Green Deal Validation Study: NOx-CEMS

Continuous Emission Monitoring Systems for maritime applications

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Summary

This validation study investigates the practical feasibility and usability of Continuous Emission Monitoring Systems (CEMS) for monitoring NO_x-emissions on sea-going vessels within the context of the Dutch Green Deal. While CEMS does not directly reduce (NO_x)-emissions, it can provide critical insight into real-world emission behaviour, enabling informed decisions for compliance, maintenance, and policy development.

To determine whether CEMS is a suitable technology for the goals under the Dutch Green Deal, this study focuses on:

- What is the practical feasibility of CEMS on the different ship types as defined for the Dutch Green Deal Programme.
- What is are the technical aspects governing the usability of CEMS based emission results. What are the main uncertainties of CEMS results.
- What are the standards and regulations governing the use of CEMS in maritime applications?

To do this, a small literature study is combined with data analysis on a provided CEMS dataset and a measurement campaign onboard a vessel equipped with a sensor based CEMS.

The key findings of this study are outline below:

CEMS can reliably monitor NO_x-emissions under real-world conditions but cannot replace certification measurements due to inherent uncertainties. For electrochemical sensor-based systems, overall uncertainty found in literature is typically ±20%. During testing on standard engine test cycles, the deviations of CEMS measurements were found to be lower with -8.6% on the D2 cycle. Higher deviations can however occur during real world conditions, influenced by factors such as NO/NO_2 ratio, SCR operation, and engine power estimation. Furthermore, installation errors can significantly increase inaccuracies—deviations of up to 140% were observed when sensors were placed too close to SCR units or stack walls. Proper sensor positioning (≥5–10 pipe diameters downstream of obstructions and away from walls) and homogeneity checks upon installation are essential to avoid these errors.

Currently, no maritime-specific standards exist for CEMS monitoring. IMO MARPOL Annex VI governs NO_x-limits but does not mandate real-world monitoring. However, discussions within IMO and parallels with automotive regulations (e.g., Euro 7 OBM) suggest that onboard monitoring could become part of future compliance strategies, making CEMS a critical technology.

CEMS is technically feasible for most vessel types in the Dutch reference fleet. Its near-term relevance is highest for vessels under public procurement contracts, where Environmental Cost Indicators (ECI/MKI) are increasingly considered. For other vessels, adoption will depend on regulatory developments.

Sensor-based CEMS offers low-cost maintenance (annual sensor replacement by crew), while analyser-based systems require frequent calibration and specialized personnel. CEMS operation does not affect the general vessel propulsion safety and operation.

Initial investment costs of CEMS range between €5,000 to €15,000 for sensor-based systems. Annual operational costs are found to be between €3,700 and €7,000. Costs are modest relative to vessel budgets but require regulatory or contractual incentives for widespread adoption.

Based on these findings, the study concludes that CEMS can be a valuable technology to provide insights into NO_x-emissions and SCR performance onboard sea going vessels, both for supporting vessel maintenance crews and informing policy makers. While uncertainties and installation sensitivity limit its use for certification purposes, CEMS is well-suited for monitoring emission trends and compliance under real-world conditions.

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1 Introduction

1.1 Background

1.1.1 Green Deal

Firm objectives have been set by the International Maritime Organization (IMO) in its strategy on reduction of GHG emissions from ships, and the Dutch Green Deal takes it a step further. The IMO agreements mean that the transport performance by seagoing vessels must improve to such an extent that CO_2-emissions per tonne-kilometre will be reduced by an average of 40-60% by 2030. The Green Deal aims for an absolute carbon reduction of 70-100% in 2050 compared to 2008, regardless of market growth.

These ambitious goals call for solutions that can be applied today, because ships that are put into service today will most likely still be operational in 2050. The potential of available sustainable maritime solutions is great and is constantly expanding, but none of the available solutions is suitable for all ship types and in all operational conditions. The decision to opt for a sustainable solution also depends on the business case in which the ship must be able to operate. Currently there is a lack of objective information on the match between sustainable solutions and type of business case.

In addition to direct CO_2-emissions, the emissions of the greenhouse gases CH_4 and N_2O and air-polluting emissions such as NO_x, NH_3, SO_x and particulate matter are of great importance for reducing air pollution. The emissions of NO_x, SO_x and particulate matter from shipping are relatively high and are decreasing slowly due to insufficiently effective emission legislation and slow fleet renewal [1].

The diversity of available sustainable maritime solutions makes it difficult to determine which solution is most suitable for application on a ship as this depends on many factors. For example, each solution differs in the required space onboard, the layout of the ship and integration with other systems, as well as for the costs and earning capacity of the ship itself. There is a large array of available sustainable solutions for various ship types, for various operational conditions and lengths of shipping routes. It is therefore important that the effects of these solutions are made transparent in an independent manner and that through validation reliable information is collected so that these solutions can be weighed against each other (ref. NL Green Deal art.12 paragraph 3: “Knowledge institutions will work with the industry to provide independent insight into and validate the effects of the sustainable maritime solutions so that comparison of these solutions is possible and it is easier for shipowners and financiers to compare”).

The results of the performed validations provide reliable information for all parties in the maritime chain, making it easier to choose sustainable solutions.

1.1.2 Validation process

Transparency towards all parties in the maritime chain (from ship owners, ship operators and other logistics operators, shippers, financiers, suppliers, shipyards, to government) is important in the implementation of these validations. The sector itself is investigating which sustainable maritime solutions have the greatest potential to accelerate the energy transition. The technologies with the greatest potential are then validated at independent knowledge institutions. We call this form a cluster study; the sector is represented in this by KVNR and NMT, the knowledge institutions involved are MARIN and TNO, possibly supplemented by an external party if this is necessary for the implementation of a concrete validation case.

Transparency is achieved by making the results public through reports that present an overview of how the various sustainable maritime solutions, grouped by theme, perform in terms of social impact, technical impact and economic impact.

1.1.3 Green deal validation

The green deal validation program of the Ministry of Infrastructure and Water management (I&W) offers the opportunity to independently review emission reduction measures. The marine sector, represented by KVNR and NMT, plays an important role in putting forward the key solutions for GHG reductions which can be implemented or scaled up in the near future. KVNR and NMT consult the sector (technology providers and ship owners) to identify the most important techniques to validate. Thereafter, the contacts are handed over to the knowledge institute that is most knowledgeable, which can also be both, making it a joint validation project.

1.2 Technology specific introduction: CEMS

This study aims to validate Continuous Emission Monitoring Systems (CEMS) for the monitoring of NO_x-emissions onboard sea going vessels. CEMS is an integrated system for the continuous measuring and monitoring of NO_x-emissions, giving more insight in the emission performance of a vessel and total emissions for certain voyages or mission profiles. While CEMS is already frequently used in industrial applications, the technology is not yet widely deployed or standardised for the maritime application to an extend that the use of these systems generates large scale insight for the different parties involved. While industrial CEMS is already used for the monitoring of multiple pollutant emission substances such as SO_x, NH_3, CO and CO_2, in this report the focus is put on the monitoring of only NO_x-emissions.

As CEMS has no direct impact on emitted greenhouse gas or pollutant emissions, this validation study shifts its focus to the usability and accuracy of these systems in providing insights on the actual NO_x-emissions under various real world conditions of sea going vessels.

Seagoing vessels emitted approximately 107 ktons of Nitrogen Oxides (NO_x) annually in 2020 in Dutch Waters [2]. Mainly international agreements, such as MARPOL under the IMO, can lead to substantial reductions of these emissions. The latest agreement under MARPOL Annex VI requires vessels to comply with Tier III emission limit values in the NO_x Emissions Control Areas (NECA). From measurements in the EU HORIZON 2020 project SCIPPER, the real world NO_x-emissions of Tier III vessels is however observed to often exceed the regulatory limit values [3]. The higher real world emissions are likely caused by poorly performing exhaust gas aftertreatment systems due to low engine load, defects, postponed maintenance or tampering.

The insights in the actual emissions onboard seagoing vessels may be useful to both the maintenance crews onboard the vessel and policy officers on shore.

1.2.1 Research questions

Validating CEMS technology in relation to the Dutch Green Deal means; to determine whether CEMS is a suitable technology for the purposes of the Dutch Green Deal. This purpose would be to provide insight into real-world emission behaviour of the engines onboard all reference ship types defined under the Dutch Green Deal.

To determine this, this study focuses on:

- What is the practical feasibility of CEMS on the different ship types as defined for the Dutch Green Deal Programme?
- What is are the technical aspects governing the usability of CEMS based emission results. What are the main uncertainties of CEMS results?
- What are the standards and regulations governing the use of CEMS in maritime applications?

Answering these research questions is primarily done by performing a small literature study. In addition, the uncertainties associated to CEMS results are researched by performing data analysis on a provided CEMS dataset from test on an engine test bed, and by performing a real world measurement campaign onboard a sea going vessel equipped with a sensor based CEMS. The latter was performed to specifically determine the measurement uncertainties associated to sensor or instrument installation faults. The details of the performed data analysis and the measurement campaign can be found in a separate technical addendum [4] and in 0 of this report. Note that the analysis and measurements performed in this study are an important step in broadening the knowledge on the topic of CEMS result uncertainty, but cannot provide universally applicable insights as only single CEMS configuration is studied.

2 Technical impacts and safety aspects

2.1 Technology types and standards

Continuous Emission Monitoring Systems (CEMS) can be used to monitor the NO_x-emissions in the exhaust stacks of each engine onboard a sea going vessel. To do this, CEMS needs to measure NO_x-emission concentrations in the stack of each monitored engine to be able to calculate the total emitted NO_x to the environment. NO_x-concentration measurements can be carried out with different existing technologies; ranging from advanced optical analysers to the use of simple electrochemical sensors. While the NO_x technical code [5] prescribes the use of (heated) Chemiluminescent detectors (CLD) for onboard NO_x-compliance measurements, no actual standards exist on the use of measurement technologies for use in onboard monitoring applications.

Based on technical and practical considerations, the selection criteria on the measurement technology for this application are summarized in Scipper D1.1 [6] as:

- Robustness: resistance towards ship engine exhaust conditions, including temperature, fouling and vibrations.
- Accuracy: error in percentage or ppm value
- Sensitivity: ability to detect small traces of a substance
- Costs: costs of the instrument or sensor

In literature, the most common sensor technologies used in CEMS are therefore Non-dispersive infrared (NDIR) optical sensors, Non-dispersive ultraviolet (NDUV) optical sensors and electro-chemical sensors such as the zirconia based NO_x-sensor which is also frequently applied in the automotive sector. The optical NDIR and NDUV offer very good robustness, accuracy and sensitivity but are slightly more expensive [6]. In contrast, the electro-chemical sensor has slightly lower robustness due to direct contact with the sample. However, it is available at a very low price (€100-€500) [6], making replacement every one to two years possible to keep the monitoring system up and running. For all possible measurement technologies, measures can be taken to increase the lifespan of the sensor by for example air shielding the sensor, measuring in diluted exhaust gas, or intermittent sampling with a bypass option on the sensor [6]. Note that such measures in general make the measurement setup significantly more complex and therefore also more expensive. For continuous monitoring of NO_x-emissions of Tier III sea going vessels, the use of an annually exchanged continuously sampling electro-chemical NO_x-sensor is already found to be a feasible and effective option in literature [7].

To calculate the total- or work specific emission from the stack, the CEMS system needs additional information on the fuel, engine and the exhaust gas composition. Two of the main calculation strategies are listed in Table 2.1 with the required additional parameters from the vessel. Where engine power and exhaust gas flowrate are often difficult to obtain accurately onboard the vessel, static parameters such as the Specific Fuel Consumption (SFC) and carbon content are often included in the parent engine test sheet and the fuel specifications.

Therefore, the simplified procedure proposed in [6] and variations on this strategy are the most cost effective and practical calculation strategies for low cost sensor based CEMS systems. Note that for the simplified procedure the CO_2-concentration can be approximated with an O_2 reading which is available in electro-chemical NO_x-sensors.

Table 2.1: Main calculation strategies for onboard monitoring.

Calculation strategy	Required parameters
IMO MARPOL onboard procedure [5]	NO_x-concentration, Engine power, Exhaust gas flowrate
Simplified procedure for onboard monitoring [6]	NO_x-concentration, CO_2-concentration, engine Specific Fuel Consumption (SFC), fuel properties

Finaly, two main strategies exist on the handling of data from CEMS systems. Traditionally, measurement systems onboard ships used onboard data storage to capture measurement results. While this is still possible for modern CEMS, real-time remote reporting offers many benefits over onboard storage with regard to giving real time insight in emission behaviour to shore crews and being able to share data with external parties.

2.2 Existing standards and effect on the technology

Currently, no specific standards exist on the maritime application of CEMS for monitoring purposes. While CEMS may be used for the verification procedures described in resolution MEPC 177(58) (NO_x technical code 2008) [5] when the analysers are specified according to the requirements in this same resolution, this resolution offers no defining guidelines for the continuous monitoring application CEMS is meant for.

Some standards exist for industrial CEMS applications on stationary sources:

- EN 14181 on the general certification, calibration, and ongoing quality assurance of CEMS.
- EN 16911-2 on the calibration of flow monitoring devices for CEMS.

While these standards may offer some guidance on the implementation on a CEMS for sea going vessels, the standards are by no means directly applicable due to the stationary nature of these applications.

At the moment, CEMS technology for maritime applications is therefore largely defined by good measuring practices and specific vessel requirements. Standardisation is likely to occur if CEMS would get a defined role in regulatory aspects of vessel emissions (see Paragraph 3.1).

2.3 Additional potential risks of the technology (technical and operational)

While achievable accuracy of the analysers and sensors used in CEMS are reasonably well known, a frequently posed question is if the total system accuracy of CEMS can be high enough with the required assumptions and simplifications in the calculations.

CEMS is in the first place meant as a tool to monitor real world emissions. In contrast to emissions measured on a standardised test cycle, real world emissions tend to vary significantly more depending on the operating conditions. Monitoring should therefore not focus on determining emitted emissions to a very high precision, but should be able to show the overall trends in emission behaviour and associated reliable indication of absolute emissions dependent on the usage of the ship and it's engines.

In previous work, the combined uncertainty related to an electrochemical NO_x sensor based CEMS was estimated to be around ±20% for Stage V inland shipping engines [8]. Note that the NO_x emission limits for Stage V engines are slightly more stringent than the Tier III limits for sea going vessels, therefore the estimated uncertainty would be a little lower for Tier III engine monitoring.

For this work, additional analyses have been performed to broaden the available knowledge on the accuracy of CEMS for sea going vessels. This analysis is described in detail in a technical addendum to this report [4]. One analysis focused on the resulting uncertainties arising from assumptions and simplifications made in the calculation of CEMS monitoring results. The results of this analysis are meant as a direct supplement to the estimated uncertainties from previous work noted above. In addition, an analysis has been performed to identify the effect of installation faults of the sensors or analysers on the measurement uncertainty.

2.3.1 CEMS measurement uncertainties

An analysis has been performed on a test bench dataset of an inland shipping engine made available by Multronic. Note that while inland shipping engines in general deviate in size and emission regulation compared to engines for sea going vessels, the general behaviour of CEMS on both types of engines should be comparable. In this dataset, the calculated results from an electrochemical NO_x-sensor based CEMS were compared to the emission results from official lab analysers to determine the uncertainty on the CEMS results. Note that the uncertainty related to the concentration measurement of an electrochemical sensor is in general higher than for an analyser based measurement. However, the uncertainties related to the remainder of the assumptions and calculation methods should be equal.

In this study, four main causes for these measurement uncertainties are determined:

- Sensitivity of the sensor to NO/NO_2 ratio.
- Cross-sensitivity of the sensor to ammonia (NH_3).
- Error on engine power estimation.
- Error on exhaust mass flow estimation.

Sensitivity of NO_x-sensor to the ratio of NO to NO_2, in particular the lower sensitivity of the sensor to NO_2, as well as the cross-sensitivity to NH_3 in the exhaust gas are known properties of these sensors. For both sensitivities, the resulting uncertainty or error is mostly dependant on the operating mode of the Selective Catalytic Reduction (SCR) system. Typical values for the sensitivity of electrochemical NO_x-sensors to NH_3 and NO_2 are 1.0 and 0.8, respectively [9]. The analysis of testbed data also indicates a lower response of the used electrochemical sensor to NO_2 compared to NO which yields an underestimation of NO_x at high shares of NO_2 [4]. For the D2 cycle, the relative difference between the average NO_x reading of the CEMS compared to the laboratory equipment was between -1.5 % and 7.7 % [4, p. Table 3.7], where the lowest value correlated with the highest share of NO_2.

For the E3 cycle, the relative differences were found to lie between -8.0 % and 3.0 % [4, p. Table 3.10]. Again, the minimum value occurred in the mode with the highest share of NO_2.

In the analysis, a difference in engine power registered in the CEMS system compared to the actual output power of the engine is found to be a major contributor to the uncertainty in CEMS monitoring results. In the analysed dataset, there was a general overestimation of the engine power that was logged by CEMS from the CAN-bus [4, p. Tables 3.6 & 3.9]. For the D2 cycle the relative differences range from 1.3 % at high engine load to 64.7 % at low engine load. The total cycle work differs by 8.2 %. For the E3 cycle, the relative differences at high engine load, low engine load and the total cycle work are -1.2 %, 11.3 %., and 1.2 %, respectively.

Finally, the measurement uncertainty coming from the error in exhaust mass flow (EMF) estimations based on the calculations made by CEMS are found to be almost negligible in the performed analysis [4, p. Tables 3.6 & 3.9]. The total mass flow as determined based on CEMS was 0.3 % and 0.2 % higher in the D2 and E3 cycles, respectively. The differences at the different engine loads ranged from -0.5 % to 2.0 % and from -1.0 % to 3.5 % for D2 and E3, respectively. While the exhaust mass flow estimations can have very significant effects on the calculated emissions, the proposed Speed Density (SD) method approximated the EMF very well during steady state operation. This high accuracy over a wide range of operating conditions can, however, only be achieved by using an accurate engine map of the volumetric efficiency. It is very likely the real world uncertainty on this result will be higher due to errors in transient behaviour of the engine. However, the overall effect on monitoring results will be limited for most vessels as transients only occur for short durations during a trip.

In general, the difference between the weighted brake-specific NO_x-emissions obtained from the sensor-based CEMS monitoring system compared to the reference was found to be -8.6 % and -1.4 % for the D2 and E3 test cycles, respectively.

While the obtained CEMS results and their associated uncertainties prohibit the use of CEMS monitoring results as a direct replacement for the current certification measurements, these results are very well suited for general monitoring purposes such as:

- The monitoring of SCR system performance.
- The monitoring of emissions behaviour per operational load profile.
- The monitoring of average and accumulated emission levels over time.

The detailed approach and results of this uncertainty study can be found in [4].

2.3.2 Uncertainties due to sensor installation faults

A small measurement campaign and analysis has been performed onboard of a suction hopper dredger to obtain an indication of the possible additional measurement uncertainty from sensor or analyser installation faults. While the measurements and subsequent analysis was only performed on a single engine, the results can serve as a global reference for considerations on good sensor placement and possible effects of faulty placement.

Measurements were performed onboard a vessel adhering to the requirements of the ULEv label [10], meaning the exhaust gas emission aftertreatment system of this vessel is equipped to reduce the emissions below the limit values specified for Stage V compliant inland shipping vessels.

While emission concentration levels in the exhaust stack are in general lower than those found in the exhaust stack of Tier III vessels, the observed errors with respect to installation faults are expected to remain the same between both types of vessels.

In this study, both lateral (depth in the stack) and axial (along the axis of the stack) misplacement of NO_x-concentration measurement equipment in the exhaust stack is found to have significant influence on the measured and calculated emissions onboard the vessel. Deviations in emission results of up to 140% or 150 ppm are observed for axial positioning of the sensor close to the SCR system. However, also lateral positioning of sensing equipment can have a significant influence with deviations up to 65% observed on measurements close to the stack wall. A possibly cause for both deviations may be the inhomogeneous exhaust gas just after the SCR catalyst. Reagent dosed before the catalyst may not distribute evenly over the catalyst surface, leading to zones of lower and higher NO_x-reductions and inhomogeneous exhaust regarding NO_x just after the catalyst. Sample location related errors can be unpredictable and vary with engine load, therefore proper positioning of the measurement equipment is key to ensure reliable monitoring results.

For proper positioning of the NO_x-measurement equipment of a CEMS, the following guidelines should be taken into account:

- Locate the sampling point at least 5 to 10 pipe diameters away from the nearest upstream obstacle such as the engine or SCR system in line with the current best practices for certification measurements.
- Preferably mount the NO_x-sensor as far away from the stack wall as possible to avoid boundary flow effects at lower engine loads.
- In addition, verify the suitability of the measurement location and depth by performing a homogeneity check at the sampling location across the entire expected engine load range.

More details on the setup and results of the small measurement campaign on the effects of sensor positioning can be found in 0 of this report.

2.4 Impact on maintenance and reliability of operations

The continuous operation of CEMS requires regular maintenance to ensure good operation of the system. Especially the sensor part of CEMS operates in a very harsh environment due to for example potential high concentrations of SO_x and particulate matter (PM) in the sampled exhaust gases. The standalone nature of CEMS however limits the impact of potential system failure on the normal operation of the vessels powertrain.

Maintenance requirements on CEMS vary significantly between the use of advanced exhaust gas analysers or simple sensor systems. With advanced exhaust gas analysers, frequent – up to daily - calibration of the instrument may be necessary to guarantee accurate measurements. A lot of commercially available CEMS based on these analysers have however implemented automatic calibration and flushing capabilities to reduce the maintenance requirements on the system [11]. Monthly to yearly service requirements on these systems are however a realistic estimate, depending on the exposure of the analyser to exhaust gasses. Maintenance service on these systems often requires specialised personnel onboard the ship to carry out these tasks [6], making maintenance difficult in remote locations.

Maintenance requirements on sensor-based CEMS can be significantly simplified due to the low costs of the sensor. In previous studies, annual or bi-annual replacement of the sensor is often indicated as a good replacement interval to prevent deterioration of the measurement results. These intervals are based on an expected sensor lifetime between 2 000 and 4 000 operating hours for NO_x-sensors operating in raw marine exhaust gas [12]. In addition these sensors often have their own status and failure checks which can be used as an additional means to signal a need for replacement. Replacement of the sensor can be carried out by the regular vessel crew without specialised training onboard the ship. Furthermore, electrochemical sensors often make use of internal zero calibrations, making external calibrations in a one year period unnecessary.

3 Environmental impact and applicability

3.1 Regulatory framework

Currently, no regulatory framework exists that mandates or incentivizes the implementation of Continuous Emission Monitoring Systems (CEMS) on sea-going vessels for monitoring their environmental impact. Pollutant emissions of ship engines are controlled via IMO MARPOL Annex VI regulations. The requirements on NO_x-emissions of ship engines are specifically described in regulation 13 of this annex by the International Maritime Organization (IMO) NO_x technical code [5] ((MEPC.177(58) and MEPC.251.(66)). The maximum NO_x-emissions of seagoing vessels are defined based on the maximum (rated) engine speed and become more stringent for newer vessels. In practice, emissions measured on the ISO test cycle comprise of the averaged emissions on 4 to 5 engine load and/or speed points in the full range of the engine. The different functions for the NO_x-emissions limits expressed in g/kWh (gram per unit of engine work) for Tier I, II and III vessels are shown in Table 3.1. The newest engines - Tier III engines - usually require the use of exhaust gas aftertreatment systems to comply with the posed NO_x limit values.

Table 3.1: IMO MARPOL NO_x-requirements dependent on the maximum engine speed denoted as *n* in rotations per minute.

Tier	Ship keel laying date on or after	Total weighted cycle emission limit (g/kWh)		
		$n < 130$	$n = 130 – 1\,999$	$n \geq 2\,000$
I	1 January 2000	17.0	$45 \cdot n^{(-0.2)}$	9.8
II	1 January 2011	14.4	$44 \cdot n^{(-0.23)}$	7.7
III	1 January 2016 (USA) 1 January 2021 (Europe)	3.4	$9 \cdot n^{(-0.2)}$	2.0

In order to proof NO_x-compliance of the powertrain onboard a sea going vessel, the Engine International Air Pollution Prevention (EIAPP) Certificate needs to be valid. This also requires mandatory periodic surveys when the vessel is in operation. The EIAPP certificate is usually issued by a classification society on behalf of the flag state. At the moment, no monitoring of real world emissions or compliance is required by MARPOL.

Ongoing discussions within the IMO Pollution Prevention and Response (PPR) Committee have, however, raised concerns regarding the effectiveness of Tier III legislation for real-world NO_x-emissions. These discussions are substantiated by recent studies showing the actual performance of Tier III-compliant vessels falling short of expectations based on measurements in the north sea NO_x-emission control area (NECA) [13]. A key issue identified is the limited real-world representativity of certification test cycles, leading to an overrepresentation of high load conditions in testing [14] while vessels also often operate at low load conditions, especially in port areas [15].

Similar challenges have been observed before in the automotive sector, where discrepancies between laboratory test cycles and real-world performance prompted regulatory changes. The introduction of Real Driving Emissions (RDE) legislation mandated testing of vehicles under (close to) real world conditions to demonstrate compliance with in-service conformity requirements [16]. In combination with an onboard diagnostic (OBD) system that signals errors in among others the emission aftertreatment system, this meant automotive emissions on the road significantly reduced. In the new Euro 7 regulation, an additional step is made with the inclusion of onboard monitoring (OBM), making monitoring of emissions onboard the vehicle in all driving conditions mandatory for all new vehicles [17]. If the IMO were to adopt a comparable strategy, CEMS could – depending on the regulatory implementation – become a critical technology for demonstrating compliance under real-world operating conditions. In addition, insights from CEMS data could be used to optimize operational profiles of the engines onboard a vessel to, for example, minimize low load ops.

3.2 Applicability on Dutch fleet categories

From a technical perspective, CEMS can in general be retrofitted to all ship and engine types specified under the Dutch green deal reference ships (see Table 3.2), where special care is mostly needed for engines also running on heavy fuel oils due to possible fouling of the sensor element. The risk on the later can for example be reduced using diluted measurement setups as described in Paragraph 2.2. A difficulty with retrofitting CEMS to existing vessels may be the routing of communication lines needed between sensors, data acquisition and data transmission systems. Vessels with existing data infrastructure onboard the vessel may therefore be easier to retrofit than vessels with no or very limited data infrastructure. In vessels where a selective catalytic reduction (SCR) system is present with well positioned NO_x-sensors (see paragraph 2.3.2), these existing sensors may also be used for monitoring purposes, therefore reducing the total number of sensors requiring maintenance and calibration in the system.

From a use case perspective, CEMS may be less applicable as no clear benefits exist for some of the Dutch reference ships within the current regulatory framework. In the Netherlands, RWS recently did a study and practical trial together with Jan de Nul on the use of CEMS for contract management of utility vessels [18], showing interest of governmental agencies to factor in actual emissions in the granting and follow-up of contracts for public procurement. It is likely this strategy which emphasises Environmental Cost Indicator (ECI – Dutch: Milieu Kosten Indicator (MKI)) enforcement will be applied more often in the future due to local air quality and deposition limits. This would be especially applicable to utility vessels and vessels often operating in harbours such as dredging vessels, TUG's, crew tenders and offshore supply vessels.

For vessels operating outside of public procurement such as general cargo vessels and super yachts, CEMS would mainly be of interest for regulatory compliance in case monitoring of emissions would become a mandatory element of updated MARPOL legislation. At the moment, applicability of CEMS for these vessels is therefore very limited.

Table 3.2: The six Dutch reference ships used for the Green Deal validation projects.

Nb	Vessel type	Length (m)	DWT	Total max power (kW)	Engine type	Main fuel type
1	General Cargo	112	9 200	4 290	Medium Speed	MGO
2	TUG	32	285	5 000	High Speed	Diesel ULSFO
3	Offshore supply	82	2900	6 000	High Speed	MGO
4	Crew Tender	25	20	2 100	High Speed	Diesel ULSFO
5	Dredging	125	21 000	12 000	Medium Speed	MGO
6	Super yacht	100	460	13 000	High Speed	Diesel ULSFO

3.3 Economic aspects

Cost related to the use of CEMS onboard sea going vessels can be split into the initial investment costs and the annual operational costs.

In literature, initial investment costs of commercially available systems have a wide range, typically between €20 000 and €80 000 [11]. These estimates are based on industrial style CEMS with multiple high end analysers for multiple emission components.
For simpler CEMS focused on NO_x-measurements with electrochemical sensors, initial investment costs are estimated at €5 000 to €15 000, excluding labour [11]. The final costs depend on factors such as the number of monitored stacks and additional features (e.g., data transmission, reporting, sensor shielding). Note that installation labour costs can be significant compared to the hardware costs due to the potential required modifications to the exhaust stack and routing of data carriers though the ship. These costs are however very dependent on the vessels existing infrastructure.

Annual operational costs are primarily driven by sensor maintenance and calibration, or replacement. For electrochemical sensor-based systems, annual operating costs for a CEMS are estimated at €3 700 to €7 000, excluding the cost related to off-board data infrastructure [19], for vessels with up to two stacks. Costs may decrease if existing sensors in the stack can be utilized for monitoring.

Annual onboard monitoring costs typically represent 0.1% to 2.3% of external damage costs[1], depending on ship type, sea area, and emission requirements [13]. For vessels with multiple monitored stacks, annual costs can become significant relative to initial investment costs. However, for vessels operating for public procurement, these costs remain negligible compared to overall tender budgets.

[1] External damage costs: The monetized societal damage caused by pollutant emissions, typically expressed in €/kg emitted.

4 Conclusions

This ‘Dutch Green Deal’ validation study assessed the practical feasibility and usability of Continuous Emission Monitoring Systems (CEMS) for the monitoring of NO_x-emissions in maritime applications. While CEMS has no direct effect on the emissions of sea-going vessels, it can provide critical insight into real-world NO_x-emissions, supporting informed decision-making by both vessel owners, operators and legislative bodies. The conclusions of this study are outlined below:

Applicability and potential impact
CEMS technology is technically feasible for retrofitting or direct installation on most vessel types included in the Dutch Green Deal reference fleet. Electrochemical sensor-based systems offer a cost-effective solution, while optical analysers provide higher accuracy at increased complexity and cost. However, no maritime-specific standards currently exist, therefore implementation relies on good measuring practices and vessel specific requirements.

Currently, NO_x-CEMS is not mandated under MARPOL Annex VI. However, ongoing discussions within IMO and experiences from the automotive sector suggest that real-world monitoring may become part of future compliance strategies. If adopted, CEMS could play a key role in demonstrating compliance and supporting emission reduction goals.

For now, the use of NO_x-CEMS is mainly advantageous to vessels working under public procurement where an Environmental Cost Indicator is used for the assessments of bids. This is mainly applicable for utility type vessels. For vessels operating outside of public procurement this means there are currently no major drivers for the implementation of CEMS.

Operational aspects
The main operational aspects related to the use of NO_x-CEMS are related to the maintenance of the monitoring system. Maintenance requirements vary by system type. Sensor-based CEMS can be maintained by vessel crews with cheap annual sensor replacement, whereas analyser-based systems require more frequent calibration and specialised or trained personnel. Despite some additional maintenance work, the use of CEMS does not affect the safety or operation of the vessels propulsion systems.

Economic aspects
Initial investment costs for sensor-based CEMS range from €5,000 to €15,000, with annual operational costs between €3,700 and €7,000. While these costs are modest compared to overall vessel operating budgets, their economic justification may depend on regulatory developments and other potential incentives such as public procurement rules.

Measurement accuracy and uncertainties
CEMS can provide valuable insights into real-world NO_x-emissions based on simple concentration measurements and digital information obtained from the engine system. CEMS results are however less accurate than measurements from dedicated emission measurement equipment. Therefore, CEMS results should not be directly used for certification purposes.

Uncertainties of electrochemical NO_x-sensor based CEMS results are usually within ±20%, mainly influenced by sensor cross-sensitivities, faults in the engine power estimation and faults in the exhaust gas mass flowrate. In this study, the deviation of CEMS to dedicated emission measurement equipment on standard engine test cycles was found to be -8.6% and -1.4% for the D2 and E3 test cycle respectively. However, potential increased deviations in real world use are expected due to for example high NO_2 concentrations in the exhaust stack or low engine load conditions. Furthermore, installation faults of the measurement equipment can lead to significant errors (up to 140% observed in a small scale experiment). Proper sensor installation—at least 5–10 pipe diameters downstream of flow obstructions and away from stack walls— and validation of the measurement and the location are therefore critical to ensure reliable results.

Future research
In future research, the uncertainties on CEMS results could be further classified based on a larger sample size and for different CEMS sub-technologies to provide broader applicable insights. Furthermore, the accuracy of CEMS concentration measurements at very low engine loads (below 25%) should be further examined as load was seen to influence the errors in the concentration measurements during the small scale measurement campaign described in this report.

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Signature

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Appendix A
Sensor installation errors study

A.1 Introduction

Continuous Emission Monitoring Systems (CEMS) onboard maritime vessels are able to monitor NO_x-emissions by measuring in-stack NO_x-emission concentrations and combining this information with engine operational data to calculate the total emissions in g/kWh or g/h from the stack. To measure the NO_x-concentrations, a CEMS needs to make use of in-stack installed sensors or analysers. Gaseous concentrations in the exhaust stack can however not be expected to be uniform along the axial and lateral directions of the exhaust stack. Therefore, installation faults can introduce additional measurement uncertainties in the CEMS results.

Inhomogeneous gaseous concentrations in the exhaust stack can be the result of various flow and dispersion effects such as:

- Inhomogeneous dispersion of reagent before an SCR catalyst due to insufficient mixing length or poor atomization at the injection site
- Uneven distribution of urea over the SCR catalyst due to sub-optimal thermolysis and hydrolyses of the urea.
- Uneven flow distribution due to flow obstructions or boundary layer effects.
- Temperature gradients due to flow obstructions or cold spots.

Good measuring practices therefore suggest a minimal distance from any upstream flow obstruction or injection location of 5 to 10 pipe diameters [20] [5]. In practice, installation locations of sensors in the stack can however be located much closer to for example the SCR installation due to practical constraints or considerations.

This small scale study serves as a reference for the effects of installation errors in both the axial and lateral positioning of the sensor or analyser in the stack. Various NO_x-concentration measurements have been performed at multiple sampling locations and depths in the exhaust stack of a marine diesel engine. By comparing the results at stable engine operating conditions, the absolute concentration measurement error relative to measurements at a reference location are determined, and the expected effects on monitoring results are explained.

A.2 Method

To assess the effect of the sensor installation locations on the monitored emissions, various emission concentration measurements are performed in the stack of a maritime diesel engine of a modern trailing suction hopper dredger. Concentration measurements are measured with two exhaust gas measurement instruments.

One instrument - the reference instrument - is stationary at the reference measurement location while the second instrument – the mobile instrument - measures NO_x-concentrations at various sample locations and sample depths in the stack. Comparison between the measured concentrations of the reference instrument and the mobile instrument yields the concentration measurement faults at the various sample locations.

Note that the vessel used in this measurement campaign is equipped with both a Selective Catalytic Reduction (SCR) system and Diesel Particulate Filter (DPF) to comply with the requirements of the ULEv label. This label can be given to maritime vessels which demonstrate emissions below the emission limits posed on Stage V inland shipping engines. While emission levels in the tailpipes of these types of vessels are in general lower than those in a Tier III compliant vessel, the results of this campaign should still be valid for Tier III due to the similar influences of the SCR system on the exhaust gas concentrations and behaviour.

A.2.1 Measurement locations

Measurement locations were chosen at three different axial distances from upstream flow obstructions as shown in
Figure A.1. The properties of each measurement location are shown in Table A.1, Table A.2 and Table A.3. Note that location B and C are located in different sections of the exhaust stack due to availability of existing sample ports. Exhaust gas is routed either through the DPF or through the DPF-bypass tube by the DPF-bypass valve. Sampling locations above the DPF installation are not usable in this study due to the addition of clean air to the exhaust stream from the DPF regeneration burner.

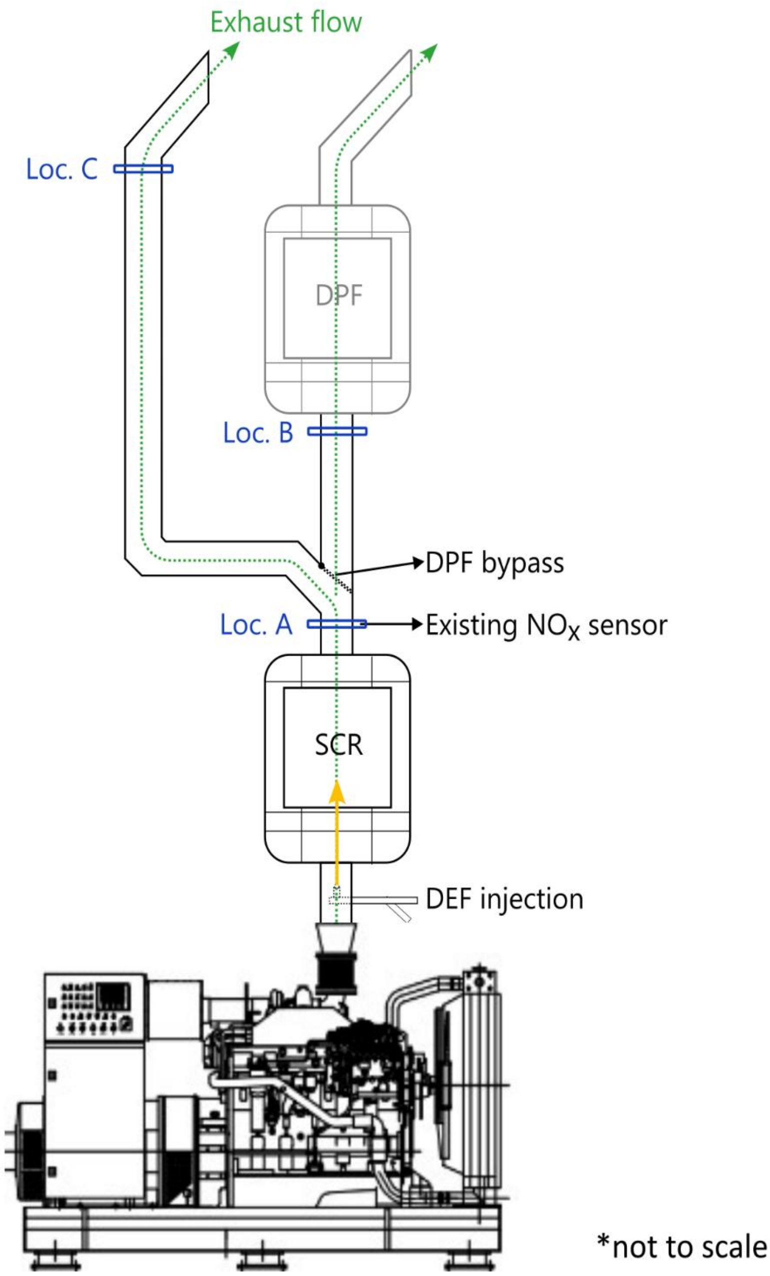

Figure A.1: Schematic representation of the exhaust stack architecture and measurement locations used in this study.

Location B is chosen as the reference location where the reference instrument is installed due to its distance from the SCR and availability of multiple sample ports close together. Location A coincides with an existing NO_x-sensor for monitoring purposes and therefore represents an often used location of existing sensors. Location C is located at the top of the stack and gives insight in the homogeneity of exhaust gases after longer distances away from the engine and exhaust gas aftertreatment systems.

Table A.1: Measurement location A - properties.

Property	Value
Function	Represents often used sensor location.
Distance to upstream flow obstacle	1.15 m (1.6 diameters)
Distance to downstream flow obstacle	7.12 m (10.2 diameters)
Upstream flow obstacle	SCR catalyst blocks
Downstream flow obstacle	DPF
Internal pipe diameter	70 cm

Table A.2: Measurement location B - properties.

Property	Value
Function	Reference location.
Distance to upstream flow obstacle	7.75 m (11.1 diameters)
Distance to downstream flow obstacle	0.52 m (0.7 diameters)
Upstream flow obstacle	SCR catalyst blocks
Downstream flow obstacle	DPF
Internal pipe diameter	70 cm

Table A.3: Measurement location C - properties.

Property	Value
Function	Represents measurements at the top of the stack.
Distance to upstream flow obstacle	9.8 m (14 diameters)
Distance to downstream flow obstacle	-
Upstream flow obstacle	90 degree angle in the stack
Downstream flow obstacle	-
Internal pipe diameter	70 cm

At each location, gas concentration measurements are performed at different depths in the stack to determine the lateral homogeneity of the exhaust gas at this measurement location. The different measured depths are listed below in Table A.4 with respect to the inside wall of the stack. Note that the reference instrument was always installed in the middle of the stack at 35 cm.

Table A.4: Measurement depth specifications.

Absolute sample depth	Relative sample depth	Remark
0 cm	0.00 radius	Optional, where possible
2.5 cm	0.07 radius	
8.0 cm	0.23 radius	
12.5 cm	0.36 radius	
22.5 cm	0.64 radius	Optional, where possible
35.0 cm	1.00 radius	

A.2.2 Measurement instruments

Two measurement instruments are used to perform in-stack NO_x concentration measurements:

- The reference instrument is a Horiba OBS-ONE Portable Emission Measurement System (PEMS)[2]. This instrument is permanently mounted at the reference measurement location (Location B, see paragraph A.2.1).
- The mobile instrument is a Testo 350 portable analyser with a long probe. This instrument was used at all measurement locations at various depths in the exhaust stack.

Sampling at different depths in the stack is achieved by sliding the probe of the mobile instrument through a matching diameter tube fitting as schematically represented in Figure A.2.

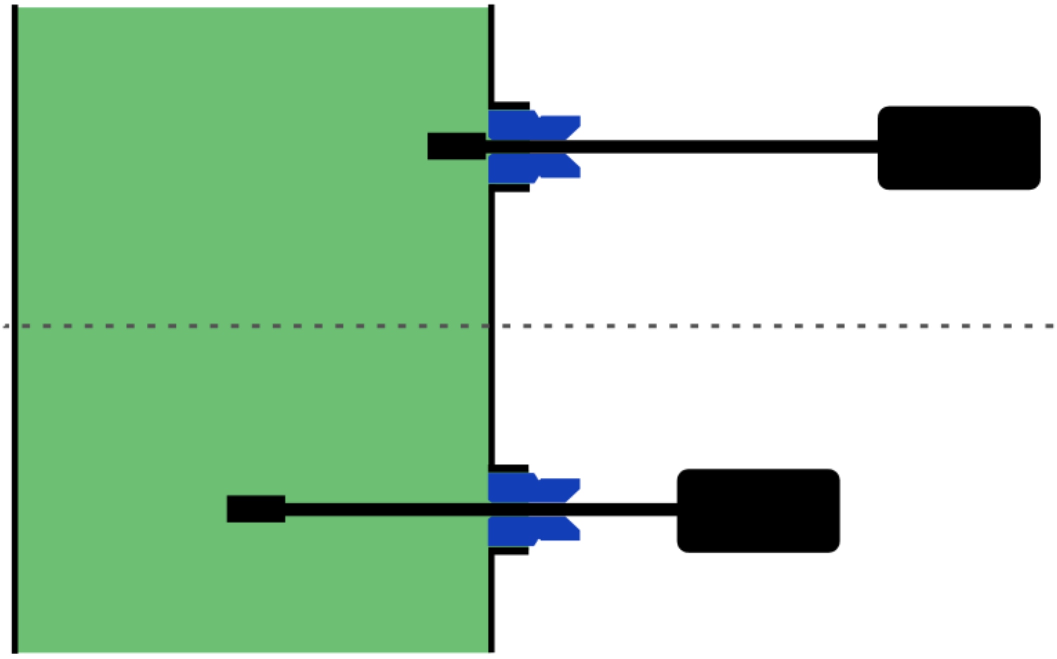

Figure A.2: Schematic representation of different sampling depths in the exhaust stack with a sliding probe.

The reference instrument will not be measuring the same exhaust gas during sampling at measurement location C due to the routing options with a DPF bypass valve in the exhaust stack (see paragraph A.2.1). An existing NO_x-sensor at measurement location B (see paragraph A.2.1) will be used as an additional reference device while measurements are being performed at measurement location C.

[2] According to requirements laid out in: US EPA 40 CFR, Part 1065 Subparts D and J, EU Regulation No. 692/2008 and its amendments 2016/427 and 2016/646, EU Regulation No. 2017/1151 and its amendment 2017/1154

A.2.3 Measurement steps

Instrument reference measurements

First, an instrument reference measurement is performed to determine the correlation between the different NO_x-concentration measurement of the two analysers and the NO_x-sensors. The engine is operated at a stable load while different measurements are performed by both the reference instrument and the portable instrument at the same sampling location and depth. Potential deviations between both instruments can later be corrected based on the correlation during these measurements.

Note that correlation between the reference instrument and the existing NO_x-sensor at measurement location A will be evaluated in a similar way during these measurements.

Concentration variation measurements

After the different instruments are referenced with each other, the actual emission concentration variation measurements between the various sampling locations and depths are performed. At each measurement location, measurements are performed at the depths specified in Table A.4 while the engine is running at stable load. All depth measurements are repeated three times with different load conditions of the engine to obtain different NO_x-concentration levels in the exhaust stack. The load conditions used during the measurements are listed in Table A.5. The load conditions were chosen such as to enable measurements could be conducted during normal operation of the vessel.

Table A.5: Engine load conditions.

Configuration	Engine load	SCR mode	Representative NO_x concentration
1	80%	Mode 2 (ULEv)	~ 80 ppm
2	40%	Mode 2 (ULEv)	~ 150 ppm
3	40%	Mode 1 (Tier II)	~ 200 ppm

Data analysis

All measured data from the mobile instrument is compared with the reference concentration measurements of the reference instrument at location B. First, the measured data is corrected for possible instrument deviations measured during the instrument reference measurements. The differences in measured concentrations Δ_C are then calculated according to:

$$\Delta_C = \frac{\sum_{i=1}^{n} C_{n,mobile}}{n} - \frac{\sum_{i=1}^{n} C_{n,reference}}{n} \qquad (A1)$$

Here, C_{mobile} are the measured and corrected concentrations by the mobile instrument at a given location, depth and engine load condition. $C_{reference}$ are the measured concentrations by the reference instrument in the same temporal window as C_{mobile}. Finaly, n is the number of measurement samples taken at the given location, depth and engine load condition. Note that the reference instrument is represented by the corrected data of the existing in-stack NO_x-sensor at location A during measurements at location C.

A.3 Results and discussion

A.3.1 Instrument reference measurements

To ensure comparisons on measured NO_x-concentrations between different instruments is not governed by differences in calibration or sensitivity of these instruments, a reference measurement between instruments is performed. Data of these reference measurements is used to correct the data of the mobile instrument and existing NO_x-sensor with respect to the reference instrument, and to determine the remaining uncertainty on the obtained signals.

Correlation between the reference instrument (PEMS) and the mobile instrument (Testo) was measured during two different stable engine load conditions. During these measurements both instrument measurement probes were installed at location B in the middle of the stack. The correlation between both instruments is shown in Figure A.3 and is found to be very good. The correlation is well explained with a linear regression fit obtaining a coefficient of determination of 0.99. Correcting the Testo NO_x-data with Equation [A2] yields a remaining uncertainty on the data of ±7.8 ppm with a 95% confidence interval[3].

$$C_{Testo,corrected}[ppm] = \frac{C_{Testo}[ppm]}{0.95} + 2.07 \qquad (A2)$$

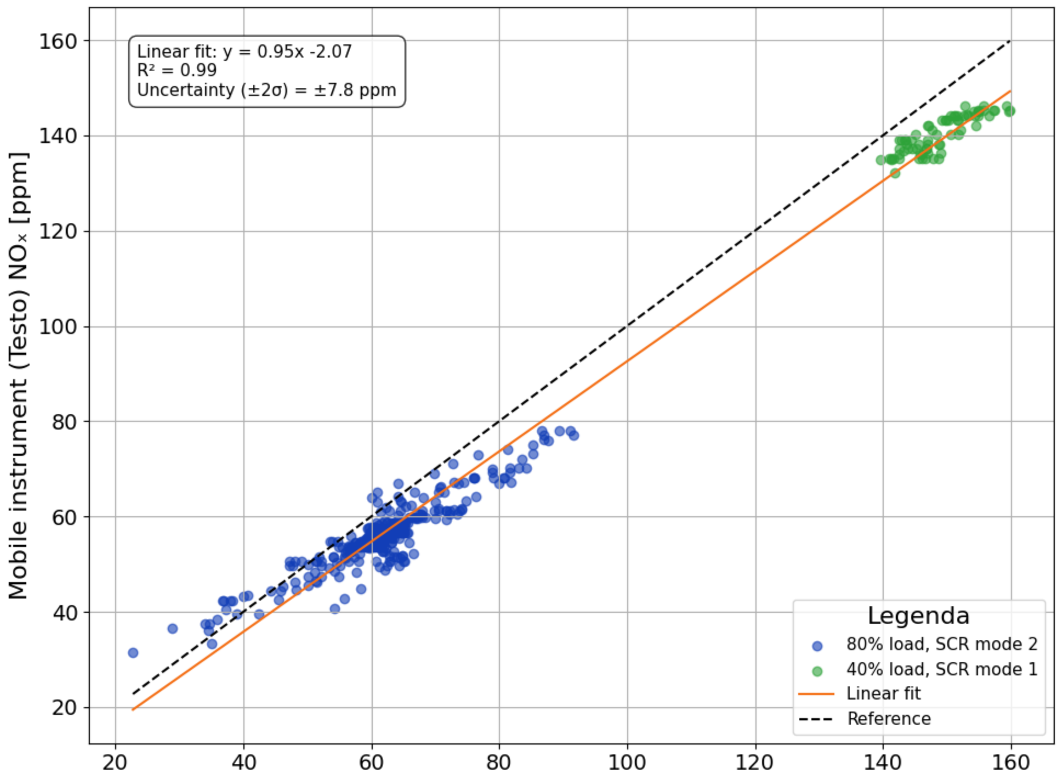

Figure A.3: Correlation between the reference instrument (PEMS) and mobile instrument (Testo) during simultaneous measurements at the same sample location and depth.

[3] Assuming a gaussian distribution of the data.

Correlation between the reference instrument (PEMS) and the existing NO_x-sensor at location A is also studied. Data of this NO_x-sensor is used as an additional reference during measurements at location C as the reference instrument at location B cannot be used during these measurements. Correlation between the NO_x-sensor and the reference instrument is determined separately for high and low load conditions due to significant differences in the correlation between both conditions, and can be seen in Figure A.4 and Figure A.5. Note that corrected NO_x-sensor data is only used for global comparisons as the observed correlations may be significantly influenced by any flow or dispersion related event at the bottom of the exhaust stack and is therefore cross sensitive to the effects being researched in this study.

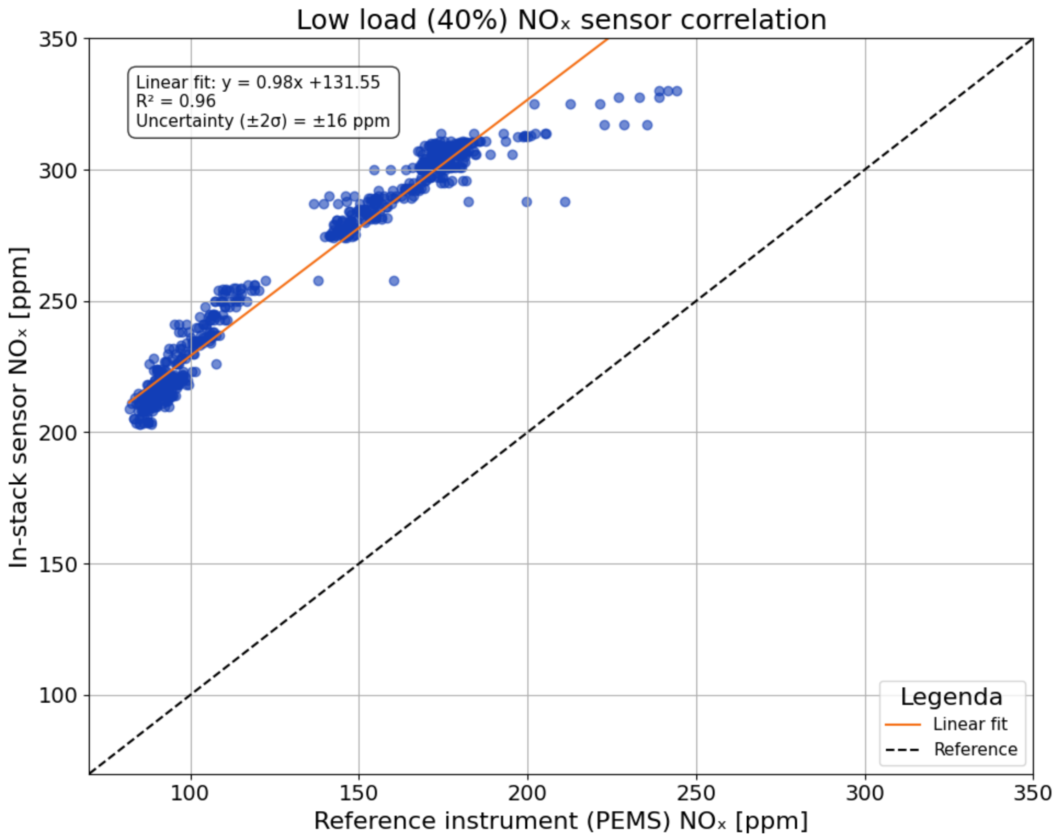

Figure A.4: Correlation between the reference instrument (PEMS) and existing in-stack NO_x-sensor during low load conditions.

The correlation of the sensor and reference instrument during low load conditions shows a significant offset of approximately 100 ppm from the reference and a slight difference in gain. The correlation can be reasonably well represented by a local linear regression fit resulting in a coefficient of determination of 0.96. After correction of the sensor data at low load conditions with Equation [A3], data of this sensor yields a remaining uncertainty of ±16 ppm with a 95% confidence interval[3].

$$C_{sensor_{LL},corrected}[ppm] = \frac{C_{sensor_{LL}}[ppm]}{0.98} - 131.55 \qquad (A3)$$

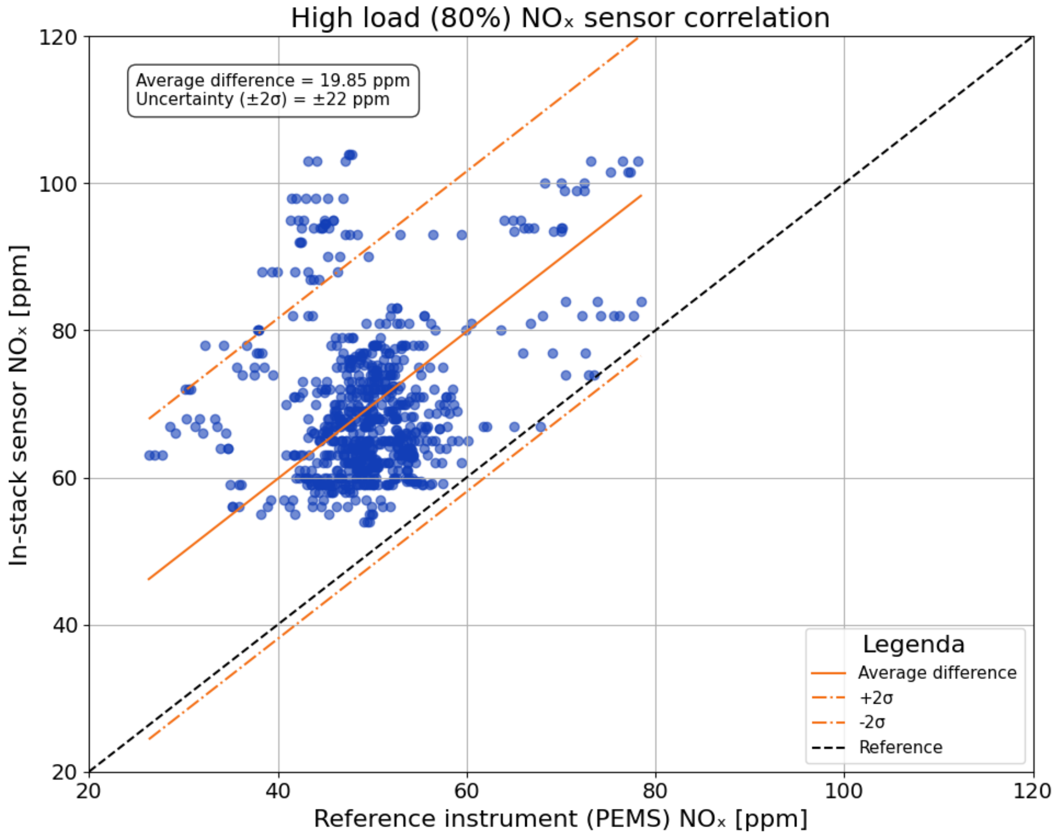

Figure A.5: Correlation between the reference instrument (PEMS) and existing in-stack NO_x-sensor during low load conditions.

Correlation data of the sensor and reference instrument at high load conditions is very limited. As such, the correction approach for this dataset is simplified to correction with the average difference between both instruments. After correcting the NO_x-sensor data with Equation [A4], an uncertainty of ±22 ppm is found with a 95% confidence interval[3]. Note that the calculated uncertainty should be interpreted carefully due to the limited sample set size.

$$C_{sensor_{HL},corrected}[ppm] = C_{sensor_{HL}}[ppm] - 19.85 \qquad (A4)$$

Note that the total uncertainty used in the interpretation of the analysis results is determined by the root sum square of the uncertainties associated to each individual instrument used in the data comparison.

A.3.2 Concentration variation measurements

At each measurement location, NO_x-concentration measurements are taken at the depths shown in Table A.4 with the mobile instrument. The measured concentrations at each tested engine load condition are shown in Figure A.6. Similarly, the differences in measured concentrations between the mobile instrument at the different locations, and the reference instrument(s) at a fixed location are shown in Figure A.7. Note that the shown data can be interpreted as the cross section of the exhaust stack as the x-axis of the figure represents the diameter of the exhaust stack.

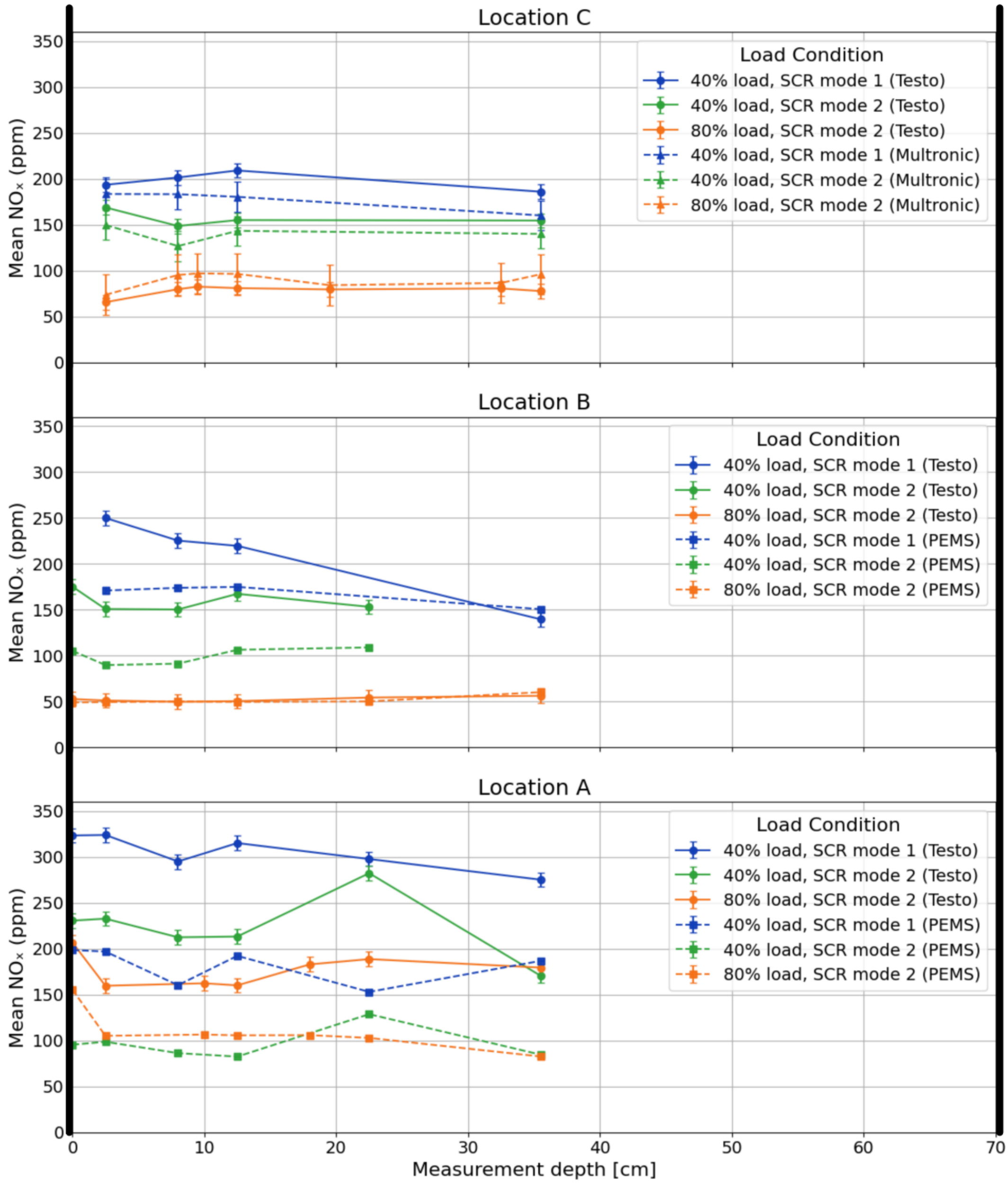

Figure A.6: Average (corrected) NO_x concentrations at different depths at three locations in the exhaust stack during three different engine load conditions. Locations A, B and C are located progressively further away from the SCR system. Note that data of the reference instrument(s) shown with the dots of the dashed lines represent the measured concentrations at the location of the reference instrument during the same temporal window as the measured concentrations of the mobile instrument (solid line) at the different locations and depths. Error bars represent the instrument specific uncertainty (±2σ). The lines between dots are for better visualization of the trends.

At measurement location A, just downstream of the SCR installation, high differences in measured NO_x-concentrations are observed relative to the reference instrument in the middle of the stack at location B. Especially at low load the observed differences go up to 150 ppm above the reference.

While a radial difference in concentrations is observed during all engine load conditions, the different responses between high and low load conditions may be the result of different flow patterns and the associated mixing of gases at different exhaust gas flow speeds. These flow patterns are likely due to the presence to the SCR elements just upstream of the measurement location.

At measurement location B – approximately 11 pipe diameters upstream of the SCR elements – the observed differences in measured concentrations are significantly reduced compared to those found at location A. In the middle of the stack, differences in measured emissions are not expected as both the mobile and reference instrument are measuring at the same location here. Increasing differences in measured concentrations towards the wall of the stack at low engine load conditions indicates either significant boundary flow effects or incomplete mixing of the exhaust gasses at the measurement location. The relatively stable concentration measurements by the reference instrument in the middle of the stack during all measurements on the same engine load condition however suggests boundary flow effects are more likely. Boundary flow effects could also be influenced by the close proximity of the DPF filter elements downstream of this sampling location, as boundary flow related errors are not observed at measurement location C. At high engine load conditions, differences in measured emissions stay very close to zero throughout the entire depth range. This shows the gaseous emissions are well mixed (homogeneous) and not significantly influenced by boundary flow at this location at higher emission flow rates.

Finally, at measurement location C – approximately 14 pipe diameters upstream of the SCR elements – the observed differences in measured concentrations at all engine load conditions show a flat profile indicating homogenous exhaust gas composition and low effects of boundary flow. While the absolute differences are slightly higher compared to the differences found in the middle of the stack at location B, the uncertainty ranges of the data at this location all cover the zero difference line. Low differences at this location confirm the suitability of the middle of the stack sample location at location B as no significant differences are observed between measurements at both locations. Note that the absence of boundary flow effects at low load at location C makes this location more suitable for monitoring of emissions across the entire engine load spectrum.

As the total NO_x-emissions from the stack in g/h or g/kWh are linearly proportional to the measured concentrations, differences in measured concentrations result in a proportional change of the NO_x-monitoring results. While the results in this small scale study cannot be used to determine a fleet wide applicable error margin for all possible NO_x sensor installation faults, the observed errors can serve as a first indication of the potential introduced faults in the monitored emissions. An overview of the rounded percentual errors at different locations in the exhaust stack is given in Table A.6. Especially at the sampling location just downstream of the SCR (Location A), relative errors of the measured concentrations between 45% to 140% are observed at low load. Here the lower error is representative for the Tier II mode (SCR mode 1) of the vessel while the high error is representative for ULEv emission levels (SCR mode 2). The error for Tier III vessels is expected to be similar to the errors found for ULEv emission levels due to their similar exhaust stack architecture and NO_x-emission aftertreatment technologies. In the middle of the stack further downstream of the SCR (location B and C) the relative error significantly reduces to between 0% and 15% for both Tier II and Tier III/ULEv emission levels.

Table A.6: Rounded percentual difference with the reference instrument at different measurement locations close to the stack wall and in the middle of the stack. Shown errors are formatted as 'close to the stack wall error' / 'middle of the stack error'.

	Low load – SCR mode 1	Low load – SCR mode 2	High load – SCR mode 2
Location C	5% / 15%	15% / 10%	-10% / -5%
Location B	45% / -5%	65% / --%	5% / -5%
Location A	65% / 45%	140% / 100%	30% / 120%

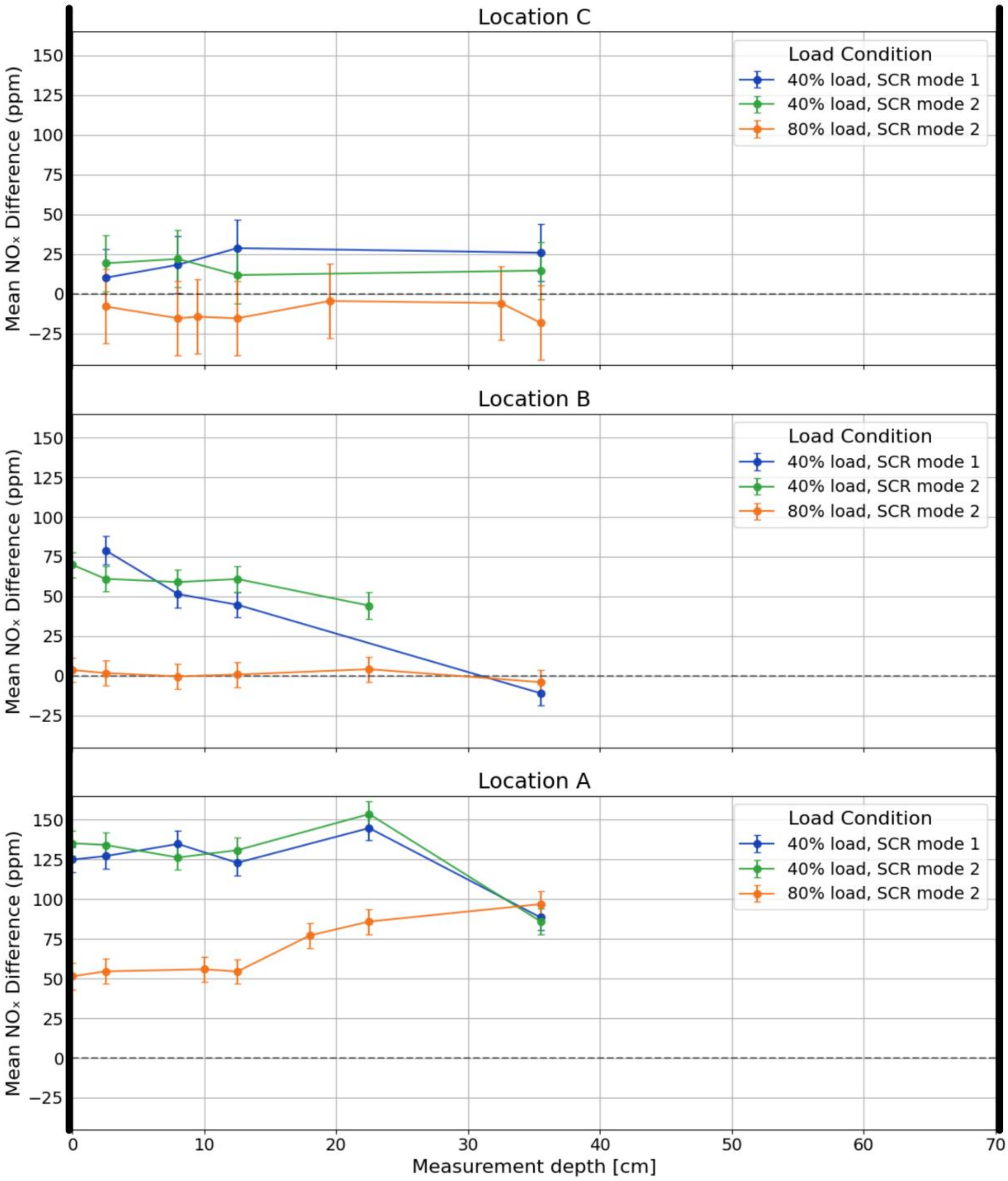

Figure A.7: Average difference in NO_x-concentrations between the mobile and reference instrument at different depths at three locations in the exhaust stack during three different engine load conditions. Error bars represent the total uncertainty (±2σ) on the compared datasets. At high load, absolute differences seem to decrease while at lower load absolute differences increase close to the SCR and closer to the wall of the stack.

A.4 Conclusion

This measurement programme focused on the effects of installation errors in both the axial and lateral positioning of the NO_x-sensor in the exhaust stack in emission monitoring results. While results of this small scale study cannot be used to determine universally applicable error margins for all possible NO_x-sensor installation faults, it serves as a reference for the importance of good sensor placement. The NO_x-emission levels were evaluated and compared to a reference instrument at multiple locations and probe depths within the exhaust stack at various in-stack NO_x concentration levels. The results show that sampling location and probe depth indeed strongly influence NO_x-measurement accuracy of the continuous emission monitoring system.

In general, this study found that the error on measured NO_x-concentrations decreases the further the measurement location is situated downstream from the SCR and the further the measurement location is situated from the stack wall. These differences seem to increase at lower load conditions. Measurement errors close to the SCR for well performing Tier III and ULEv vessels went up to 140% or 150 ppm in this study. As NO_x-concentration measurement errors propagate linearly to the monitored NO_x-emission results, this could result in emission results 2.4 times higher than the actual emitted emissions in this case. It is however important to note that rather than portraying a possible error, these results show NO_x-sensors in close downstream proximity to the SCR or other flow obstruction cannot serve as reliable input for CEMS. The variations in obtained errors at different engine loads and measurement depths at this location also show that measurement errors are not constant or predictable, meaning a slight difference in operating conditions could just as well result in higher, lower, or even negative measurement errors. While many existing NO_x-sensors are mounted close to the SCR due to ease of access and even certification requirements in case of OEM sensors used in the control of the SCR, this location should be avoided for use in monitoring programmes.

Close to the recommended sampling location in the NO_x technical code [5] of 10 pipe diameters downstream of the SCR, the performance of a potential NO_x-sensor in the middle of the stack is found to be good as only minor deviations are found to the observed concentrations further downstream in the stack. However, especially at lower engine loads, installation of a
NO_x-sensor close to the wall of the stack at this location still can result in significant measurement errors. In this case errors up to 65% were found for well performing Tier III and ULEv vessels. Even at recommended distances away from the SCR or other flow obstructions, measurement errors can occur. It is therefore always recommended to perform a homogeneity check at the chosen sampling location across the entire expected engine load range as load seems to influence the absolute error.

Based on the measurements performed in this small scale study, the following installation guidelines for NO_x-sensors of a CEMS can therefore be recommended:

- Locate the sampling point at least 5 to 10 pipe diameters downstream from the nearest obstacle such as the engine or SCR system in line with the current best practices for certification measurements.
- Preferably mount the NO_x-sensor as far away from the stack wall as possible to avoid boundary flow effects at lower loads.
- Alternatively – or in addition –, verify the suitability of the measurement depth by performing a homogeneity check at the sampling location across the entire expected engine load range.
- When CEMS is to be used for some form of NO_x-compliance monitoring purposes, verify correct measurements with a reference instrument upon commissioning of the CEMS and at regular intervals.

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