.17	0.94	0.94	0.93	0.93	0.93
Humidity correction factor	0.98	0.98	0.97	0.98	0.98	0.98
O_2 [V%], dry	15.97	14.24	13.50	13.25	13.01	12.78
CO_2 [V%], dry	3.77	5.04	5.54	5.66	5.84	6.05
CO [ppm], dry	241.09	211.85	134.49	96.88	108.74	92.09
NO_x – instr. [ppm], dry	367.73	53.07	114.12	37.76	24.30	39.47
NO_x – sensor 2 [ppm], wet	380.36	64.92	123.55	57.19	46.09	61.25
HC [ppm propane eq.], wet	3.79	2.83	2.01	3.26	4.46	2.14
PM [mg/Nm^3], dry	0.36	0.75	0.9	0.68	0.73	-
PN [#/cm^3], dry	2.10E+04	1.21E+04	1.68E+04	3.51E+03	5.46E+03	1.61E+04
NH_3 [mg/Nm^3], dry	2.55	26.47	27.2	18.12	18.05	-
CO [g/kWh] [11]	3.99	1.96	0.98	0.67	0.74	0.60

NO_x – instr [g/kWh][11,12]	9.82	0.79	1.32	0.42	0.27	0.41
NO_x – sensor 2 [g/kWh][,11]	10.68	1.03	1.53	0.68	0.54	0.69
HC [mg/kWh] [11]	13.42	12.93	7.26	11.26	15.17	6.94
PM [mg/kWh] [11]	4.76	5.54	5.23	3.78	3.99	-
PN [#/kWh] [11]	2.78E+11	8.94E+10	9.77E+10	1.95E+10	2.99E+10	8.37E+10

A.2.1 PM filters

Engine 2 - 10 %

Engine 2 - 25%

Engine 2 - 50 %

Engine 2 - 75%

Engine 2 - 100 %

Table A.4: PM measurement specifications – engine 2

Load steps	10%	25%	50%	75%	100%	75% regen
PM filter mass [mg]	<0.1[13]	0.2	0.2	0.2	0.2	-
Volume Flue gas [Nm³]	0.2761	0.2651	0.2225	0.2931	0.2727	-
Dilution Air Volume [Nm³]	0.5310	0.5250	0.5230	0.5250	0.5280	-
Total volume [Nm³]	0.8071	0.7901	0.7455	0.8181	0.8007	-
Dilution	2.9	3.0	3.4	2.8	2.9	-
Tmax Filter [°C]	32.5	34.8	49.2	30.6	31.4	-

Appendix B
TNO onboard procedure

In general there are two options to calculate g/kWh emissions:

1. Conventional: calculating emission mass flows and measuring or estimating engine power. Then weighing of emissions can be based on g/h emissions (as is normally required).
2. Using emission concentrations in combination with the specific fuel consumption characteristic of the engine.

It should be noted that also with option 2 a(n) (indicative) power or fuel consumption is needed to correctly weigh the emissions for an official test cycle like the E2 or E3 test cycle.

The conventional ISO onboard procedure is based on the fact that engine torque or power and air or exhaust mass flow (through the engine) are directly measured. For onboard monitoring this is not a practical solution. Torque meters and flow meters are rarely installed (PROMINENT D5.8). The conventional method measures emission concentrations in the exhaust flow. Combining these concentrations with the exhaust mass flow rate results in g/h emissions. Together with the measured engine power, the g/kWh emissions can be calculated. A detailed explanation of the conventional onboard test procedure is found in IMO MARPOL section 2.1.

For option 2, the description below is directly taken over from SCIPPER D1.6, 2022. The method is based on the Specific Fuel **Consumption (SFC) and carbon balance. The method is schematically presented in** Figure B.1 (right) and compared with the IMO MARPOL onboard procedure for a single test according to the ISO 8178 test procedure (left).

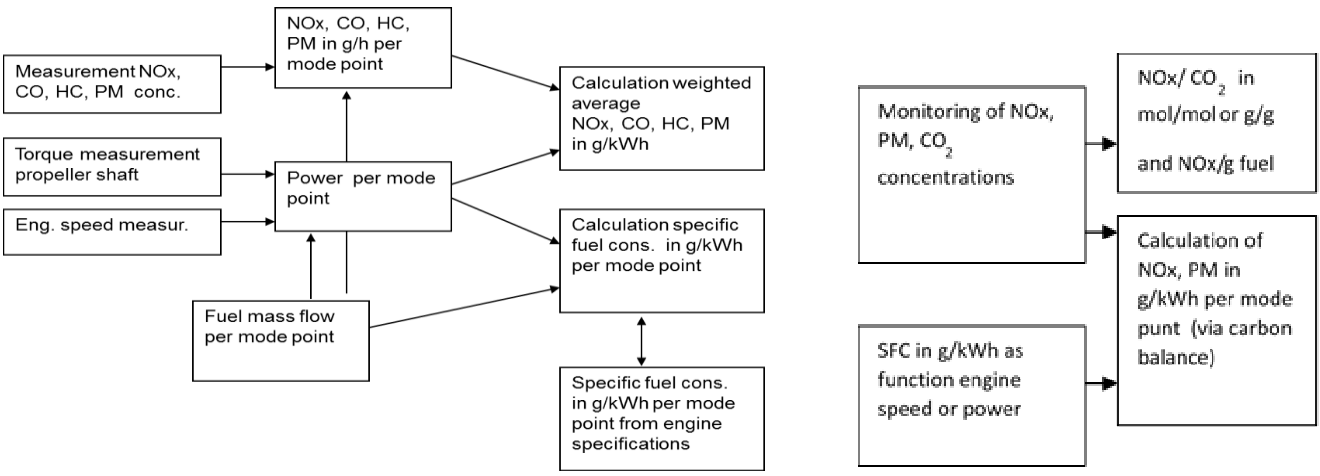


Figure B.1: Comparison of IMO onboard test procedure (left) with simplified procedure for onboard monitoring (right)

The simplified calculation method is somewhat flexible to allow slightly different approaches based on either specific CO_2 emissions of the fuel or based on the fuel carbon content. The only needed parameters for the first option are exhaust concentrations (in ppm) and specific CO_2 emissions of the fuel type used (kg CO_2 per kg fuel).

To obtain the emissions mass ratios, the molar ratios (concentration ratios) have to be multiplied by the ratio of the molar mass of NO_x[14] and the one of CO_2:

$$\frac{NO_x^{g}}{CO_2^{kg}} = \frac{NO_x^{ppm}}{CO_2^{ppm}} \cdot \frac{M_{NO_x}}{M_{CO_2}} \cdot 1000 \qquad \text{gram } NO_x \text{ per kg } CO_2 \qquad (1)$$

The mass of NO_x per kg fuel is determined by multiplying the mass ratio $\frac{NO_x^{g}}{CO_2^{kg}}$ by the fuel coefficient for specific CO_2 emissions C_F, which is 3.17 for MGO:

$$\frac{NO_x^{g}}{m_{fuel}^{kg}} = \frac{NO_x^{g}}{CO_2^{kg}} \cdot c_F = \frac{NO_x^{g}}{CO_2^{kg}} \cdot 3.17 \qquad \text{gram } NO_x \text{ per kg fuel} \qquad (2)$$

This can be converted to a NO_X per engine work (g/kWh) value by multiplying it with the specific fuel consumption, SFC in kg/kWh:

$$\frac{NO_x^{g}}{W_{engine}^{kWh}} = \frac{NO_x^{g}}{m_{fuel}^{g}} \cdot SFC \qquad (\text{g/kWh } NO_x) \qquad (3)$$

There are some variations on these equations possible. Instead of the specific CO_2 emission factor for the type of fuel, also the fuel carbon content, $Fuel_C$, multiplied by the molecular mass ratio of CO_2 and C. Equation (2) is then written as follows:

$$\frac{NO_x^{g}}{m_{fuel}^{kg}} = \frac{NO_x^{g}}{CO_2^{kg}} \cdot \frac{M_{CO2}}{M_C} \cdot \text{Fuel}_C \qquad \text{gram } NO_x \text{ per kg fuel} \qquad (4)$$

M_{CO2}/M_C in Equation (4) is 44.06/12.01.
Equation (4) can be combined with Equation (1), and molecular mass of CO_2 falls out of the equation:

$$\frac{NO_x^{g}}{m_{fuel}^{kg}} = \frac{NO_x^{ppm}}{CO_2^{ppm}} \cdot \frac{M_{NO_x}}{M_C} \cdot \text{Fuel}_C \cdot 1000 \qquad \text{gram } NO_x \text{ per kg fuel} \qquad (5)$$

It should be noted that in the equations above, only the CO_2 concentration is used to make the 'carbon balance' between fuel input and exhaust flow. A small part of the carbon is however emitted as CO or HC (or even PM). If CO and HC concentration are added, these can simply be added to the CO_2 concentration in the equations above. So, in that case CO_2 (ppm) is replaced by the sum of $[CO_2+CO+HC]^{ppm}$.

In Equation (5): M_{NOx}/M_C = 46.01/12.01. For NO_x always the molecular mass of NO_2 must be used. Multiplying (5) with the SFC again provides the NO_x in g/kWh.

[14] For NO_x, the molecular mass of NO_2 was used.

There are several options for SFC value:

- SFC as function of load, provided by the engine supplier of the engine pass-off test.
- Generic SFC as function of engine load per engine type such as for example is used in the IMO fourth GHG study.
- Constand SFC per engine type. In that case the NO_X calculation in g/kWh at low loads (<30% about) will be underestimated by some 5% to 10%.

The first two options, SFC as function of engine load is certainly preferable. In that case it is necessary, that the monitoring system receives a reliable engine load or fuel consumption signal. When the engine load is quite dynamic, it will then also be important that the time phasing and averaging of the different signals are in par.

A fuel analysis can be done, in order to obtain the carbon content of the fuel.
If no fuel analysis is done, also default values can be used for the fuel carbon content or specific CO_2 emissions. These are for example presented in (IMO MEPC 245(66), 2014) and (EC COM(2021) 562 final, 2021) and shown in Table 2.1. In case of dual fuel operation, the calculation becomes somewhat more complex since also the correct specific CO_2 emission and SFC for the fuel mixture needs to be calculated. Based on the mass ratios of the fuels, this can be calculated as follows

$$C_{F\ dual\ fuel} = mass\%_{fuel1} \cdot C_{f\ fuel\ 1} + mass\%_{fuel2} \cdot C_{F\ fuel2}$$

The NO_x emissions in g/kg methanol (or dual-fuel mixture) cannot directly be compared with those of diesel fuel, because the LHV is more than two times lower and consequently also more than twice the amount of fuel in kg is needed. To make diesel and methanol results comparable the emissions can be expressed in gram per MJ fuel or per kg diesel equivalent LHV. The lower heating value in case of a dual-fuel mixture (e.g. diesel and methanol) can be calculated by:

$$LHV_{dual\ fuel} = mass\%_{fuel1} \cdot LHV_{fuel\ 1} + mass\%_{fuel2} \cdot LHV_{fuel2}$$

PM and PN emissions can be calculated in a similar way. Only the concentrations are expressed in gram per standard m^3. The PM and carbon concentrations can both be measured in the diluted exhaust flow used for the PM measurement. In that way, there is no need to calculate dilution ratios for the measurement points.

$$\frac{PM_x^{g}}{m_{fuel}^{kg}} = \frac{PM_x^{g/m3}}{C^{kg/m3}} \cdot Fuel_C$$

concentrations in (diluted) PM sample flow

The carbon concentration is calculated using the ideal gas law, as follows:

$$C^{kg/m3} = CO_2^{ppm} \cdot \frac{P_{ref} \cdot M_c}{R_u \cdot T_{ref}} \cdot 10^{-6}$$

For the reference ambient pressure and temperature, P_{ref} and T_{ref}, the same values should be used as for the PM (g/m^3) calculation. The universal gas, R_u is 8.31432 J/mol.K.
Particle number, PN, can be calculated in the same way by just substituting the PM value by the PN value in $\#/m^3$.

Table B.1: Fuel carbon specifications of several fuels based on Annex-2014 of MEPC245 (66) and Annex II of EU regulation COM(2021) 562 final.

	Lower combustion value MJ/kg	Fuel carbon content kg/kg fuel	Specific CO_2 emissions kg / kg fuel	Note
Diesel, gasoil, VLSFO, MDO	42.7	0.8774	3.206	ISO 8217 grades DMX through DMB
HFO, LSFO, ULSFO	40.5	0.9493	3.114	ISO 8217 grades RME through RMK
LFO	41	0.8594	3.151	ISO 8217 grades RMA through RMD
LNG	49.1	0.750	2.750	Pure methane
Methanol	19.9	0.375	1.375	Pure methanol

If directly g/kWh emissions are calculated, it is consequently not possible to process the average emissions for an official test cycle (E2, E3) or across a trip with different load points (PROMINENT D5.8). The calculation of the average emissions (weighing of emissions) should be done according to the following equation (E= NO_x, HC, CO in g/kWh, E_i in g/h, P=power in kW):

$$E\left(\frac{g}{kWh}\right) = \sum_{i=0}^{n} Ei\left(\frac{g}{h}\right).WFi \;\;/\;\; \sum_{i=0}^{n} Pi\,.WFi$$

P is engine power, which can be derived from fuel flow or electrical power (diesel-electric powertrain). We sum over the segments of the trip with a constant load.

Calculation of g/h emissions can be avoided by using the (indicative) power both in the counter and in the denominator of the equation above, so:

$$E\left(\frac{g}{kWh}\right) = \sum_{i=0}^{n} Ei\left(\frac{g}{kWh}\right).Pi\,.WFi \;\;/\;\; \sum_{i=0}^{n} Pi\,.WFi$$

E_i emission in g/kWh in this case. The accuracy of the power measurement is then less important, because it is only used to correctly weight the g/kWh emissions, and therefore relative rather than absolute values are important. By doing this, P could also be replaced by another parameter which scales with power, such as N^3 (engine speed to the third power).

Appendix C
Alternative calculation results

C.1 Calculated flow method

The calculated flow method uses flow and engine power to calculate the work specific emissions. While this method is more dependent on accurate engine power readings, the results can be used to assess the plausibility of the results from the main calculation method.

Total flow in the exhaust stack is calculated according to Equation C.1, Equation C.2 and Equation C.3. Using the calculated flow, the work specific pollutant emissions are calculated with Equation C.4.

Equation C.1: Intake airflow calculation.

$$Flow_{air}\left[\frac{g}{h}\right] = \frac{P_{manifold}\,[Pa]\cdot S_{engine}\,[RPM]\cdot V_{engine}[m^3]\cdot \eta_{vol}[-]}{2\cdot R\left[\frac{Pa\,m^3}{kg\,K}\right]\cdot T_{manifold}\,[K]}\cdot 60\left[\frac{min}{h}\right]\cdot 10^3\left[\frac{g}{kg}\right]$$

Equation C.2: Fuel flow calculation

$$Flow_{fuel}\left[\frac{g}{h}\right] = Flow_{air}\left[\frac{g}{h}\right]\cdot\frac{\left(CO_{2,eq}[vol.\%] - CO_{2,amb}[vol.\%]\right)\cdot\frac{M_{CO_2}}{M_{exh}}}{100\cdot\frac{M_{CO_2}}{M_c}\cdot y_c - CO_{2,eq}[vol.\%]\cdot\frac{M_{CO_2}}{M_{exh}}}$$

Equation C.3: Total exhaust flow calculation

$$Flow_{exh}\left[\frac{g}{h}\right] = Flow_{air}\left[\frac{g}{h}\right] + Flow_{fuel}\left[\frac{g}{h}\right]$$

Equation C.4: Flow based work specific pollutant emission calculation.

$$Pollutant\left[\frac{g}{kWh}\right]^{15} = \frac{Pollutant[ppm]\cdot Flow_{exh}\left[\frac{g}{h}\right]\cdot M_{Pollutant}\left[\frac{g}{mol}\right]}{10^6\cdot M_{exh}\left[\frac{g}{mol}\right]\cdot Power[kW]}$$

Parameter	Description	Unit
Pollutant	Measured pollutant concentration	ppm
$CO_{2,eq}$	Measured CO_2 equivalent concentration (CO + CO_2 + HC)	Vol. %
$CO_{2,amb}$	Ambient CO_2 concentration	Vol. %
$M_{Pollutant}$	Molar mass of the pollutant	g/mol

[15] This equation deviates for pollutants with different concentration units.

Parameter	Description	Unit
M_{CO_2}	Molar mass of CO_2	g/mol
M_{exh}	Molar mass of exhaust gas	g/mol
M_c	Molar mass of carbon	g/mol
y_c	Fuel carbon content	-
Power	Engine power	kW
$P_{manifold}$	Absolute manifold pressure	Pa
$T_{manifold}$	Manifold air temperature (after cooler)	K
S_{engine}	Engine speed	RPM
η_{vol}	Volumetric efficiency of the engine	-
R	Specific gas constant for air	J/(kg K)

The work specific emissions for each load point and both the E2 and D2 cycle are listed in Table C.1 and Table C.2 for engine 1 and engine 3 respectively. The comparable values from the main calculation method are listed for reference. Work specific emissions are seen to increase slightly with the calculated flow method compared to the main carbon balance method. The deviations are in range of +2.4% to +6.6% and fall therefore in the expected deviation range between different calculation methods.

Table C.1: Emission cycle result comparison of flow method vs carbon balance – engine 1.

	E2		D2	
	Calculated flow method	**Main method**	**Calculated flow**	**Main method**
CO [g/kWh]	0.62 (-8.2%)	0.68	0.75 (-6.6%)	0.80
NO_x – instr. [g/kWh]	0.33 (-9.1%)	0.36	0.42 (-7.2%)	0.45
NO_x – sensor [g/kWh]	0.75 (-9.2%)	0.83	0.96 (-7.2%)	1.03
HC [mg/kWh]	13 (-9.9%)	15	12 (-8.2%)	13
PM [mg/kWh]	2.21 (-9.2%)	2.43	2.70 (-7.3%)	2.91
PN [#/kWh]	4.01E+10 (-8.9%)	4.41E+10	5.38E+10 (-6.9%)	5.78E+10

Table C.2: Emission cycle result comparison of flow method vs carbon balance – engine 2.

	E2		D2	
	Calculated flow method	**Main method**	**Calculated flow**	**Main method**
CO [g/kWh]	0.73 (-7.9%)	0.80	1.13 (+7.8%)	1.05
NO_x – instr. [g/kWh]	0.47 (-7.9%)	0.49	1.24 (+30.7%)	0.95
NO_x – sensor [g/kWh]	0.69 (-8.2%)	0.75	1.17 (-2.5%)	1.20
HC [mg/kWh]	11 (-8.8%)	12	10 (-2.6%)	11
PM [mg/kWh]	3.75 (-8.5%)	4.10	4.43 (-2.9%)	4.56
PN [#/kWh]	3.23E+10 (-7.3%)	3.49E+10	6.84E+10 (+10.4%)	6.20E+10

C.2 Measured flow method

The measured flow method relies on flow measurements at the pollutant emissions concentration sampling locations. Here Equation C.4 is reused where $Flow_{exh}\left[\frac{g}{h}\right]$is replaced by the measured flow value.

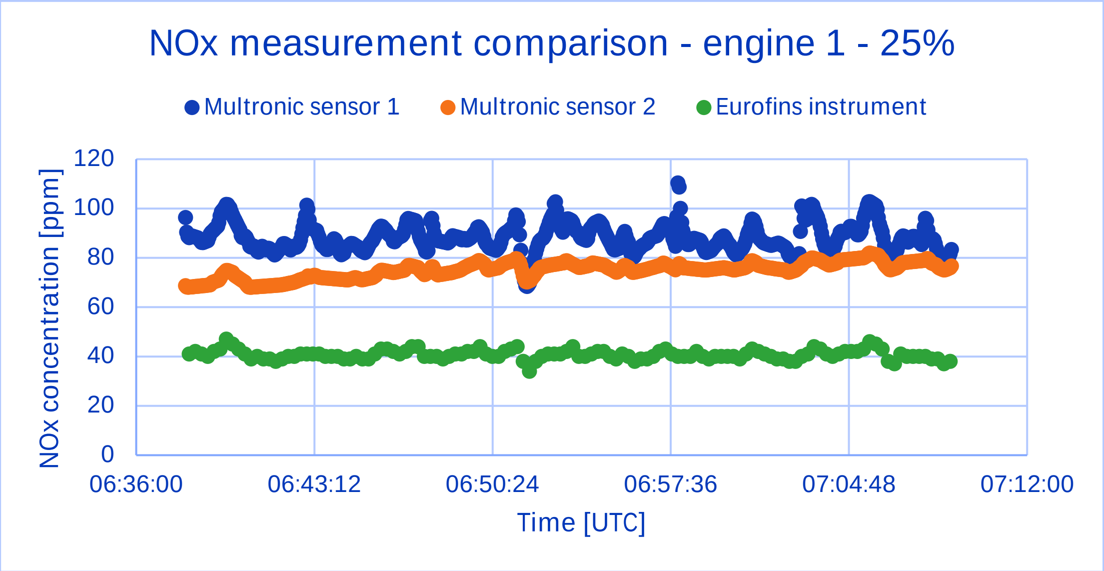
Flow measurements are often performed as volume flow measurements with a pitot tube. To obtain the desired exhaust mass flow rate for emissions mass flow calculation, the following equations are used:

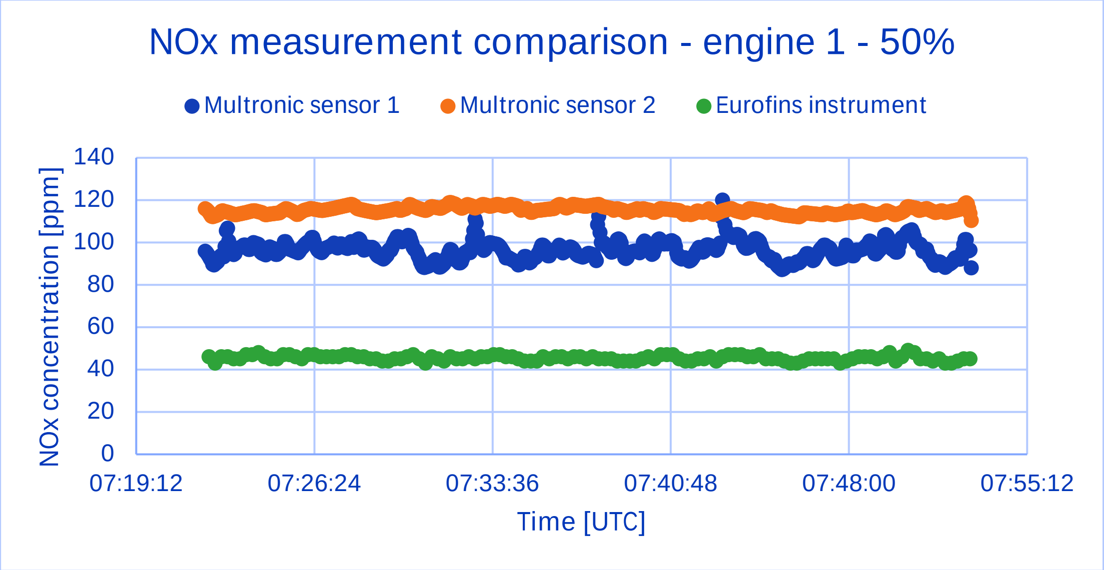
$$\dot{m}\left[\frac{g}{h}\right] = \frac{P\ [Pa] \cdot \dot{V}\left[\frac{m^3}{h}\right] \cdot M_{exh}\left[\frac{g}{mol}\right]}{R\left[\frac{J}{mol\ K}\right] \cdot T[K]}$$

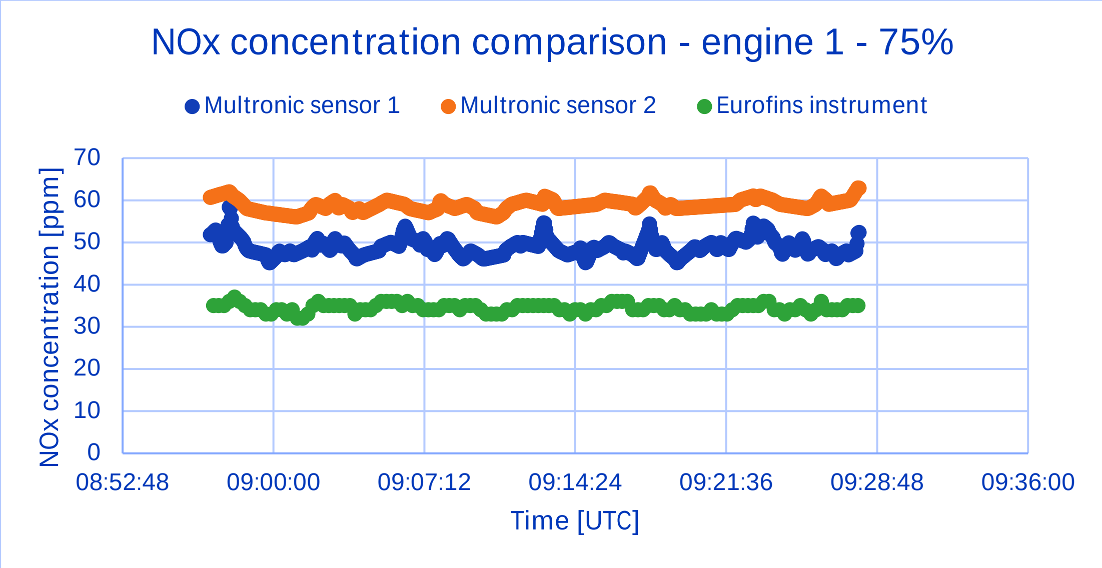
Here, the pressure P can be simplified to the ambient pressure in case measurements are performed near the end of the exhaust stack. The temperature T is the temperature of the exhaust gas at the measurement location in Kelvin. The molar mass of exhaust gas for diesel combustion can be taken as 29 [g/mol]. Finaly, the gas constant R is equal to 8.314 J/mol.K.

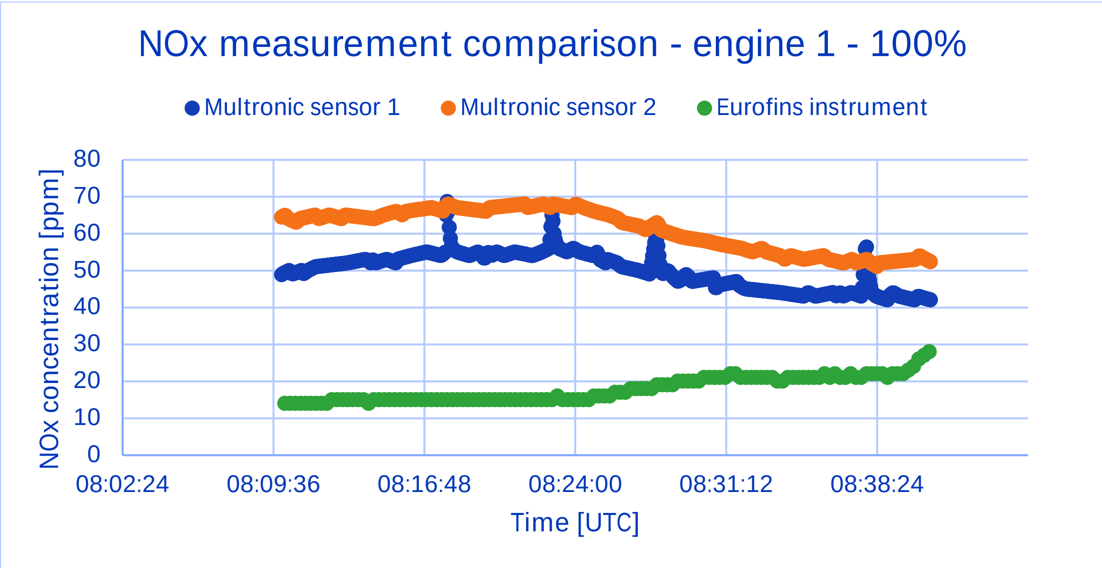
Appendix D
NO_x emission plots

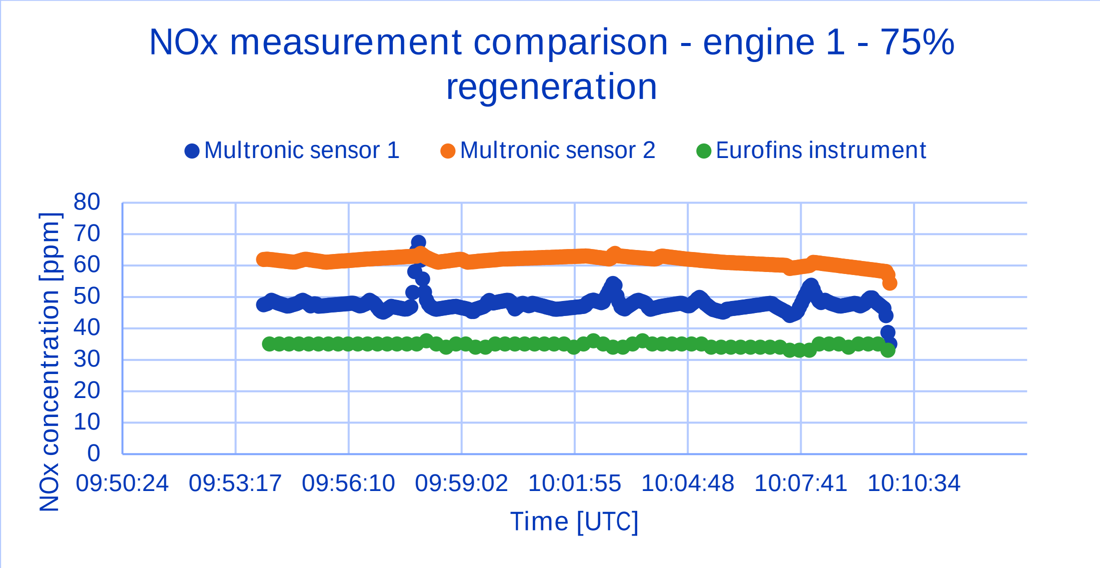
D.1 NO_x emission results – engine 1



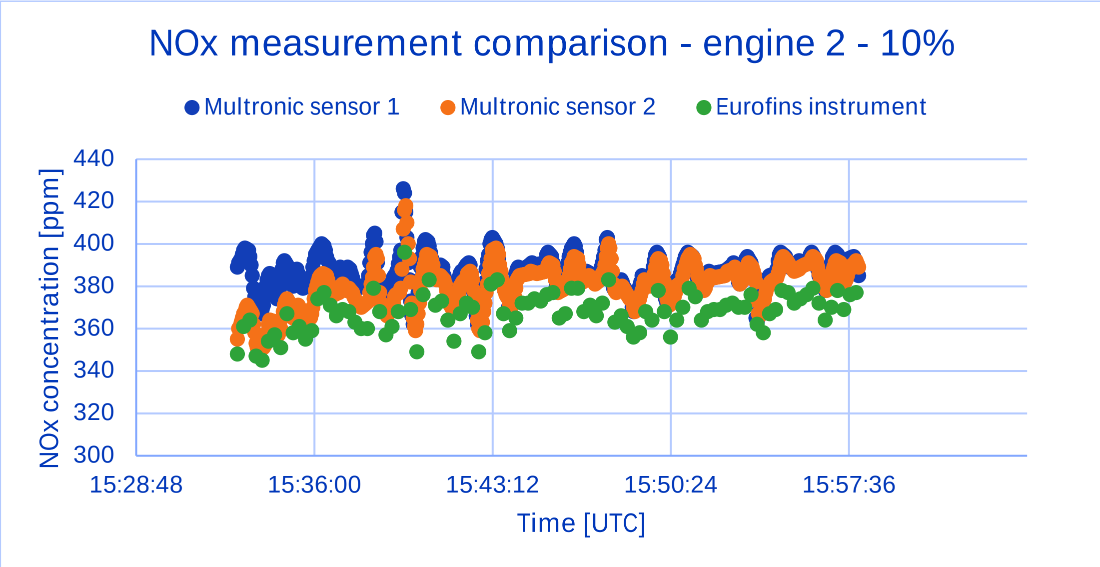


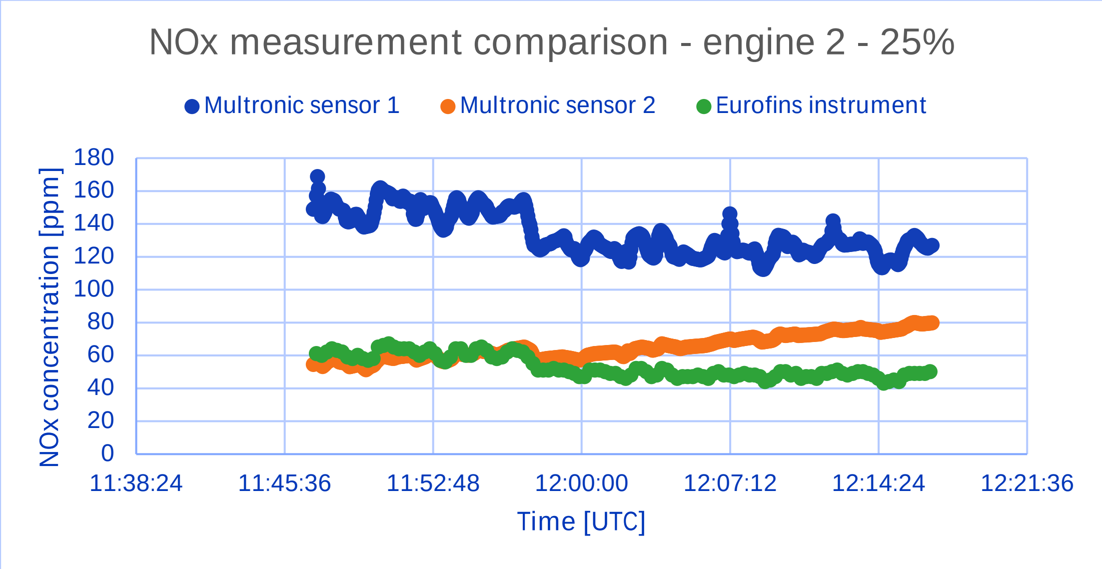

NOx concentration comparison - engine 1 - 75%
Multronic sensor 1
Multronic sensor 2
Eurofins instrument
NOx concentration [ppm]
70
60
50
40
30
20
10
0
08:52:48
09:00:00
09:07:12
09:14:24
09:21:36
09:28:48
09:36:00
Time [UTC]

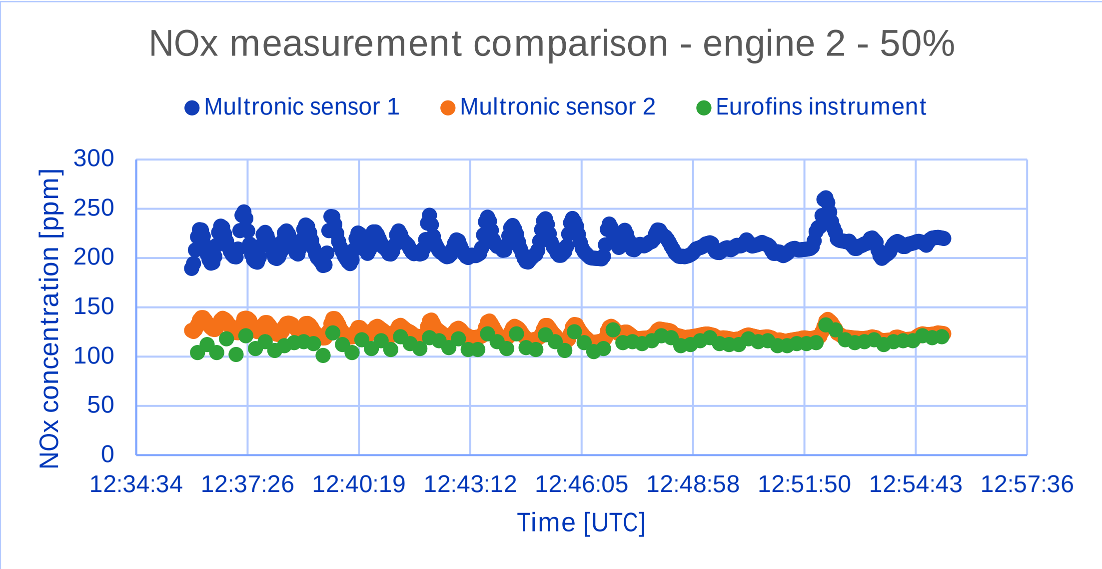

NOx measurement comparison - engine 1 - 100%
Multronic sensor 1
Multronic sensor 2
Eurofins instrument
NOx concentration [ppm]
80
70
60
50
40
30
20
10
0
08:02:24
08:09:36
08:16:48
08:24:00
08:31:12
08:38:24
Time [UTC]

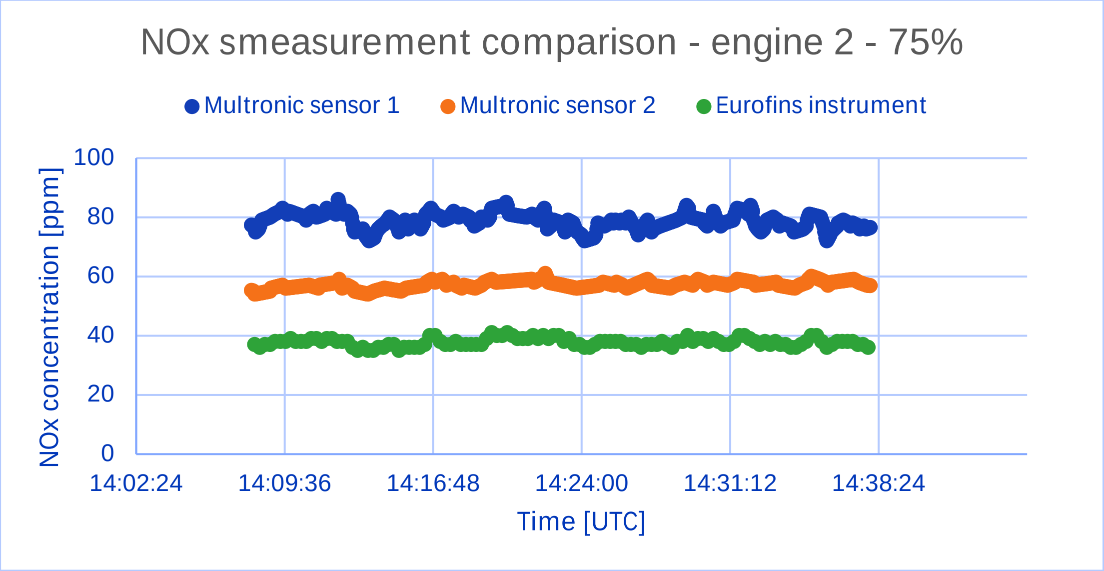


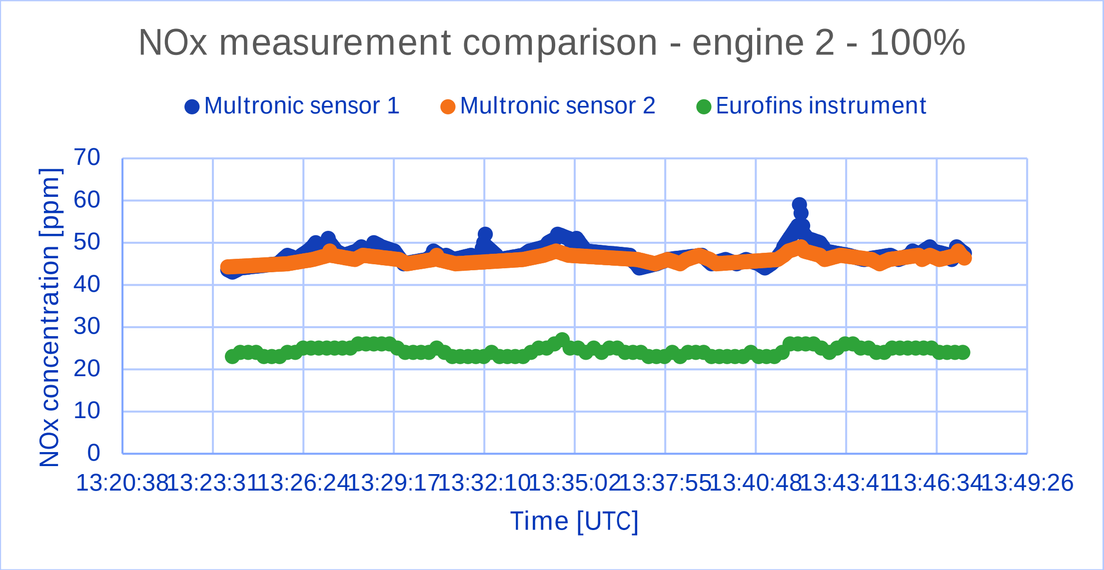
D.2 NO_x emission results – engine 2

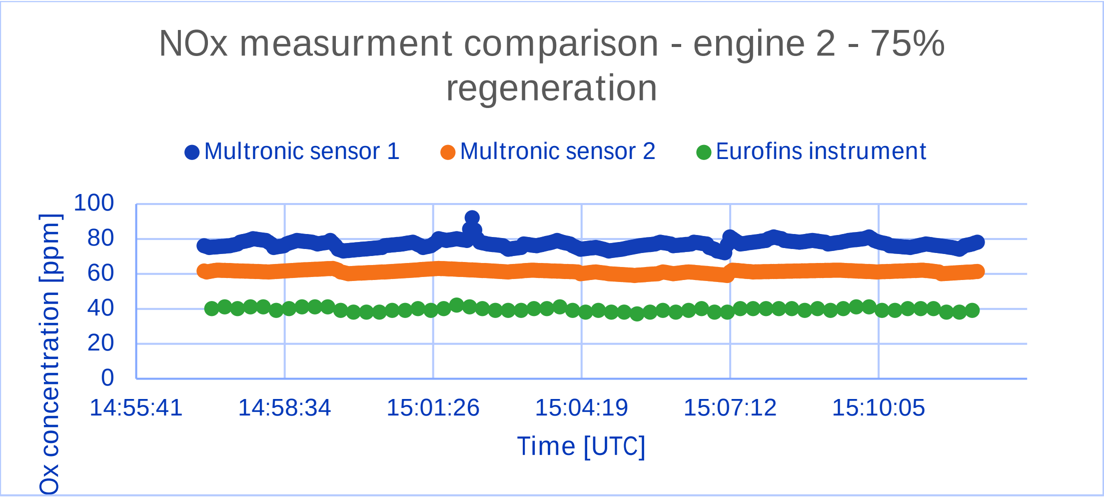



NOx measurement comparison - engine 2 - 25%
Multronic sensor 1
Multronic sensor 2
Eurofins instrument
NOx concentration [ppm]
180
160
140
120
100
80
60
40
20
0
11:38:24
11:45:36
11:52:48
12:00:00
12:07:12
12:14:24
12:21:36
Time [UTC]


NOx measurement comparison - engine 2 - 50%
Multronic sensor 1
Multronic sensor 2
Eurofins instrument
NOx concentration [ppm]
300
250
200
150
100
50
0
12:34:34
12:37:26
12:40:19
12:43:12
12:46:05
12:48:58
12:51:50
12:54:43
12:57:36
Time [UTC]


NOx smeasurement comparison - engine 2 - 75%
Multronic sensor 1
Multronic sensor 2
Eurofins instrument
NOx concentration [ppm]
100
80
60
40
20
0
14:02:24
14:09:36
14:16:48
14:24:00
14:31:12
14:38:24
Time [UTC]


NOx measurement comparison - engine 2 - 100%
Multronic sensor 1
Multronic sensor 2
Eurofins instrument
NOx concentration [ppm]
70
60
50
40
30
20
10
0
13:20:38
13:23:31
13:26:24
13:29:17
13:32:10
13:35:02
13:37:55
13:40:48
13:43:41
13:46:34
13:49:26
Time [UTC]


NOx measurment comparison - engine 2 - 75% regeneration
Multronic sensor 1
Multronic sensor 2
Eurofins instrument
Ox concentration [ppm]
100
80
60
40
20
0
14:55:41
14:58:34
15:01:26
15:04:19
15:07:12
15:10:05
Time [UTC]

Appendix E
Documentation

E.1 Fuel analysis

E.1.1 MGO (engine 1)

VPS

Test Results

	Unit	Test Results	DMA Spec	Test Method
Density @ 15°C[2]	kg/m3	827.4	890.0	ISO 12185
Viscosity @ 40°C	mm2/s	2.852	2.000\6.000	ISO 3104
Micro Carbon Residue 10%	%m/m	< 0.10	0.30	ISO 10370
Sulfur	%m/m	< 0.03	1.50	ISO 8754
Ash	%m/m	< 0.01	0.01	LP 2605
Pour Point	degC	< -6	-6\0	ISO 3016
Visual Appearance	-	Pass	Bright&Clear	LP 1902
Calculated Cetane Index[1]	-	58	40	ISO 4264
FAME content	%V/V	**1.0**	0.1	EN 14078
Lubricity (HFRR) - Wear scar diam.	µm	380	520	ISO 12156
Acid Number	mg KOH/g	< 0.1	0.5	ASTM D664
Water	%V/V	< 0.01		ASTM D6304-B
Vanadium	mg/kg	< 1		LP 1105
Sodium	mg/kg	< 1		LP 1105
Aluminium	mg/kg	< 1		LP 1105
Silicon	mg/kg	< 1		LP 1105
Iron	mg/kg	< 1		LP 1105
Nickel	mg/kg	< 1		LP 1105
Calcium	mg/kg	1		LP 1105
Magnesium	mg/kg	< 1		LP 1105
Zinc	mg/kg	< 1		LP 1105
Phosphorus	mg/kg	< 1		LP 1105
Potassium	mg/kg	< 1		LP 1105
Cloud Point	degC	-7		LP 1305
Net Specific Energy[1]	MJ/kg	43.01		ISO 8217
Aluminium + Silicon	mg/kg	< 2		
Temp.@ 10% recovery	degC	212		ISO 3405
Temp.@ 50% recovery	degC	276		ISO 3405
Temp.@ 90% recovery	degC	336		ISO 3405
FTIR Screening	-	Pass		LP 2403
Sulfur (Low Level)	mg/kg	12		ASTM D4294

[1] Calculated value; [2] Retested parameters

Specification Comparison

Results compared with your amended ISO 8217:2010 specification DMA, table 1 and annex A. Based on this sample please note the following:

Outside specification limit: FAME content

E.1.2 HVO (engine 2)

VPS

Test Results

	Unit	Test Results	DMA Spec	Test Method
Density @ 15°C	kg/m3	784.3	890.0	ISO 12185
Viscosity @ 40°C	mm2/s	3.142	2.000\6.000	ISO 3104
Micro Carbon Residue 10%	%m/m	< 0.10	0.30	ISO 10370
Ash	%m/m	< 0.01	0.01	LP 2605
Pour Point	degC	< -6	-6\0	ISO 3016
Visual Appearance	-	Pass	Bright&Clear	LP 1902
Calculated Cetane Index[1]	-	93	40	ISO 4264
Acid Number	mg KOH/g	< 0.1	0.5	ASTM D664
FAME content	%V/V	< 0.1	0.1	ASTM D7371
Water	%V/V	< 0.01		ASTM D6304-B
Sulfur (Low Level)	mg/kg	< 10		ASTM D4294
Vanadium	mg/kg	< 1		LP 1105
Sodium	mg/kg	< 1		LP 1105
Aluminium	mg/kg	< 1		LP 1105
Silicon	mg/kg	< 1		LP 1105
Iron	mg/kg	< 1		LP 1105
Nickel	mg/kg	< 1		LP 1105
Calcium	mg/kg	< 1		LP 1105
Magnesium	mg/kg	< 1		LP 1105
Zinc	mg/kg	< 1		LP 1105
Phosphorus	mg/kg	< 1		LP 1105
Potassium	mg/kg	< 1		LP 1105
Net Specific Energy[1]	MJ/kg	43.49		ISO 8217
CCAI (Ignition Quality)[1]	-	741		ISO 8217
Aluminium + Silicon	mg/kg	< 2		
Temp.@ 10% recovery	degC	270		ISO 3405
Temp.@ 50% recovery	degC	284		ISO 3405
Temp.@ 90% recovery	degC	298		ISO 3405
FTIR Screening	-	Pass		LP 2403

[1] Calculated value

Specification Comparison

Results compared with your amended ISO 8217:2010 specification DMA, table 1 and annex A. Based on this sample and the tested parameters the specification is met.

Mobility & Built Environment

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