

Green Deal validation

Measurement report

- Jan de Nul - Vessel

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Measurement report - Jan de Nul - Vessel 1

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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 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 the performance of in stack NO_x sensors is evaluated with certified measurement instruments.

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. Both engines were measured while operating on low sulphur maritime gas oil (MGO). Emission evaluations are performed on to 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 6.0×10^9 to 9.6×10^9 #/kWh and between 9.1×10^9 to 1.3×10^{10} #/kWh respectively. Particle mass emissions over the E2 and D2 cycles measured between 10 to 12 mg/kWh and between 10 to 11 mg/kWh respectively. There is no significant increase of particulate emissions measured compared to its operation at comissioning of the vessel which happened in 2019. 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 on average 2.3 g/kWh and 2.0 g/kWh repectively. The emissions are seen to fluctuate significantly with emission concentration peaks above 500 ppm for higher loads and significant NH₃ slip up to 37 mg/Nm³ is observed. The observed emissions are likely the result of a faulty AdBlue injection control strategy, possibly influenced by reduced catalyst element efficiency.

After the measurement program, SCR elements were replaced by PON (CAT) and the SCR software was reset. This resolved the dynamic emission behaviour and brought emission levels back to at or below the regulatory limit value according to the on-board sensor data.

NO_x sensor results deviated significantly from measurements with certified instruments due to the cross sensitivity of the sensor with NH₃ emissions. Qualitative analysis shows a reasonable correspondence of sensor based results with certified measurements when measured NO_x values are corrected for the NH₃ cross sensitivity. Strong cross sensitivity of a NO_x sensor to NH₃ can also be regarded advantageous for monitoring, because the sensor value also accounts for NH₃ as a pollutant.

The observed high NO_x emissions and NH₃ slip show that correct functioning of the SCR system is not a given. While the tested systems were equipped with an OEM engine monitoring system, only reduced efficiency of the catalyst was signaled and potential ammonia 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 NH₃ emissions. In contrast to ULEv ships, inland shipping vessels fulfilling 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 NH₃ monitoring capabilities to such a system in combination with a regulatory NH₃ limit could aid in ensuring good functioning 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 $\text{NO}_{x,\text{lim}} \left[\frac{\text{g}}{\text{kWh}} \right] = 9 \cdot n^{-0.2}$ 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 \(bureauveritas.com\)](https://www.bureauveritas.com/marine-offshore/ultra-low-emission-vessels)

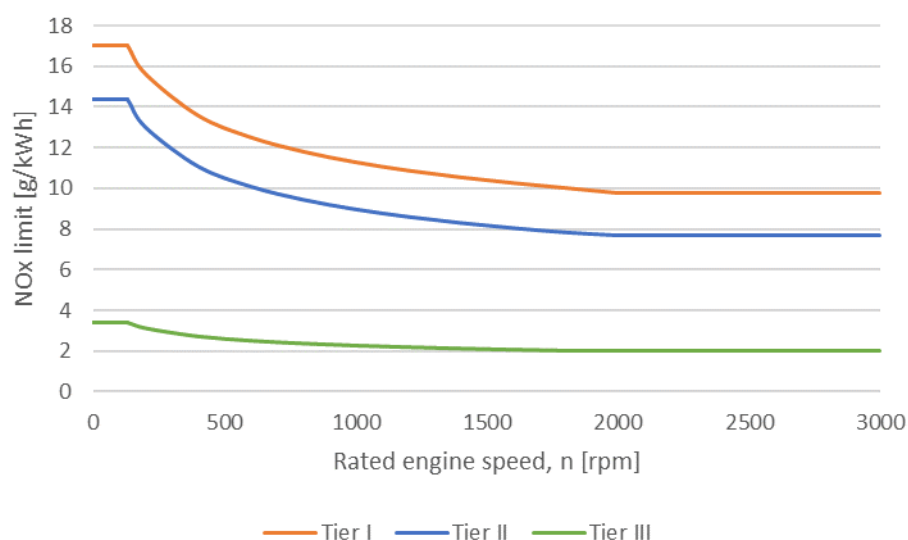


Figure 1.1: IMO Tier III emission requirements compared to IMO Tier I and II (Vermeulen, Verbeek, & Dinther, 2023).

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	10 ¹²

1.3 Objectives

The objectives of the measurements carried out onboard the vessel are threefold. 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 are to 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.
- Evaluation of onboard NO_x sensors for long term onboard monitoring of NO_x emissions.

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 CO₂, CO, NO_x, PM, PN, NH₃ and HC emission concentrations were 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). NO_x emission concentration measurements between the in-stack measurement equipment and permanent in-stack NO_x sensors are compared to evaluate the sensors for use in a possible monitoring program. The measurements discussed in this report will be repeated on a different ULEv vessel in the future to gain more insight in emission behaviour on vessels complying to the ULEv notation.

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 ship engine. This additional load point is repeated while DPF regeneration is active to compare emissions during normal operation and during regeneration cycles.

The vessel uses a diesel-electric architecture. As such, the main generators onboard the ship supply power for both the main propulsion and utility consumers. For constant speed main propulsion engines 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

The additional load point measurements are performed at 100% engine speed and 85% engine load. This corresponds to a typical use case of the engines aboard the vessel. All noted load points are attainable during measurements along the kay with a combination of dredge pump, jet pump, bow thruster and main thruster activation.

Engine load points are monitored based on the electrical generator power output during the measurements.

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 2.3. Note that measured CO₂ concentrations in this study are used to enable calculation of fuel and energy specific emission values.

Table 2.3: Measured emission components.

Emission component	Shorthand	Measurement 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 Long term monitoring

Stationary measurements on a ship give a good impression of pollutant emission levels at defined load points under stable conditions. While these types of measurements are easier to carry out and yield relatively high-quality results, the resulting calculated cycle results don't necessarily match the real-world emissions of the ship.

The difference in emissions can be caused by a variety of factors including:

- Mismatch between cycle composition and actual use loading conditions.
- Variation in emissions in dynamic conditions.
- Malfunction, ageing or failure of systems during use.

While above effects are not very noticeable for particulate matter emissions in systems with DPF aftertreatment, NO_x emissions in systems with SCR aftertreatment are highly dependent on the engine power conditions. To verify the actual real world sailing emissions of the measured vessel, a long-term NO_x monitoring campaign is useful. Long term monitoring is not part of this project, but would be achieved with logging of the NO_x emission concentrations in the tailpipe using Multronic NO_x sensors along with other necessary ship and engine parameters. While monitoring is not applied in this project, the preparations for such a campaign are mentioned in the report with the focus on comparison of the installed NO_x sensor results with in-stack measurements.

2.3 Analysis of test results

2.3.1 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 propeller 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 found to be $\pm 20\%$.

2.3.2 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.

2.3.3 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.

2.3.4 NO_x sensor comparison

The vessel is equipped with a NO_x monitoring system from Multronic². NO_x sensors are permanently placed in the exhaust stack of each engine upstream of the DPF system. The full exhaust stack architecture of the measured vessel is discussed in Section 3.1.2. To enable the use of these sensors in a long term monitoring campaign of the real world NO_x emissions of the measured vessel, a check on the concentrations reported by the sensors is required.

This check is performed by comparison of the temporarily installed in-stack emission measurement instruments measurements and the NO_x sensor measurements. From correlation curves the error bandwidth can be determined and compared to the sensor manufacturer specifications. In general, a bandwidth of $\pm 10\%$ is to be expected.

² [Multronic Emission Systems](#)

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 Group³. 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	***** ⁴
Build year	2019
Hopper capacity	⁴
Length	⁴
Breadth	⁴
Draught (loaded)	⁴
Main generators	3 x CAT 3512E (1700kW at 1800RPM)
Total installed diesel power	5510 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 Caterpillar 3512E diesel generator sets. The engines are operated at a constant speed of 1800 RPM and can deliver a maximum electrical power of 1700kW. 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 be achieved with a seamless power transition. Running engines can both be operated in symmetrical or asymmetrical loading configurations.

Efficiency of the CAT 3512E 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: CAT 3512E specific fuel consumption.

Power setting [%]	Mechanical Power [kW]	SFC [g/kWh]
10%	187	338.5
25%	458	241.5

³ [Homepage | Jan De Nul](#)

⁴ Information removed for confidentiality reasons.

Power setting [%]	Mechanical Power [kW]	SFC [g/kWh]
50%	897	208.2
75%	1341	202.3
100%	1789	200.9

Table 3.3: Electrical and mechanical power output mapping of the CAT 3512E 1700kW generator set.

Generator power [%]	Generator power [kW]	Engine power [kW]	Engine power [%]
10%	170 kW	187 kW	10.45%
25%	425 kW	458 kW	25.60%
50%	850 kW	897 kW	50.14%
75%	1275 kW	1341 kW	74.96%
100%	1700 kW	1789 kW	100%

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

Table 3.4: Engine serial numbers onboard the vessel.

Engine name	Serial number	Type	Measured?
Engine 1	MR800206	CAT 3512E	Yes
Engine 2	MR800207	CAT 3512E	No
Engine 3	MR800208	CAT 3512E	Yes

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 CAT 3512E engine in combination with the SCR, the DPF is installed upstream of the SCR system. A schematic representation of the exhaust stack architecture valid 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 90 degree angle. Note the positions of the various permanently mounted NO_x sensors in the exhaust stack. Only the Multronic NO_x sensor data is accessible to the user.

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 are noted in 0. The calculated DPF air flow values are used as correction factors in the calculation of in stack emissions with data from different locations.

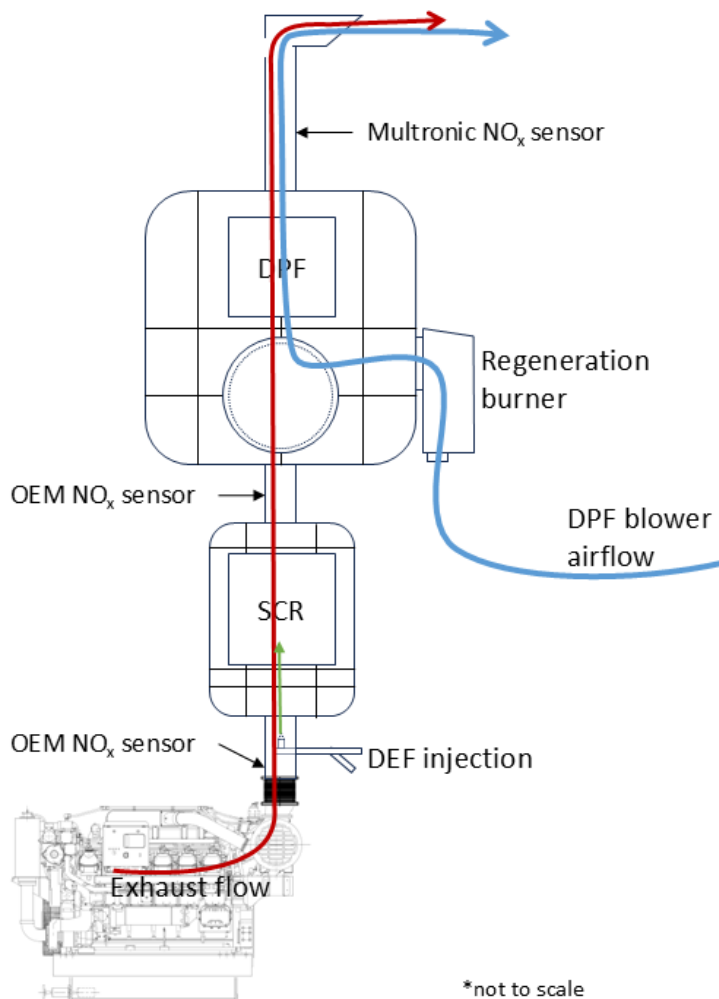


Figure 3.1: Schematic representation of the exhaust stack architecture onboard the vessel.

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. Here the normal operation is used to comply with IMO Tier III and Stage V regulation (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). It should be noted the vessels SCR system is mostly operated on the reduced settings during normal use. For testing, the normal SCR mode was used to measure the emissions under the ULEv notation.

The SCR elements onboard the vessel were still the original elements installed at commissioning of the vessel in 2019. 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, some additional data from the ship and engine during the measurement period is required.

The vessel is equipped with an onboard digital alarm system connected to the majority of sensors on-board the ship. The majority of required signals is therefore available in a digital logfile from the alarm system. Some additional signals were measured manually in the engine room. 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	Analog gauge	
LT in & out	°C	Analog gauge	
SCR temperature in	°C	Alarm system	
SCR temperature out	°C	Alarm system	
Urea dosing pressure	kPa	Alarm system	
DEF pump drive	%	Alarm system	
DEF consumption	L	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 2019, Eurofins was involved with the first onboard measurement campaign onboard the vessel. Results of this measurement campaign are documented in (Goderis, 2019).

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 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 ₂ SO ₄ sampling bath	NH ₃	Absorption in H ₂ SO ₄ -solution and analysis by IC.

Table 3.7: Information sources onboard the vessel.

Information sources	Parameters	Comment
Multronic NO _x sensors	NO _x [ppm] O ₂ [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. Concentration measurements of O₂, CO, CO₂, NO_x and HC are measured continuously through two separate probes in the sampling hole of the exhaust extension tube during each full measurement day. The line sampling O₂, CO, CO₂ and NO_x is run through a dryer first, resulting in dry concentration measurement. The HC sample is not dried and therefore measured wet.

PM measurements run continuously for each separate load point, it should be noted that dilution flow to the filter is regulated 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. NH₃ sampling is performed by continuous volume sampling through an H₂SO₄ bath for each load point. NH₃ content is later analysed in the lab.

Each load point measurement runs for 30 minutes. In between load points a similar stabilisation time is 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). To enable measurements in a straight pipe segment, a straight pipe extension is added to the end of the exhaust stack. The straight pipe extension is located horizontal on top of the exhaust stack tower and contains an open sampling location as is shown in Figure 3.4.

The permanently mounted Multronic NO_x sensors are situated halfway the exhaust stack segment between the DPF and stack outlet. The location of the Multronic NO_x sensor on a single engine exhaust stack is shown in Figure 3.3.

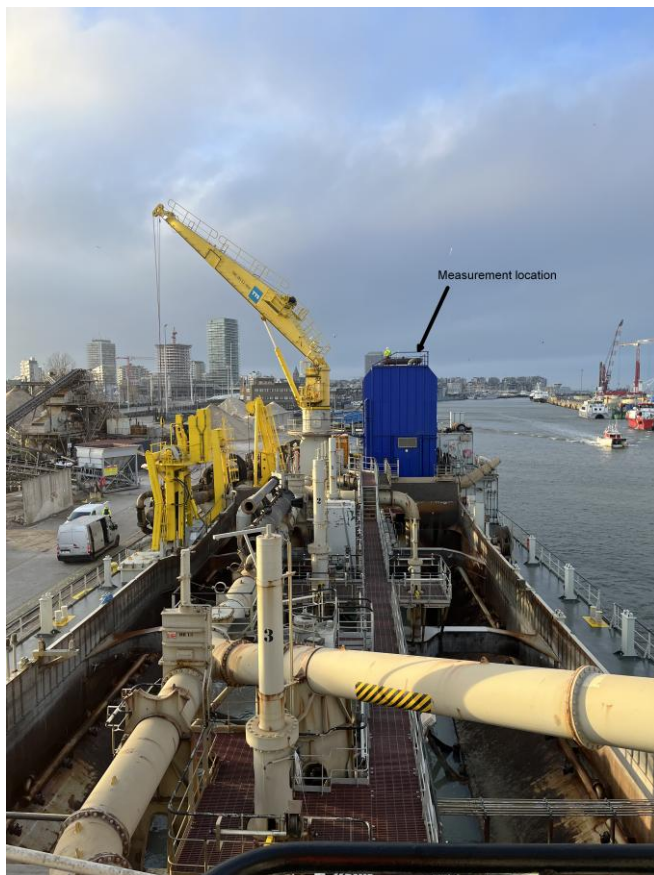


Figure 3.2: Global measurement location (exhaust stack).



Figure 3.3: Position of Multronic NO_x sensor just under the stack tower roof.



Figure 3.4: Straight pipe extension tubes with sampling hole on top of the stack.

3.4 Fuel specifications

Measurements are performed on 10ppm MGO fuel. The main properties of the fuel used are shown in Table 3.8. The bunker note and fuel analysis specification are shown in Appendix E.1 and E.2 respectively.

Table 3.8: Test fuel properties.

Property	Value	Unit
Fuel type	MGO 10ppm	-
Density @ 15°C	838.2	kg/m ³
Viscosity @ 40°C	2.6	mm ² /s
Sulphur	0.0008	%m/m
Sulphur (Low Level)	<10	mg/kg
Water	<0.01	%V/V
FAME content	0.1	%V/V
Cetane Index	49	-
Net Specific Energy	42.88	MJ/kg

3.5 Measurement planning

Measurements onboard the vessel are planned in three days after bunkering of the test fuel. An overview of the test planning is given in Table 3.9.

Table 3.9: Vessel measurement planning.

Date	04/01/2024	31/01/2024	01/02/2024	02/02/2024
Location	Zeebrugge (BE)	Oostende (BE)	Oostende (BE)	Oostende (BE)
Measurements	Initial ship visit TNO	Onboard preparation for emission testing	Emission measurements on engine 1: 10%, 25%, 50%, 75%, 85%, 100%, 85% (regeneration) load points	Emission measurements on engine 3: 10%, 25%, 50%, 75%, 85%, 100%, 85% (regeneration) load points

4 Results and discussion

4.1 Measurement observations

Measurements were performed along the quay in the harbour of Oostende. Weather conditions were clear skies and close to no wind. By the end of the second measurement day overcast started developing. No precipitation occurred during the measurement days.

To achieve the different loading conditions of the engine being tested, several onboard power consumers are 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 power supply should the tested engine fail during the test work.

During the measurements, several SCR system errors were displayed on the engine information panel. Errors started occurring on both engines just before start of the measurements after running in the engines in the correct SCR mode.

During the measurements, error's propagated in the order shown below:

1. 4364/17: SCR Catalyst Conversion Efficiency Low
2. 4364/18: SCR Catalyst Conversion Efficiency Low
3. 3516/18: SCR Catalyst Reagent Concentration Low

Next to the SCR errors, also highly dynamic emission behaviour was observed from the in-stack NO_x sensors.

4.2 NO_x emissions

Nitrogen oxides (NO_x) emissions are evaluated to verify the proper functioning of the Selective catalytic Reduction catalyst (SCR). NO_x emissions are regulated by the IMO in Tier I, II and III emission standards, but have a more stringent limit value in the Stage V regulation (which applies for the ULEV notation) as shown in Section 2.3.3. As the SCR relies on a NH₃ reaction to reduce NO_x emitted from the exhaust stack, NH₃ emissions are also evaluated in this paragraph.

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. 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 2019. 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.

Measured concentrations in general show much higher emissions at higher load points compared to the concentrations measured during the commissioning tests in 2019.

Some load points also show large deviations between the average measured concentrations of the Eurofins instrument and Multronic sensor. An example of the time dependant NO_x emission behaviour for 75% load on engine 1 is shown in Figure 4.1. The time dependant emissions show a high variability in the NO_x concentrations measured in the exhaust stack. Deviations between measured concentrations in the emission peaks between the NO_x instrument and sensor are mostly due to under sampling of the used instrument. Deviations in the baseline emission values however seem to correspond to physical differences. Emission behaviour of different load points and the other measured engine are shown in Appendix D. As SCR elements were approximately 5 years old at time of testing, catalyst degradation most likely plays a role in the observed high NO_x emissions.

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 [ppm] (wet)	Eurofins 2019 [ppm] (dry)
10% load	100	112	-
25% load	53	86	70
50% load	184	198	82
75% load	171	263	88
85% load	310	329	-
85% load (regeneration)	326	341	-
100% load	348	376	89

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

Avg. NO _x measurements – engine 3	Eurofins 2024 [ppm] (dry)	Multronic sensor [ppm] (wet)	Eurofins 2019 [ppm] (dry)
10% load	126	127	-
25% load	58	97	73
50% load	169	186	83
75% load	158	266	87
85% load	350	354	-
85% load (regeneration)	365	364	-
100% load	403	409	83

From the pump drive signal of the DEF injection system, emission peaks seem to occur mainly due to variations in the amount of DEF injected in the SCR system. Together with the low conversion warnings from engine diagnostics during the measurements, a fault in the control of the SCR is the most likely culprit of the observed emission behaviour.

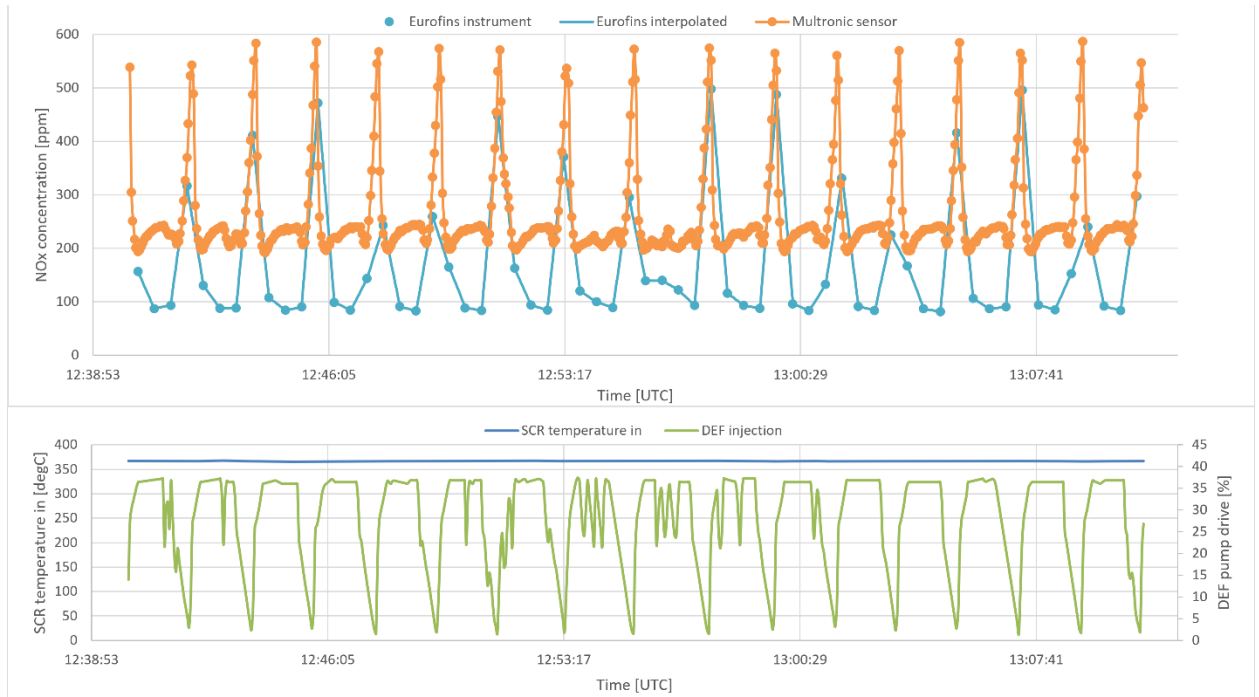


Figure 4.1: NO_x concentration measurements on engine 1 - 75% load.

Mismatches in the instrument and sensor data are mainly observed at instances with high DEF flow and lower NO_x concentrations. It should be noted that the used NO_x sensors are 1-to-1 cross sensitive to NH₃ (ammonia) up to 300 ppm. The NO_x instrument used by Eurofins during the measurements has no cross sensitivity to NH₃. As the measured concentrations from the NO_x sensor tend to increase with more DEF injected, it is very likely the mismatch in measured concentrations is due to NH₃ slip. NH₃ slip can for example be caused by DEF over-injection or a bad urea spray pattern. Cross sensitivity in NO_x sensors is not necessarily a bad property as NH₃ emission indicates a problem with the SCR system. Moreover both NH₃ and NO_x cause acidification and eutrophication and have adverse health effects. Cross sensitivity of the NO_x sensor indirectly ensures NH₃ slip is partially captured in the emission results. The possibility of NH₃ slip is further detailed in Section 4.2.2.

4.2.2 NH₃ slip

Measurements on NH₃ concentration in the exhaust are performed using a H₂SO₄ sampling technique. This measurement technique results in the average NH₃ emissions in mg/Nm³⁵ for each load point. During the measurements, NH₃ slip up to 37 mg/Nm³ was observed. To verify the NH₃ slip assumption, the observed average NH₃ emissions are mapped to time resolved concentrations based on the difference between measured NO_x concentrations with the Eurofins instrument and Multronic sensor. Note that, while there is no applicable Stage V limit on NH₃ slip, other regulations requiring SCR installations impose a limit on emitted NH₃ concentrations to control slip. For Euro VI heavy duty engines, this limit is defined at 10ppm.

⁵ Normalised cubic metre referring to 273.15K and 1013hPa.

Average NH₃ concentrations in ppm are calculated from:

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

Here $NH_{3,SpecificDensity}$ is the measured specific density of NH₃ in the stack emissions, $V_{m,air}$ is the molecular volume of air and M_{NH_3} is the molar mass of NH₃.

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

Table 4.3: Calculated average NH₃ concentrations per load point.

Avg. dry NH ₃ [ppm]	10%	25%	50%	75%	100%	85%	85% regen
Engine 1	5	16	20	47	14	28	45
Engine 3	9	21	26	49	8	26	16

Mapping the NH₃ 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 Multronic NO_x signal corrected for NH₃ cross sensitivity with $NO_{x,corrected} [ppm] = NO_x [ppm] - C_{NH_3} [ppm]$ is shown next to the NO_x measurements by Eurofins in Figure 4.2. While the full difference between measurements cannot be explained using this approximation, the figure clearly shows at least a large fraction of the measured differences can most likely be explained by NH₃ slip in the exhaust gas. With average NH₃ levels between 5 and 50 ppm depending on the engine and load point, the Stage V regulatory limit value is exceeded on multiple load points. Estimated NH₃ slip at all engine load points is shown in Appendix D.

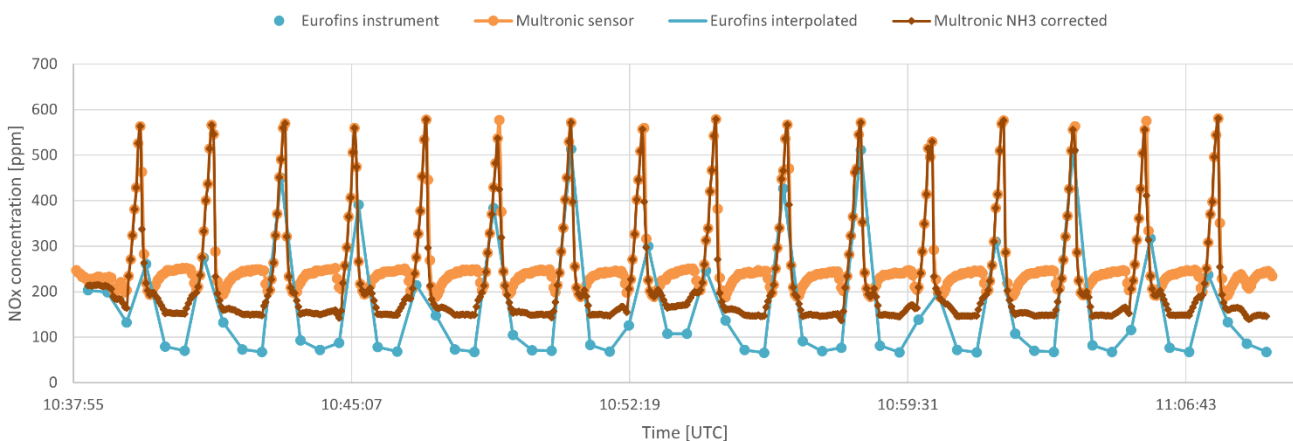


Figure 4.2: NO_x concentrations with NH₃ correction on Multronic sensor readings on engine 1 - 75% load.

4.2.3 Work specific 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 2.3.1. The calculated work specific NO_x emissions per load point are shown in Figure 4.3. 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. NH₃ 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).

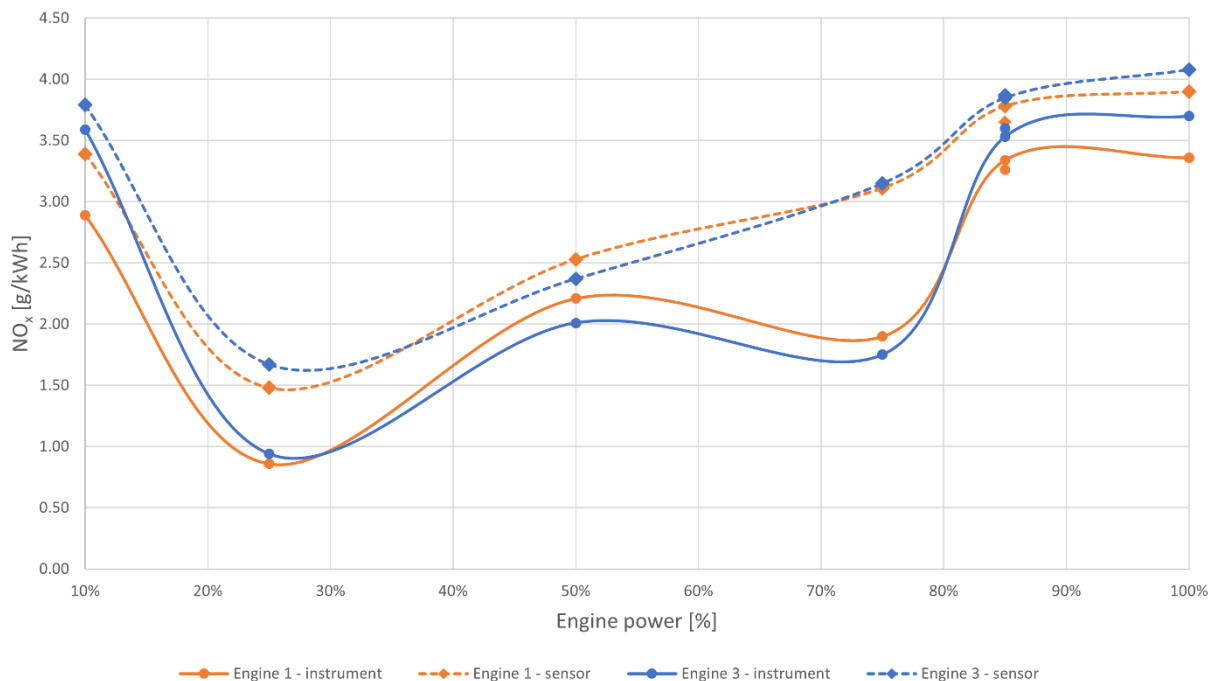


Figure 4.3: Work specific NO_x emissions for engines 1 and 3. Lines between measurement points are added for visual clarity but do not correspond to actual measured data. Emission values are corrected with a humidity correction factor and where applicable for the added airflow from the DPF. No NH₃ correction 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 85% load point measurements are not part of this weighted NO_x emission result. 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 4.4: 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 ULEV (Stage V) limit value
	NO _x	NO _x corrected	NO _x	NO _x corrected		
	[g/kWh]					
Engine 1	2.37	2.30	3.28	3.18	2.01 ⁶	1.80
Engine 3	2.28	2.30	3.23	3.25		

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

D2 cycle NO _x emission results	Instrument (Eurofins) based		Sensor (Multronic) based		NO _x Tier III limit value	NO _x ULEV (Stage V) limit value
	NO _x	NO _x corrected	NO _x	NO _x corrected		
	[g/kWh]					
Engine 1	2.08	2.01	2.86	2.75	2.01 ⁶	1.80
Engine 3	1.95	1.95	2.78	2.78		

Cycle weighted work specific NO_x emissions of both engine 1 and 3 exceed the IMO Tier III limit value over the E2 cycle, but not over the D2 cycle. For both engines and both cycles the Stage V limit value needed for the ULEV notation is exceeded. The elevated emissions are most likely due to reduced SCR efficiency and faulty DEF injection control as explained in Section 4.2.1. The sensor based emission factor is significantly higher compared to the emission factor derived from the instrument readings. The mismatch in instrument and sensor based results is explained by NH₃ cross sensitivity and the lower sampling frequency of the instrument measurement in combination with a highly dynamic emission behaviour due to possible SCR malfunction. Taking above considerations into account together with the higher potency of NH₃ compared to NO_x in the environment, the sensor based result show a more accurate representation of the actual emission result for the different cycles.

It should be noted that SCR elements of all SCR systems onboard the vessel were replaced and the software controlling DEF injection was updated after the measurement campaign as a result of the various SCR system warnings and initial emission observations. From onboard NO_x sensor data, emission behaviour is seen to return to normal after this action.

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 2.3.3.

4.3.1 Particle number emissions

Particle number (PN) concentrations are measured as particles per volume in the exhaust flow.

⁶ Based on a IMO Tier III constant speed engine operating at 1800 RPM.

The measured concentrations of both engines on the various load points are shown in Table 4.6. It should be noted that measured particle number concentrations in the exhaust were very similar to concentrations in ambient conditions during the measurements.

Table 4.6: PN measurement results per load point – engine 1 & 3.

Avg. PN measurements	Engine 1		Engine 3	
	Eurofins 2024 [#/cm ³] (dry)	Eurofins 2019 [#/cm ³] (dry)	Eurofins 2024 [#/cm ³] (dry)	Eurofins 2019 [#/cm ³] (dry)
10% load	2.10E+03	-	4.50E+03	-
25% load	2.00E+03	4.05E+05	3.60E+03	3.47E+05
50% load	1.70E+03	9.72E+04	1.30E+03	1.02E+05
75% load	9.00E+02	3.98E+04	1.40E+03	4.05E+04
85% load	1.20E+03	-	1.50E+03	-
85% load (regeneration)	1.00E+03	-	1.70E+03	-
100% load	9.00E+02	1.37E+05	1.90E+03	1.02E+05

Therefore, the measured PN concentration values are considered to be very low. Even during regeneration events, the PN concentration remains low with no significant changes to the PN emissions compared to measurements on the same load point without regeneration. In comparison to the measurement results from the commissioning test, the measured concentrations are one to two orders of magnitude lower. This reduction is not unlikely as diesel particulate filter efficiency increases with initial use due to formation of a soot layer.

PN cycle emission results are calculated according to the method described in Section 2.3.1, 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 indicate a proper operation of the DPF system.

Table 4.7: Cycle PN emission results.

Cycle PN emission results	E2	D2	PN Tier III limit value	PN ULEV (Stage V) limit value
	[#/kWh]			
Engine 1	6.0E+09	9.1E+09	-	1.0E+12
Engine 3	9.6E+09	1.3E+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.

Table 4.8: PM RAW measurement results per load point - engine 1 & 3.

PM measurements	Engine 1		Engine 3	
	Eurofins 2024 [mg/Nm ³] (dry)	Eurofins 2019 [mg/Nm ³] (dry)	Eurofins 2024 [mg/Nm ³] (dry)	Eurofins 2019 [mg/Nm ³] (dry)
10% load	1.81	-	1.14	-
25% load	0.97	0.45	1.07	<0.25 ⁷
50% load	2.06	0.21	2.29	<0.22 ⁷
75% load	<0.92 ⁷	<0.21 ⁷	<1.18 ⁷	<0.21 ⁷
85% load	1.98	-	4.31	-
85% load (regeneration)	<1.15 ⁷	-	3.70	-
100% load	4.02	0.44	4.54	0.21

In contrast to the PN measurements, the PM measurements are somewhat higher compared to the measurements during commissioning. In combination with the lower PN concentrations found, this may indicate emissions of larger particles. Filters were visually clean after the measurements (see Appendixes A.1.1 and A.2.1), as such, composition of the emitted particulate matter can be assumed to be mainly made up of volatile particles such as hydrocarbons and sulphates plus adsorbed water.

PM cycle emission results are calculated according to the method described in Section 2.3.1, 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	10	10	-	15
Engine 3	12	11		

4.3.3 DPF operation

From the measured PN and PM emissions in Sections 4.3.1 and 4.3.2, the DPF is observed to operate effectively over all engine load points. While particle emissions may vary with soot loading of the DPF, no significant variation in emissions is observed during active regeneration events of the DPF. A frequent regeneration strategy has therefore no adverse effects on the absolute particle emission levels of the vessel.

It should be noted that to ensure proper DPF operation, monitoring of soot loading or pressure differentials is required. Very high soot loading might introduce non-particle related issues for the engine, leading to possible knock on effects.

⁷ Filter loading below detection limit, the shown maximum value is used in calculated results when applicable.

On the other hand, alignment of filter elements and proper sealing are important to ensure the filter retains its filtration efficiency. Frequent inspections for soot after the DPF system can aid in mitigating filter leaks fast to keep particle emissions low.

4.4 Other emissions

4.4.1 CO emissions

Carbon monoxide (CO) emissions are the result of 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 2.3.1, the resulting values are shown in Table 4.11. Cycle values for both engines remain one order of magnitude below the Stage IV limit value applicable for the ULEv notation.

Table 4.10: CO measurement results per load point - engine 1 & 3.

CO measurements	Engine 1		Engine 3	
	Eurofins 2024 [ppm] (dry)	Eurofins 2019 [ppm] (dry)	Eurofins 2024 [ppm] (dry)	Eurofins 2019 [ppm] (dry)
10% load	124	-	114	-
25% load	65	23	71	24
50% load	33	21	32	19
75% load	23	17	21	15
85% load	19	-	20	-
85% load (regeneration)	20	-	17	-
100% load	27	22	27	19

Table 4.11: Cycle CO emission results.

Cycle CO emission results	E2	D2	PM Tier III limit value	PM Stage V limit value
	[g/kWh]			
Engine 1	0.2	0.3	-	3.5
Engine 3	0.2	0.3		

4.4.2 HC emissions

Hydro carbon (HC) emissions signify the emission of unburned or partially burned 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.

No substantial difference is observed between measurements with and without DPF regeneration active.

Compared to measurements at commissioning of the ship, HC concentrations only show a very small increase. HC emissions remain however well below the Stage V limit value.

Table 4.12: HC measurement results per load point.

Avg. HC measurements	Engine 1		Engine 3	
	Eurofins 2024 [ppm] (wet, propane equivalent)	Eurofins 2019 [ppm] (wet, propane equivalent)	Eurofins 2024 [ppm] (wet, propane equivalent)	Eurofins 2019 [ppm] (wet, propane equivalent)
10% load	6	-	8	-
25% load	3	1	6	0
50% load	1	1	5	0
75% load	1	1	3	0
85% load	2	-	2	-
85% load (DPF regeneration)	1	-	2	-
100% load	2	1	2	0

HC cycle emission results are calculated according to the method described in Section 2.3.1, the resulting values are shown in Table 4.13. Cycle emission results fall well below the applicable Stage V or ULEV regulatory limit value.

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	5	7	-	190
Engine 3	12	17		

5 NO_x sensor evaluation

The NO_x sensor is evaluated based on the data gathered during the cycle measurements of engine 1 and 3. Comparison of the sensor data with the in stack measurements is performed to give a global indication of the possible monitoring accuracy when monitoring is solely based on installed sensors.

Due to the dynamic NO_x emission behaviour and NH₃ slip at high DEF flow, correlation of the NO_x instrument and sensor is reduced significantly. To enable a comparison of the NO_x sensor, estimated NH₃ concentrations are subtracted from the sensor data as shown in paragraph 4.2.2 prior to determining correlations. Due to the lower sampling frequency of the instrument, data of the instrument is interpolated to match the sensor sampling frequency of 1/3th Hz.

Correlation plots for engine 1 and 3 with the uncorrected (RAW) and corrected sensor data are shown in Figure 5.1 and Figure 5.2 respectively. Corrected data has an average deviation from the in stack measurements of 9 and 14 ppm for engine 1 and 3 respectively with standard deviations around 30 ppm. It is worth noting that a large share of larger deviations is expected to be the result of incomplete correction for NH₃ emissions and differences in sampling rates between the sensor and instruments. When NO_x and NH₃ emissions are evaluated together, the real world performance of the NO_x sensors is expected to be better than shown.

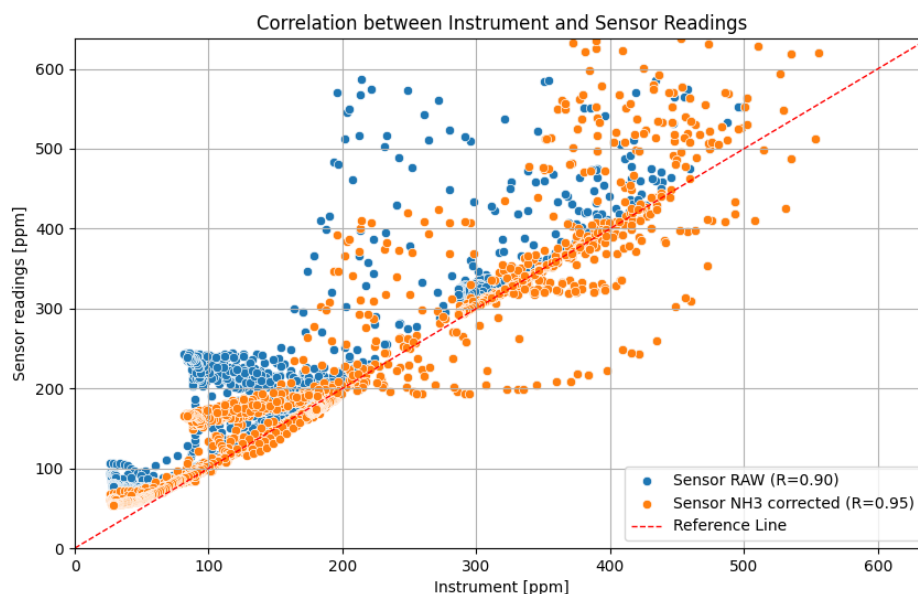


Figure 5.1: NO_x sensor correlation to certified instrument results – engine 1.

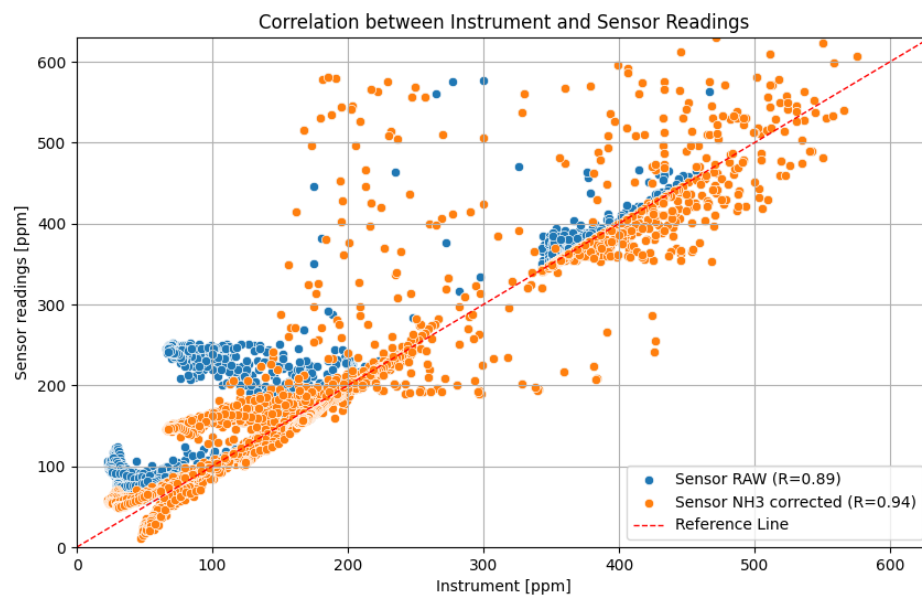


Figure 5.2: NO_x sensor correlation to certified instrument results – engine 3.

6 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 low sulphur MGO (10 ppm). Both the SCR and DPF systems onboard this ship were evaluated with in-stack measurements and references of the on-board 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, cycle weighted NO_x emissions are measured on average at 2.3 g/kWh and 2.0 g/kWh for the E2 and D2 cycle respectively, therefore exceeding the emission limit value of 1.8 g/kWh applicable for the ULEv notation.⁸
- Only on the D2 cycle, NO_x emissions are found to remain below or at the TIER III emission limit of 2.01 g/kWh. On the E2 cycle, also the TIER III limit value is exceeded.
- Emissions of PN, PM, CO and HC are all found to remain below the limit values applicable to the ULEv notation.
- PN emissions on both measured engines remain between 6.0×10^9 to 9.6×10^9 #/kWh and 9.1×10^9 to 1.3×10^{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 10 to 12 mg/kWh and between 10 to 11 mg/kWh for the E2 and D2 cycles respectively. Below the Stage V limit value of 15 mg/kWh

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 observable change in emitted particles.
- For both measured engines, the DPF system reduces particle mass and number emissions well below the limit values which apply for the ULEv notation (at IWP engine Stage V level).
- Changes in 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 observed. It should be noted that, in addition to automatic active regeneration, DPF elements are manually cleaned with pressurised air in a specialised enclosure when ash loading increases.

⁸ Maintenance and calibration actions of the SCR system were organized by the ship owner immediately after the finalization of the measurement campaign to correct the high NO_x emissions.

- A small reduction in particle number emissions between old and new measurements is observed. This decrease is most likely 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 did not reduce NO_x emissions to sufficiently low values to fulfil the requirements of the ULEv label (Stage V limit values)
- From observations on SCR parameters, the injection of urea in the SCR was seen to fluctuate significantly during operation pointing to a control strategy fault. As a result, high NO_x en NH₃ concentrations are measured in the exhaust stack. A problem with the efficiency of the SCR was also signalled on the engine control interface.
- NH₃ emissions are not limited under the Stage V inland shipping regulation, however, their potential for acidification is comparable to that of NO_x. NH₃ emissions therefore add to the pollution from 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 is necessary to ensure continuous proper operation of the SCR in practice.

From the measurement results and analysis, the following conclusions can be drawn on the on-board NO_x sensors:

- Although NO_x sensors are cross sensitive to NH₃ emissions, sensor results with correction for NH₃ emissions show correlation with in-stack NO_x measurements with average deviations around 10 ppm. The observed correlation is promising for monitoring applications considering the comparison conditions (dynamic emission behaviour).
- Strong cross sensitivity of a NO_x sensor to NH₃ can also be regarded advantageous for monitoring, because the sensor value also accounts for NH₃ as a pollutant.

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Signature

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Appendix A

Emission measurement results

A.1 Engine 1 – MR800206

Table A.1: Emission measurement results – engine 1

Load point	10%	25%	50%	75%	100%	85%	85%
TIME start [UTC]	09:00	10:22	11:50	12:40	14:43	15:22	13:21
TIME stop [UTC]	09:30	10:52	12:20	13:10	15:13	15:52	13:51
Duration [min]	30	30	30	30	30	30	30
Engine speed [RPM]	1800	1800	1800	1800	1800	1800	1800
Electrical load [kW]	185.1	428.6	843.6	1266.3	1683.0	1434.1	1458.3
Mechanical power [kW]	204.3	458.8	892.5	1334.2	1769.6	1509.5	1534.8
Ambient T [degC]	19.6	20.4	21.6	22.4	27.0	26.8	25
Ambient P [hPa]	1032	1033	1033	1033	1033	1032	1033
Relative humidity [%]	36.2	34.2	32.0	30.4	23.9	24.1	26.7
Manifold T [degC]	31.98	32.60	32.32	32.14	33.48	32.48	32.49
Manifold rel P [hPa]	179.60	508.00	1170.20	1941.90	2398.50	2192.58	2218.07
SCR T inlet [degC]	285.7	334.0	360.9	366.9	432.7	384.2	387.0
SCR T outlet [degC]	285.0	333.2	361.0	365.2	429.3	384.4	385.0
DPF T inlet [degC]	265.0	307.8	342.1	348.7	430.0	373.7	447.4
DPF T outlet [degC]	266.0	304.1	340.4	348.0	429.4	378.4	423.8
Exhaust P [hPa]	1032.4	1034.1	1042.4	1041.3	1046.7	1043.0	1048.7
Exhaust T [degC]	200	242	255	237	280	270	360
Flow [Nm ³ /h], dry	3265	3848	6500	8287	10112	9440	9951
Flow [Nm ³ /h], wet	3409	4056	6905	8830	10878	10084	10672
DEF pump drive [%] ⁹	4.72	10.89	16.44	27.94	24.51	19.96	20.44
DPF backpressure [mbar]	14.8	22.3	37.0	55.1	71.1	60.5	68.8
DPF blower pressure [mbar]	35.9	51.2	62.5	98.5	122.4	112.1	121.9
DPF blower flow [m ³ /h]	155	180	170	215	228	236	229
DPF regeneration active?	No	No	No	No	No	No	Yes

⁹ Averaged reading but high variation during measurement.

HT in/out [degC]	39/84	42/86	40/86	40/88	45/90	44/90	42/88
LT in/out [degC]	18.6/24.6	21.1/28.2	17.4/27.0	16.5/27.7	17.6/28.3	16.8/27.3	17.5/28.8
Fuel T [degC]	38.0	38.0	38.0	38.0	38.2	37.4	38.0
Oil T [degC]	91.8	93.5	95.6	97.8	100.0	98.6	98.0
Fuel use [l/h]	110	149	235	320	400	351	355
Dry to wet factor	0.958	0.949	0.941	0.939	0.930	0.936	0.932
Humidity correction factor	0.948	0.948	0.957	0.967	0.983	0.982	0.976
O ₂ [V%], dry	16.22	14.88	13.77	13.30	12.02	12.99	12.38
CO ₂ [V%], dry	3.74	4.76	5.60	5.95	6.90	6.18	6.62
CO [ppm], dry	124.28	64.91	32.86	23.12	27.14	19.22	19.98
NO _x – instr. [ppm], dry	99.81	52.89	184.19	171.33	348.26	309.98	326.10
NO _x – sensor [ppm], wet	112.05	86.28	198.33	262.97	375.66	328.68	340.87
HC [ppm propane eq.], wet	6.13	2.55	1.24	1.19	1.59	2.24	1.18
PM [mg/Nm ³], dry	1.81	0.97	2.06	<0.92	4.02	1.98	1.15
PN [# /cm ³], dry	2.10E+03	2.00E+03	1.70E+03	9.00E+02	9.00E+02	1.20E+03	1.00E+03
NH ₃ [mg/Nm ³], dry	3.59	12.05	15.49	35.43	10.27	21.30	34.17
CO [g/kWh] ¹⁰	2.31	0.68	0.25	0.16	0.16	0.13	0.12
NO _x – instr [g/kWh] ¹⁰	2.89	0.86	2.21	1.90	3.36	3.34	3.26
NO _x – sensor [g/kWh] ¹⁰	3.39	1.48	2.53	3.11	3.90	3.78	3.65
HC [mg/kWh] ¹⁰	55.4	13.0	4.7	4.1	4.8	7.4	3.7
PM [mg/kWh] ¹⁰	27.0	8.1	12.6	<5.1	19.2	10.6	5.7
PN [# /kWh] ¹⁰	3.13E+10	1.67E+10	1.04E+10	5.03E+09	4.30E+09	6.42E+09	4.99E+09

¹⁰ Referenced to mechanical engine power.

A.1.1 PM filters



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APPENDIX 1: Filter-photos (PM-measurements)

Engine 1 - 10 %



Engine 1 - 25 %



Engine 1 - 50 %



Engine 1 - 75 %



Engine 1 - 85 %



Engine 1 - 100 %



Engine 1 - Regeneration



ELO2401-111_TNO_JDN_TristãoDaCunha_v2

Table A.2: PM measurement specifications – engine 1

Load steps	10%	25%	50%	75%	100%	85%	85% regen
PM filter mass [mg]	0.4	0.2	0.4	<0.2	0.8	0.4	<0.2
Volume Flue gas [Nm ³]	0.2209	0.2062	0.1938	0.2172	0.1988	0.2024	0.174
Dilution Air Volume [Nm ³]	0.518	0.52	0.524	0.523	0.525	0.526	0.525
Total volume [Nm ³]	0.7389	0.7262	0.7178	0.7402	0.7238	0.7284	0.699
Dilution	3.3	3.5	3.7	3.4	3.6	3.6	4
Tmax Filter [°C]	40.5	37.6	48.5	48.9	51.5	53.5	49.5

A.2 Engine 3 – MR800208

Table A.3: Emission measurement results - engine 3

Load point	10%	25%	50%	75%	100%	85%	85%
TIME start [UTC]	08:25	09:07	09:53	10:38	13:00	12:00	13:41
TIME stop [UTC]	08:55	09:37	10:23	11:08	13:30	12:30	14:11
Duration [min]	30	30	30	30	30	30	30
Engine speed [RPM]	1800	1800	1800	1800	1800	1800	1800
Electrical load [kW]	183.2	418.8	857.1	1274.2	1682.9	1467.0	1444.7
Mechanical power [kW]	202.4	448.6	906.6	1342.4	1769.5	1543.9	1520.6
Ambient T [degC]	24.5	25.6	27.0	28.0	29.0	29.4	27.7
Ambient P [hPa]	1029	1029	1029	1029	1027	1028	1027
Relative humidity [%]	34.5	33.4	31.5	30.3	30.2	28.6	31.7
Manifold T [degC]	36.16	34.66	33.54	30.45	33.82	30.50	31.41
Manifold rel P [hPa]	165.1	492.7	1163.9	1896.3	2250.7	2037.3	2099.3
SCR T inlet [degC]	293.4	339.4	370.4	380.4	464.0	427.1	406.1
SCR T outlet [degC]	289.8	332.7	365.7	376.6	459.2	423.3	404.7
DPF T inlet [degC]	266.2	300.8	341.6	357.1	434.5	401.7	466.5
DPF T outlet [degC]	267.7	295.9	338.2	356.9	432.3	401.6	443.6
Exhaust P [hPa]	1029.9	1031.5	1035.1	1039.0	1039.9	1039.5	1041.0
Exhaust T [degC]	256	258	280	271	320	307	315
Flow [Nm ³ /h], dry	3196	4787	6603	8852	9250	8207	9566
Flow [Nm ³ /h], wet	3349	4430	7050	9490	10035	8850	10325
DEF pump drive [%] ¹¹	4.17	9.54	16.84	28.10	23.26	18.40	17.83
DPF backpressure [mbar]	14.0	21.2	36.7	54.4	66.8	61.0	60.2
DPF blower pressure [mbar]	36.4	50.8	63.4	98.8	120.3	114.8	116.1

¹¹ Averaged reading but high variation during measurement.

DPF blower flow [m³/h]	155	180	170	215	230	234	235
DPF regeneration active?	No	No	No	No	No	No	Yes
HT in/out [degC]	36/82	40/82	40/84	43/86	50/86	46/86	46/86
LT in/out [degC]	21.4/25.7	21.1/26.2	18.3/26.9	18.8/28.2	20.4/30.1	19.7/29.1	18.7/28.2
Fuel T [degC]	37.6	37.6	37.5	37.7	38.3	37.9	38.2
Oil T [degC]	92.2	92.0	95.0	95.2	97.0	96.8	91.1
Fuel use [l/h]	114	152	245	333	412	365	359
Dry to wet factor	0.954	0.945	0.937	0.933	0.922	0.927	0.926
Humidity correction factor	0.966	0.975	0.989	1.010	1.014	1.019	1.012
O ₂ [V%], dry	16.09	14.79	13.50	12.95	11.33	12.13	12.01
CO ₂ [V%], dry	3.87	4.86	5.83	6.24	7.46	6.85	6.95
CO [ppm], dry	114.20	70.71	31.53	20.68	27.43	20.39	17.05
NO _x – instr. [ppm], dry	125.98	57.66	169.09	158.05	402.78	350.31	364.59
NO _x – sensor [ppm], wet	132.94	102.32	198.64	285.70	443.63	381.95	392.48
HC [ppm propane eq.], wet	8.16	6.21	4.54	3.46	2.46	2.24	1.75
PM [mg/Nm³], dry	1.14	1.07	2.29	1.18	4.54	4.31	3.70
PN [# /cm³], dry	4.50E+03	3.60E+03	1.30E+03	1.40E+03	1.90E+03	1.50E+03	1.70E+03
NH ₃ [mg/Nm³], dry	6.91	15.87	19.99	37.35	6.27	19.43	12.43
CO [g/kWh] ¹⁰	2.05	0.72	0.23	0.14	0.15	0.12	0.10
NO _x – instr [g/kWh] ¹⁰	3.59	0.94	2.01	1.75	3.70	3.53	3.60
NO _x – sensor [g/kWh] ¹⁰	3.79	1.67	2.37	3.15	4.08	3.85	3.87
HC [mg/kWh] ¹⁰	71.47	31.18	16.53	11.48	6.85	6.76	5.21
PM [mg/kWh] ¹⁰	17.6	9.4	14.4	6.7	21.5	22.3	18.9
PN [# /kWh] ¹⁰	6.95E+10	3.16E+10	8.19E+09	8.01E+09	9.01E+09	7.76E+09	8.67E+09

A.2.1 PM filters



Air Monitoring

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Engine 3 - 10 %



Engine 3 - 25%



Engine 3 - 50 %



Engine 3 - 75%



Engine 3 - 85 %



Engine 3 - 100 %



(*): During sampling a piece of rust from the flue gas channel came on the filter. This was not included in the weighting.

Engine 3 - Regeneration



Field Blanc



ELO2401-111_TNO_JDN_TristãoDaCunha_v2

Table A.4: PM measurement specifications – engine 3

Load steps	10%	25%	50%	75%	100%	85%	85% regen
PM filter mass [mg]	0.4	0.2	0.4	<0.2	0.8	0.4	<0.2
Volume Flue gas [Nm ³]	0.2209	0.2062	0.1938	0.2172	0.1988	0.2024	0.174
Dilution Air Volume [Nm ³]	0.518	0.52	0.524	0.523	0.525	0.526	0.525
Total volume [Nm ³]	0.7389	0.7262	0.7178	0.7402	0.7238	0.7284	0.699
Dilution	3.3	3.5	3.7	3.4	3.6	3.6	4
Tmax Filter [°C]	40.5	37.6	48.5	48.9	51.5	53.5	49.5

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 flowmeters are rarely installed (PROMINENT D5.8). The conventional method measures emission concentrations in the exhaust flow. Combining these concentrations with the 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).

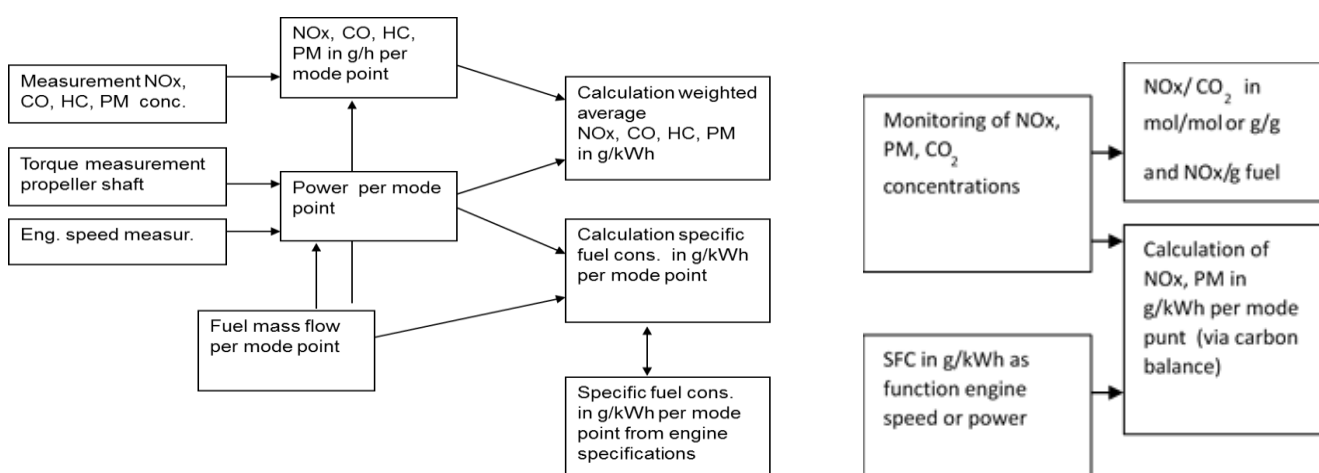


Figure B.1: Comparison of IMO onboard test procedure (left) with simplified procedure for onboard monitoring (right)

The simplified calculation method is somewhat flexible to allow slightly different approaches based on either specific CO₂ 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 CO₂ emissions of the fuel type used (kg CO₂ 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_x¹² and the one of CO₂:

$$\frac{\text{NO}_x^g}{\text{CO}_2^{\text{kg}}} = \frac{\text{NO}_x^{\text{ppm}}}{\text{CO}_2^{\text{ppm}}} \cdot \frac{M_{\text{NO}_x}}{M_{\text{CO}_2}} \cdot 1000 \quad \text{gram NO}_x \text{ per kg CO}_2 \quad (1)$$

The mass of NO_x per kg fuel is determined by multiplying the mass ratio $\frac{\text{NO}_x^g}{\text{CO}_2^{\text{kg}}}$ by the fuel coefficient for specific CO₂ emissions C_F , which is 3.17 for MGO:

$$\frac{\text{NO}_x^g}{\text{m}_{\text{fuel}}^{\text{kg}}} = \frac{\text{NO}_x^g}{\text{CO}_2^{\text{kg}}} \cdot C_F = \frac{\text{NO}_x^g}{\text{CO}_2^{\text{kg}}} \cdot 3.17 \quad \text{gram NO}_x \text{ per kg fuel} \quad (2)$$

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:

$$\frac{\text{NO}_x^g}{W_{\text{engine}}^{\text{kWh}}} = \frac{\text{NO}_x^g}{\text{m}_{\text{fuel}}^{\text{kg}}} \cdot \text{SFC} \quad (\text{g/kWh NO}_x) \quad (3)$$

There are some variations on these equations possible. Instead of the specific CO₂ emission factor for the type of fuel, also the fuel carbon content, Fuel_C , multiplied by the molecular mass ratio of CO₂ and C. Equation (2) is then written as follows:

$$\frac{\text{NO}_x^g}{\text{m}_{\text{fuel}}^{\text{kg}}} = \frac{\text{NO}_x^g}{\text{CO}_2^{\text{kg}}} \cdot \frac{M_{\text{CO}_2}}{M_C} \cdot \text{Fuel}_C \quad \text{gram NO}_x \text{ per kg fuel} \quad (4)$$

M_{CO_2}/M_C in Equation (4) is 44.06/12.01.

Equation (4) can be combined with Equation (1), and molecular mass of CO₂ falls out of the equation:

$$\frac{\text{NO}_x^g}{\text{m}_{\text{fuel}}^{\text{kg}}} = \frac{\text{NO}_x^{\text{ppm}}}{\text{CO}_2^{\text{ppm}}} \cdot \frac{M_{\text{NO}_x}}{M_C} \cdot \text{Fuel}_C \cdot 1000 \quad \text{gram NO}_x \text{ per kg fuel} \quad (5)$$

It should be noted that in the equations above, only the CO₂ 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 CO₂ concentration in the equations above. So, in that case CO₂ (ppm) is replaced by the sum of [CO₂+CO+HC]^{ppm}.

In Equation (5): $M_{\text{NO}_x}/M_C = 46.01/12.01$. For NO_x always the molecular mass of NO₂ must be used. Multiplying (5) with the SFC again provides the NO_x in g/kWh.

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.

¹² For NO_x, the molecular mass of NO₂ was used.

- 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 CO₂ 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 CO₂ 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

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

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:

$$\text{LHV}_{\text{dual fuel}} = \text{mass}\%_{\text{fuel1}} \cdot \text{LHV}_{\text{fuel1}} + \text{mass}\%_{\text{fuel2}} \cdot \text{LHV}_{\text{fuel2}}$$

PM and PN emissions can be calculated in a similar way. Only the concentrations are expressed in gram per standard m³. 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.

$$\frac{\text{PM}_x^g}{\text{m}_{\text{fuel}}^{\text{kg}}} = \frac{\text{PM}_x^{g/\text{m}^3}}{C^{\text{kg}/\text{m}^3}} \cdot \text{Fuel}_C \quad \text{concentrations in (diluted) PM sample flow}$$

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

$$C^{\text{kg}/\text{m}^3} = \text{CO}_2^{\text{ppm}} \cdot \frac{P_{\text{ref}} \cdot M_C}{R_u \cdot T_{\text{ref}}} \cdot 10^{-6}$$

For the reference ambient pressure and temperature, P_{ref} and T_{ref} , the same values should be used as for the PM (g/m³) 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 #/m³.

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):

$$E \left(\frac{g}{kWh} \right) = \sum_{i=0}^n E_i \left(\frac{g}{h} \right) \cdot WFi / \sum_{i=0}^n Pi \cdot WFi$$

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:

$$E \left(\frac{g}{kWh} \right) = \sum_{i=0}^n E_i \left(\frac{g}{kWh} \right) \cdot Pi \cdot WFi / \sum_{i=0}^n Pi \cdot WFi$$

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.

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

Equation C.2: Fuel flow calculation

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

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.

$$Pollutant \left[\frac{g}{kWh} \right]^{13} = \frac{Pollutant [ppm] \cdot Flow_{exh} \left[\frac{g}{h} \right] \cdot M_{Pollutant} \left[\frac{g}{mol} \right]}{10^6 \cdot M_{exh} \left[\frac{g}{mol} \right] \cdot Power [kW]}$$

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

¹³ 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] ¹⁰	0.21 (+3.5%)	0.20	0.33 (+4.6%)	0.32
NO _x – instr. [g/kWh] ¹⁰	2.36 (+2.7%)	2.30	2.09 (+3.4%)	2.01
NO _x – sensor [g/kWh] ¹⁰	3.28 (+2.8%)	3.18	2.86 (+3.9%)	2.75
HC [mg/kWh] ¹⁰	5.01 (+3.3%)	4.85	7.17 (+4.5%)	6.86
PM [mg/kWh] ¹⁰	10.46 (+2.4%)	10.21	10.32 (+4.0%)	9.93
PN [# /kWh] ¹⁰	6.26E+09 (+3.6%)	6.04E+09	9.48E+09 (+4.7%)	9.06E+09

Table C.2: Emission cycle result comparison of flow method vs carbon balance – engine 3.

	E2		D2	
	Calculated flow method	Main method	Calculated flow	Main method
CO [g/kWh] ¹⁰	0.19 (+6.0%)	0.18	0.32 (+6.6%)	0.30
NO _x – instr. [g/kWh] ¹⁰	2.42 (+5.1%)	2.30	2.06 (+5.9%)	1.95
NO _x – sensor [g/kWh] ¹⁰				
HC [mg/kWh] ¹⁰	12.47 (+6.1%)	11.76	18.11 (+6.6%)	16.99
PM [mg/kWh] ¹⁰	12.63 (+5.0%)	12.03	12.08 (+6.0%)	11.40
PN [# /kWh] ¹⁰	1.02E+10 (+5.9%)	9.60E+09	1.41E+10 (+6.6%)	1.32E+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:

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

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]. Finally, the gas constant R is equal to 8.314 J/mol.K.

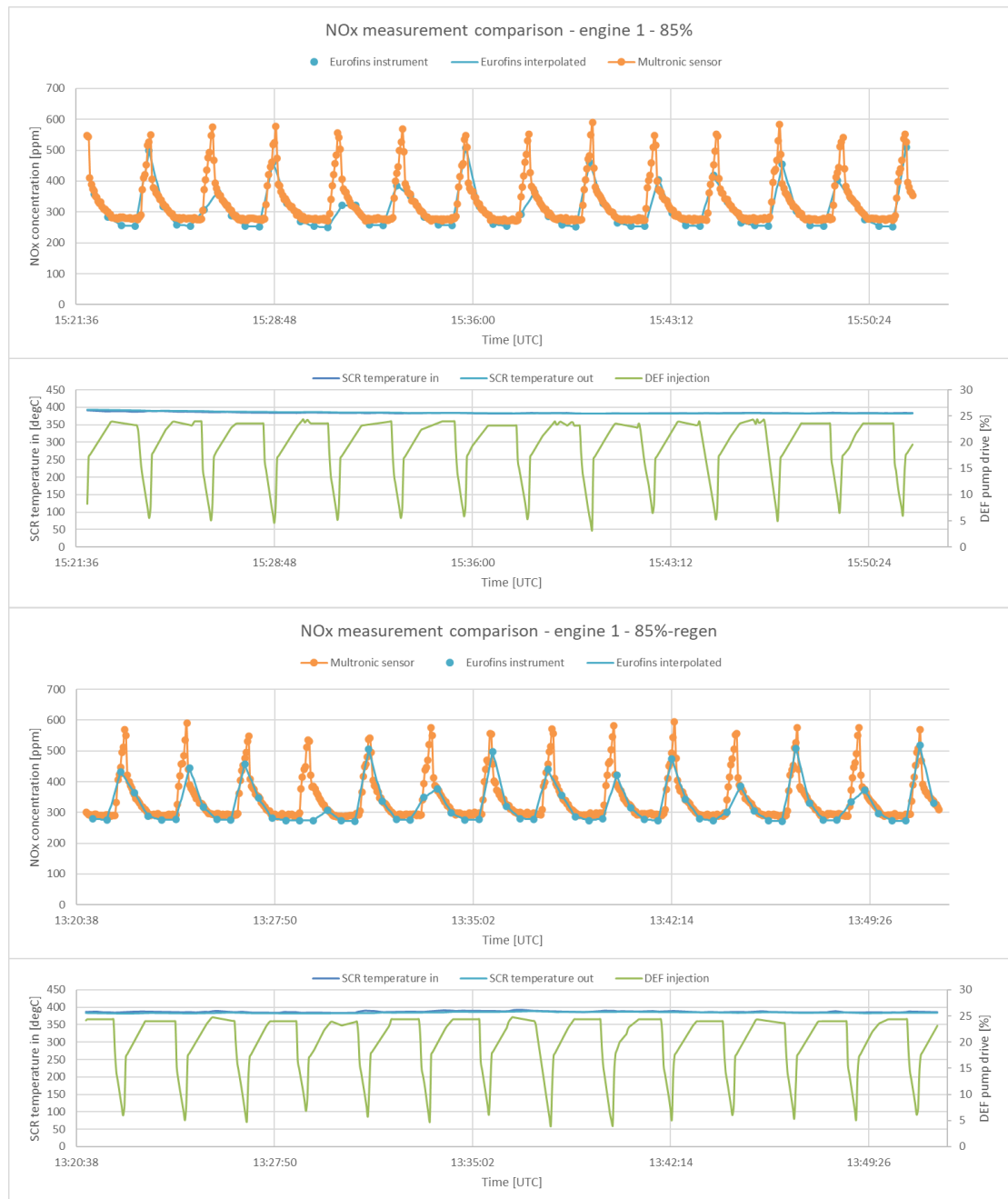
Appendix D

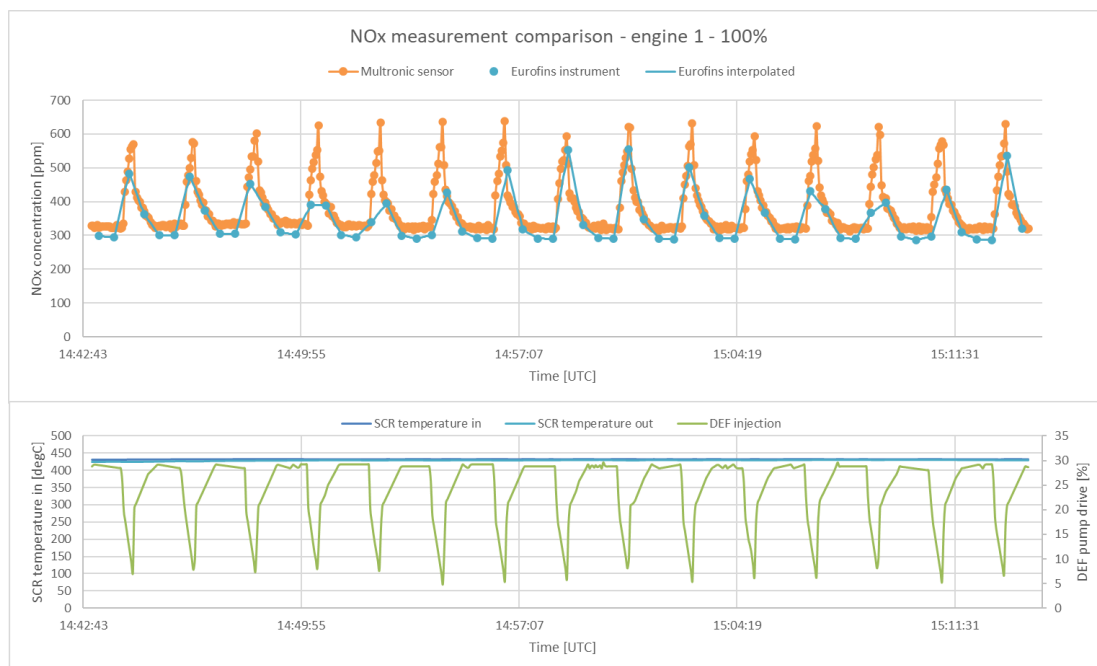
NO_x emission plots

D.1 NO_x emission results – engine 1

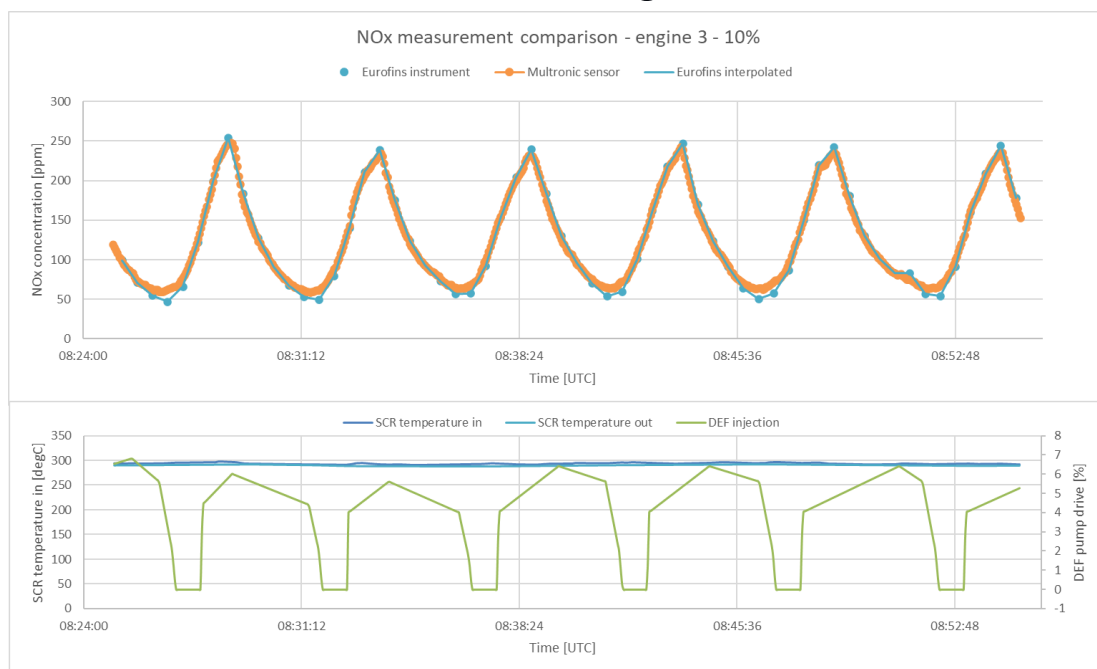




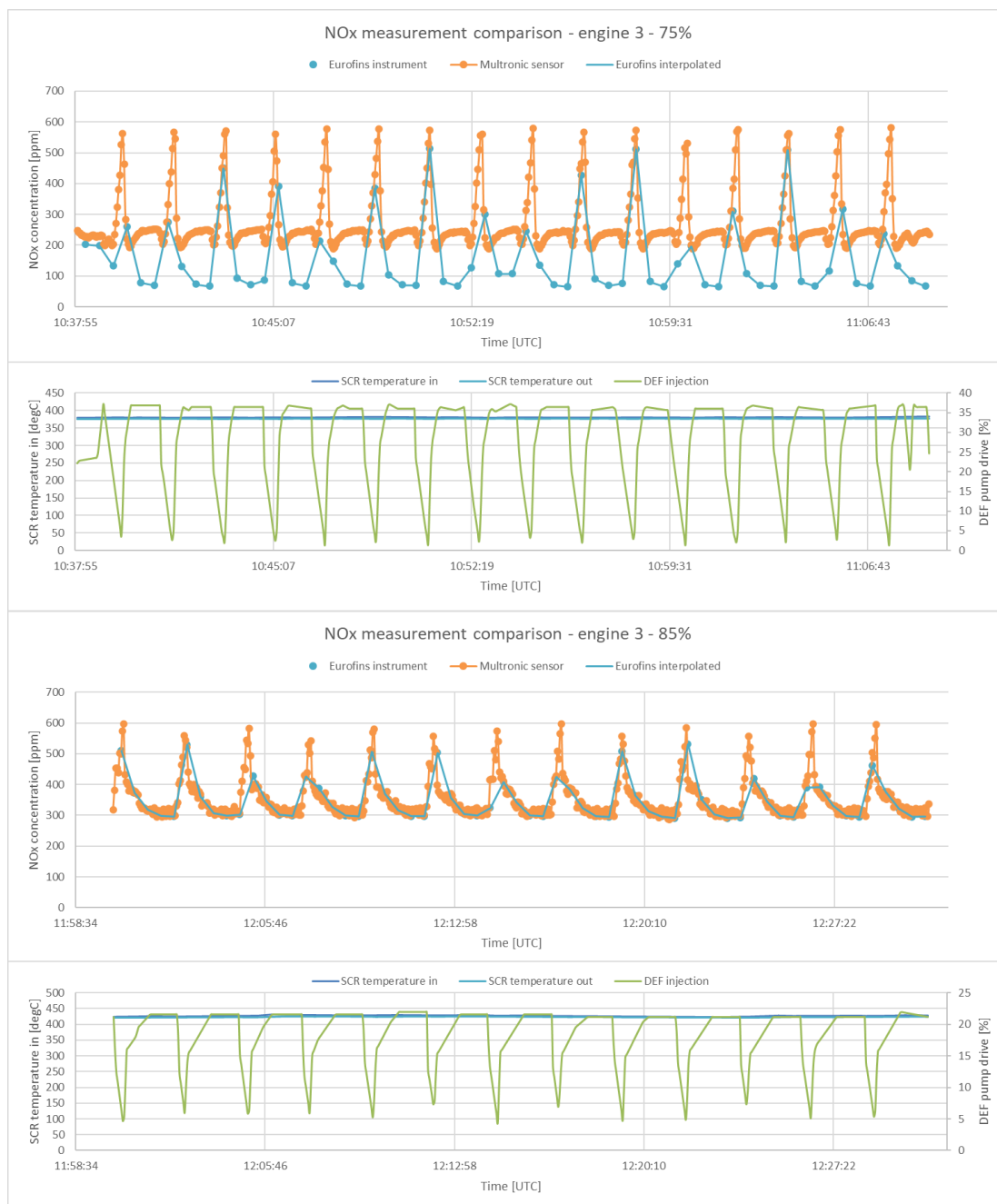


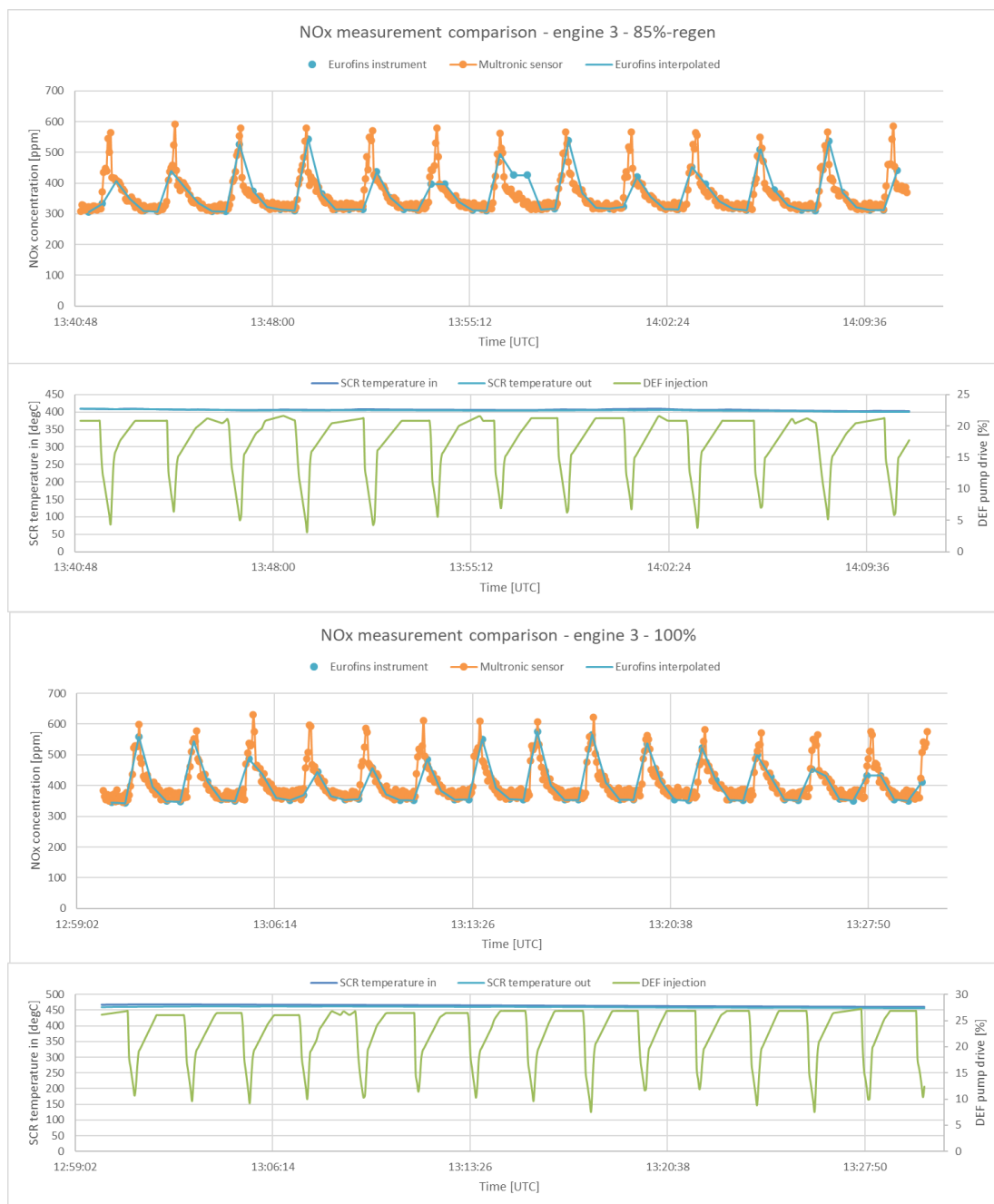


D.2 NO_x emission results – engine 3









Appendix E

Documentation

E.1 Fuel Bunker Delivery Receipt

	Vossesdijnsstraat, Kaal 140 - 2030 Antwerpen Tel. +32 (0)3 641 63 18 E-mail: bunkers@vansbunkers.be - www.vansbunkers.com VAT BE 0437.247.987
Bunker Delivery Receipt (BDR with purpose of delivery of Mineral Oil on board of Seagoing Vessels.) BRVBUT202400006	
Delivery date: 31-01-24	Barge + Reg. number: HEITE PETROLEUM
Receiving vessel: Tristao de	Truck ID: 2CBV030 / 1QCW616
IMO number: 9823	Alongside: 31-01-24 7H45
Owner charterer:	Hose connected: 31-01-24 8H00
Flag: Luxemb	Commenced pumping: 31-01-24 8H10
Port/Location: Ostend	Completed Pumping: 31-01-24 9H45
Next port: Sea	Hose disconnected: 31-01-24 9H50
Delivered by: Barge/Truck	Departure: 31-01-24 10H15

Description Product delivered	Liters Net @ 15° C	Metric tons
1 Diesel 10PPM EN590	70004 Liters	58.677 t
2		
3		
GN Code/Excise Product Code	27101943 / E440	
	Fuel Oil HS	Fuel Oil LS
Kinematic Viscosity @ 40° C		2,632
Density in kg/m³ at 15° C		0,8382
Water content, %		-
Sulphur content in %		0,0008
Flashpoint, ° C		60
Cloud Point, ° C		-8
CFPP, ° C		-25
Marker		Solvent Yellow
Delivered temperature ° C		15° C

Sample Seal Numbers			
barge retained Sample 1	barge retained sample 2	ships MARPOL sample	ships retained sample
1 A2455172	A2454886	A2454783	A2455198
2			

You are kindly requested to witness the opening and closing meter reading and barge soundings before commencing and after completion of bunkering operations. These readings will be used as final means of measurement and will be the official basis to determine the quantity delivered to vessel.

ALL DELIVERIES ARE SUBJECT TO VANS BUNKERS BV:

I confirm I have received the above product quantity in good order and condition for use as marine bunkers only, together with a sealed representative sample of each, as indicated above. The Marpol sample is to be kept under the ship's custody at least 12 months. Seller shall not be bound neither by Buyer's charterparty terms nor by any No Lien stamps or any wording similar in nature and/or meaning on any delivery documents.

The supplier (or its representative) hereby declares that the fuel oil supplied is in conformity with regulation 18.3 of the Revised MARPOL 73/78 Annex VI (the "Annex") and that the sulphur content of the fuel oil supplied does not exceed*:

☐ the limit value given by regulation 14.1 of the Annex; (Applicable for 3.5% sulphur fuel oil, reduced to 0.5% from 1 January 2020).

☐ the limit value given by regulation 14.4 of the Annex; or (Applicable to 0.1% sulphur gas oil and low-sulphur fuel oil).

☐ the buyer's specified limit value of ____ (% m/m), as completed by the supplier (or its representative) and on the basis of the buyer's notification that the fuel oil is intended to be used:

☐ In combination with an equivalent means of compliance in accordance with regulation 4 of the Annex; or

☐ is subject to a relevant exemption for a ship to conduct trials for sulphur oxides emission reduction and control technology research in accordance with regulation 3.2 of the Annex.

*The declaration shall be completed by the supplier (or its representative) by marking the applicable box(es) with a cross (x).

Gauges witnessed by ship's representative:

☐ Before ☐ After ☐ Declined

Captain/Chief Engineer Stamp

Delisting Entrepot: BE1A000093100
Zeevaart Bunkering: BE1A000067

For Vans Bunkers BV

E.2 Fuel analysis



Test Results

	Unit	Test Results	DMA	Test Method
Density @ 15°C	kg/m ³	838.8	890.0	ISO 12185
Viscosity @ 40°C	mm ² /s	2.633	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	-	49	40	ISO 4264
Acid Number	mg KOH/g	0.2	0.5	LP 2003
FAME content	%V/V	0.1	0.1	EN 14078
Water	%V/V	< 0.01		ASTM D6304-C
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	-6		LP 1305
Net Specific Energy ¹	MJ/kg	42.88		ISO 8217
Aluminium + Silicon	mg/kg	< 2		
Temp.@ 10% recovery	degC	199		ISO 3405
Temp.@ 50% recovery	degC	259		ISO 3405
Temp.@ 90% recovery	degC	328		ISO 3405
FTIR Screening	-	Pass		LP 2403
Sulfur (Low Level) ²	mg/kg	< 10		ASTM D4294

¹ Calculated value, ² Retested parameters

Mobility & Built Environment

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