Analysis of operating conditions and NOx-emissions of Tier III ships

Engine load and NO_x-performance in Dutch sea and port areas

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Engine load and NOx-performance in Dutch sea and port areas

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Contents

1 Abstract

Despite overall reductions in transport-related NO_x-emissions, maritime sources remain a concern for the Netherlands, particularly in Dutch coastal waters and major port areas. While NO_x-emissions from the road transport sector show a downward trend, reductions from shipping activities are less pronounced. Commissioned by the Ministry of Infrastructure and Water Management, this study by TNO combines quantitative analysis of shipping operation and NO_x-emissions with qualitative insights from stakeholders to assess the real-world effectiveness of the latest IMO Tier III nitrogen oxide (NO_x)-emission standard for maritime engines.

The focus is on comparing actual operating loads of marine diesel engines used for ship propulsion with the certification loads under Annex VI Regulation 13 (Tier III) NO_x-limits. Several sources report that these engines often run below 25% engine load—the lowest load considered in the test cycles for certification of engines for the main propulsion. At these low loads, low NO_x-emissions aren't guaranteed. Using AIS-derived sailing profiles, the study quantified low-load operation shares and estimated the proportion of NO_x emitted at low load in the total NO_x-emissions for Tier III ships in the sea and seaport areas of the Netherlands[1]. These effects are also assessed by ship type, size and different areas to identify where the impact is the biggest.

The results of the research indicate that, according to the method used, marine engines spend a significant fraction of their time below 25% load. On average, engines spend about 28% of the time below 25% load. For large ports areas this fraction of time is the highest (about 55-77%) and for regions further away from the coast, outside the 12-miles zone, the lowest (about 20%).

The operating profiles were used to calculate the total NO_x-emissions and the share of NO_x emitted at low load in the total. Using the official Dutch emission factors for this calculation, on average about 21% of the NO_x emitted in Dutch sea and seaport areas is emitted at low load. This share is the highest for the ports areas (45%) and the lowest for the region further from the coast (outside 12-mile zone: 17%). Most of the NO_x is, however, emitted in the area the furthest away from the coast (outside 12-mile zone) due to the highest shipping intensity and the larger fraction of heavier ships in this area. Out of the ship types container ship stand out, as it was calculated that these ships emit half of their NO_x-emissions at low load in Dutch sea and port areas.

These low-load conditions represent a substantial share of activity and NO_x-emissions in Dutch sea and seaport areas. Addressing these conditions is essential for achieving NO_x-reductions where environmental and public health benefits are the greatest. This may be achieved by aligning IMO regulations with real-world operations regarding NO_x-emissions at low engines loads: parts of the NO_x Technical Code of MARPOL Annex VI or the SCR-guidelines could be adapted to explicitly include engine loads below 25% and to use representative weighting factors for the certification of main propulsion engines. Such adaptations would probably sort an effect on the longer term.

[1] The researched areas include the Dutch part of the North sea, its coastal regions, Wadden Sea and Dutch sea port regions: Amsterdam, Den Helder, Eemshaven, Rotterdam and Westerschelde.

For the shorter term, the introduction of a requirement for low load emission management down to 10%, separate from test cycle values, and the application of emissions monitoring and reporting requirements, could be considered as part of the regulation to improve the NO_x-emissions during low load operations.

Interviews with three shipowners revealed differences in how SCR systems for NO_x-control are managed. Two rely mainly on OEM control systems, alarms, and prescribed routines, with no (emissions) trend data available from these systems. The third actively monitors NO_x-performance and optimizes engine operation, using data from a retrofitted Continuous Emission Monitoring System (CEMS).

This research was conducted to obtain an indication of the real sailing load profiles of maritime engines and to determine if low-load operation has a substantial share in NO_x-emissions from Tier III engines. While this is indeed indicated by the analysis based on a limited dataset, we recommend to further investigate the impact over the longer term and with a larger dataset.

We also recommend estimating the potential effect of options for adaptation of the NO_x Technical Code on maritime NO_x-emissions, especially for Dutch port areas and coastal waters.

2 Introduction

Background

Nitrogen oxide (NO_x)-emissions remain a significant environmental concern in the Netherlands, especially emissions close to vulnerable areas like protected nature areas and coastal communities. Maritime NO_x-emissions are primarily regulated through the International Maritime Organization (IMO), with progressive standards from Tier II to Tier III aiming to curb NO_x-emissions from the newest ship engines. However, the implementation of Tier III standards has encountered challenges. There are indications that Tier III may not be delivering the expected reductions in NO_x-emissions ([1], [2], [3], [4], [5], [6]), especially in areas where such reductions are most needed, such as in ports and near the coast. This is particularly relevant for the Netherlands, which experiences high volumes of shipping traffic in its coastal waters and where several major ports are located.

One of the potential causes reported, is that ships main propulsion engines may spend time below 25% of their rated engine power, which is the lowest engine load point which applies for the certification of main propulsion engines according to the Annex VI Regulation 13 of the NO_x technical code ([7], [8]). At loads below about 20-25% engines generally tend to produce insufficient heat to keep the Selective Catalytic Reduction (SCR) system for NO_x-reduction warm enough to work, which leads to elevated levels of NO_x-emissions at these low loads. For SCR used in motor vehicles similar issues were observed, when vehicles drive at low speeds. Regulation for motor-vehicles has already tackled this issue by decreasing the average loads of the test cycles of real-driving tests, which for vehicles as of Euro 6dtemp/VI step-D has led to a significant decrease of NO_x-emissions. In addition, manufacturers may choose to apply an Auxiliary Control Device, which allows switching off reagent dosing at low engine load to protect the SCR system. On the other hand the recently adopted resolution MEPC.397(83) [9] amends the NO_x Technical Code regarding the loads below 25% by requiring that a rational emission control strategy is to be applied. The amendment only applies to new engines or engines which were subject to a substantial modification, which are to be certified on or after 1 January 2028. Therefore, the effects will probably only be relevant several years or even decades after this date. Nevertheless, the efficiency of the SCR will still rely on sufficient temperature of the exhaust gas and low NO_x-emissions aren't guaranteed without substantial technical adaptation such as thermal management. Hence, without further control, the load of the engine remains an important factor which determines the level of work specific NO_x-emissions at low engine loads.

Given the shortfall in NO_x emission reductions from maritime ship main propulsion engines at low engine loads, it is essential to quantify the impact and to determine if there are ship types, operations or areas for which this is most prominent. In response to this concern, the Ministry of Infrastructure and Water Management (IenW) has commissioned TNO to quantify the impact. The study consists of a quantitative analysis of location data and interviews with ship-owners. The shipping location data (AIS, Automatic Identification System) of the first quarter of 2023 is analysed to determine the share of operation spend at low engine loads and the share of NO_x that is emitted at these low loads, as compared to the total NO_x-emissions. The shipowners gave insight to their experiences with Tier III-compliant vessels. This report presents the results of those analyses.

Objectives

The objective is to evaluate the effectiveness of IMO Tier III NO_x emission standards within the Dutch sea and sea port areas.

Specifically, the study aims to:

- Determine the shares of main engine operation at low engine load, which for these engines is outside of the regulatory testing scope below 25% engine power for real sailing conditions for different maritime zones, from Dutch sea ports areas to ‘out-side the 12-mile zone’ and for different ship types and sizes.
- Determine the share of the NO_x-emission of low load operation of main propulsion engines in the given Dutch sea and seaport areas for the various ship types and sizes.

Approach

Data analysis of shipping traffic and emissions

The main component of the research involves a comprehensive analysis of maritime traffic data (AIS-based) of Tier III vessels in Dutch sea and sea port areas and the calculation of NO_x-emissions related to low load engine operation.

This includes:

- Operational profiles: Distributions of main engine load per area and ships type.
- NO_x-emissions: Use main engine load profiles to determine the share of NO_x-emissions emitted at low engine load, per area and ship type and size.

Stakeholder Interviews

To complement the quantitative analysis, interviews were conducted with three key stakeholders to see how experience from shipowners and operators of Tier III-compliant vessels compare to results found in the data set. The interviews aimed to gather insights on operational experiences with Tier III technologies and perceived effectiveness of NO_x-reduction measures.

3 Methodology

This chapter has three paragraphs; the first paragraph explains the methodology for the evaluation of the operational data to determine the engine load distribution. The second paragraph explains the calculation of NO_x-emissions and the third paragraph briefly explains how the interviews with shipowners were set up and conducted.

3.1 Modelling of the main engine load

As a first step, an overview of all Tier III vessels in the world fleet was made using the World Fleet Register from Clarksons Research Ltd. Only Tier III vessels were taken into account in this analysis to specifically pinpoint the effects of low engine loads for these vessels. The data from the register included the *Marine Mobile Service Identifiers* (MMSI) of the vessels, as well as technical characteristics, such as ship type and engine characteristics. Based on MMSI, the Tier III vessels that have sailed in Dutch sea and seaport areas were identified by *Maritime Research Institute Netherlands* (MARIN). From the list of over 5,000 Tier III vessels that are active in the World Fleet in 2025, 538 vessels were active in the Dutch sea and seaport areas in the first quarter of 2023. The population of Tier III vessels is large enough to give valid statistical results (see Table 3.1). The data was enriched by MARIN with the operational and emissions data that was used in the Dutch emission inventory (Pollutant Release and Transfer Register (PRTR)) for 2023. Details on the model and the simulation approach can be found in [10]. For privacy reasons, the MMSI's have been anonymized by MARIN before sharing the dataset. The final dataset contains per ship, the ships specifications, the modelled fraction of Maximum Continuous Rated Power (fMCR) of the main propulsion engines and the modelled NO_x-emissions of Tier III vessels for these engines. This for each bin of fMCR of sailing in the first quarter of 2023 for the regions (Dutch sea and seaport areas).

These were grouped by:

- Region (specific areas, such as port areas, 12 mile zone, etc.),
- Vessel type, and
- 5 % Bins of fMCR (fraction of Maximum Continuous Rated Power of active engines, taking account of NoEA (number of active engines depending on ships speed)).

The different regions are illustrated in Figure 3.1 below. Throughout this study, the 'Dutch sea and sea port regions' are defined as the regions indicated in this picture. A more detailed breakdown can be found in Figures 2-2 to 2-4 on [10, pp. 3–6]. An overview of the ship types can be found in Table 3.1 on page 10. In total, the data consisted of 33,050 sailing hours. Furthermore, the EMS-type and EMS-size of the vessels were included. EMS-size refers to the classification of a ship based on its gross tonnage or overall capacity, while EMS-type refers to the category of ship operation or function (e.g., container ship, tanker, passenger vessel). Besides that, some derived quantities that were not used in this study were available in the table. A detailed overview of the columns and their descriptions are given in **Table A.1** in Appendix A.

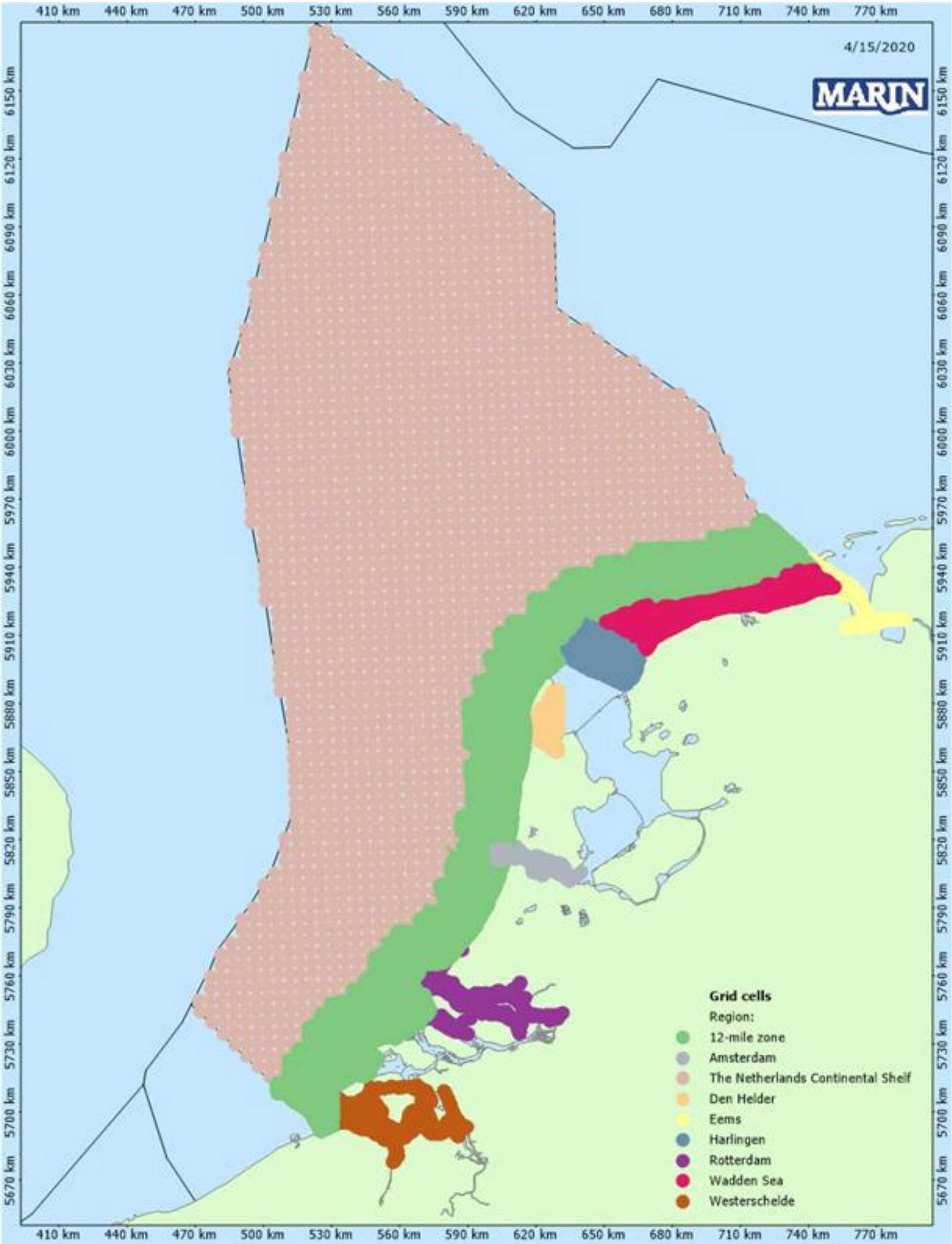

Figure 3.1: Definition of regions, the areas used for this investigation (taken from [10, Fig. 2.1] with kind permission of the authors). The sea and seaport areas contain the Netherlands National Continental Shelf, the 12-miles zone, the Wadden Sea and six seaport areas.

The actual power of the main propulsion engines was determined based on the actual vessel speed, the design speed, the installed engine power and number of engines and are binned as fraction of the *Maximum Continuous Rated* (MCR) power (fMCR) which represent the percentage-ranges of main engine load. fMCR is calculated based on vessel speed by:

Equation 3.1: Calculation of the fraction of MCR [10, p. A-8]:

$$fMCR = \frac{Engines\ Operational}{NoEA} \cdot CRS_{corr} \cdot MCR_{ss} = \frac{NoEO}{NoEA} \cdot \frac{\left(\frac{v_{act}}{v_{design}}\right)^{3.1} + 0.1}{1.1} \cdot MCR_{ss}$$

Where NoEO and NoEA denote the number of operative (installed) and active (running) main propulsion engines, respectively. Furthermore, CRS_{corr} is a correction factor, defined and replaced by variables v_{act} and v_{design},which represent the actual and the design speed of the vessel. The factor MCR_{ss} is the assumed fraction of installed power (MCR) that is required to sail at service speed according to [10, Tbl. A-2].

Further exploration of the data shows that the dataset is dominated by chemical/LNG/LPG tankers with 219 of them in the dataset, which is 41 % of all the ships in the data and representing 37 % of all data in terms of hours. There are only two fishing ships with 16 hours of data. This is quite insignificant and unrepresentative and the ships are hence removed from the analysis. All the other ships were included in the analysis. The distribution of the data with regard to the type of ships can be seen in Table 3.1 below.

Table 3.1: Overview of ship types in the dataset.

Type of ship	Number of ships	% Of the data w.r.t number of total ships	Total time [h]	% Of total time
Bulk carrier	52	10%	1,283	4%
Chemical/LNG/LPG tanker	219	41%	12,202	37%
Container ship	20	4%	1,043	3%
Fishing	2	0%	16	0%
General Dry Cargo	46	9%	4,924	15%
Miscellaneous	22	4%	2,465	7%
Oil tanker	99	18%	2,672	8%
Passenger	4	1%	479	1%
RoRo Cargo / Vehicle	36	7%	5,384	16%
Tug/Supply	38	7%	2,581	8%

The data also shows the regions from where the ship AIS data was retrieved. There were nine regions where the data was collected, see Figure 3.1 on page 9. Out of the nine locations, most (62 %) of the data origins from ‘out of the 12-mile zone’. 17 % Of the data comes from the area designated as ‘within the 12-mile zone’. The distribution of other locations, and how many hours of data and shares they represent, can be found in **Table 3.2** below. This table also elaborates on the abbreviations used in the data and later in this report.

Table 3.2: Data per region.

Region Code	Region name	Total time [h]	% Of total time
12Mile500	12-milezone (500m x 500m grid)	5.458	17%
Adam	Amsterdam	460	1%
DH	DenHelder	356	1%
Eems	Eems(haven)	992	3%
Harl	Harlingen	285	1%
OutOf12	Out of 12-milezone (5000m x 5000m grid)	20,641	62%
Rdam	Rotterdam	1,747	5%
WS	Wadden Sea	1,701	5%
WS_SAMSON	Westerschelde (Safety Assessment Model for Shipping and Offshore on the North Sea)	1,408	4%
Total		**33,049**	**100** %

The distribution of ship size in the dataset is illustrated in Table 3.3 below. Except for the smallest size bin, we consider this sufficient data for the analyses. Here, gross tonnage (GT) represents the total internal volume of all enclosed spaces of a vessel, serving as a standardized indicator of its overall size and capacity.

Table 3.3: Distribution of the size of ship in the dataset along with the sailing time for each.

Ship size [GT]	Total time [h]	% Of total time
0 - 99	12	0%
100 – **1,599**	897	3%
1,600 – **2,999**	4,280	13%
3,000 – **4,999**	5,428	16%
5,000 – **9,999**	5,476	17%
10,000 – **29,999**	6,742	20%
30,000 – **59,999**	3,017	9%
60,000 – **99,999**	4,042	12%
Over 100,000	3,154	10%
Total	**33,049**	**100%**

3.2 Modelling the NO_x-emissions

One of the main objectives of the study at hand is to estimate the contribution of low (main) engine loads on NO_x-emissions of seafaring vessels with Tier III certified engines. Ships at berth are not included. To that end, the NO_x-emissions are calculated for the time the ship's main engines are running at low load (fMCR <25%) and the share of the NO_x-emissions at low load is determined in the total NO_x emitted. This is aggregated over regions, vessel types, and vessel sizes and compared to each other to determine if cases differ as to what share of NO_x is emitted at low engine loads.

SCR systems work best in a specific temperature window: light-off is usually at temperatures above 200°C.

Just above these temperatures NO_x-conversion efficiency isn't optimal yet, highest NO_x-conversion rates are at temperatures around 300°C [11], [12]. Auxiliary control devices (ACD), allowed by Regulation 13 and the NTC 2008 with Administration approval, disengage the SCR system at low load to protect the engine against operating conditions that could result in damage or failure.

For the calculation of the absolute NO_x-emission, the modelled fMCR was multiplied by a base emission factor [10, Tbl. A-8], which depends on the rated speed of the main engine, and a load correction factor. The latter is described in more detail below. For every row of the dataset, the total NO_x-emissions of the main engines and the time the vessel spent in this region/fMCR-bin were obtained from the MARIN data set. The calculation of the NO_x-emissions is also described in [10, App. A].

For every bin, a load correction factor is defined that takes the raised levels of NO_x-emissions at low loads into account for all Tier III certified main engines. The assignment of correction factors to engine load bins can be found in Table 3.4. These numbers originate from a desk study that was done by TNO in 2019 [13]. These Correction Factors are used in the national model for the calculation of emissions from the Maritime sector [14]. The approach includes adjustments to the E3-cycle, which is a steady-state test procedure consisting of four load points (100%, 75%, 50%, and 25% of the engine's maximum continuous rating) used to determine the certified NO_x-emission level of propulsion engines.

These load points would have to be adjusted meeting the following criteria:

- The total brake-specific NO_x-emissions of the cycle were equal to a set limit of 2.0 g/kWh minus a margin of 0.1 g/kWh, and
- The NTE (Not-to-Exceed)-limit of 1.5 (cf. [8, Sec. 3.1.4]) minus a margin of 0.1 g/kWh was met for every load point.

Here, the NTE-limit defines the maximum allowable NO_x-emissions during real-world engine operation.

Table 3.4: NO_x-correction factors for reciprocating diesel engines (from [10, Tbl. A-14]) which are applied to the base emissions factor of 0.95xTier III limit to calculate the NO_x-emissions factor per load bin.

fMCR	Correction factor for reciprocating diesel engines (CEF)
10	6.00
15	3.00
20	1.75
25	1.45
30	1.45
35	1.45
40	1.45
45	1.45
50	1.45
55	1.45
60	1.40
65	1.25
70	1.00
75	0.85
80	0.85
85	0.85
90	0.85
95	0.85
100	0.85

3.3 Interviews

Interviews with two shipowners, who operate seagoing vessels equipped with Selective Catalytic Reduction (SCR) systems running on heavy fuel oil (HFO), were held. Information provided by a third shipowner was added later. Results are presented in section 4.3.

The interviews have the objective to retrieve information of shipowners about the practical operation of SCR systems on ships with Tier III certified engines using SCR. Aside from a number of technical specifications of the ships and the engines, information was gathered to gain insight into the technical functioning of the SCR system in daily normal operations. This includes the role in daily sailing routines, shipowners' experiences and perceived challenges, the level of interaction with the system, and the identification of bottlenecks or inefficiencies. Furthermore, the interviews explore the availability and usability of emission and system data. This is done with a focus on the extent to which shipowners can access and use this information for monitoring, optimization, and reporting purposes.

The shipowners were selected based on the number of Tier III-certified vessels in their fleet, with specific focus on vessels equipped with two-stroke engines. This focus is applied since it allows for the evaluation of emission-reduction strategies using SCR in the most critical segment of the fleet, where regulatory compliance and technological innovation may have the largest potential environmental impact.

This selection resulted in two shipowners being included in the interviews:

1. Shipowner 1 with:
    a. 6 Tier III 1800 TEU container ships operating vessels equipped with MAN two-stroke engines running on heavy fuel oil (HFO) and,
    b. 6 Tier III 1800 TEU and 2 Tier III 2800 TEU 2-stroke engines currently under construction,
2. Shipowner 2 with:
    a. 1 Tier III liquefied gas tanker 2-stroke engines and
    b. 8 Tier III liquefied gas tankers 4-stroke engines, which apply SCR on auxiliary generator engines.

In total, there are 24 registered Tier III vessels equipped with two-stroke engines under the Dutch flag. The two participating shipowners together operate approximately 29% of Dutch Tier III vessels with 2-stroke engines. When compared to the fleet of 100 Tier III vessels equipped with other engine types, these shipowners represent around 8% of that group.

The interviews have been structured in a set of segments to discuss the different relevant topics with the shipowners. Overall, it is structured in two parts: A request for technical specifications on the relevant ships and systems and questions regarding the experience in usage of the SCR systems. The full list of questions can be found in Appendix B.

In addition, the findings of a third shipowner are described, where a recent on-board measurement has been performed. This vessel is equipped with a diesel-electric propulsion system powered by three identical MAN 8L27/38 Tier III generator engines, each rated at 2,640 kW at 750 RPM. Together, these engines provide a total installed diesel power of approximately 7,700 kW.

4 Results

4.1 Engine load

This section presents the results for the operational conditions for Tier III vessels in the regions part of the investigation with a focus on the share of the time ships spent at the various engine loads, with engine load expressed as a percentage of the maximum continuous rating (fMCR) of the main engine running. In **Table 4.1** the distribution of hours over the full range of fMCR is shown for the whole data set.

Table 4.1: Distribution of the fMCR in the dataset along with the total time spent in each fMCR bin.

fMCR [%]	Total time [h]	% Of total time	Cumulative percentage
10	3,927	12%	12%
15	1,891	6%	18%
20	1,574	5%	22%
25	1,817	5%	28%
30	2,918	9%	37%
35	2,513	8%	44%
40	2,317	7%	51%
45	2,836	9%	60%
50	2,021	6%	66%
55	1,705	5%	71%
60	1,773	5%	77%
65	1,187	4%	80%
70	1,036	3%	83%
75	1,624	5%	88%
80	395	1%	89%
85	1,102	3%	93%
90	84	0%	93%
95	874	3%	96%
100	1,454	4%	100%
Total	**33,049**	**100%**	

It can be observed that for 12% of the time, the ships are operating at or below 10% fMCR, 28% of the time at or below 25% fMCR and at or below 65% fMCR for 80% of the time.

During certification and surveys the compliance of marine diesel engines with the Tier-limits, set out in Regulation 13 of Annex VI of MARPOL [15], is verified by determining the weighted NO_x-emissions over defined engine test cycles. The details of the tests can be found in the NO_x Technical Code [7], [8] and part 4 of ISO 8178 [16].

These cycles assume certain time shares (by weighing) of load points which are considered representative for the operation of the engine. The load points of the E2 and E3 cycles, which apply for main engines, are stated in Table 4.2 below. The focus of the cycles is clearly on Mode 3 (75% engine load).

Table 4.2: Load points and weighting factors of E2/E3 cycles [8]

Cycle	Mode 1 25% load	Mode 2 50% load	Mode 3 75% load	Mode 4 100% load
Weighting factor	0.15	0.15	0.50	0.20

Figure 4.1 below compares the time shares of engine loads obtained from the data to the E2 and E3 test cycles. The latter applies for main engines which are directly connected to the propellor shaft and therefore follow a propellor law in operation whilst the former applies for constant speed main engines, including diesel-electric drives. The cumulative distribution function (CDF) of engine loads – which is the same for both cycles – is skewed to the right, which means that the shares of higher engine loads are overestimated compared to the results of the MARIN simulated data set. In particular, there is no 10% load point for these two cycles. As a consequence, the adverse effect of low engine loads at low sailing speeds might be underestimated by the certification tests and the real-world brake-specific emissions of NO_x might be significantly higher than the applicable Tier limits.

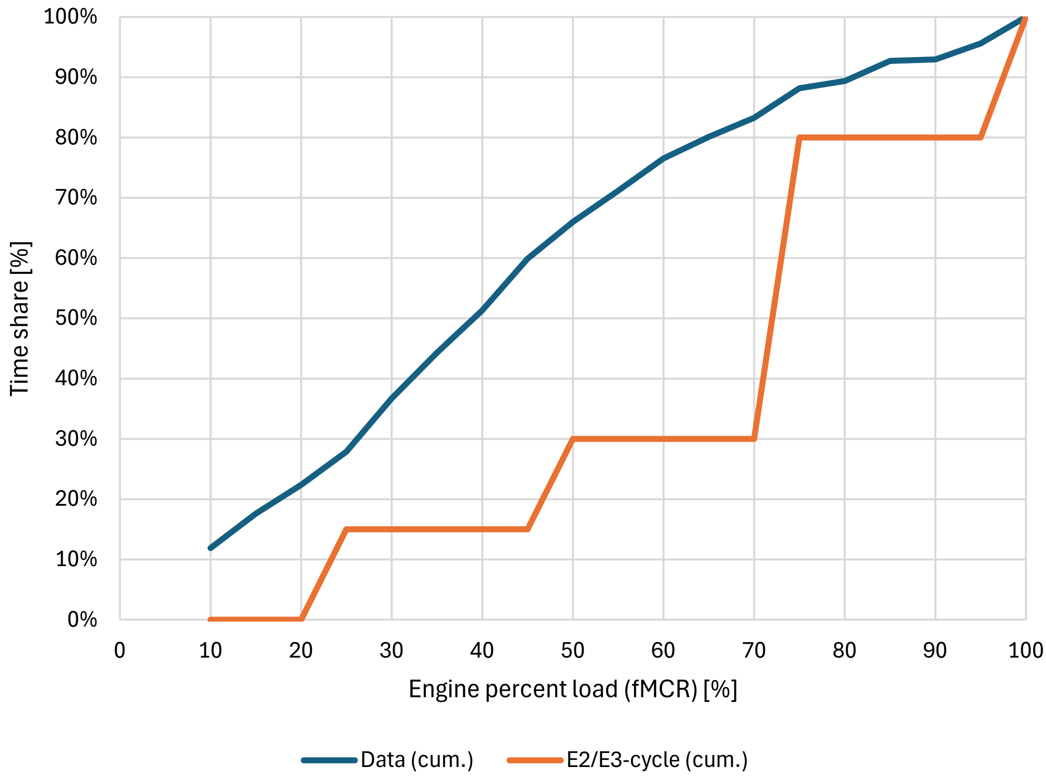

Figure 4.1: Comparison of weights of engine load bins in the operational data and according to the certification test cycles to the NO_x Technical Code [7], [8].

Main engine load per ship type

If the fMCR of the tier III vessels is related to the type of ship, it can be observed that all the ship types operate in the lower fMCR ranges for a majority of the time.

Figure 4.2 shows the percentage of time each ship type spends in a particular fMCR-bin. All ship types spend over 70 % of the time in fMCR less than and equal to 65. Miscellaneous ships, Container ships and Tug/Supply ships spend the most time sailing at lower fMCR. This should correspond to them having the biggest difference between emissions before and after applying a load correction factor. Chemical/LNG/LPG tanker ships, General Dry Cargo ships, Oil Tankers, Passenger ships and RoRo Cargo/Vehicle ships on the other hand, sail at comparatively higher fMCR. This should correspond to them having a relatively smaller difference in emissions before and after applying a load correction factor.

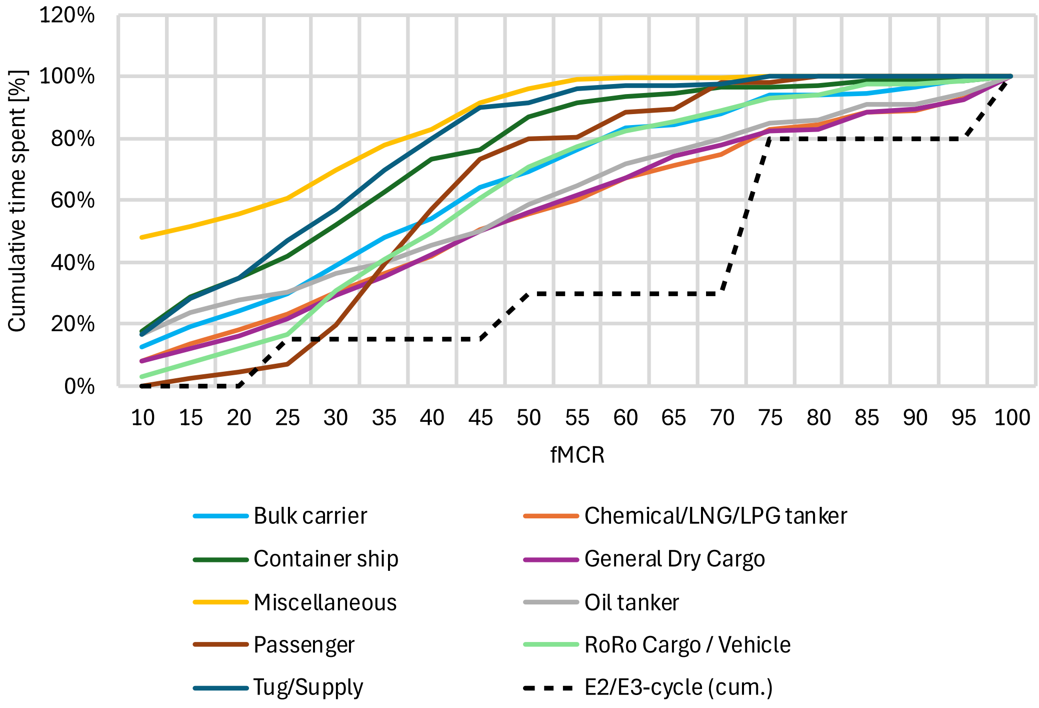

Figure 4.2: Cumulative time spent by the ships active main engines in each fMCR bin per ship type.

Main engine load per ship size

Following a similar methodology, the fMCR is related to the size (Gross Tonnage: GT) of the ships. It can be observed that all the ship sizes operate in the lower fMCR ranges for a majority of the time. Figure 4.3 shows the percentage of time each ship spends in a particular fMCR. All ships spend over 70 % of the time in fMCR less than and equal to 70. The lightest ship bin of 0-99 GT has been excluded from the analysis since the number of sailing hours (12) is not sufficient to be representable. Ships in the 100-1599 GT category sail the most at the lower engine loads. On the other hand, ships in the 10,000-29,999 GT category sail the least at lower engine loads.

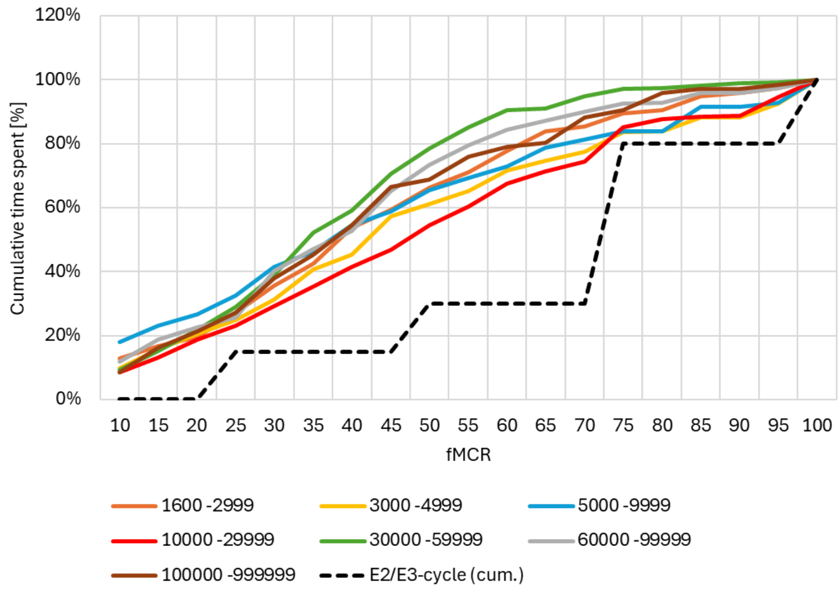

Figure 4.3: Cumulative time spent by the ships active main engines in each fMCR bin per size (gross tonnage) of the ship.

Main engine load per region

The differences in sailing at lower engine loads is significant between different regions. Ships sailing in Amsterdam, Rotterdam, and the Westerschelde spend a lot of time at lower engine loads. This should also correspond to higher emissions in those regions. Harlingen, Den Helder, Eems(haven) and the out of 12-mile zone on the other hand, have ships sailing less at lower engine loads. This should then correspond to lower differences in emissions before and after applying a load correction factor in these regions, which is covered in the following section.

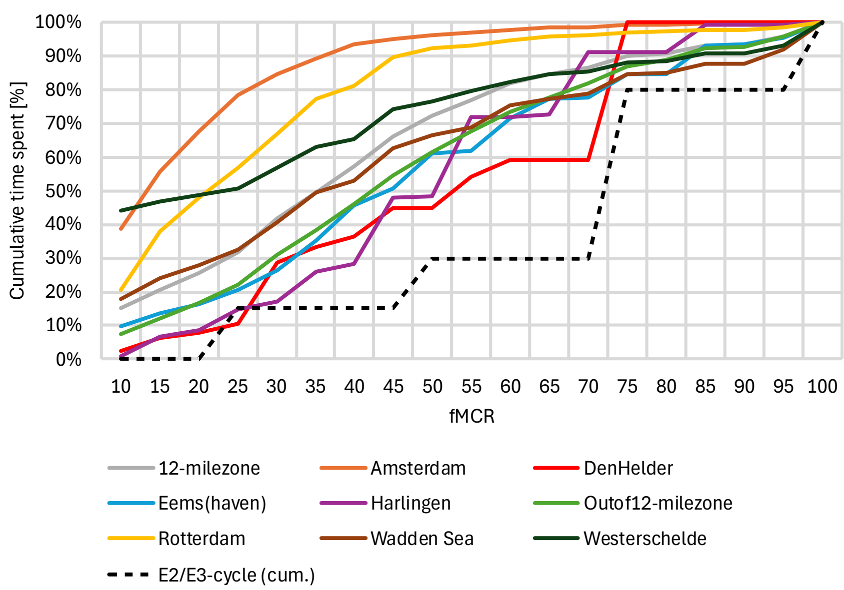

Figure 4.4: Cumulative time spent by the ships active main engines in each fMCR bin per region.

The out of the 12-mile region and the 12-mile zone region together have about 80 % of the entire data of sailing, hence it also translates to the most emissions.

4.2 NO_x-emissions

Subsequently to the determination of the share of operating loads in regular operating conditions, the NO_x-emissions are modelled as described in Chapter 3. In this section, the NO_x-emissions are quantified and shown per variable ship size, type and operating area, the contribution of NO_x-emissions coming from low-load operating conditions of the main engines are quantified. In these scenarios, low load is defined as fMCR of the main engines below 25%. The share of the NO_x-emissions produced at these low loads emissions in the total emissions is determined. In addition, the NO_x-emissions are computed for the dataset itself, meaning the absolute values represent the NO_x-emissions of a quarter of the year 2023.

Overall, the estimated NO_x-emissions coming from engine loads below 25% fMCR add up to a total of 21% of the total NO_x-emissions, being 565 tonnes.

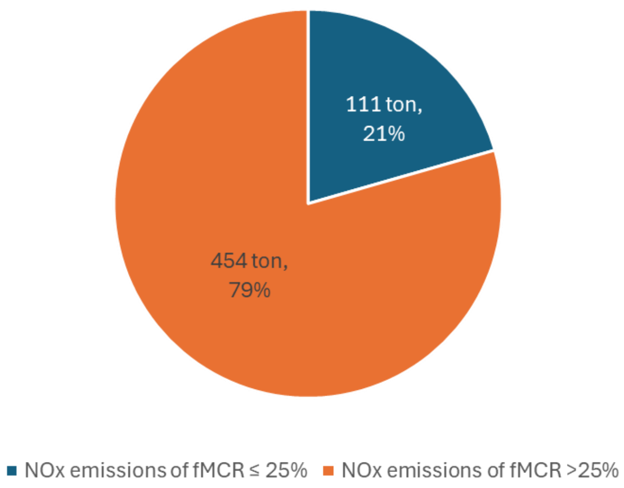

Figure 4.5: NO_x-emissions from main engine loads equal and above and below 25%.

NO_x-emissions per ship type

The distribution of total NO_x-emissions among the different ship types is shown in Figure 4.6. The results indicate that chemical/LNG/LPG tankers are the dominant contributors to the overall NO_x-emissions in the dataset. This aligns with their representation in the dataset as indicated in Table 3.1, where this type of ship represents 37% of the total sailing hours in the dataset. Translated to emissions, they contribute to 32% of the total emissions, which is considerably higher than other categories.

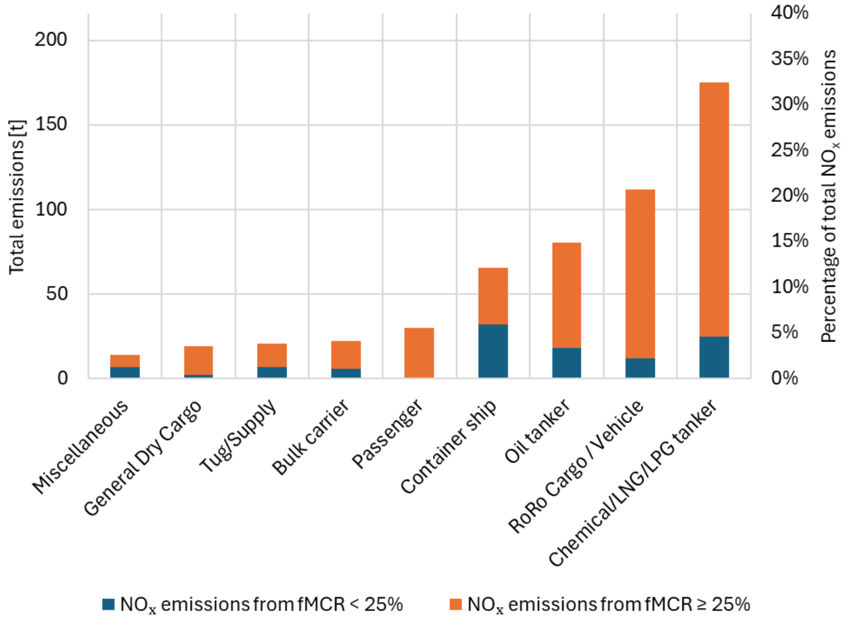

Figure 4.6: Total main engine NO_x-emissions by ship type, divided into the contributions from main engine loads below or equal and above 25%.

The chemical/LNG/LPG tanker category is subsequently followed by RoRo cargo, oil tankers and container ships. Much more noticeable is the share of emissions resulting from low load conditions as depicted in Figure 4.6. Although they are the same four categories contributing most to these emissions, the container ships contribute most to the NO_x-emissions generated by low loads while being the fourth in overall emissions. To quantify, container ships hold a share of 12% of all emissions while contributing to 29% of the emissions from low load operation. This is also indicated in Figure 4.7, where it can be seen that almost 50% from all NO_x-emissions from container ships are generated at fMCR <25%.
The share of low load emissions is also significantly high in miscellaneous and tug/supply ships, but these have a significantly smaller contribution to the overall emissions.

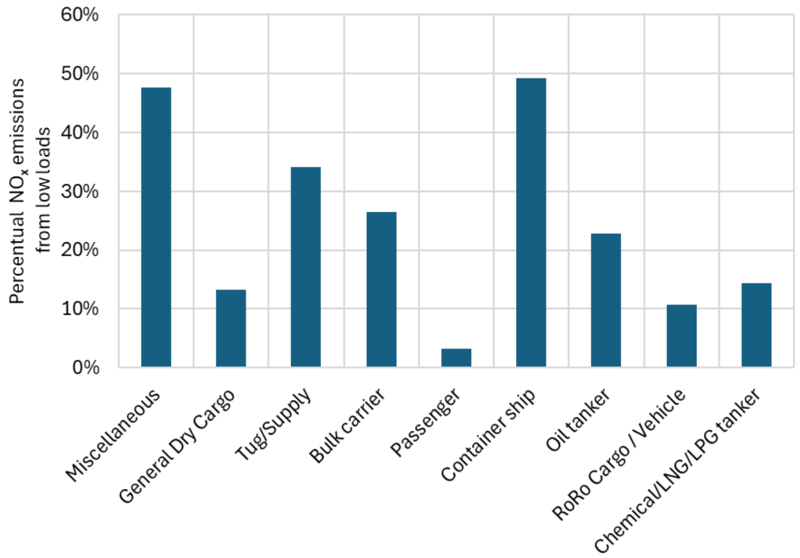

Figure 4.7: The percentage of NO_x emitted by the main engines in fMCR <25% of the main engines per region.

NO_x-emissions per ship size

The larger ships, even when they do not have the most sailing hours (as shown earlier Table 3.3), contribute the most to the absolute emissions. This reflects the higher installed engine power and fuel consumption typical of larger vessels. An exception are the 30,000-59,000 GT ships, that contribute to less absolute emissions than the 10,000-29,000 GT ships. This is due to the larger share of sailing hours from the 1,000-29,000 GT ships in the data set, which again indicates a larger active fleet in this ship size. This is visualized in Figure 4.8, where it is shown that the NO_x from low load conditions also increase with size, with a similar exception in the 10,000 to 29,999 GT class. Consequently, the emissions in low load conditions from this segment slightly outweigh those of the next to larger category despite individual ships being smaller.

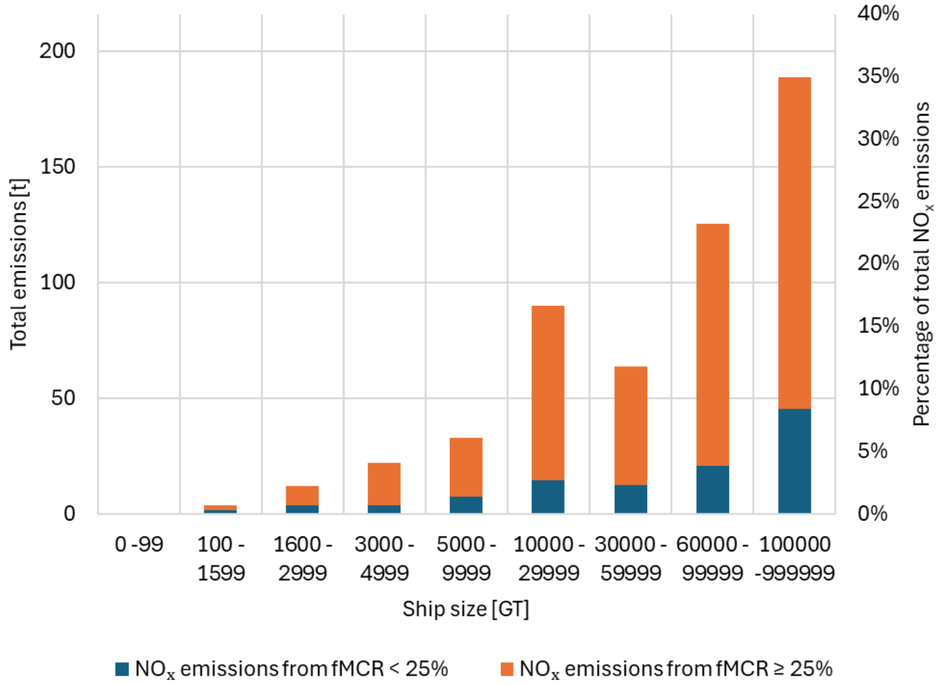

Figure 4.8: Total NO_x-emissions by ship size (gross tonnage), divided into the contributions from main engine loads below and equal and above 25%.

The share of low load emissions of the main engines per ship size is shown in Figure 4.9, where only the two lightest categories of ships indicate a higher contribution of emissions by low load conditions. When considering the absolute emission levels from **Figure 4.8,** smaller vessels represent only a minor portion of total NO_x-emissions. Therefore, although the relative share of low-load emissions is high for smaller ships, their overall contribution to total NO_x-emissions remains limited.

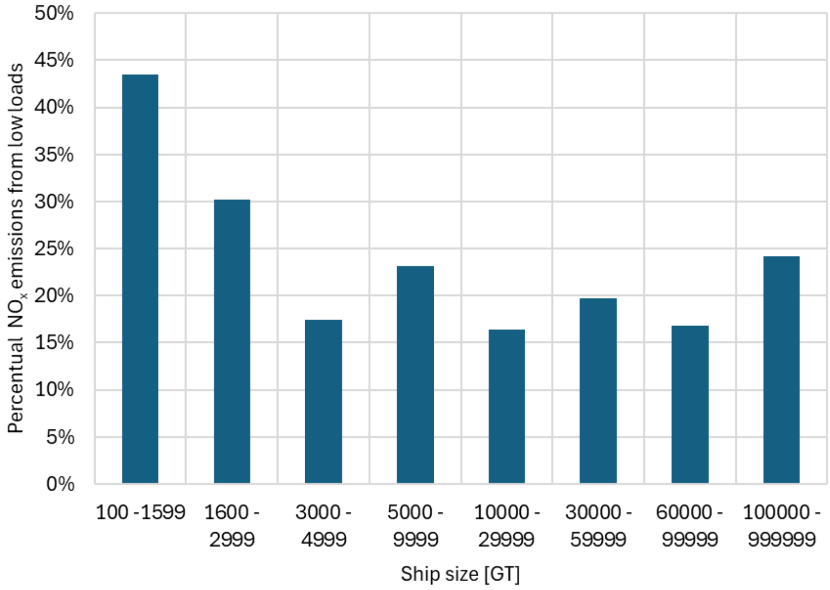

Figure 4.9: The percentage of NO_x emitted in fMCR <25% of the main engines per ship size.

NO_x-emissions per region

The final division is made by categorizing the emissions per region. Again, the Dutch sea port regions (Amsterdam, Den Helder, Eemshaven, Harlingen, Rotterdam, Westerschelde) are combined to indicate the combined contribution of these regions in comparison to the total emissions. The results are shown in Figure 4.10 where it is clearly visible that most emissions, 77%, occur in the out-of-12 mile zone. Additionally, the emissions from low loads have the largest share in this region. This is explained by the number of sailing hours, 62%, as depicted in **Table 3.2.**

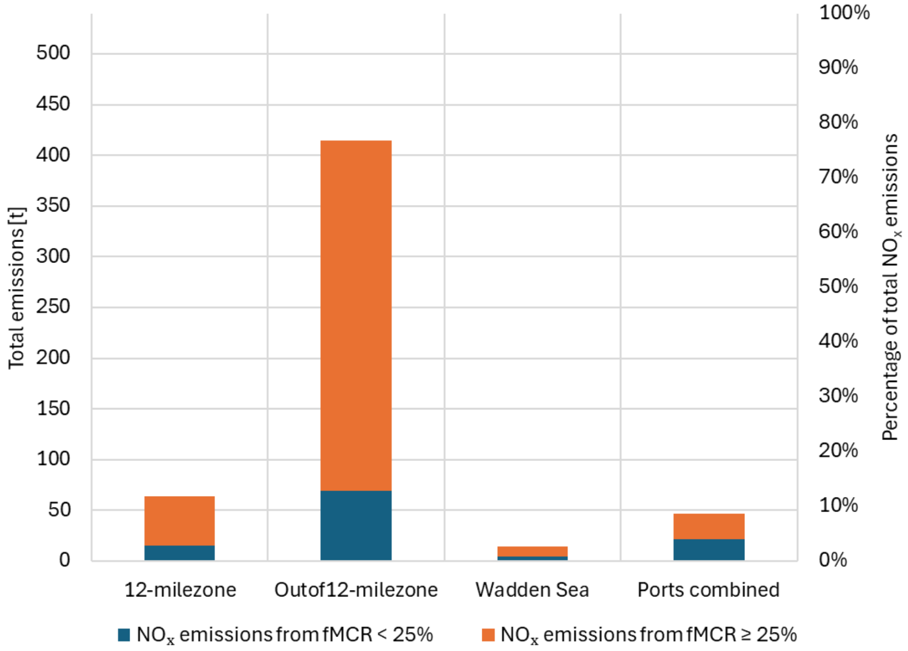

Figure 4.10: Total NO_x-emissions per region, divided into the contributions from main engine loads below and equal and above 25%.

Although emissions are highest at areas further from the coast, it is relevant to zoom in on the emissions occurring in more critical locations, such as coastal zones and port areas. In these areas, the local concentration of NO_x-emissions has a disproportionate impact due to the proximity to densely populated regions and ecologically sensitive environments. Port areas and the 12-mile zone contribute to only 10% each of the emissions, but reducing emissions here can have a more significant impact for human health and the environment.

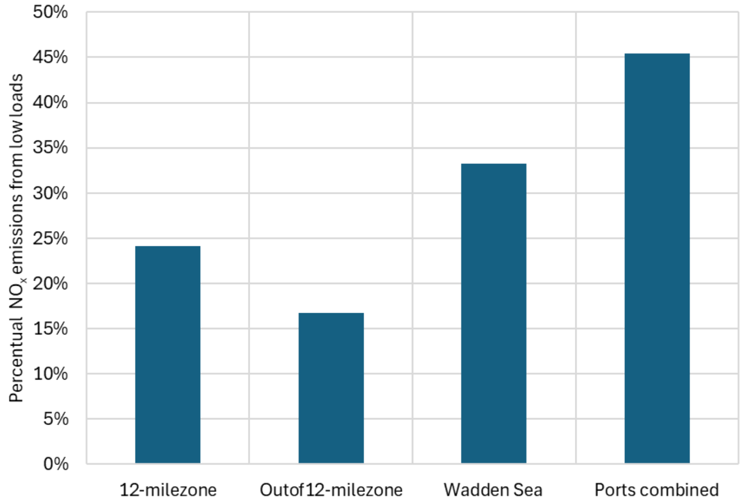

Figure 4.11: The percentage of NO_x emitted in fMCR <25% operating conditions per region.

In Figure 4.11 the share of low load emissions per region is visualized. As shown, ports show the highest percentage share of low load emissions, while areas further onto the open water indicate a smaller share of these emissions. This can be explained by vessels operating at higher fMCR out of port regions, where they do not need to reduce speeds or manoeuvre. This indicates that regulation of emissions at low loads can significantly impact overall NO_x-emissions in these specific regions.

4.3 Interviews

This sections describes the findings of three shipowners in their experience with NO_x-emissions and systems to reduce these emissions. The details of the ships these owners hold in their fleet is described in the methodology.

Application per shipowner

Two shipowners were interviewed and information from a third one was added, as described in the methodology. Here, the specifications of the ships of the shipowners is also given. Below shows the perceived overall application of SCR systems.

- **Shipowner 1:**
  The SCR system is integrated into MAN two-stroke main engines. The system becomes operational only when exhaust temperatures exceed approximately 200°C, which is generally achieved at higher engine loads. This presents a limitation during low-power operations, such as port approach or manoeuvring, when the exhaust temperature is insufficient to trigger the SCR reaction needed for NO_x-reduction. The SCR system requires significant power input (around 50 kW) for urea injection and air compressors and is physically large and complex in design.

- **Shipowner 2:**
  The SCR system is installed on the ship's generator engines and operates independently of the main propulsion engine. The system functions continuously under normal operating conditions. The company reports no major technical issues or operational disruptions. The system runs autonomously, with limited crew interaction unless an alarm is raised.

- **Shipowner 3:**
  The SCR system is integrated in the control of the diesel main engines. Aside from the manufacturers control system, the engines are equipped with retrofit NO_x-CEMS systems which enables the owner to measure, monitor and report it's NO_x-emissions and to monitor independently for degradation or malfunctions.

Operational usage

- **Shipowner 1:**
  SCR operation is restricted to high engine loads, as the exhaust temperature at lower loads remains below the threshold required for effective NO_x-conversion. During port manoeuvring or low-speed operations, the system is inactive. The crew monitors the system using MAN's proprietary software, which provides limited trend data but lacks detailed real-time insights. As a result, the crew has a minimal role in system optimization or performance analysis.

  The NO_x abatement technology, in our case SCR, is only activated within designated NECA zones (NO_x Emission Control Areas), which include the North Sea, the Baltic Sea, and the 20-mile zone around the USA. Outside these areas, the systems are switched off and our vessels operate on VLSFO (Very Low Sulphur Fuel Oil), a heavy fuel oil with a maximum sulphur content of 0.49%. In NECA zones, the vessels operate on ULSMGO (Ultra Low Sulphur Marine Gas Oil), a marine gas oil with a maximum sulphur content of 0.09%. This is because NECA zones are also SECA (Sulphur Emission Control Area) zones, and from a technical perspective (due to contamination and certification requirements), SCR systems can only be used with marine gas oil.

- **Shipowner 2:**
  The SCR system on auxiliary generators is considered part of routine operations. No active emission logging or real-time performance tracking is conducted. Instead, monitoring focuses on system functionality rather than emission outcomes. Class inspections are intended to verify compliance, though these have not yet been carried out for all vessels in the fleet. Consequently, insight into real-world operational effectiveness remains limited.

- **Shipowner 3:**
  The diesel-electric propulsion with three gensets allows engine loads to be managed for the typical dredger cycle. The operator switches engines on and off depending on the required power for the operations. By keeping engine loads high, engines run at a higher efficiency and SCR can work optimally at these engine loads. Active load management prevents the low engine loads where SCR is outside its operational temperature window. This application of load management can be demonstrated by the data obtained from the installed CEMS.

Experience and reflection

The experiences of the shipowners reveal distinct operational challenges and attitudes toward SCR management.

- **Shipowner 1:**
  The company highlights several issues affecting SCR usability. The system does not function during cold starts or low-load operations, resulting in periods of unmitigated NO_x-emissions. The investment and operating costs are substantial with capital expenditures around €1.5 million and operational expenses estimated at €133 per hour for urea consumption. Maintenance challenges include the risk of urea nozzle blockages and inconsistent test results between vessels, as each ship has unique operational characteristics. Each of the vessels is also equipped with SCR systems on the generators (Yanmar) consisting of four units of 1300 kW per vessel. These SCR systems operate reliably with minimal maintenance requirements. However, crew engagement remains low, as the systems are only checked when an alarm occurs.

- **Shipowner 2:**
  The company reports that the SCR systems operate reliably with minimal maintenance requirements. However, crew engagement remains low, as the systems are only checked when an alarm occurs. Preventive inspections or proactive performance assessments are not part of standard procedures. The company's focus lies primarily on operational continuity.

- **Shipowner 3:**
  The company reports that the SCR systems operate reliably, but with maintenance requirements. Catalysts degrade and need to be replaced periodically (each 3 years approximately). Live NO_x monitoring and NO_x reporting is part of the operational routines of the dredger vessels, because this is required by some of the contractors.

Data Availability

Data accessibility and utilization are key challenges for two of the companies.

- **Shipowner 1:**
  Emission data are collected and stored by the engine manufacturer (MAN), and onboard access for the crew is highly restricted. The data are not routinely analysed or used for internal performance tracking. They have expressed willingness to share anonymized data with research organizations such as TNO, provided that such data are relevant and compliant with confidentiality agreements.

- **Shipowner 2:**
  No active emission data logging is conducted. Data are primarily available through vessel management systems responsible for maintaining SCR units and generators. However, emission data are not currently prioritized for retrieval or analysis. Monitoring focuses on system functionality (e.g., alarm status, urea levels) rather than emission outcomes.

- **Shipowner 3:**
  The OEM engine and SCR control system has a GUI to show NO_x-emissions and system malfunctions and alarms. The system does not allow monitoring and reporting. For this reason a NO_x-CEMS is retrofitted to all main engines.
  The system can report emissions data live to the owners back office.

5 Discussion

Comparison of fMCR of real sailing with the test cycles applicable for the NO_x technical code

When the data is put in perspective of the NO_x technical code, it turns out that the test cycles used for NO_x technical code underestimate the sailing at lower main engine load (fMCR) in the Dutch sea and seaport areas. The data shows a shift of fMCR to lower loads in comparison to the E2 and E3 cycles. A significant amount of low fMCR sailing is observed, – on average about 28% of the time the fMCR is below 25%, while this load range isn't part of the E2 and E3 cycles. Also, 80% of the total time sailing is done at fMCR lower than and equal to 65%. In comparison, for the E3 cycle ships sail at fMCR lower than and equal to 65% for 30% of the time,. The latter assumes a big part of sailing is done at higher fMCR, cf. Figure 4.1 on page 15.

Analysis of real sailing data for different regions, ship types and sizes and the estimated impact of low engine load operation on NO_x-emissions.

The data analysis showed the clear relationship between the sailing at lower fMCR to the NO_x-emissions. All the ship types, sizes and regions where ships sail at lower fMCR have a higher share of the NO_x-emissions at low load engine operation compared to the total NO_x-emissions.

The load correction factors for engine loads are based on limited data and engineering judgement and apply for all Tier III certified main engines. Since low-load conditions are characterized by low exhaust gas temperatures, they limit the effective use of SCR systems and promote the formation of Ammonium Bisulfate (ABS) [6, pp. 61–65]. Moreover, SCR performance is influenced by manufacturer-specific design and control strategies, introducing uncertainty in the applied load correction factors. In addition, a certain share of the engines is equipped with exhaust gas recirculation (EGR) instead of SCR to reduce engine NO_x-emissions. EGR also has challenges for low load operation (switch-off at low load and reduced EGR rates). To verify these load-dependent NO_x-emission correction factors, real-world data from emission inventories would be required.

From the analysis of the different types of ships, Chemical/LNG/LPG tankers and passenger ships have the highest total NO_x-emission. This can mostly be attributed to higher tonnage of these vessels. The total emissions are also in a direct proportion to the hours of sailing data in the dataset.

Despite the high total emissions of Chemical/LNG/LPG tankers and passenger ships, the container ships have the highest share and the highest total NO_x-emissions produced at low engine load, see Figure 4.6 and Figure 4.7. For container ships this can probably largely be attributed to the higher share engine operation at low loads compared to the other ship types. The cause of this high share of low-load operation would have to be investigated further.

From the analysis of the different sizes of ships, the heavier ships have the highest share in the total emissions, see Figure 4.8. This is in line with the expectations since heavier ships generally need more power for propulsion. This leads to more emissions.

From the analysis of the region of sailing, the ‘out of 12-mile zone’ has the highest total emissions when compared to the other regions. This can mostly be attributed to the higher sailing intensity and the larger fraction of heavier ships in this region. The total emissions are in proportion to the amount of sailing hours in each region and to the ship size.
For the port of Amsterdam and port of Rotterdam the share of NO_x-emissions at low load operation are the highest, see Figure 4.10 and Figure 4.11. This is in line with the high fraction of low engine load operation in these two ports (Figure 4.4**).**

Interviews with shipowners

The interviews provide some insight into the practical use of SCR systems on seagoing vessels as three shipowners have reflected on their operational experience with SCR systems.

This revealed differences in how SCR systems for NO_x-control are managed. Two rely mainly on OEM control systems, alarms, and prescribed routines, with no (emissions) trend data available from these systems. The third actively monitors NO_x-performance and optimizes engine operation using data from a retrofitted Continuous Emission Monitoring System (CEMS).

One of the shipowners mentioned SCR inactivity for low-power operations, such as during port approach or manoeuvring. While the findings of the interviews are not representative of the wider fleet, the experiences described do align with commonly reported challenges in obtaining reliable and accessible emissions data from these systems.

Initially, the aim was to obtain operating power data from these vessels, but it has been found that this data is difficult to obtain. The issue lies not within the willingness of shipowners to share the data, but in the accessibility to the people involved. Actual data from the engines and emission control system can most of the times be observed from instrument panels of these systems in the engine control room. Availability of trend data however, often depends on whether the owner purchased additional functionality to present or extract longer term trend data from these systems.

Given the small sample size in representation of shipowners, further information from a larger group of shipowners and vessels is needed to validate these observations. Additional operational data and actual on-board emission and engine monitoring would help to form a more complete picture of how SCR systems function in practice and could support future efforts to improve data availability, monitoring practices, and the overall effectiveness of NO_x-reduction measures.

Directions to address the shortcomings of the regulation 13 NO_x-emissions air pollution reduction programme

The analyses conducted, showed substantial engine low-load operation of main propulsion engines and consequently substantial shares of NO_x emitted in environmentally critical areas, the coastal waters and sea port areas of the Netherlands. Until now, IMO Regulations targeted NO_x-emission reduction by means of certification procedures that do not reflect the actual operation of engines in the environmentally critical areas because low load engine operation isn’t part of the official test cycles which are used for the certification of marine engines.

NO_x-emission reductions are also needed in the low load part of the engine map of propulsion engines. The most obvious adaptation to make, would be to include low load, such as 10% in the certification test cycles for main propulsion engines and to use representative weighting factors for the test cycle load points. Such adaptations would not guarantee good emission performance at low loads, however, since emissions may be balanced at the cost of an increase of emissions over the high load points. Additional requirements are probably necessary to secure low NO_x-emissions over the whole engine map and it needs to be investigated what is technically feasible. These kind of adaptations to the NO_x Technical Code or SCR-guidelines would probably lead to substantial effects for the longer term. Adaptations that could lead to substantial NO_x-reductions for the short term would be the exclusive management of low load emissions down to 10%, separately from the other load points and the introduction of NO_x-monitoring and reporting which could be used to incentivise low emissions and good operating practices.

6 Conclusions and recommendations

Using AIS-derived sailing profiles, the study quantified low-load operation shares and estimated the share of NO_x emitted at low load in the total NO_x-emissions for Tier III ships sailing in the Dutch sea and seaport areas. The method used a dataset which is also used for calculation of NO_x-emissions for the Maritime sector for the Dutch Pollutant Release and Transfer Register. Correction factors for Tier III engines from the same Register were used to calculate NO_x-emissions from Tier III ships in the Dutch sea and seaport areas. The effects were assessed by ship type, ship size and Dutch maritime region, to identify areas with the greatest impact.

The results of the analysis indicate that according to the method used, marine engines spend a significant fraction of their time below 25% load, which is the lowest power in the test used for certification of main engines.

On average, engines spend about 28% of the time below 25% load. For large ports this fraction of time is the highest (about 55-77% of the time) and for regions further away from the coast, outside the 12-miles zone the lowest (about 20% of the time).

On average in the Dutch sea and seaport areas about 21% of the NO_x is emitted at low load. These shares are the highest for the port areas (45 %) and is the lowest for the region further from the coast (outside 12 mile zone: 17%).

Out of the vessel types, container vessels stand out, and it was calculated that these ships emit about half of their NO_x-emissions at low load in the Dutch sea and seaport areas.

These low-load conditions and related NO_x-emissions represent a substantial share of activity and NO_x-emissions in Dutch port areas and coastal waters. Addressing them is essential for achieving NO_x-reductions where environmental and public health benefits are greatest.

Interviews with three shipowners revealed differences in how SCR systems for NO_x-control are managed. Two rely mainly on OEM control systems, alarms, and prescribed routines, with no (emissions) trend data available from these systems. The third actively monitors NO_x-performance and optimizes engine operation using data from a retrofitted Continuous Emission Monitoring System (CEMS).

This study was conducted to obtain an indication of the real sailing load profiles of maritime engines and to determine if low-load operation has a substantial share in NO_x-emissions from Tier III engines. While this is indeed indicated by the analysis based on a limited dataset, we recommend to further investigate the impact for the longer term and with a larger dataset.

We recommend to investigate options for revision of the requirements as part of the regulation, such as the use of more representative weighting factors and adding a low load point to the test cycles for main propulsion engines. For the shorter term, the introduction of a low load emission management requirement down to 10% separate from test cycle values and the application of emissions monitoring and reporting requirements, could be considered as part of the regulation to improve the NO_x-emissions during low load operations. We also recommend to determine the effect of these scenario's on maritime NO_x-emissions, especially for port areas and coastal waters.

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Signature

TNO ⟩ Mobility & Built Environment ⟩ The Hague, 5 December 2025

ValidSigned by Jan Hoegee on 2025-12-05 14:20:52	ValidSigned by Robin Vermeulen on 2025-12-05 14:21:46
Jan Hoegee Research manager	R.J. Vermeulen Author

Appendix A
Supplementary information on the simulation of NOx-emission

Table A.1: Columns in the dataset received from MARIN along with their definitions.

Column name	Definition
region	Area in which the (modelled) emissions occurred.
mmsi_anon	Anonymized MMSI number
ems_type	EMS-type of ship
ems_size	EMS-size of ship
stofnr	Substance number (NO_x)
moving	Boolean showing ship moving or stationary
fmcr	Fractional Maximum Continuous Rating
sumofkw_me_used	Cumulated power of main engines
sumof_kw_ae_used	Cumulated power of auxiliary engines
hours	Cumulated time spent in a region and fMCR bin
gthours	Hours times the GT of the vessel
emission_aeport_kg	Cumulated emissions of auxiliary engines in port
emission_me_kg	Cumulated emissions of main engines
sumofspeed_ais	Cumulated speed
speed_ais	Speed acc. to AIS message
gt_nm	GT multiplied with the distance sailed in the bin

Appendix B
Interview structure and questions

The interviews have been structured in a set of segments to discuss the different relevant topics with the shipowners.

Overall, it is structured in two parts:
- A request for technical specifications on the relevant ships and systems and
- Questions regarding the experience in usage of the SCR systems.

1. **Experience with SCR After-Treatment Systems**
   - Could you share your experiences with SCR after-treatment systems on Tier III ships with two-stroke engines?
   - Do these systems function properly in practice? Are there operational challenges or points of attention?
   - Are emission data generated by these systems stored and analyzed?
   - Have any interesting insights emerged from this data?
   - Do you see possibilities to share this data (anonymized) with TNO for policy development and technical optimization?

2. **Experience with NO_x Emission Monitoring System**
   Is there a NO_x Emission Monitoring System (CEMS) installed on your ship?
   If no:
   - Have you previously attempted to install an emission monitoring system? (If yes, what challenges did you encounter?)
   - Why did you decide not to install such a system?

   If yes:
   - Why did you decide to install an emission monitoring system? What were your considerations?
   - When was the system installed?
   - Who installed the system?
   - What problems did you encounter during installation?
   - How did you get the system operational?
   - How do you experience using the system?
   - Are the results reliable?
   - Have reference measurements ever been conducted to validate the system? (If yes, can this data be made available for the research?)
   - Are there differences in measured values between sensors in the system?
   - How do you experience system maintenance?
     - How often and how is the system maintained? Do you perform this yourself?
     - How often is the system calibrated? Do you perform this yourself?
     - How do you determine when maintenance is needed? Does the system indicate this?

3. **Desired Data Set for NO_x Monitoring (Per Engine)**
   Time-Based Data:
   - NO_x-tailpipe concentration (ppm) – downstream of NO_x after-treatment system
   - Ambient air pressure (Pa)
   - Manifold air temperature (°C)
   - Manifold air pressure (Pa)
   - Engine speed (RPM)
   - Engine power (kW) – if available, electrical generator power, fuel rack position, fuel flow, etc.

   Fixed Parameters:
   - Engine cylinder volume (m^3)
   - Volumetric efficiency map (%) – from test bench data, otherwise default value
   - Specific fuel consumption map (g/kWh) – from test bench data
   - NO_x-sensor installation location
   - NO_x-sensor specification sheet
   - NO_x-sensor calibration specifications

4. **Vessel Information**
- Ship name
- IMO number
- Flag state
- Year of construction
- Length, width, and draft
- Gross tonnage
- Ship type (e.g., cargo ship, tanker, passenger vessel)
- Number of engines
- Engine configuration
- Engine power
- Exhaust gas after-treatment system configuration
- Fuel type(s)
- Propulsion type

5. **Specifications of the NO_x Emission Monitoring System (If Present)**
- Name of the CEMS system
- Manufacturer of the CEMS system
- How does the system measure NO_x?
  - Are sensors/analyzers used?
  - Which substances/parameters does the system measure?
  - Which data/parameters can you view/use from the system?
  - What do you do with the data from the system?
- What is the system configuration?
  - How many sensors are there?
  - Where are they located?
    - How deep are the sensors placed in the exhaust?
    - How far from the after-treatment system are the sensors placed?
  - Are photos and/or technical drawings of the system available? Can these be shared?

Mobility & Built Environment

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