Review of status quo and options for mitigation

Real sailing NOx emissions of sea-going ships with Tier III certified engines

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Summary

TNO conducted a study for the Dutch Ministry of Infrastructure and Water Management about real sailing NO_x emissions performance of seagoing vessels with Tier III certified engines. Particularly the emissions performance in the North Sea and in general the European ECA zones were the focus of the study, including technical and regulatory measures for improvement.

The main objectives are:

- Based on available studies and data, to determine the real sailing emissions of ships with IMO Tier III certified engines, and to determine whether shortfalls occur between observed emissions levels and applicable limits, possibly distinguishing between types, sizes and usages of ships.
- To provide options to mitigate NO_x emissions on the North Sea (including specific port and coastal areas) of ships with IMO Tier III certified engines.

The study led to the overall conclusion that the NO_x emissions of Tier III ships are higher than aimed for with the Tier III legislation.

The shortfall cover both regulatory and technology aspects:

- The legislative test procedure is not suitable and effective monitoring and enforcement options are not implemented in legislation.
- Independent (remote) monitoring techniques need further improvement and validaton.
- Technical solutions for NO_x reduction need improvement.

Real world NO_x emissions
- Remote sensing of NO_x/CO_2 ratios in the exhaust plumes in ECA zones (North Sea and Baltic Sea) show that emissions of Tier III vessels vary a lot from below Tier III levels to higher than Tier II emissions. About 50% of Tier III vessels (all with low speed engines) emit in practice more than two times the NO_x NTE (Not To Exceed) limit value. There are individual ships which show that low NO_x emissions are possible, also at very low vessel speed.
- Emission measurements in the plume can be 0% to 50% lower than the actual emissions measured in the stack of the main engine, so the problem with high NO_x from the stack might be more severe than remote sensing can show, due to its measurement limitations. It is recommended to further investigate the correlation of the in-stack and plume measurements.
- Ship owners report a substantial number of technical issues with SCR systems, among which blockage of systems due to deposits formation (dependent on fuel type), reduced lifetime of catalysts, lack of spare parts, and poor low-load performance. More research is needed to identify the frequency of these problems and the possible dependencies on fuel type used.

IMO MARPOL NO_x Regulation

NO_x regulations aim to secure low real world NO_x emissions of Tier II and Tier III ships, but based on remote measurements only about a quarter of the ships shows real world emissions in line with the Tier III objectives.

The general known shortfalls are:

- The ISO test procedure (E2, E3, D2) puts the emphasis on high (75%) and maximum (100%) engine load, while in practice most of the time spend in ECA zones the engine load is below 60% and in port areas even below 30% engine load.
- The NTE requirement (150% of limit value) is only applicable to the test points and only for Tier III. There are no emission requirements for engine load points below 25% power.
- Lack of options for enforcement: continuous NOx emissions monitoring is not required. Monitoring and enforcement is not secured in the current regulations.

Technical solutions for low NO_x emissions in ECAs

There are many options to reduce low-load NO_x emissions of marine diesel engines. Especially an improved catalyst system, which can be supported if needed by engine tuning, fuel with lower sulphur content, alternative reagent or EGR complementary for low load conditions. Also ‘EGR-only’ (without SCR) is a realistic option with good NO_x reduction at low load. All of these measures have a high Technological Readiness Level. Thus they can be applied quickly. They are broadly implemented for HD vehicles and also on a smaller scale on ship and stationary diesel engines.

There is a potential fuel penalty of retuning the engine for a better fit with an SCR system. This will depend on the base engine and the magnitude of retuning which is necessary. It can for example go up to some 5% fuel penalty in a part of the engine map.
In practice, the fuel penalty will be likely limited to a few percent dependent on the time spend in that part of the engine map. Also over time engine manufacturers may find and implement improvements which will further reduce this penalty.

On a ship level NO_x emissions can be reduced by shutting off engines which are not needed and/or different powertrain configurations with avoids running engines on low load for long periods.

Recommendations for improvement of regulations

- A minimum set of measures include the expansion of the ISO test cycles (E2, E3, D2) with a low load point, e.g., 10% low load, including a Not-To-Exceed (NTE) for this load point and adapted weight factors to better represent load profiles in ECA zones.
- The NTE should be expanded to all load points and all engine conditions (at least > 10% engine load). The NTE should preferably be defined as g/kg fuel. This wil ensure that monitoring and onboard validation will become easier and more accurate and the NTE can be extended down to 0% load.
- Implement onboard NO_x monitoring requirements preferably with a Continuous Emissions Monitoring System (CEMS) with sensors (which is relatively cheap) or emissions analysers. Alternatively, monitoring can be limited to continuous urea consumption (and quality) in relations to fuel consumption and engine load. Monitoring should be made available to authorities and certification organisation online and/or directly accessible during onboard inspections.
- Implement lifetime requirements for emission control systems onboard of ships.
- Regulate methodology and requirements for periodic inspections onboard of vessels by certification organisation.

- Implement formal status of remote sensing for enforcement purposes. For example as preselection methodology for inspections onboard by authorities or certification organisation or for compliance testing.

Recommendations for further research

- Indications were found for the cause of high NO_x emissions. Further research is needed linking high NO_x to a cause. More insight is needed in precise NO_x emissions of Tier III ships in normal operation. The NO_x emissions of all engines onboard should be analysed in relation to engine load and ship activities. Currently implemented monitoring systems on many ships can provide sufficient insight. Different types of ships with low-speed, medium-speed and high-speed Tier III diesel engines should be evaluated.
- It is recommended to investigate the current and future impact of higher than anticipated NO_x emissions on national emissions (at the NCP, inland waterways and ships at berth).
- Remote sensing of NO_x emissions in the plume seem to often underestimate NO_x emissions (up to 50%) of the main engines. Contributing to this difference may be auxiliary engines onboard, atmospheric phenomena, methodology, or instrument shortcomings. Precise cause(s) should be identified and improvements should be implemented. This can be done by one or more controlled comparison(s) between stack and remote measurements, e.g., with low and high NO_x levels, frequent repetition of measurements, also with different atmospheric conditions. Also periodic round robin and validation testing of remote sensing equipment is also recommended.
- Lifetime and reliability of NO_x emission control systems. Catalyst systems and EGR systems contain components which may be sensitive to fouling, poisoning, aging and wear. Particularly fuel specification including fuel sulphur content, impurities and heavy hydrocarbons may influence the efficiency and lifetime of the systems. CEMS systems would identify such issues, on the other hand (pre-scheduled) replacement of components is costly and should be avoided.
- Present remote sensing data, in more detail, such as NO_x/CO_2 ratios over time with the vessel speed. This avoids a number of uncertainties and takes stakeholders along in the data processing. Also always separate vessel types to allow differentiation
- Study the technical feasibility and acceptability of an appropriate NTE limit value in g/kg fuel down to 0% load.

It is also recommended to expand on remote NO_x monitoring equipment at the Dutch sea ports including continuous monitoring of NO and NO_2. In addition, periodic reporting and cooperation with other European sea ports is recommended.

List of abbreviations

CEMS - Continuous Emissions Monitoring Systems
ECA – Emission Control Area
EGCS – Exhaust Gas Cleaning System
EGR – Exhaust Gas Recirculation
FSC – Fuel Sulphur Content
FTIR - Fourier transform infrared
HFO – Heavy Fuel Oil
IMO – International Maritime Organization
ISO – International standardization organization
KLD – Keel Laying Date
LNG – Liquefied Natural Gas
MARPOL – International Convention for the Prevention of Pollution from Ships (Marine Pollution Act)
MCR - Maximum Continuous power Rating
MGO – Marine gasoil
MRV – Monitoring, reporting and verification; EU:s database for fuel consumption and CO_2 emissions from ships
NCP - Netherlands Continental Plat (Netherlands part of North Sea)
NECA – NO_X Emission Control Area
NO_X – Nitrogen Oxides
NTE – Not-to-exceed limit
OBD – On-board Diagnostics
PTI - Periodic Technical Inspections
RSE - Real Sailing Emissions
SCR – Selective Catalytic Reduction
SFC – Specific Fuel Consumption
SECA – Sulphur Emission Control Area
SFC – Specific fuel consumption
SO_X – Sulphur oxides

Contents

1 Introduction

1.1 Background

Seagoing vessels emitted approximately 107 ktons of NO_x (Nitrogen Oxides) annually in 2020 in Dutch waters. Only international agreements, such as MARPOL under the IMO (International Maritime Organization), can lead to substantial reductions of these emissions. An important regulation is regulation 13 of Annex VI of MARPOL 73/78 and the Technical Code on Control of Emission of Nitrogen Oxides from Marine Diesel Engines which specifies the requirements for the testing, survey and certification of marine diesel engines to ensure they comply with the nitrogen oxides (NO_x) emission limits. NO_x Emission Control Areas (NECA) in the North Sea are defined For ships with a keel laying data as of 1-1-2021 sailing in the NECA the Tier III limits apply. The Tier III limit requires compression ignition engines to be equipped with a form of emissions abatement to reduce the NO_x emissions complying to the specified limit under formal test conditions as laid down in the IMO ship pollution rules.

In the EU HORIZON 2020 project SCIPPER[1] (*THE SCIPPER PROJECT*, n.d.), (Frydell et al., 2023) NO_x emissions from Tier III ships in the North Sea and the Baltic Sea were measured remotely and analysed. The analysis revealed that a significant portion of these ships seems to have NO_x emissions levels under real sailing conditions that are higher than the level of the Tier III limit which applies under formal test conditions of the engines. This would mean that ships, including those off the Dutch coast, emit more nitrogen oxides than could be expected.

The most common form of emissions abatement technology is called SCR (Selective Catalytic Reduction) and uses a catalytic converter which is placed in the stack of the engine and a reagent to reduce the NOx emissions from the engine. The efficiency of SCR largely relies on the amount of reagent being dosed before a catalyst and sufficient temperature in the exhaust to break down the reagent and have an efficient reaction in the catalyst in harmless substances. Emission inventories and real-world testing in other sectors where diesel engines are used, such as road transport (commercial vehicles, passenger cars), construction (construction machinery) has shown that SCR can perform suboptimal under certain conditions of use, especially when the engine is running at a low load providing to little exhaust gas heat to break down the reagent and to activate the catalytic reaction. Aside from SCR also EGR (Exhaust Gas Recirculation) is used to comply to the Tier III standard. The EGR affects the combustion process and hereby reduces the NO_x emission from the engine itself. Issues are noted with regard to these emissions control systems include the occurrence of malfunctions and even tampering with the systems to reduce the costs of operation.

In recent years, the share of sea vessels in the NO_x emissions from traffic and transportation has increased. However, current analyses, including those in the Climate and Energy Outlook, assume that ship emissions will decrease significantly by 2030 compared to the current situation due to the introduction of new Tier III engine-equipped ships largely relying on the effectiveness of emissions abatement systems in real sailing conditions.

[1] SCIPPER – Shipping Contributions to Inland Pollution Push for the Enforcement of Regulations (scipper-project.eu)

The impact of Tier III introduction may fall short if actual emissions substantially deviate from the emission limits.

The DGLM (Directorate-General for Mobility and Transport) of the ministry of Infrastructure and Water management would like to know if the research results are representative of all Tier III ships and what are possible causes. If so, which types of ships and engines are involved. DGLM has asked TNO (Netherlands Organization for Applied Scientific Research) to prepare a quotation for this research.

1.2 Objectives

The main objectives are:

- Based on available studies and data, to determine the real sailing NO_x emissions of ships with IMO Tier III certified engines and to determine whether shortfall occurs between observed emissions levels and applicable limits, possibly distinguishing between types, sizes and usages of ships.
- To provide options to mitigate NO_x emissions in the North Sea (including specific port and coastal areas) of ships with IMO Tier III certified engines.

Specifically, insight is needed into the following elements:

- An analysis of the current available literature and data on NO_x emissions from ships with Tier III engines to explore which types of ships emit more nitrogen oxide than expected. A comparison is requested between the impact on large and small vessels.
- An investigation into the conditions under which high NO_x emissions occur in combination with the configurations of emission control technology on board Tier III ships, and their compliance with MARPOL regulations.
- An assessment of the possible causes of higher nitrogen oxide emissions from ships with Tier III engines.
- An exploration of technical and policy options to reduce nitrogen oxide emissions in the North Sea (including specific port and coastal areas).

1.3 Approach/methodology

This study is meant to summarize recent literature on real world emissions performance of Tier III vessels in European and also to further analyse available remote sensing data from the measuring station at the Seagate of Rotterdam. This data was already summarised in the SCIPPER project, particularly in deliverable D5.5. Moreover, this study focusses on some knowledge aspects which are not widely available in public literature.

These are:

- The reliability and accuracy of remote sensing data. This is investigated by collecting the latest information from several projects, as well as by some further data processing of available information.
- Ship owner’s experiences with SCR aftertreatment. This is done via an inquiries among ship owners.
- The technical options to reduce NO_x at low engine load (below 25%), which is generally known to be one of the main problems of achieving low NO_x emissions in Emission Control Areas (ECAs). This is done via literature study and also using TNO’s experience in the road transport domain.

Finally, a summary will be made of the shortcomings of current MARPOL NO_x regulation. Information is available from several recent projects such as SCIPPER, RBINS and projects from ICCT (The International Council on Clean Transportation) and Explicit and also from IMO regulation and INF documents. Consequently recommendations are done for improvement of the NO_x regulation, also making use of the mentioned literature as well as experiences in the automotive domain.

Section 2.1 and 2.2 discuss respectively the IMO Regulation and NO_x emissions on Dutch territory. Furthermore, section 2.3 of this report contains the remote sensing results, the comparison of the remote data with stacks measurements, remote sensing uncertainties (2.4) and the ship owner's inquiry (2.5). Section 2.6 discusses all the findings. Section 3 focusses on the mitigation options for both technical measures (3.1) to reduce real world NO_x emissions as well as regulatory measures 3.2. Finally conclusions and recommendations are summarised in section 4.

2 NO_x emissions of IMO Tier III engines

2.1 Regulation

(IMO, 2019) summarizes the Nitrogen Oxides (NO_x) – Regulation 13 : "…*The control of diesel engine NO_x emissions is achieved through the survey and certification requirements leading to the issue of an Engine International Air Pollution Prevention (EIAPP) Certificate and the subsequent demonstration of in service compliance in accordance with the requirements of the mandatory, regulations 13.8 and 5.3.2 respectively, NO_x Technical Code 2008 (resolution MEPC.177(58) as amended by resolution MEPC.251.(66), MEPC.286(71), MEPC.301(72) and MEPC.305(73)). The NO_x control requirements of Annex VI apply to installed marine diesel engine of over 130 kW output power other than those used solely for emergency purposes irrespective of the tonnage of the ship onto which such engines are installed….Different levels (Tiers) of control apply based on the ship construction date…and within any particular Tier the actual limit value is determined from the engine's rated speed…. The emission value for a diesel engine is to be determined in accordance with the NO_x Technical Code 2008 in the case of Tier II and Tier III limits…*".

Table 2-1 and Figure 2.1 show the applicable limit values for the three Tiers.

Table 2-1: Specification of the Tier limit values for the three Tiers (weighted average of applicable ISO test cycle.

Tier	Ship construction date on or after	Total weighted cycle NO_x emission limit (g/kWh) n = engine's rated speed (rpm)		
		n < 130	130 ≤ n ≤ 2000	n ≥ 2000
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	Weighted test cycle average Not-To-Exceed: Test cycle points not exceeding 150% of limit value 1 January 2016: North American ECA and the United States Caribbean Sea ECA or January 1, 2021: Baltic Sea ECA or the North Sea ECA	3.4 5.1	$9 \cdot n^{(-0.2)}$ $13.5 \cdot n^{(-0.2)}$	1.96 2.94

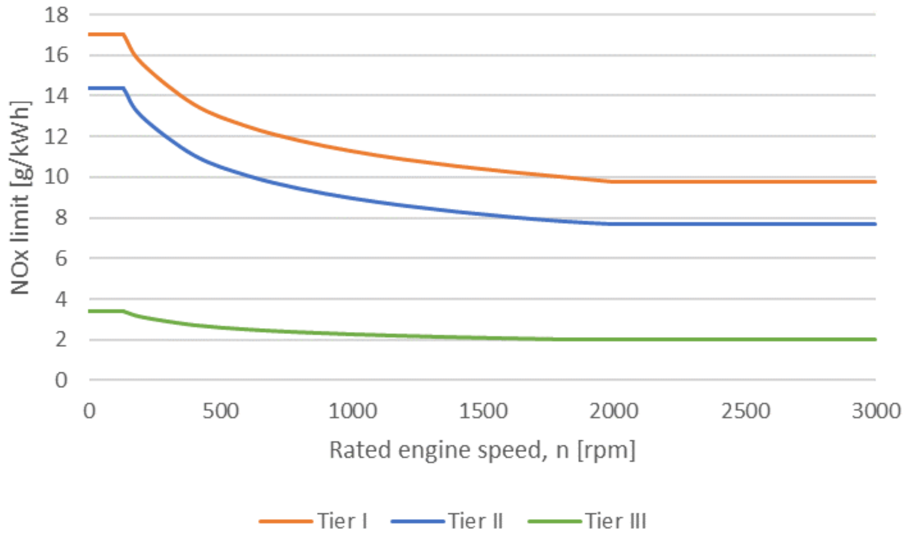

Figure 2.1: Graphical representation of the Tier limit values related to the engines rated engine speed.

Test cycles

The NO_x Technical Code 2008 has the purpose to specify the requirements for the testing, survey and certification of marine diesel engines to ensure they comply with the nitrogen oxides (NO_x) emission limits of regulation 13 of Annex VI of MARPOL 73/78.

For every individual engine or parent engine of an engine group or family, one of the test cycles, see Table 2-2, shall be applied for verification of compliance with the NO_x emission limits in accordance with regulation 13 of Annex VI.

Table 2-2: Overview of marine diesel engine test cycles and the respective speed and load test points.

E2	Constant Speed Main Propulsion, including Diesel Electric Drive and Variable Pitch Propeller Installations								
	Speed	100%	100%	100%	100%				
	Power	100%	75%	50%	25%				
	Weighting Factor	0.2	0.5	0.15	0.15				
E3	Propeller law operated main and propeller law operated auxiliary engines								
	Speed	100%	91%	80%	63%				
	Power	100%	75%	50%	25%				
	Weighting Factor	0.2	0.5	0.15	0.15				
D2	Constant speed auxiliary engines								
	Speed	100%	100%	100%	100%	100%			
	Power	100%	75%	50%	25%	10%			
	Weighting Factor	0.05	0.25	0.3	0.3	0.1			
C1	Variable speed, variable load auxiliary engines								
	Speed	Rated	Rated	Rated	Rated	Intermed.	Intermed.	Intermed.	Idle
	Power	100%	75%	50%	10%	100%	75%	50%	0%
	Weighting Factor	0.15	0.15	0.15	0.1	0.1	0.1	0.1	0.15

Table 2-3: Overview of the most important elements of the regulation.

Pre certification of an engine, group or family	Engine test bed test over the applicable engine test cycle to certify that the engine, group or family meets the applicable NOx limit.
Certification after installation	Inspection for modifications.
Technical file	The 'Technical File' defines the engine's approval status and includes details of the applicable survey regime and must be on board of the ship at all times.
Record book	The Record Book of Engine Parameters, outlined in NOx Technical Code 2008 regulation 6.2.2.8, is a key document in the Parameter Check procedure, recording all replacements and changes to NOx critical components, settings, and operating values
Issuance of IAPP Certificate	If all of the engines installed on board are verified to comply to the requirements an IAPP Certificate should then be issued to the ship.
On-board verification	If any adjustment or modification is made which is outside the approved limits documented in the technical file, the IAPP Certificate may be issued only if the overall NOx emission performance is verified to be within the required limits by onboard simplified measurement
Demonstrating on-board compliance	- Parameter check method. As of October 2010, most engines need to undergo surveys using the Parameter Check method. This method checks the actual duty, rating, NO_x critical components, settings, and operating values against the data provided in the Technical File. - Monitoring of consumption information in technical file to demonstrate correct operation. - Direct measurement or monitoring.

Surveys

- A pre-certification survey that that shall be conducted to an individual engine, a parent engine group and consists of engine testing on a test bed over the prescribed test cycle.
- An initial certification survey that shall be conducted on board a ship after the engine is installed but before it is placed in service.
- Renewal, annual and intermediate surveys, that shall be conducted as part of a ship's surveys required by regulation 5, to ensure the engine continues to comply fully with the provisions of this Code.
- An initial engine certification survey that shall be conducted on board a ship every time a major construction modification has taken place.

Survey methods
To comply with the various survey and certification requirements, there are methods included in the Code from which the engine manufacturer, shipbuilder or shipowner, as applicable, can choose to measure, calculate, test or verify an engine for its NO_x emissions, as follows:

- test-bed testing for the pre-certification survey;
- onboard testing for an engine not pre-certificated for a combined pre certification and initial certification survey in accordance with the full test-bed requirements;
- onboard engine parameter check method, using the component data, engine settings and engine performance data as specified in the technical file, for confirmation of compliance at initial, renewal, annual and intermediate surveys for pre-certified engines or engines that have undergone modifications or adjustments to NO_x critical components, settings and operating values, since they were last surveyed
- onboard simplified measurement method for confirmation of compliance at renewal, annual and intermediate surveys or confirmation of pre-certified engines for initial certification surveys,; or
- onboard direct measurement and monitoring method for confirmation of compliance at renewal, annual and intermediate surveys only.

Only for Tier III, an onboard "not-to-exceed" limit (NTE) has been defined, which stipulates that the NO_x limit should not be exceeded by more than 50% for any of the individual engine load points of the main engines (Appendix II, MARPOL Annex VI) [19]. However, no emission limits have currently been set for any of the tiers below 25% main engine load (E2 and E3 test cycles). The C1 and D2 test cycles do have the 10% load point, but without this NTE limit.

Fuel
Engines are tested using distillate fuels, while often residual fuels are used in real life operation.

2.2 NO_x emissions on Netherlands territory

In 2020, maritime shipping emerged as the foremost contributor to nitrogen oxide emissions in the realm of mobility, as highlighted by (Geilenkirchen et al., 2023). Specifically, maritime shipping accounted for the largest share of nitrogen oxide emissions within the mobility sector. These emissions concern seagoing vessels navigating or anchoring on the Dutch Continental Shelf (NCP), seafaring vessels traversing inland waterways (within port areas), and vessels berthed in ports.

With a total emission volume of 107 kilotons NO_x, maritime shipping constituted 34 percent of the overall nitrogen oxide emissions on Dutch territory in 2020. Notably, maritime shipping alone was responsible for nearly half of the emissions arising from mobility. Among the 107 kilotons, 79 kilotons were emitted offshore, with emissions occurring on the NCP. The remaining 28 kilotons originated from inland activities, including vessel navigation and onshore operations, see Figure 2.3. The offshore emissions from seagoing vessels on the NCP occurred both in the proximity of the mainland and at a distance from the Dutch mainland. It should be noted that the share of NO_x deposition on land of shipping is much smaller than the contribution to the Dutch territory. This is because the majority of the deposition takes place within 25 km of the emissions source. So most relevant is deposition to the dunes and port vicinities of shipping and offshore activities close to shore.

Table 2-4: Annual emissions of nitrogen oxides of maritime shipping on Dutch territory have been determined according to the estimate and proposed policy, in kilotons. (Geilenkirchen et al., 2023). Excluding fishery and recreational. For reference the total annual NO_x emission of mobility is given.

Total annual NOx [kton]		2020	2025	2030
Maritime shipping	Inland waterways	14.6	13.5	12.2
Maritime shipping	Netherlands Continental Plat (NCP)	79.3	72.6	64.7
Maritime shipping	Berthed in ports	13.2	9.3	8
Total Maritime shipping		107.1	95.4	84.9
Total mobility (including shipping)		222.8	197.5	177.7 [162-204][1]

[1]) In 2030, the certainty bandwidth in which all uncertain factors in mobility are taken into account are shown in square brackets.

Output of the Dutch emissions inventory model Poseidon (Hulskotte, 2021) (version 1.41) was used to obtain an estimation of the development of the NO_x emissions towards 2030 and the contribution of Tier III certified ships to the total annual emissions on Netherlands territory (the NCP and inland waterways for sailing ships), see Figure 2.2 and Figure 2.3 for the emissions of ships at berth.

The total annual NO_x emissions of sailing ships decrease towards 2030. The share of NO_x emissions from ships with Tier III certified engines increases to about 15% in 2030, which equals roughly 11 kton in that year.

Results are indicative and based on Poseidon's 'middle' scenario and 'emissions_C scenario', the latter meaning that the effect of engine load on NO_x emission is taken into account, but no effects of growth of 'scale', i.e., ships' Gross Tonnage, have been taken into account. Output of Poseidon in annual kton of NO_x per location was scaled to fit the values in Table 2-4, as provided by (Geilenkirchen et al., 2023) in order to obtain a quick view on the share and contribution of Tier III ships.

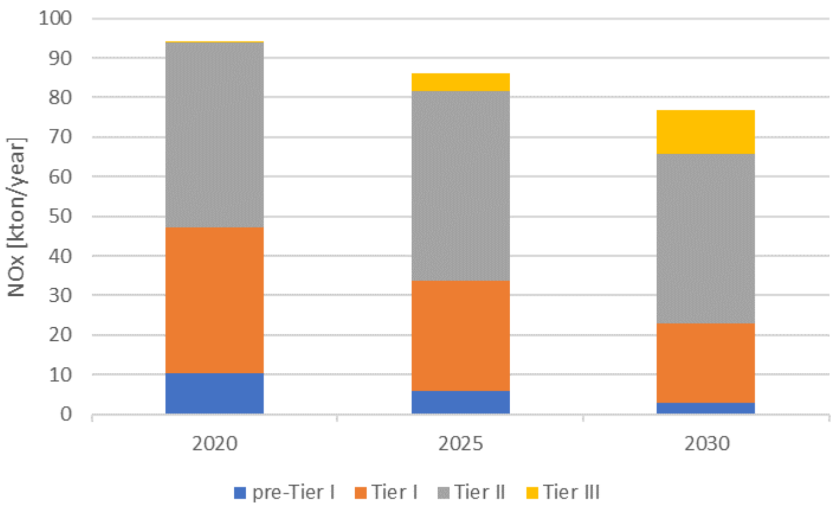

Figure 2.2: Indication of the total annual NO_x emission by maritime shipping sailing NCP and inland waterways for 2020, 2025 and 2030.

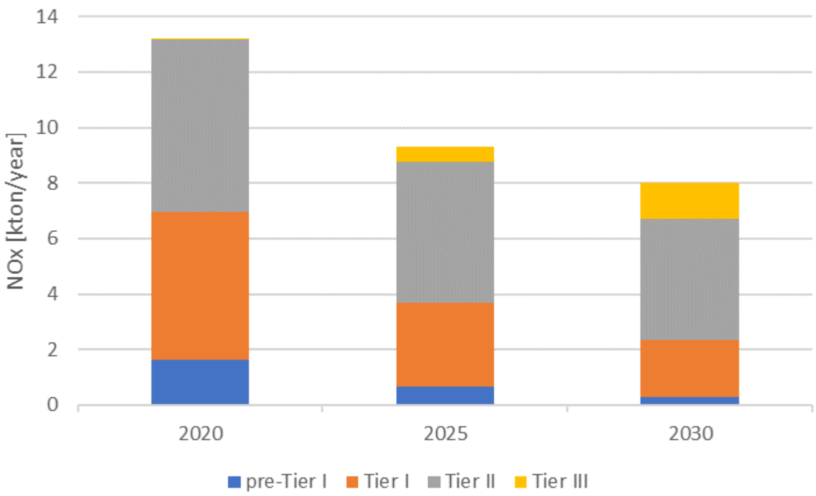

Figure 2.3: Indication of the total annual NO_x emission by maritime shipping of ships at berth in Dutch ports.

Poseidon uses correction factors applied to the applicable emissions Tier III NO_x limit to determine NO_x emissions in g/kWh per load bin. This is done with higher factors up to 6 for 10% load, around 1.45 for the middle load range and 0.85 for high loads, see Figure 2.4. This already takes into account a certain surplus of NO_x emissions, especially in and near ports, as compared to the Tier III limit taking account of real sailing performance of NO_x reduction systems and the fact that a Not-To-Exceed limit is applicable of +50% on top of the Tier III limit. This aims to control NO_x emissions of engine usage not to exceed the limit with an additional margin of +50% on top of the limit, meaning the weighted emissions limit for an engine cannot be exceeded by more than 50% for any individual test load point.

The remote sensing data indicate that NO_x emissions of ships with a keel laying date as of 1-1-2021 have NO_x emissions on average around 10 g/kWh for the Seagate of Rotterdam, see Figure 2.9, Figure 2.10 and Figure 2.14. When the NO_x limit of low speed Tier III engines of 3.4 g/kWh is taken, the emissions are roughly three times higher than the test cycle limit and twice the NTE limit of 5.1 g/kWh. Apart from the very low loads, both factors are clearly higher than the estimated emission factors used in the emissions model. If these kind of NO_x emission gap for Tier III vessels between the Poseidon model and the real sailing emissions persist in the coming years, this could lead to a much higher contribution of Tier III vessels. For instance for the NCP the estimated NO_x emissions in 2030 could increase about 100%.

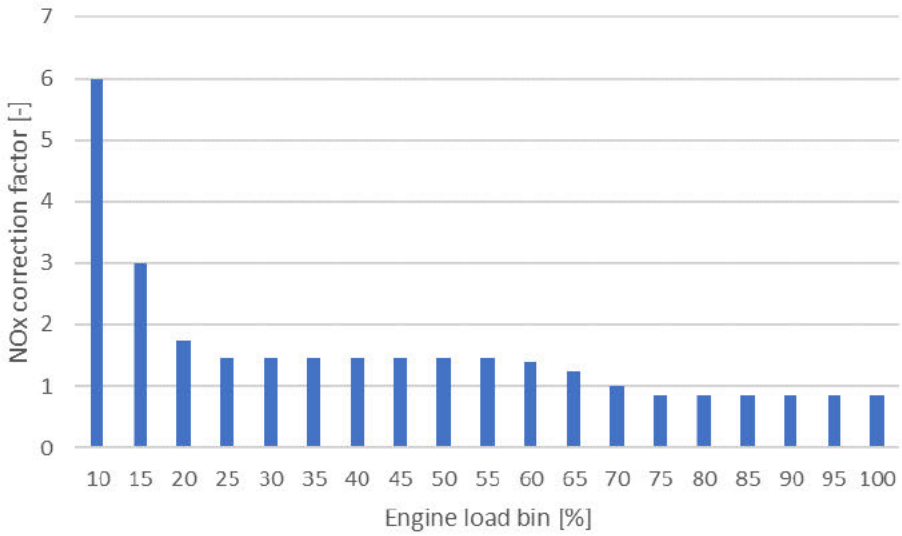

Figure 2.4: NO_x correction factors to be applied to the Tier III NO_x limit to determine an engines work specific NOx emissions as used in the emissions model Poseidon for the calculation of national total emissions (Hulskotte, 2021).

Table 2-5: NO_x correction and emission factors used for Dutch emissions inventory. Source (van Eijk et al., 2020).

Tier and engine size		NCP outside 12 miles zone	NCP 12 miles zone	Rotterdam	Amsterdam
		Area-weighted correction factors			
Tier I		1.01	1.02	1.08	1.10
Tier II		1.29	1.30	1.36	1.38
Tier III		1.44	1.44	1.81	1.90
		Effective emission factors in g/kWh			
Tier I - MS	9.8	9.9	10.0	10.6	10.8
Tier II -MS	7.7	10.0	10.0	10.4	10.6
Tier III -MS	2	2.9	2.9	3.6	3.8
Tier I - SP	17	17.2	17.4	18.4	18.7
Tier II -SP	14	18.1	18.2	19.0	19.3
Tier III - SP	3.4	4.9	4.9	6.1	6.5

MS = medium speed and high speed; SP = slow speed

2.3 Real sailing NO_x emissions performance

Many publications have shown that the load profiles in Emission Control Areas (ECA) are very low, much lower than according to the emissions test cycles E2, E3 and D2.

The figure below (Frydell et al., 2023) shows several projected engine load patterns on the North Sea, particularly the Netherlands Continental Plat (NCP) and the Port of Rotterdam. The figure shows that the closer to shore, the lower the load pattern of the engines. Within the Port of Rotterdam, the engine power as calculated from AIS data is at least 40% of the time below 25% engine power and about 80% of the time below 30% engine power.

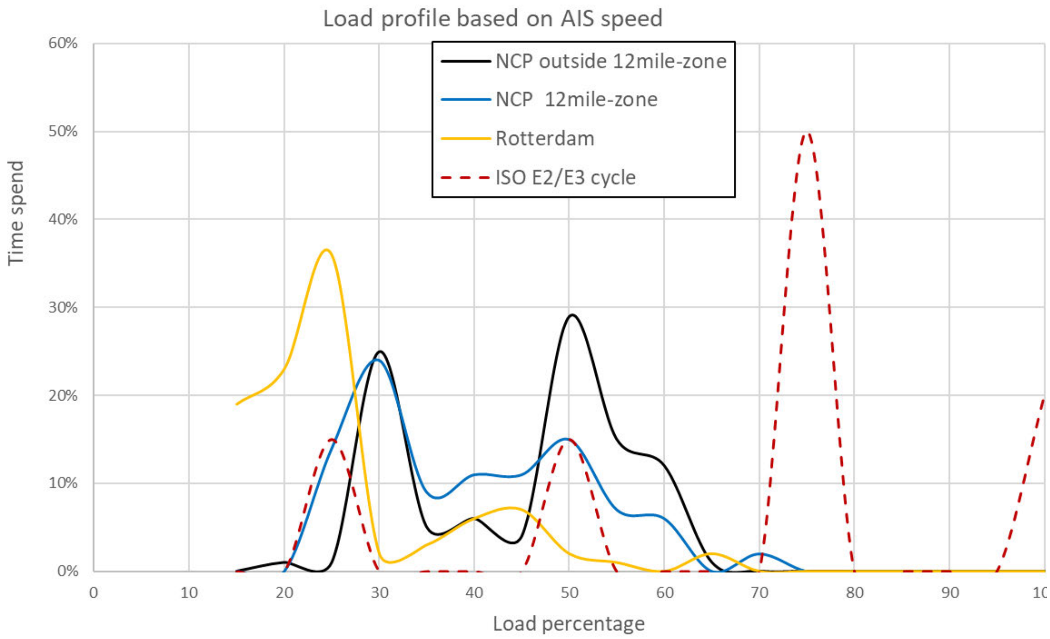

Figure 2.5: Projected average load profile on the North Sea, Netherlands Continental Plat. (Frydell et al., 2023).

2.3.1 Examples stack measurements

In the SCIPPER project extensive emission measurement within the stack of main engine 2 were done and also extensive remote and drone measurements, The SCIPPER project (Weisheit et al., 2022), (*THE SCIPPER PROJECT*, n.d.). The long-term measurements over a period of about 4 months were done with automotive sensors with the TNO SEMS system. The NO_x emissions and SCR NO_x conversion are presented in the figure below. The NO_x in g/kWh is presented as a function of vessel speed in km/h (left). The SCR conversion efficiency in percent is presented as a function of propulsion power 1. This latter is the sum of power of main engines 1 and 2. The figure clearly shows the high stable NO_x conversion efficiency of up to 90% above about 40% engine load and above vessels speeds of 25 km/h. Between 18 and 25 km/h the NO_x conversion is quite variable between zero and some 80%. Below 20 km/h the SCR system is mostly switched off. It should be noted that the Stena Germanica is not an official Tier III vessel, albeit with advance emission control.
Possibly the engine-SCR system was not configured to meet all Tier III requirements such as the NTE requirement for the 25% load point.

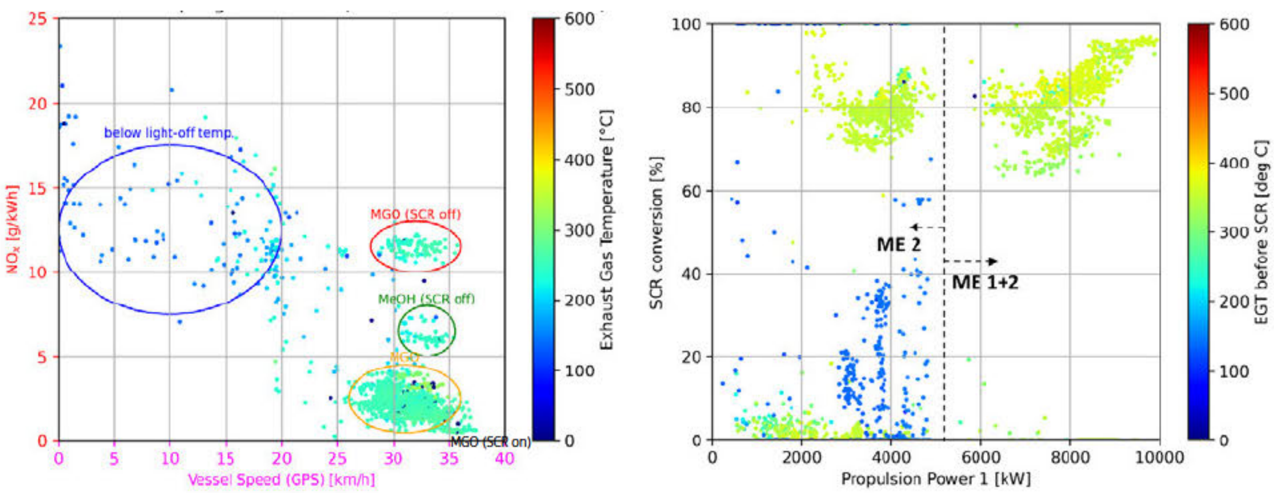

Figure 2.6: Emission maps based on monitoring data (automotive sensors) for the period 31 August – 16 September 2021. Left: After-catalyst NO_X as function of vessel speed and exhaust gas temperature. Right: SCR conversion rate as a function of propulsion power and exhaust gas temperature. Note the magnitude of propulsion power 1 is based on ME 1 and ME 2. Source: SCIPPER D1.6.

The figure below (Abma et al., 2018) shows the NO_x emissions before and after the SCR system of a dredger vessel. Apart from the E3 cycle data points, two additional frequently used engine load points were measured. These are 80% and 10% engine load. The figure shows a consistently high NO_x conversion of some 85% to 92% across the entire load range. This shows that a high NO_x conversion can be achieved at 10% engine load, in this case without specific engine tuning or measures to achieve these results.

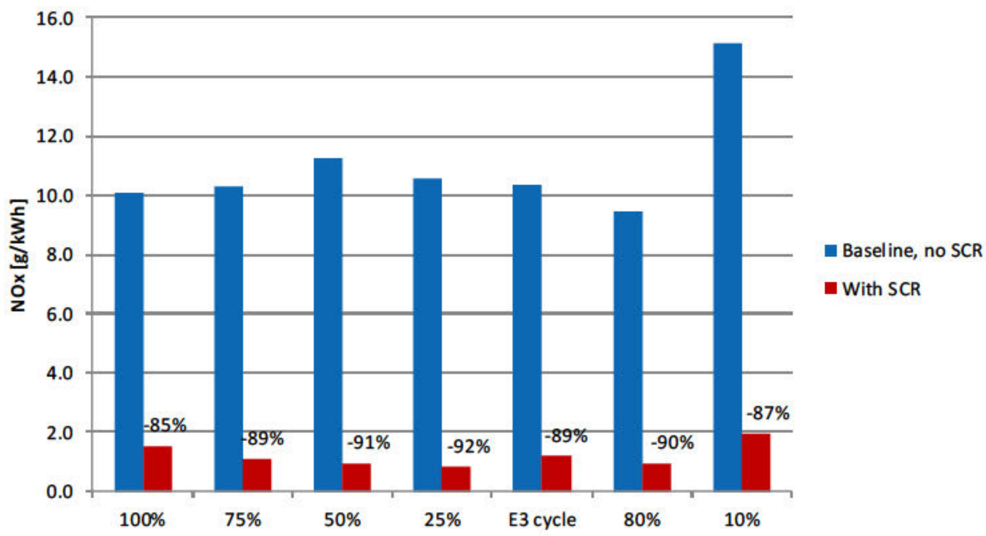

Figure 2.7: Results of NO_x emissions without and with SCR, in g/kWh over the tested mode points and as weighted over the E3 cycle. Source (Abma et al., 2018).

2.3.2 Remote and plume measurement data

2.3.2.1 Calculation of NO_x emissions

A brief explanation is given as to how the NO_x emissions can be derived from remote measurement and expressed in various units. The basic principle of a remote measurement is that in the plume of a ship both the NO_x concentration and the CO_2 concentration are measured, e.g., by a drone, helicopter or by a remote instrument. Estimations of fuel carbon content and actual specific fuel consumption are used to calculate NO_x emission related to for fuel consumption and engine work (Weisheit et al., 2022), (Van Roy et al., 2022), (Knudsen et al., 2022), (NO_x Emission from Ships in Danish Waters, 2022) each describe slightly different formulas but are based on the same approach and principles. In Table 2.5, 3.15 is the mass ratio between CO_2 and diesel fuel, which is often taken. In reality this value can vary from 3.11 to 3.20 depending on the fuel composition. See also MEPC.308(73) or Annex II of EU regulation COM (2021) 562 final.

For methanol and natural gas, single or dual fuel engines these numbers should be adjusted. M_{xyz} is the molecular mass of the mentioned components (46 g/mol for NO_x and 44 g/mol for CO_2). SFC is the Specific Fuel Consumption of the engine. For this a constant value can be taken (e.g. 0,2 kg/kWh) or a load dependent value. In the latter case generally the engine type specific curves of the IMO fourth GHG study are used.

Table 2-6: Basic formulae used with remote sensing.

$\frac{NO_x}{CO_2} = \frac{NO_x^{ppm}}{CO_2^{\%} \cdot 10000} \cdot \frac{M_{NO_x}}{M_{CO_2}}$	[gNO$_x$/gCO$_2$]
$\frac{NO_x}{m_{fuel}} = \frac{3{,}15 \,.\, NO_x^{ppm}}{CO_2^{\%} \cdot 10000} \cdot \frac{M_{NO_x}}{M_{CO_2}}$	[gNO$_x$/kg fuel]
$\mathrm{NO_x} = SFC \,.\, \frac{3{,}15 \,.\, NO_x^{ppm}}{CO_2^{\%} \cdot 10000} \cdot \frac{M_{NO_x}}{M_{CO_2}}$	[gNO$_x$/kWh]

2.3.2.2 Remote data seaport Rotterdam

A dataset from the EU Horizon 2020 project SCIPPER was made available for analyses. The dataset contains on-shore remote measurements conducted at the Seagate of the port of Rotterdam. For the remote measurements only the concentrations of NO was measured while NO_x consists of NO and of a smaller fraction NO_2 which actual fraction often depends on the specific emission control technology. The NO_x concentration emission was estimated to be 20% higher than the measured NO concentration. See 2.4.2. for a discussion on this.

The dataset contains ships that either enter the port or exit the port in respectively almost westbound (~100º heading) and eastbound directions (~300º heading). The dataset contains data from remote measurements from 24-1-2022 to 4-1-2023. The dataset contains 43 individual Tier III ships and 70 individual measurements, meaning several ships where measured more than once.

From the total of 43 ships, 25 of the ships have a keel laying data (KLD) as of 1-1-2021 and 18 before 1-1-2021. 5 of 43 ships are container ships. The 25 with KLD as of 1-1-2023 are all tanker ships.

23 Of these with KLD as of 1-1-2021 have fuel ME code ‘HFO’ and 2 have code ‘LNG’, the 21 HFO fuelled ships are almost all MAN B&W low-speed 2-stroke engines. According to (*Tier III NOx-Abatement Engine Orders Pass 2,000 Mark*, 2022) MAN offers SCR and EGR as NO_x reduction technology solutions for Tier III diesel engines. EGR accounts for 724 (36%) versus 1,292 (64%) SCR solutions. The two LNG-fuelled ships are WINGD.

Figure 2.8 shows the results of individual plume measurements plotted for ships with Tier III certified engines with Keel Laying Date before 1-1-2-21 and as of 1-1-2021. The emission of NO_x in g/kg fuel is plotted against the vessel speed. For the calculation of the NO_x emission in g/kg fuel only the molar mass of NO_x and CO_2 and an estimate of the mass fraction of carbon in the fuel are involved which therefore represents a straightforward approach as to presenting results of plume measurements.

The two Tier III groups with different KLD periods show a rather scattered picture with NO_x emissions from 1.4 to 120 g/kg. On average the ships with KLD after 1-1-2021 show a lower spread up to 95 g/kg. This also shows in the average NO_x emission for each KLD period which is lower for the ships with KLD after 1-1-2021. It should be noted that ships with KLD before 1-1-2021 are not required to have their SCR system operational. They may turn off their urea injection and also feed the exhaust gas via a bypass to the funnel outlet. Nevertheless we see an number of these ships with NO_x emissions as low as ships with KLD after 1-1-2021.

There is no clear relation of specific NO_x emissions (g/kg fuel) with vessel speed. For ships with KLD after 1-1-2021 the average is more or less constant independent of vessel speed. For ships with KLD before 1-1-2021 the average specific NO_x emissions even seams to go up with vessel speed. A conclusion from all this, is that engine load apparently does not play a significant role in the level of NO_x emissions per kg fuel (all KLDs).

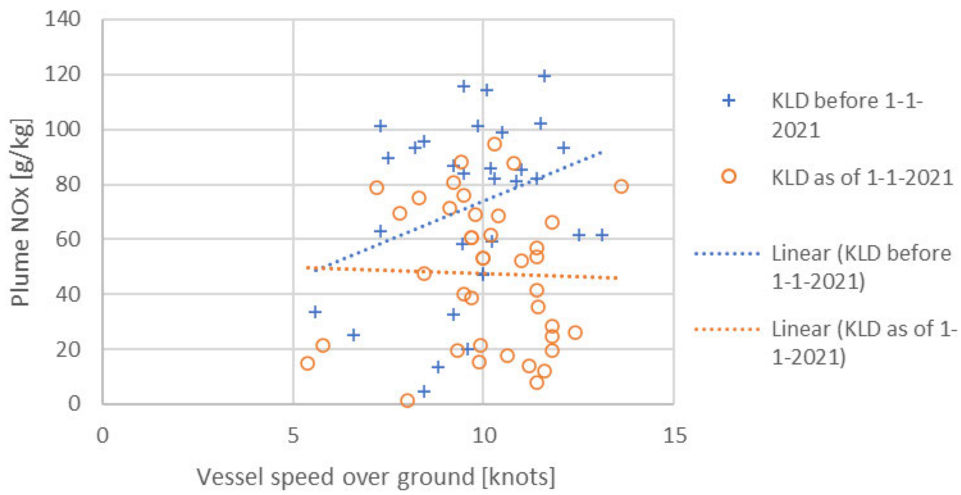

Figure 2.8: Plume NO_x measurement results of all ships measured at Seagate Rotterdam in the SCIPPER project measured up to 1-1-2023. The ships have Tier III certified engines and are divided by two Keel Laying Date periods, respectively before and as of 1-1-2021. NO_x is expressed in g/kg fuel and is plotted against measured vessel speed.

Figure 2.9 shows the NO_x emission in gram per kilowatt-hour of engine work (g/kWh) against the engine load (as a percentage of maximum continuous power rating). Compared to the NO_x emission as determined in g/kg there are additional estimations included in the calculation.

Engine power is directly based on the vessel speed in relation to the design speed of the vessel. These are the specific fuel consumption (SFC) and the engine load for which the SFC accounts. The work specific NO_x emission in g/kWh varies between measurements from 0.3 g/kWh to 23.9 g/kWh. For reference the Tier III limit for low-speed engines is 3.4 g/kWh and the NTE based on this limit is 5.1 g/kWh.

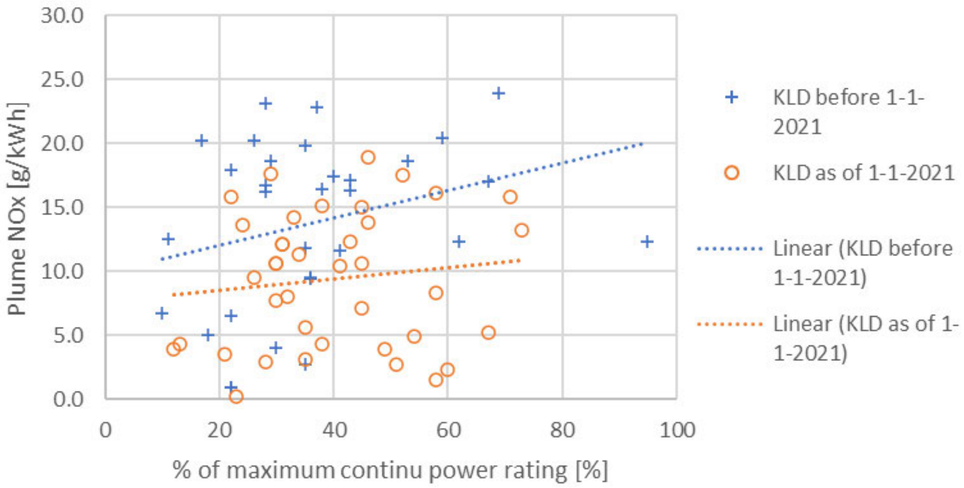

Figure 2.9: Plume NO_x measurement results of all ships measured at Seagate Rotterdam in the SCIPPER project measured up to 1-1-2023. The ships have Tier III certified engines and are divided over two Keel Laying Date periods, respectively before and as of 1-1-2021. NOx is expressed in g/kWh as derived from estimated engine load and brake specific fuel consumption of and is plotted against derived engine load.

Figure 2.10 shows the box plots of the ships with Tier III certified engines with two different keel Laying date periods. The ships with KLD as of 1-1-2021 show a slightly lower spread and also the average NO_x emissions are lower than the ships with KLD before 1-1-2021.

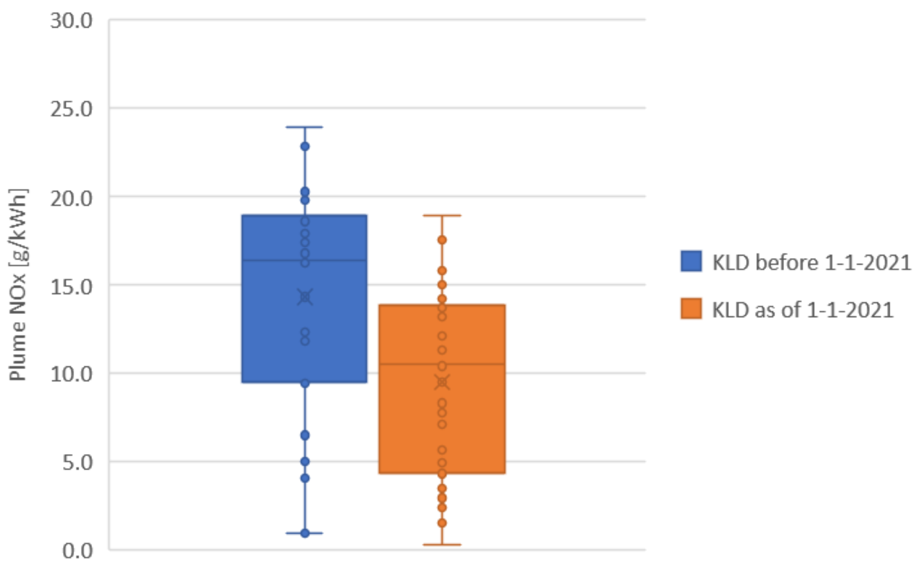

Figure 2.10: Plume NO_x measurement results of all ships measured at Seagate Rotterdam in the SCIPPER project measured up to 1-1-2023. The ships have Tier III certified engines and are divided over two Keel Laying Date periods, respectively before and as of 1-1-2021. NO_x is expressed in g/kWh as derived from estimated engine load and brake specific fuel consumption. The box plot shows minimum, maximum, quartiles (box), average (x) and median.

Figure 2.11 shows the NO_x emissions for two different headings near the Port of Rotterdam, namely inbound (100°) and outbound (~300°) of the Seagate. On average, the work specific emissions tend to be slightly higher for the outbound heading. No conclusions can be drawn on the influence of engine load.

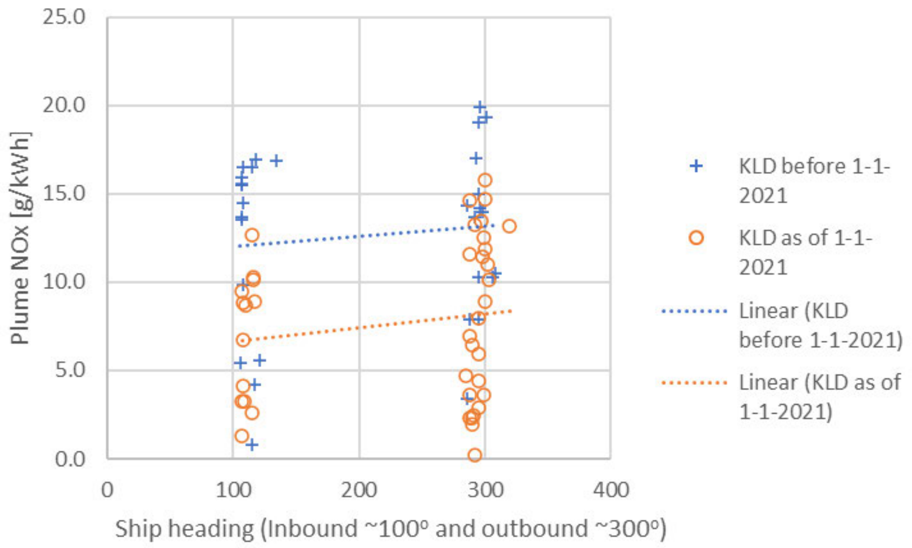

Figure 2.11: Plume NO_x measurement results of all ships measured at Seagate Rotterdam in the SCIPPER project measured up to 1-1-2023. The ships have Tier III certified engines and are divided over two Keel Laying Date periods, respectively before and as of 1-1-2021. NO_x is expressed in g/kWh as derived from estimated engine load and brake specific fuel consumption. The plot shows all results for two different heading, inbound and outbound of the Seagate.

In Table 2-7 it is shown that the amount of remote measurements with estimated emissions levels higher than the Tier III NTE for low-speed engines is clearly lower for ships with a keel laying date (KLD) as of 1-1-2021 compared to before 1-1-2021. 25 out of 40 of measurements of ships with a KLD as of 1-1-2021 are higher than the Tier III NTE.

Table 2-7: Count of measurements of 70 individual remotely measured (up to 1-1-2023) real sailing NO_x emissions, for ships with Tier III engines, for the two KLD periods and above and below the NTE NO_x limit of 5.1 g/kWh (1.5 x 3.4 g/kWh) for low speed engines (<130 rpm).

# of measurements NO_x NTE	KLD before 1-1-2021	KLD as of 1-1-2021
>5.1 g/kWh	27 (90%)	25 (63%)
<= 5.1 kWh	3 (10%)	15 (37%)

2.3.2.3 Additional data analysis Port of Rotterdam

A newer data set was provided at the end of the project. Measurements up to 31-8-2023 were added to the existing dataset that was discussed above in this paragraph. A quick review of the newer data set (24-1-2022 to 31-8-2023) shows that it contains data of 178 measurements of 120 individual ships with Tier III certified engines and a keel laying date as of 1-1-2021. The majority of these ships are tankers (93), cargo ships (20), a small group of special ships, such as dredging and under water ops (2), tug boats (3) and 'other' (2). There is not a clear dependency on speed or maximum continuous power rating (MCR).

On average, the work specific NO_x emissions tend to be slightly higher for the outbound heading. The average NO_x emission of around 10 g/kWh roughly corresponds to that of the first dataset with fewer measurements. About half of the measurements show NO_x emissions higher than 10 g/kWh. The results are presented below in Figure 2.12, Figure 2.13 and Figure 2.14.

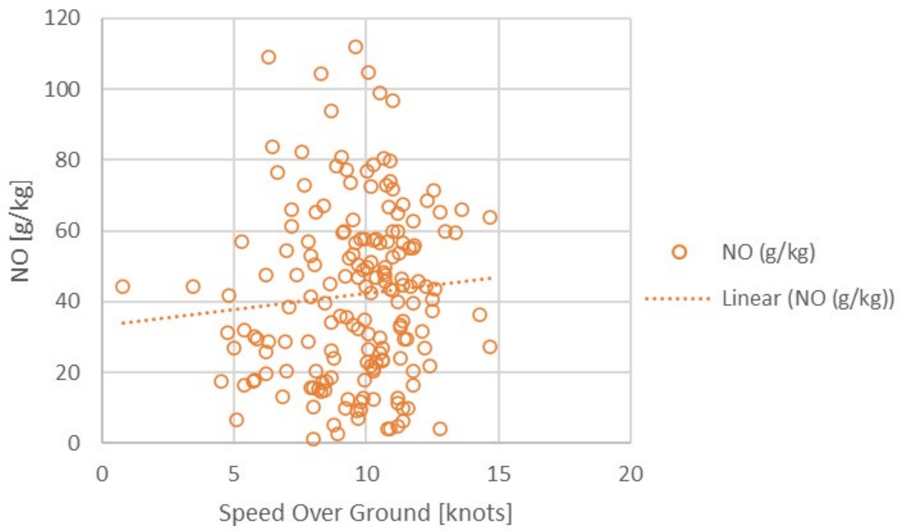

Figure 2.12: Plume NO measurement results of all ships measured at Seagate Rotterdam in the SCIPPER project measured up to 31-8-2023. The results are expressed in gram NO per kg of fuel and plotted against measured speed over ground.

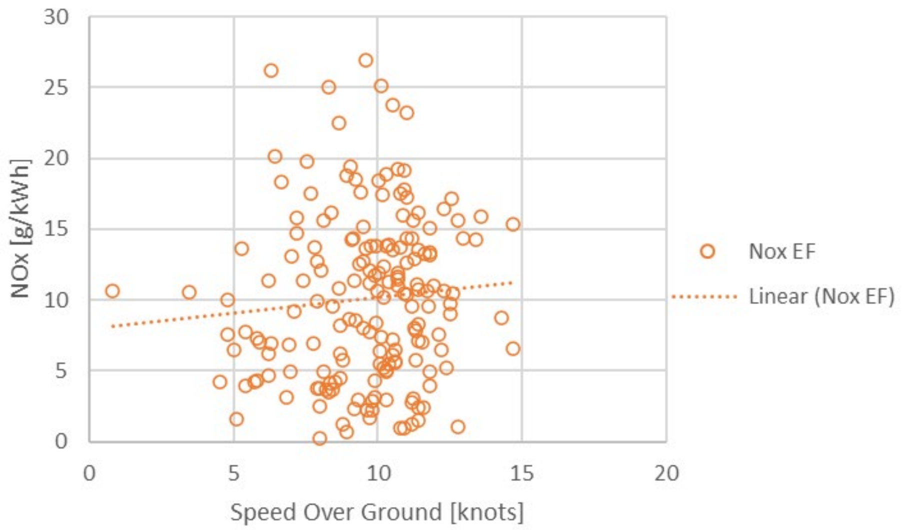

Figure 2.13: Plume NO measurement results of all ships measured at Seagate Rotterdam in the SCIPPER project measured up to 31-8-2023. NO_x is expressed in g/kWh as derived from estimated engine load and brake specific fuel consumption and is plotted against measured speed over ground.

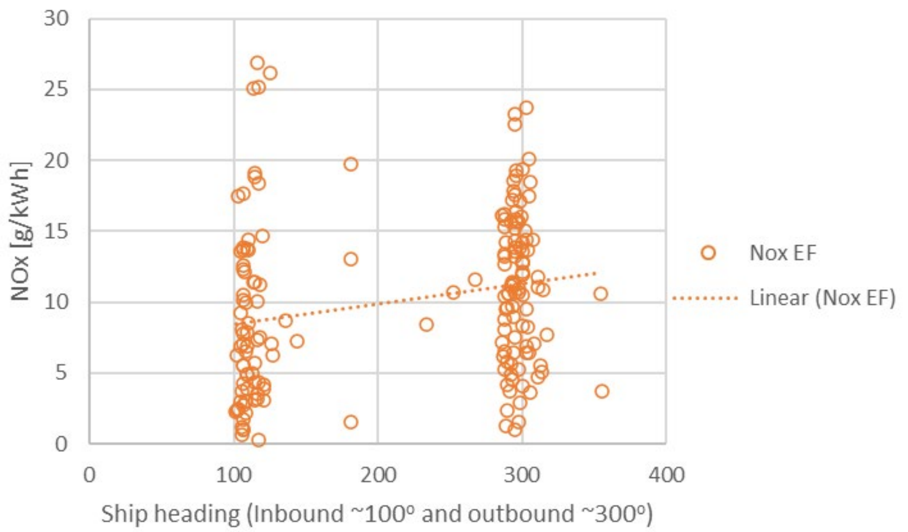

Figure 2.14: Plume NO_x measurement results of all ships measured at Seagate Rotterdam in the SCIPPER project measured up to 31-8-2023. NO_x is expressed in g/kWh as derived from estimated engine load and brake specific fuel consumption. The plot shows all results for two different heading, inbound and outbound of the Seagate.

A distinction was made for the plume NO_x emission of the main ship types, being tankers, cargo ships and other ships, see Figure 2.15. For tankers and cargo ships the spread is large. The averages of tanker and cargo ships don't differ much and are about 10 to 11 g/kWh. Other ships have somewhat lower average, about 7 g/kWh and spread, but the amount of ships and measurements is lower than for cargo and tanker.

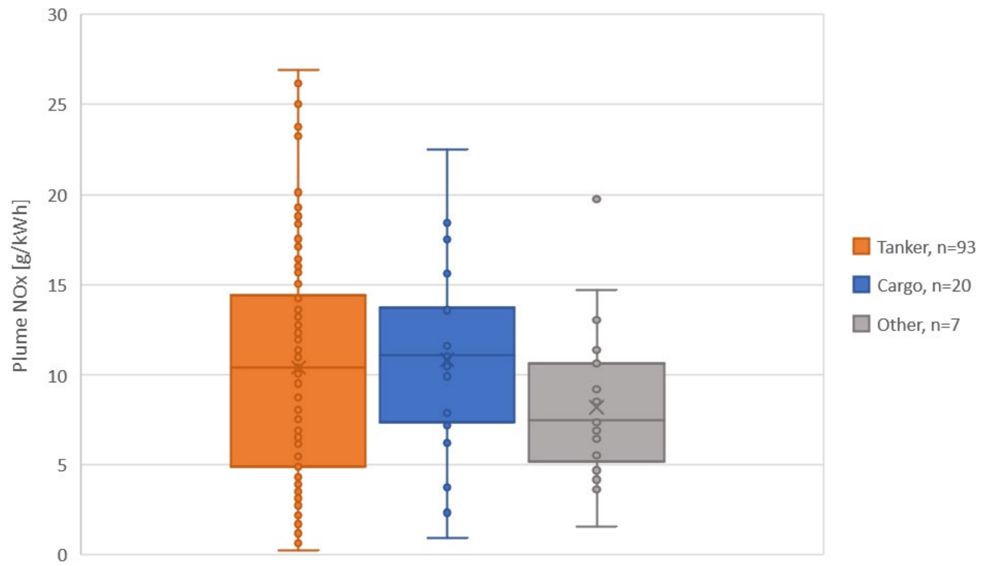

Figure 2.15: Box plot for individual measurements of plume NO_x emissions of three different ship types in the data set. The box plot shows minimum, maximum, quartiles (box), average (x) and median.

Of the 170 measurements 24% showed NO_x emissions lower than or equal to 5.1 g/kWh. 76% showed NO_x emissions higher than 5.1 g/kWh (i.e. above the NOx NTE limit).

Table 2-8: Count of measurements of 178 individual remotely measured (up to 31-8-2023) real sailing NOx emissions, for 120 ships with Tier III engines with keel laying data as of 1-1-2021 for above and below the NTE NOx limit of 5.1 g/kWh (1.5 x 3.4 g/kWh) for low speed engines (<130 rpm).

NO_x NTE	# of measurements
>5.1 g/kWh	135 (76%)
<= 5.1 kWh	43 (24%)

2.3.3 Remote sensing data European ECAs

During the SCIPPER project and also other programs measurements were conducted which provides NO_x emissions levels by means of remote/plume measurement and hereby insight into real sailing emission levels of NO_x under various conditions and for various types of ships and for different Tiers.

Within the SCIPPER project remote sensing data of Tier III vessels (with keel laying data 2021 onwards) was pulled together for the Baltic Sea and the North Sea, namely at the Great Belt Bridge, in Danish waters and at the ports of Rotterdam and Hamburg (Frydell, 2023). The results show that about one third of the vessels showed NO_x emissions in line with the Tier III legislation. However about 50% of measurements indicate emission levels that are more than a factor of two, and up to a factor five, higher than the expected Tier III levels.

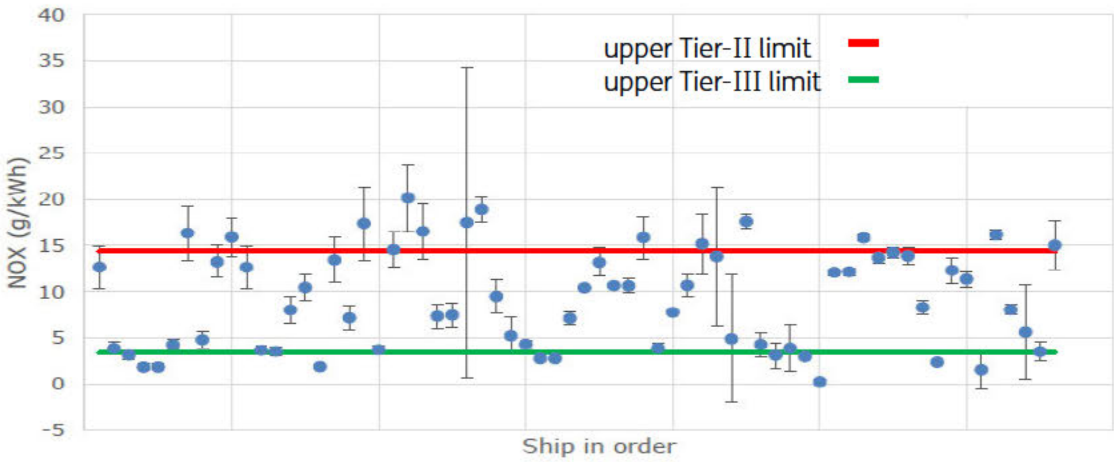

Figure 2.16: Remote sensing observations of Tier III ships keel laid from 2021 within the North European NECA. The measurements include fixed remote measurements at Great Belt bridge (13 measurements, Chalmers), Rotterdam (73 measurements , TNO and Wedel (1 measurement, BSH) and by drone-based measurements in Danish waters (10 ships, Explicit)). The green line shows the Tier III limit value (all ships have slow speed engines); the red line shows the Tier II limit value. Source Frydell, 2023.

The Royal Belgian Institute of Natural Sciences conducted remote measurements on the North Sea with a coastguard aircraft (vanRoy, 2022). Some 78 flights were conducted in 2020 and 2021 during which the emissions of more than 1400 vessels were measured (Tier 0, Tier I and Tier II vessels). One of the outcomes from this work is, that the NO_x emissions on the North Sea of Tier II vessels are not lower than those of Tier I vessels. The contrary was the case, the average NO_x emission for Tier II vessels was with 13.5 g/kWh) higher than the average NO_x emissions for Tier I vessels with 12.6 g/kWh. Tier II vessels had very similar emissions than Tier).

Very similar results were shown in a report for the Danish EPA (Knudsen et al., 2022). The average NO_x emissions were measured to be 12.5 g/kWh for Tier II vessels and 10.7 g/kWh for Tier I vessels (based on respectively 1192 and 457 measurements for Tier I and Tier II, measured with drones). The data also clearly shows that the NO_x emissions are inversely proportional to engine load, so higher NO_x emissions at low load. The report also shows the results for different engine sizes and vessels types. The highest average emissions are seen for container vessels (14.1 g/kWh) followed by passenger vessels and reefers (≈ 12.5 g/kWh). The remaining classes ranges from 9.4 to 11.4 g/kWh). These results were on the total dataset with a mix of Tier 0, Tier I and Tier II vessels (about 2250 measurements).

2.4 Remote measurement uncertainties

2.4.1 Comparison stack versus plume measurements

SCIPPER project

In the SCIPPER project measurements in the exhaust plume from fixed stations on shore, the cay and from drones were compared with the measurements in the stack of main engine 2 within a period of 11 days in August/September 2021 with 6 actual days with measurements (Verbeek et al., 2022). In Figure 2.17 , the NO_x/CO_2 ratio of the measurements in the exhaust stack are compared with the plume measurements from two fixed stations; from BSH and Chalmers and the drone measurements from Explicit. When IVL reference data or Aeromon sensor data was also available, the average was taken of the available measurements. Generally, the differences between these measurements were small. A time window of 10-15 minutes was taken in order to compare the data. Only time windows were selected which had reasonably stable operations, based on the stack measurement. The SCR system was turned off for most of the measurements used. For the periods with SCR on, usually sufficient stack data points were missing.

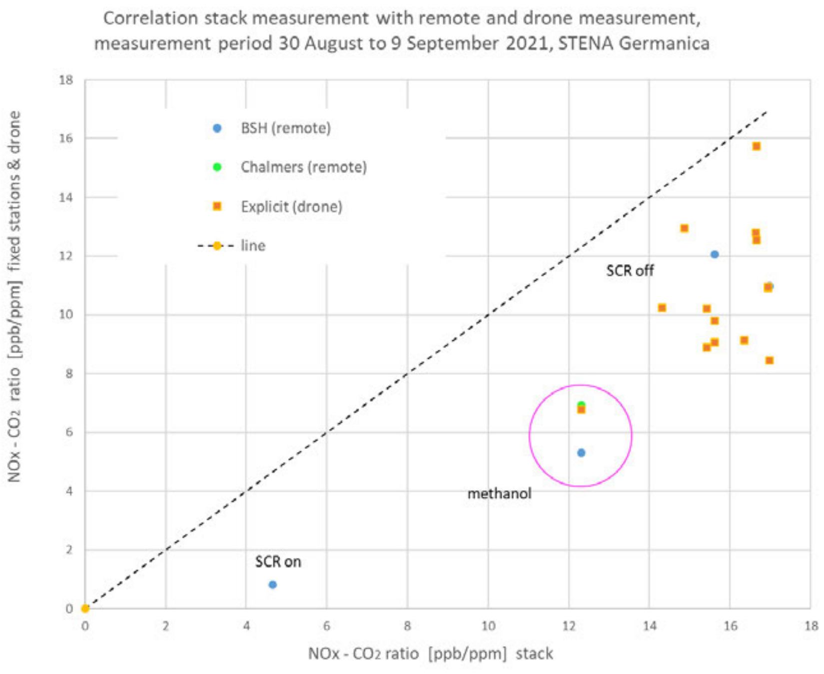

Figure 2.17: Plot of the correlation between measurements of the molar NO_x / CO_2 ratio of remote on-shore and drone measurements compared to in-stack measurement.

The following conclusions are made regarding these measurements on the STENA Germanica correlation (Verbeek et al., 2022):

- Based on 17 plume measurements (remote and drone) an underestimation of emissions is seen compared to the stack of the main engine(s). The plume measurements are 5% to 50% lower than the NO_x/CO_2 ratio in the stack of the main engine.
- The contribution of the auxiliary engines to the plume will generally lower the NO_x concentration in the plume. Originally it was estimated that this can account for up to 20% reduction in NO_x/CO_2 ratio.

In the figure below a side-by-side comparison is given for the two onshore remote measurement stations and the drone for a somewhat larger dataset for the same period as the comparison with the stack measurements. The figure clearly shows that the different plume measurement options correlate reasonably well. The measurement error (CI 95%) is determined to be 17-23% for all systems (assuming ensemble average at true value).

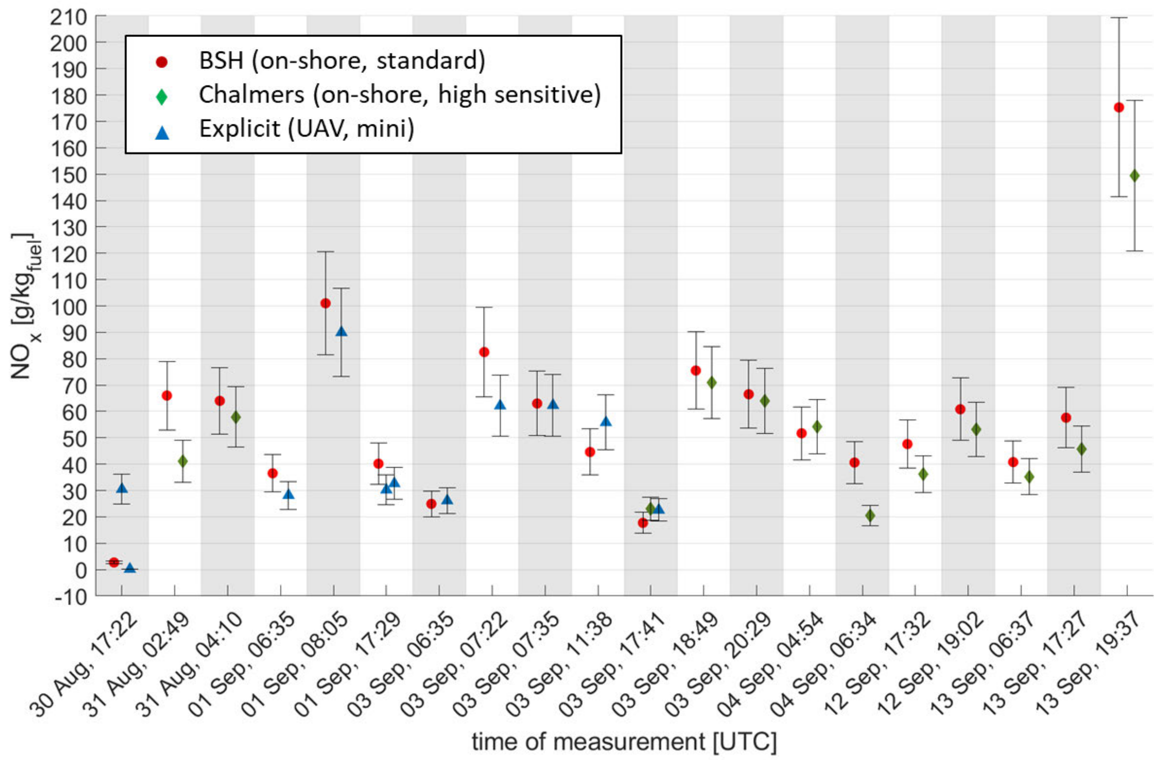

Figure 2.18: Side-by-side comparison of two different on-shore and one UAV (drone) NO_x Sniffers SCIPPER campaign 2: Kiel August/September 2021.

FUMES project

In June 2023, emissions measurements were conducted for the FUMES project (Comer, n.d.) on the Aurora Botnia, a ropax ferry with LNG-diesel low pressure 4-stroke dual fuel engines. The measurements were primarily conducted to determine typical methane emissions and methane slip from this type of engines and to compare the drone measurements of methane slip with in-stack measurements of methane slip. In parallel to the methane measurement, NO_x was measured and compared between the drone and measurement in the stack. The drone uses a mini-sniffer system.

NO and NO_2 concentrations are measured using electrochemical cells. The concentration of CO_2 is quantified based on non-dispersive infrared (NDIR) spectroscopy. For the measurement in the stack of NO, NO_2 and CO_2 concentrations, an instrument (GASMET DX4000) was used working according the principle of Fourier-Transform Infrared Spectroscopy. At the time of simultaneaous measurement by the drone and in-stack one main engine of the hybrid powertrain was running and no other combustion sources such as boilers or heaters were active.

Figure 2.19 shows the corrrelation between the drone and in-stack measurement of NO_x per CO_2 in mol/mol with some linearity, a coefficient of 0.631 ± 0.102 and a constant of 0.001 ± 0.001. The drone measured less NO_x per CO_2 in the plume than the FTIR measured in the stack. The measurements are concentrated in the range from 0.0045 to 0.007 where the deviation from in-stack (FTIR) is 0.001 mol/mol (roughly 0.5 g/kWh) with exception of one point at about 0.012 where the deviation from the in-stack instrument (FTIR) is the largest with 0.0035 mol/mol (roughly 2 g/kWh).

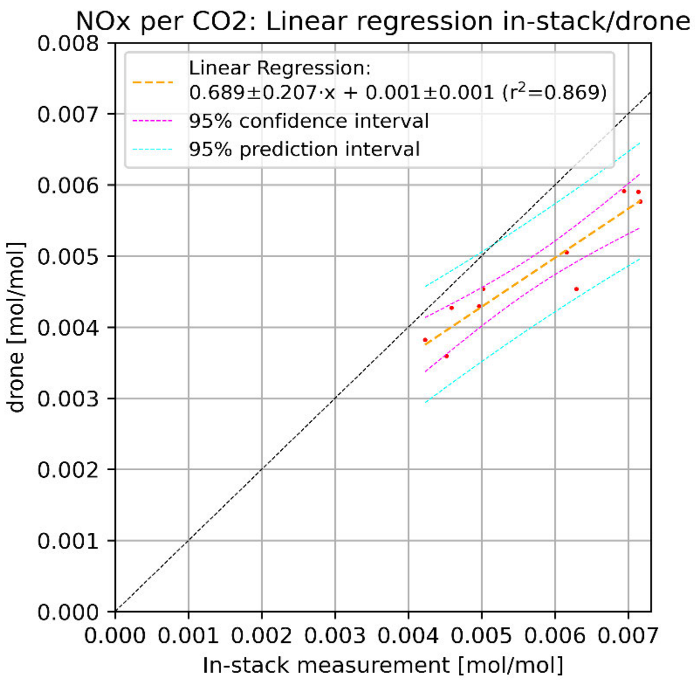

Figure 2.19: Plot of the linear regression of the measurement of the ratio of NO_x/CO_2 [mol/mol] with the in-stack measurement (FTIR) as explanatory variable and the plume measurement (drone) as the dependent variable.

It was concluded that drone-mounted sensors may underestimate NO_x emissions. The correlation to the in-stack measurement was good (r=0.941), but the linearity was poor (linear regression coefficient = 0.631), suggesting that the drone measurement underestimates the NO_x emissions in the range measured in the stack of the ferry.

Correlation measurements of molar NO_x/CO_2 ratios by means of remote or in plume measurement versus in-stack measurement as conducted on the Stena Germanica and the Aurora Botnia indicate that these remote measurements might under-estimate the molar ratios found in-stack. There has been no further investigation into the cause of this deviation.

2.4.2 Overview uncertainties

Emissions levels as determined from remote measurements have uncertainties.
The following list provides a non-exhaustive list of items causing uncertainties of the remote measurement of ship engines NO_x emissions and its expression in g/kg fuel or the same unit as used in IMO NO_x regulation (gram per kilowatt-hour).

Measurement of molar ratio NO_x/CO_2

- Accuracy of remote measurement. The remote measurements are either done by means of remote sensing techniques from the shore or by a drone or helicopter which samples gas from the ships plume. Both measurement techniques have measurement uncertainties. These types of measurements are considered experimental and are not fully standardized, nevertheless they are done on a relatively large scale around the world. There are challenges in obtaining a stable measurement in a plume, taking account of response time of the instrument, time-alignment, background concentration, and possibly stability and homogeneity of gases in a plume.
- Concentrations measured in-stack as per regulation is done shortly after formation in the engine or after the SCR catalyst. Then it takes time for the gas to be transported to the end of the stack and be mixed with air. Chemical changes may take place in the hot humid gas transport time and when the plume is cooled.
- Two programs provided comparisons of remote versus in-stack measurement of molar NO_x per CO_2 ratios and both indicated an under estimation compared to in-stack measurement of the molar NO_x per CO_2 ratio, refer to section 2.4.1. The precise cause(s) were not investigated and are not known.
- The plume can be a mix of plumes from other engines on board, such as from the auxiliary engines, and possibly heaters and boilers. Especially, when the stacks are near to each other, the plumes can be mixed to a certain extend.
- The nitrogen oxides (NO_x) emissions emitted by plumes originating from diesel engines primarily comprise nitric oxide (NO) and nitrogen dioxide (NO_2). In certain instances, remote measurement instruments exclusively quantify NO. In such scenarios, the proportion of NO_2 is approximated and combined with the measured NO concentration to determine the overall NO_x concentration. The ratio of NO_2 to NO_x in the exhaust gas exiting the stack is contingent upon the combustion process as well as potential catalytic post-treatment of the exhaust gas. Additionally, the NO_2 fraction may experience a transient increase immediately following emission from the stack due to the conversion of NO to NO_2 in ambient air.

Conversion to fuel- and work specific emissions

- Conversion to work specific emissions: to be able to compare measured concentrations in the plume to the limit value, which is applicable for the official engine test bed test, the measured concentrations need to be converted. This conversion is usually done using an estimate of the fuel’s properties (fuel carbon content), the molar masses and an estimate of the engines specific fuel consumption at the estimated engine load. This specific fuel consumption varies depending on engine technology and actual engine load. Specific fuel consumption is determined by taking the data from engine specification sheets or taking typical values for the given engine technology.

Estimation of engine load

- To investigate the emissions levels in relation to engine load, the engine load has to be determined.

This engine load is usually derived from the measurement of the ships speed and acceleration and approximation made of the total sailing resistance, for instance using the STEAM model (Ship Traffic Emission Assessment Model) or by assuming the engine load proportional to the actual speed e.g. by means of the propellor law. The engine load is however calculated as percentage of the installed main power. In reality often multiple main engines are used and engines may be switched off because they are not needed. This is especially frequently the case with diesel-electric propulsion. As a consequence, the actual engine load percentage (per running engine) may be a lot higher than the calculated engine load. The auxiliary engine load (hotel function, cargo conditioning) will also increase engine load especially for diesel electric propulsion and for power systems with shaft generators.

Other possible causes for temporal NO_x excursions

- During an engine transient, going from a low speed to a higher speed, when a ships has to accelerate, a temporal NO_x emissions peak may occur. IMO regulation regulates only weighted emissions from a number of steady state load points.
- History of engine load and SCR activity. An SCR catalyst needs to warm up until above it's typical light-off temperature. Exhaust gases need to have reached sufficiently high temperatures to decompose Adblue (a solution of urea in water), which is to be dosed before the SCR in hot exhaust gas, by means of thermolysis and hydrolysis into ammonia, the substance which is required for the SCR reaction, and CO_2. If in the time before a measurement the engine load was low, the SCR may have been cooled down or not warmed up sufficiently for it to work efficiently, resulting in temporal high NO_x emissions during the measurement.

Because of the uncertainties described above, it is recommended to be careful with piling uncertainties on top of each other, and always (also) present result which are relatively certain (with the least amount of data processing).

In that way stakeholders can be taken along instead showing end results of complex calculations:

- Show the NO_x/CO_2 molar ratio and or NO_x per kg fuel as function of vessel speed over ground (SOG). This graphs will already clearly show the high emissions issues based on directly measured quantities.
- Include water current as a next step.
- Separate results of different ship types and sizes, because load patterns are entirely different. In this way large clouds of data points and mixing of various effects are avoided.

2.5 Ship owner inquiry

To obtain a view on the experience with the operation of Tier III certified engines information was collected from ship owners via an inquiry held by the KNVR amongst members including a following technical meeting (20 June 2023 in Amsterdam). An additional limited inquiry was sent out to five ship owners/managers, one responded. It should be noted that these issues are experienced but cannot be generalised without further investigations. Some of the issues might be avoidable for example by a better fuel choice.

An overview of all issues noted is given itemized below:

In general it was mentioned that there are many issues with SCR, such as blockages and lifespan.

The following specific issues were mentioned:

- The catalytic action deteriorated prematurely. The lifespan of SCR elements is on average 3 years instead of the intended 5 years. A manufacturer prescribed interval for changing catalysts of two years was also mentioned
- Urea can sometimes clog together (form deposits) which leads to reduced SCR efficiency and blockages of dosing unit and or catalyst, the latter resulting in too high exhaust gas backpressure for the engine.
- Some parts for the SCR are poorly available; a shipowner has been waiting for half a year.
- In some cases there is ammonia slip (originating from urea).
- In case of high-speed Tier III engines with a later Stage V certification a DPF was placed after the SCR. The SCR became clogged with soot due to MDO with more heavy factions. The SCR therefore needs regular cleaning or a switch to EN590. But availability of EN590 is poor and sometimes EN590 with low flame point is offered.
- The NO_x sensors broke down during a trip due to which the SCR became deactivated until repair.
- In case of high sulphur content in the fuel the SCR may become poisoned.
- SCR seems to perform well mainly with diesel but not always with other fuels like biofuels.
- A heat recovery system in the exhaust lead to condensation, deposits and oxidation in the stack and on the catalyst. This lead to deterioration and sub optimal performance of the catalyst. As a result the heat recovery system will be removed.
- As a result, systems are often disabled (for instance STENA in Sweden due to port fees) and can lead to force majeure for shipowners. Our interpretation is that owners mean that malfunctions can’t be repaired (immediately?), leading to the force majeure.

Other issues noted are:

- Engine load regularly falls below 25%. At low engine load/low and resulting low combustion temperatures the SCR doesn't work optimally or not at all. Engines with an SCR are tuned to run more fuel efficient at the cost of more NO_x emission from the engine which can be reduced by the SCR. In the case the SCR is not working this leads to higher NO_x emissions.
- Many ships still have SCR systems from before 2021, so running SCR is not mandatory in the NECA. However, they are often turned off due to malfunctions.
- It was mentioned that in practice a ship owner cannot choose an independent SCR supplier due to certification. We note that the NO_x Technical Code arranges certification of engine and aftertreatment system together. It is not clear if retrofit of a separate system is facilitated in the certification process.
- It is not clear how the certification organisation monitors. It depends on the flag state. Sometimes they report urea, sometimes they do not (premium program?).
- The systems requires a lot of maintenance. Testing sensors, checking urea quality, measuring urea tank temperature, cleaning urea injectors, inspecting filters.

2.6 Discussion

Results of remote measurements of NO_x emission from plumes of ships with Tier III certified engines have shown that the emissions are often higher the Tier III limit and even higher than the NTE limit (1.5 times the Tier III limit), which apply for the formal test procedures as laid down in the IMO regulation. For the Netherlands, these finding were confirmed by remote measurements done at the Seagate of the Port of Rotterdam.

A significant share of the measurements and ships has NO_x emissions under real sailing conditions at port entrance or exit which are higher than the Tier III limit and the NTE limit.

The remote measurement has uncertainties. Comparative tests have indicated that in-stack measurements may be under-estimated by remote measurement. This would mean that in-stack emissions could be higher than observed from remote measurement data. Further investigation is necessary to determine the correlation and possible causes for the observed deviation.

Taking into account the uncertainty and possible under-estimation of the plume measurement techniques of in-stack emissions, the available data suggests that there are a large number of cases of ships with NO_x emissions which are under real sailing conditions higher than the applicable test cycle and Not-To-Exceed limits of the formal test procedures. The inquiries and technical discussion have given some indications as to the possible root causes, but direct causes for the high NO_x emissions, could not be determined. It is recommended to reach out to the ship owners/managers to ask for the technical files, record books and experience with operation of Tier III engines. Especially ship owners who are participating in a Green Award system or ship owners who have special contract obligations for low emissions, might be willing to participate in this in-depth analysis. Possible causes for shortfall may also be found in the emissions regulation and these and others are summarized hereafter;

Regulation
Emissions regulation conventionally aimed to control and enforce a certain emissions performance of internal combustion engines by means of a certification scheme for a new product, using test procedures and emissions limits and additional measures to control emission performance over the lifetime of a product. The regulation for NO_x emissions of ships sails along this conventional approach, but for other modalities regulation has already shown to fall short achieving agreeable emission performances in the real world. For these modalities, better regulation has been developed and is being further improved to ensure low emissions over the lifetime of a product under normal conditions of use.

For maritime engines the following issues are noted regarding the regulation of NO_x emissions:

Representativeness of the test cycles and coverage of real sailing conditions:
- As has been concluded by several studies, ships engines real sailing load profiles are often entirely different from the ones of the applicable test cycles, especially in ECA areas, coastal zones and port areas. Test cycles without low load, force technical solutions towards solutions that only work efficiently at the given higher engine loads which is the case for SCR. This solutions in its present application at Tier III engines falls short at reducing NO_x from the diesel engines at the low loads. This is a well-known and documented issue for SCR of which the efficiency largely depends on sufficiently high exhaust gas temperature. Low load engine usage occurs especially in harbours or near coasts but also in general for the entire ECA zones worldwide.
- Test cycles contain fixed load points so as to simplify the test and reduce the test burden. This leaves other areas of engine usage untested. The NTE (Not-To-Exceed) requirement is introduced to regulate emission of engine usage not to exceed the limit with an additional margin of +50% on top of the limit, meaning the weighted emissions limit for an engine cannot be exceeded by more than 50% for any individual test load point.

This controls the NO_x emissions to be below +50% of the limit for all load points within the scope of the test (e.g., from 25 to 100% for the E2 cycle but) but leaves room for sub-optimal performance in-between load points. It is also noted that cold-start, warm-up and transient use of engines is not part of any test.

- Technical equivalence IMO procedures foresee in measures which are meant to ensure that engines remain in a technical state which is equivalent to the first certification. In this way it could be checked on a regular basis that no changes are made to the engines and systems that are not allowed and can impact the NO_x emissions performance. Technical data and changes are to be recorded in a technical file and record book by the ship owner/manager.

Periodic inspection/surveys

- Surveys are to be done on a regular basis and are usually done by classification societies, non-governmental organisations for technical inspection of ships. The surveys can be seen as a form of periodic inspection. A known issue of periodic inspection is the periodicity and the time in-between inspections for which there is no control. A form of monitoring is required, by means of a Parameter Check method, reagent monitoring or a direct measurement method but it was also noted that it is not clear how, what (and how often?) the certification organisation monitors and that it was said to depend on the flag state. With periodically announced or ordered inspections any form of misuse, such as defeat device or tampering can easily bypass the inspection or survey. For road vehicles and non-road machinery the latest generations are required to run continuous diagnostics of systems and functions which are crucial for the correct operation of emission control systems and these systems are required to report malfunctions and diagnostic trouble codes if a system or part of the system fails.

Enforcement

- There is limited control of NO_x emissions through inspections, independent testing, review or monitoring by remote sensing. Ships equipped with EGCS have proven to present challenges for inspections in ports (Van Roy et al., 2023).
- For improvement of monitoring and enforcement it is important to implement a system which combines all remote measurements in the European ECAs on an individual ship level. This will give comprehensive insight of NO_x emissions performance of the ship through multiple measurements at different vessel speeds and engine load conditions.

For maritime engines the following technical issues are noted regarding the control of NO_x emissions:

- Malfunctions: Downtime of a NO_x reduction system can happen due to malfunctions such as clogging of the catalyst, dosing unit and breakdown of components of the SCR system. A system shut down results in NO_x emissions that can even be higher than engines of previous Tiers, because an engine can be tuned for optimal fuel efficiency leading through the NO_x-fuel trade-off to elevated NO_x emissions. Components for repair are not directly available on-board or even at berth and repair has to be postponed.
- Maintenance: in the case of clogged or poisoned systems, maintenance is needed such as a catalyst or dosing unit cleaning or replacement. Furthermore, replacement of catalysts at the end of its lifetime (5 to 10 years) is needed.

Netherlands emissions inventory

The national emissions model Poseidon uses correction factors for NO_x emissions of ships with Tier III certified engines to account for reduced SCR efficiency at low loads under real-sailing conditions.

However, empirical findings obtained regarding excess NO_x emissions indicate that current correction factors may still underestimate the real-sailing emissions. Consequently, the possibility exists of an underestimation in projecting the annual development of national total NO_x emissions from maritime shipping on Netherlands territory, when more Tier III engines penetrate the fleet. It is recommended to closely monitor the development of real sailing NO_x emissions of Tier III engines and to investigate the impact of higher than anticipated NO_x emissions on national emissions (at the NCP, inland waterways (ports) and ships at berth).

3 Mitigation

3.1 Technical measures

3.1.1 Improvement of SCR system

Improvement of catalyst configuration
The SCR catalyst has its optimum NO_x conversion in a certain temperature range. See the figure below. On the low side of this range, between 200° and 300°C, the NO_x conversion is limited due to the light-off temperature and the residence time within the catalyst. More temperature or more residence time is needed to increase the NO_x conversion. At the high side of this range, above 450° or 500°C, the NO_x conversion reduces due to the direct oxidation of NH_3 to N_2 and water. This NH_3 is then no longer available to NO_x reduction reaction. In the figure below the temperature window is shown for three types of SCR catalyst (Kim et al., 2020). The V2O5 catalyst and the SCR-A catalyst show a much higher NO_x conversion in the low temperature area than the Fe-Zeolite catalyst. The latter has however a much better conversion between 450° and 500°C exhaust gas temperature. In this way the SCR catalyst can be tuned to the exhaust gas temperature profile of the specific diesel engine. Apart from the catalyst choice, the NO_x conversion at low temperature can also be improved by increasing the residence time, so by increasing the size of the catalyst. In TU Delft, 2018 an example is shown, where the NO_x conversion is increased by 10% to 30% in the temperature range between 200° and 300°C exhaust gas temperature, by increasing the residence time by a factor of four. The catalyst window can be broadened by putting two different catalyst bricks in series. The first one is then optimized for the high part of the temperature window, while the second one for the lower part.

For marine application, the urea injection and thus the NO_x conversion is often limited to temperatures above 300° or even 325° C. The main reasons for that are to avoid (urea) deposits formation and possibly also reduced efficiency due to Sulphur poising of the catalyst. In 2013 EUROMOD wrote in .. '*the challenge with deterioration of the SCR catalyst caused by sulphur in the fuel has been solved by using catalyst elements that are tolerant against sulphur i.e. no deactivation occurs due to sulphur'.* They also conclude: '*the challenge of addressing the narrow exhaust gas temperature window has been solved for the entire load range of 25% to 100% of engine-MCR by modifying and tuning of the engine'.* (Euromot, 2013).

A further reason that we see no NO_x conversion may be that it is not needed to inject urea below 25% engine load, since the test cycles (E2, E3) do not require NO_x conversion. During a Workshop on NO_x regulation issues on 14 November 2023[2], it was confirmed that by lowering the Fuel Sulphur Content (FSC) from about 0.1% to about 10 ppm (i.e. EN590 road transport fuel), the NO_x conversion temperature can be lowered from about 320° to about 265°C.

[2] Workshop on NOx Regulation Issues and Potential Measures for Maritime shipping, organized by Dutch Ministry of Infrastructure and Water management, The Hague, 14 & 15 November 2023

It was also noted that the aqueous urea injection and deposits formation is often the more limiting factor than the SCR catalyst itself.

Deposits formation can be avoided by admitting a different type of reagent, namely:
- Anhydrous or hydrous NH_3
- Solid urea
- Ammonia carbamate

Consequently the low temperature SCR conversion can also be improved in this way.

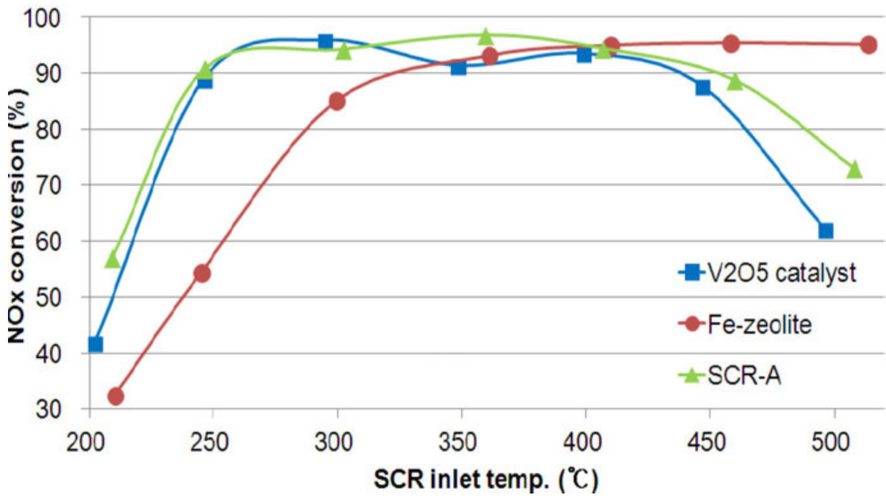

Figure 3.1: Examples of temperature window for NO_x conversion of three types of SCR catalyst. Source Kim, 2020.

Air control penalty
A diesel engine is not throttled like an petrol engine. Throttling means that the amount of combustion air is reduced to be proportional with the amount of fuel. The direct consequence of this is, that the amount air which is added, is high, thus leading to lower combustion temperature. As a consequence exhaust gas temperatures are relatively low, especially at low load.

The engine manufacturer has several options to still influence this amount of air without sacrificing fuel consumption too much. One of the main options is turbo waste gating or variable turbo geometry in order to reduce the inlet air pressure and the amount of air participating in the combustion process. Another option is variable valve timing. By closing the inlet valve early or late (compared to the usual around top dead centre), the amount of air participating in the combustion is reduced. This can both be done with a variable valve timing system or also with a fixed timing system. In the latter case this is called Miller cycle timing. The consequence of this timing is a potential shortage of combustion air at high load. This can be compensated by a different turbocharger which provides more air pressure at high load.

3.1.2 Exhaust Gas Recirculation EGR

EGR is a very common NO_x reduction technology which has been used for decades by passenger cars and trucks to comply with the NO_x emissions legislation worldwide. Basically for European cars up to the introduction of Euro 6, EGR was almost the only and dominant NO_x control technology.

Starting with Euro VI SCR was added to this for many vehicle types. For trucks EGR was introduced with Euro IV and V as alternative technology for SCR, although SCR was more common. With Euro VI (2014), EGR was combined with SCR in order to meet the very stringent NO_x requirements (NO_x < 0.4 g/kWh) and test procedures (also Real Driving Emissions, RDE test in normal driving). EGR is especially applied at low and medium load for NO_x control and is ideally complementary to SCR, which has its best performance at medium and high load.

EGR can be split in three types:
- Cooled (external) EGR
- Hot (external) EGR
- Internal (hot) EGR

With external EGR, a part of the exhaust is branched off and fed back, and mixed with the inlet air. With cooled EGR the exhaust gas is cooled before it is added to the inlet air. In that way the mixture of inlet air and EGR gas has a relatively low temperature which contributes to the amount of air-EGR which can be fed to the cylinder, and also directly contributes to a lower NO_x. A rule of thumb for cooled EGR is, that every 1% of EGR gas which is added, leads to 4% NO_x reduction. In practise the amount can be increased to some 15% which means 60% NO_x reduction.

For maritime engines EGR is suitable for low speed, medium speed and high-speed engines, although the configuration will likely vary somewhat. For high-speed engines it is probably the easiest to stay closed to the heavy-duty engines (trucks) system configuration with water cooled EGR coolers. For low-speed engines EGR cooler circuit has been proposed which includes also an sulphur scrubber and a water mist catcher (WMC). In that way fouling of the additional EGR blower and inlet system of the engine can be prevented. This system has been described by EUROMOT, the European engine association, in an IMO MEPC INF document (Euromot, 2013). Refer to the figure below. The scrubber and WMC system is probably not necessary when ULSFO is used.

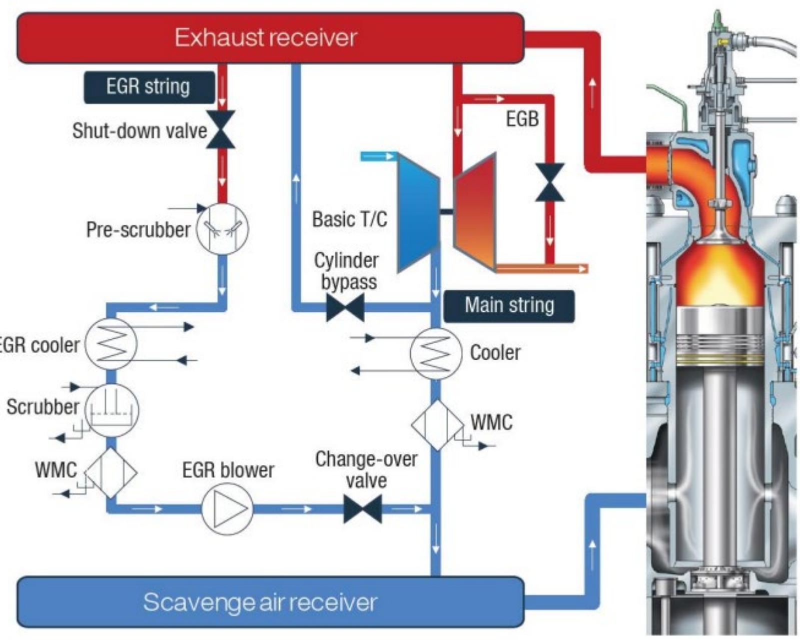

Figure 3.2: Typical EGR system configuration for a low-speed engine (Euromot, 2013).

(Euromot, 2013) concludes the following (MEPC 65/4/27):

- EGR is a feasible and mature technology by which the IMO Tier III NO_x level can be achieved.
- EGR is available for all sizes of low-speed engines
- EGR is available from more than 20 engine manufacturers
- EGR is a well-known technology with many automotive references.
- Several engine designers and engine manufacturers have published information on development of EGR technology for marine application.

EGR has one important advantage and one disadvantage when compared to SCR aftertreatment:

- Advantage: EGR works across the entire load range from idle/standby to rated power (when properly engineered).
- Disadvantage: with EGR the air control and combustion cannot be fully optimized to the lowest fuel consumption, which can be done with SCR. With SCR fuel consumption can be reduced by about 5% compared to a Tier II engine without SCR.

Due to the simplicity of the engine design (one design for ECA and non-ECA) and the advantage in fuel consumption, most of the engine manufacturers choose SCR in order to comply with Tier III emissions. The SCR also fits well with the formal Tier III test procedures which does hardly include any emission requirements below 25% engine load.

A good option that can be considered is the combination of EGR (for low load) with SCR (for medium and high load). This is the main NO_x control technology for Euro VI HD (Heavy-Duty) truck engines.
In that way the EGR system can be kept simple and also the impact on the overall engine design is limited. Moreover the specific fuel consumption advantage of SCR can be maintained to a large extend.

3.1.3 Conclusions technical measures

Based on the previous sections, it is concluded that there are many options to improve the low load NO_x emissions of diesel engines. Low NO_x below 25% engine load can be accomplished by implementing one or more of the following measures:

- SCR catalyst specification tuned more to low temperature and/or a larger catalyst size
- Injection of a different NH_3 (forming) reagent such as anhydrous or hydrous ammonia or solid urea or ammonia carbamate.
- Switching to fuel with a lower FSC such as EN590 with 10 ppm FSC.
- Increase of exhaust gas temperature at low load by engine tuning. Options include different turbo charger, waste gating, variable turbine geometry, variable valve timing, miller cycle timing, injection timing control, internal EGR and hot EGR.
- Installation of an (cooled) EGR system instead of an SCR system
- Installation of an (cooled) EGR system complementary to the SCR system, so primarily for low load.

3.1.4 Ship power distribution

On a ship level low load engine power can often be avoided by shutting of engines which are not needed. Ships are often equipped with multiple main engines and auxiliary engines. For example a ship with four main engines can generally sail on two engines during sailing at low vessel speed.

3.2 Regulatory measures

Based on observed real sailing emissions levels, user experience, inquiry results and literature and identified and reported white spots of regulation, a number of regulatory measures is thinkable that could address the shortfall of regulation:

- Addition of low load point(s) in the test cycles, below 25% with proper weighing. This would require thermal optimization to ensure SCR light-off by improved engine control and hardware. See paragraph 3.1.
- Introduce an NTE at least down to 10% engine load and applicable to all load points (also in between test points. Reduce the NTE from 150% (Tier III) down to 125% or possibly even 100%. Increasing NTE requirements is probably more effective than reducing the limit value for a weighted average for a next step in emissions legislation (e.g. Tier IV).
- In-use monitoring by means of CEMS but with clear obligations which might include online publishing of (averaged) emissions for authorities and class bureaus. SCR equipped engines often have NO_x sensors upstream and downstream of the SCR catalyst which can be used for monitoring, but it is also not expensive to install a CEMS which can independently monitor NO_x emissions.
- Surveys are conducted by certification organizations. Access to survey data and monitoring data also by 3rd independent parties to verify findings and for independent supervision.
- In-service conformity testing and monitoring: this is currently conducted via on-board confirmatory checking methods/surveys which are not well-established and allows room for interpretation.
- Random checks instead of announced or self-organized checks and surveys.
- Remote emission measurement (for screening or enforcement), but validation of the method is needed.
- A unit in g/kg fuel (or gram per kg CO_2) for NTE allows easier monitoring, onboard validation and remote validation. Dependency of hard to measure engine load is abandoned.
- Diagnostic functions and/or requirements for repair of malfunctions. E.g. obligations to keep track of malfunctions, repair within a certain time or keep spares in stock to prevent long times to repair.
- Explicitly forbid tampering and defeat devices.
- Keel Laying Date derogation limitation. Limit the time difference between keel laying year and built year. This is not harmonized between flag states. Netherlands uses a maximum lead time of six years between KLD and entry into service

4 Conclusions and recommendations

A desk review was conducted to collect insights so as to:

- determine real-sailing NO_x emissions as obtained mostly by remote emissions measurements of ships with Tier III certified ships.
- identify possible technical issues with the control of NO_x emissions of ships with Tier III certified engines
- identify shortcomings of the IMO MARPOL NO_x regulation
- identify possible technical and regulatory measures for mitigation of NO_x emissions in ECAs.

This led to the following results:

Real world NO_x emissions

- Remote sensing in ECA zones (North and Baltic sea) show that: emissions of Tier III vessels deviate a lot from Tier III objectives to higher than Tier II emissions. Half of Tier III vessels (all with LS engines) emit in practice more than two times the NO_x NTE (Not To Exceed) limit value. There are individual ships which show that low emissions are possible, also at very low vessel speed.
- Remote emission measurements in the plume can be equal or up to 50% lower than emissions measured directly in the stack of the main engine, so the actual problem with high NO_x from the stack might be more severe. It is recommended to further investigate the correlation of the in-stack and plume measurement.
- Ship owners report a substantial number of technical issues with SCR systems, among which blockage of systems due to deposits formation (influenced by fuel type), reduced life time of catalysts, lack of spare parts, and poor low load performance. More research is needed to identify the frequency of these problems and the possible dependency on fuel type used.

IMO MARPOL NO_x Regulation

NO_x regulations aim to secure low real world NO_x emissions of Tier II and Tier III ships, but only about a quarter of the ships shows real world emissions in line with the Tier III objectives.

The general known shortfalls are:

- The ISO test procedure (E2, E3, D2) puts the emphasis on high (75%) and maximum (100%) engine load, while in practise most of the time spend in ECA zones, the engine load is below 60%- and in port areas even below 30% engine load.
- The NTE requirement (150% of limit value) is only applicable to test points and only for Tier III. There are no emission requirements for engine load points below 25% power.
- Lack of options for enforcement: continuous NOx emissions monitoring is not required. Monitoring and enforcement is not secured in the regulations.

Technical solutions for low NO_x emissions in ECAs

There are many options to reduce low-load NO_x emissions of marine diesel engines. Especially an improved catalyst system, which can be supported if needed by engine tuning, fuel with lower sulphur content, alternative reagent or EGR complementary for low load conditions. Also 'EGR-only' (without SCR) is a realistic options with good NOx reduction at low load. All of these measures have a high Technological Readiness Level level. They are broadly implemented for HD vehicles and also on a smaller scale on ship and stationary diesel engines.

There is a potential fuel penalty of retuning the engine for a better fit with an SCR system. This will be dependent on the base engine and the magnitude of retuning which is necessary. It can, for example, go up to some 5% fuel penalty in parts of the engine map. In practice the fuel penalty will be likely limited to a few percent dependent on the time spend in that part of the engine map. Also over time engine manufacturers may find and implement improvements which will further reduce this penalty.

On a ship level NO_x emissions can be reduced by shutting off engines which are not needed and/or different powertrain configurations with avoids running engines on low load for longer periods.

Recommendations for improvement of regulations

- A minimum set of measures include the expansion of the ISO test cycles (E2, E3, D2) with a low load point, e.g. 10% low load, including a Not-To-Exceed (NTE) for this load point and adapted weight factors to better represent load profiles in ECA zones.
- The NTE should be expanded to all load points and all engine conditions (at least > 10% engine load). The NTE should preferably be defined as g/kg fuel. This wil ensure that monitoring and onboard validation will become easier and more accurate and the NTE can be extended down to 0% load.
- Implement onboard NO_x monitoring requirements preferably with a Continuous Emissions Monitoring System (CEMS)with sensors (which is relatively cheap) or emissions analysers. Alternatively monitoring can be limited to continuous urea consumption (and quality) in relations to fuel consumption and engine load. Monitoring should be made available to authorities and certification organisation online and/or directly accessible during onboard inspections.
- Implement life time requirements for emission control systems onboard of ships.
- Regulate methodology and requirements for period inspections onboard of vessels by certification organisation.
- Implement formal status of remote sensing for enforcement purposes. For example as preselection methodology for inspections onboard by authorities or certification organisation or for compliance testing.

Recommendations for further research

- Indications were found for the cause of high NO_x emissions. Further research is needed linking high NO_x to a cause. More insight is needed in precise NO_x emissions in normal operation. NO_x emissions of all engines onboard should be analysed in relation to engine load and ship activities. Currently implemented monitoring systems on many ships can provide sufficient insight. Different types of ships with low-speed, medium-speed and high-speed Tier III diesel engines should be evaluated.
- It is recommended to investigate the impact of higher than anticipated NO_x emissions on national emissions (at the NCP, inland waterways and ships at berth).
- Remote sensing of NO_x emissions seem to often underestimate NO_x emissions (up to 50%) of the main engines.

Contributing to this difference may be auxiliary engines onboard, atmospheric phenomena, or instrument shortcomings. Precise cause(s) should be identified and improvements should be implemented. This can be done by one or more controlled comparison(s) between stack and remote measurements e.g. with low and high NO_x levels, frequent repetition of measurements, also with different atmospheric conditions. Also periodic round robin testing of remote sensing equipment is also recommended.

- Lifetime and reliability of NO_x emission control systems. Catalyst systems and EGR systems contain components which may be sensitive to fouling, poisoning, aging and wear. Particularly fuel specification including fuel sulphur content, impurities and heavy hydrocarbons may influence the efficiency and lifetime of the systems. CEMS systems would identify such issues, on the other hand (pre-scheduled) replacement of components is costly and should be avoided.
- Present remote sensing data also in charts with less data processing, such as NO_x/CO_2 ratio as a function of vessel speed. This avoids a number of uncertainties and takes stakeholders along in the data processing. Also always separate vessel types to avoid large data clouds.
- Study the technical feasibility and acceptability of an NTE limit value in g/kg fuel down to 0% load.

It is also recommended to expand on remote NO_x monitoring equipment at the Dutch sea ports including continuous monitoring of NO and NO_2. In addition periodic reporting and cooperation with other European sea ports is recommended.

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