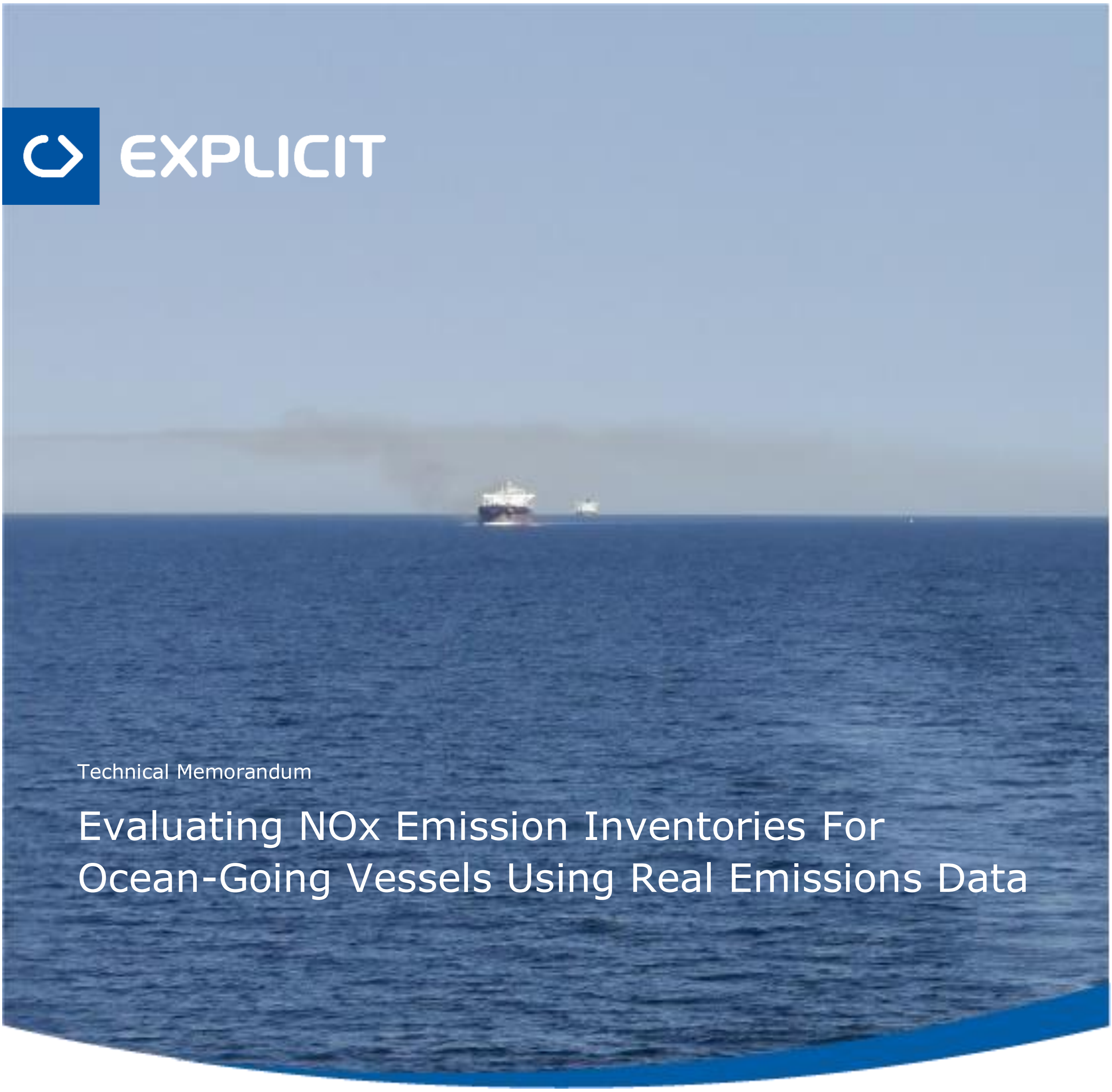

Technical Memorandum

Evaluating NOx Emission Inventories For Ocean-Going Vessels Using Real Emissions Data

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Introduction

This report has been prepared by Explicit ApS on behalf of – and in collaboration with – the International Clean Shipping Program under the South Coast Air Quality Management District (South Coast AQMD).

In connection with work on reevaluating the emissions inventory assumptions for ocean-going vessels (OGVs), the South Coast AQMD has engaged with Explicit to use the real sailing emissions (RSE) data on NOx and CO2 collected by Explicit through airborne surveillance of individual ship emissions, to establish load-dependent NOx emission rates. The derived emission patterns are subsequently used to evaluate the current load adjustment factors utilized in the current OGV emissions inventory.

Explicit ApS is a Danish company specializing in airborne surveillance of ship emissions at sea. The company has assisted, among others, the Danish Environmental Protection Agency, and the European Maritime Safety Agency in conducting multi-year airborne monitoring campaigns to help enforce low sulfur fuel requirements for the North Sea and the Baltic Sea Emission Control Areas documenting SO_2 and CO_2 emissions. As part of the quality control of samples collected, NOx sensors were also installed with NO and NO_2 measurements taken, and initial NOx/CO_2 ratios calculated for all vessels.

Over the course of the past 6 years, Explicit has collected RSE data from more than 3,000 ships operating in European waters. The NOx/CO_2 ratios are one of the few maritime RSE datasets available and thus a prominent source to understanding NOx emission patterns at sea.

A total of 929 ship observations, collected in Dutch and Danish waters in 2016 and 2020 respectively, have been made available to this project. While the data does not stem from Californian waters, the type of vessels and, in particular, the mode of operation with typical cruise speeds similar to those found in the waters leading into the San Pedro Bay, make the dataset a valuable real emissions insight with associate applicability to the South Coast area.

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Acronyms and Abbreviations

CO_2	Carbon dioxide
DWT	Deadweight tonnage
e	Specific fuel consumption (load-adjusted)
ECA	Emission Control Area (as designated by the IMO)
EF	Emission factor
EIAPP	Engine International Air Pollution Prevention Certificate
HSD	High-speed diesel, defined as >900 RPM as per the IMO4GHG
IMO	International Maritime Organization, a subsidiary body of the United Nations
IMO4GHG	Fourth IMO GHG Study: Final Report (CE Delft, 2020)
LF	Load factor for the propulsion engine
MCR	Maximum continuous rating, or the maximum power output an engine can produce while operating continuously
MSD	Medium-speed diesel, defined as >300 to 900 RPM as per the IMO4GHG
NOx	Nitrogen oxides, i.e., nitric oxide (NO) and nitrogen dioxide (NO_2).
NE-ECA	North-European Emissions Control Area
OGV	Ocean-going vessel
Reefer	Refrigerated cargo ship
Ro/Ro	Roll-on/roll-off, vessel type used to carry wheeled cargo.
RPM	Rotations per minute
RSE	Real sailing emissions
South Coast AQMD	South Coast Air Quality Management District
SFC	Specific fuel consumption (base)
SPBPEI	San Pedro Bay Ports Emissions Inventory Methodology Report, Version 1 (Starcrest, 2019)
SSD	Slow-speed diesel, defined as up to ≤ 300 RPM as per the IMO4GHG

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1 Summary

This Technical Memorandum presents an in-depth analysis of the real sailing emissions (RSE) of more than 700 ocean-going vessels (OGVs) collected via airborne surveillance for the purpose of evaluating the existing OGV emission inventory on NOx used by the South California Air Quality Management District.

This study is one-of-a-kind in its combination of real-world exhaust gas measurements on a large fleet sample with individual engine and type data on each ship. The combination enables an evaluation of the existing load adjustment factors central to the emission inventory against a broad set of maritime emissions data collected at sea under actual operational conditions. Such studies have never been done before at this scale.

The analysis includes 883 observations (post exclusions) from 749 individual ships. The RSE data is exceptionally broad, covering ships of all type classes, sizes, engines, and engine types.

While the sampling approach is unable to distinguish between emission sources (main engines, auxiliary engines, and boilers), both the transit nature and the gas concentration levels in the plume of the observed ships are consistent with main engine outputs, with other sources expected to play a relatively minor role in the measurements and unlikely to drive the observed changes in measured emissions along the range of main engine loads.

Using well-referenced scientific methodology, the existing U.S. EPA guidance on establishing emissions factors, and the 4th IMO study of Greenhouse Gas emissions from ships, the analysis establishes load-dependent emission factors for each RSE observation and presents these in various breakdowns relevant to the evaluation effort.

The main findings of the RSE load-dependent analysis are as follows:

- The average recorded AIS speed in the RSE data is 12.2 knots (kn), also referred to as *super-slow steaming*. This speed is consistent with typical ECA / near-shore operations.
- The calculated average NOx emission factor is 12.46 g/kWh. However, this average covers a significant spread of factors from 1.06 to 37.71 g/kWh.
- The top 25 ship observations with the highest NOx emission factors (ca. 3 % of the total), averaging 28.81 g/kWh, have the following main characteristics:
  - 96 % are propelled by SSD main engines
  - 76 % are container vessels
  - 64 % are operating at estimated main engine loads of 25 % or lower
  - 60 % are Tier II (incl. vessels with keels laid in 2016 or later)
  - 56 % have main engines ≥40,000 kW
  - 52 % are ≥120.000 DWT
- In general, the highest emission factors are found below an estimated engine load of 25%, i.e., below the lowest load point tested for main engines under the NOx Technical Code (MEPC.177(58)). This is also where the biggest spread in factors is found ranging from 5-38 g/kWh for all tiers.
- Tier II vessels also appear to have a bigger spread in emissions factors than older tiers, particularly at lower main engine loads.
- In particular, container vessels are found to have a distinctly different emissions pattern than other ship types, with higher emissions at low main engine loads, a higher general

average, and a big spread in factors overall. Here, the load appears to matter more towards the NOx output than for other ship types.

- Equally, the size of the vessel – both in terms MCR and DWT – appears to have a significant impact on the load factors as well as the NOx output. "Big" ships operating under super-slow steaming conditions are found to only utilize roughly max half of their load capacity while at the same time accounting for some of the highest emissions factors observed (21 g/kWh on average).
- Compared by engine type, the same large spread in NOx emission factors, with a significant number of high values, is echoed in the pattern for SSD vessels (nearly all of which are propelled by two-stroke main engines), clearly different from the profiles for MSD or HSD ships (nearly all of which are propelled by four-stroke main engines).

In the evaluation of the current NOx emission factors used in the OGV emission inventory, an array of different load-dependent NOx curves — which were derived from the default (and most conservative[1]) NOx emission factors by IMO engine tier, multiplied by the tier-invariant load adjustment factors[2] — were compared against the RSE data, focusing on the breakdown by engine type. Here the main findings are as follows:

- For MSD and HSD vessels the load-dependent NOx curves appear to fit reasonably well with the calculated NOx emission factors of the RSE data with a tendency towards underestimation for MSD vessels.
- For SSD vessels, however, on average 41 % of Tier 0, 30 % of Tier I and 56 % of Tier II observations are found to be above the applicable load-dependent NOx curves. Given that these curves are intended to serve as conservative near-upper bounds this finding is significant, indicating that the existing load-adjusted NOx emission factors used in the OGV emission inventory could potentially be underestimating the actual NOx output, in some cases significantly, particularly at main engine loads below 50 %.

The findings outlined above call for further investigation of the current NOx emissions factors used in the OGV emission inventory, especially for inventories that focus on nearshore and/or within-ECA operations where vessels are typically operated at lower main engine loads.

Additionally, as SSD vessels with higher installed power (MCR) and higher tonnage (DWT) appear to dominate the high NOx observations, this analysis also calls for further examination of the NOx emission factors in particular for these vessels, many of which are container ships similar to those calling into the San Pedro Bay ports.

Finally, it is noted that under the IMO NOx Technical Code (MEPC.177(58)), the current weighted structure of engine test cycles leaves a large opportunity for vessels to optimize fuel consumption at low engine loads at the expense of NOx emissions since the Code emphasizes NOx performance at high loads (≥75 %). According to the test cycles, lower NOx emission rates achieved at higher engine loads on the test bed can offset, or even more than make up for, any increase in NOx emitted at lower engine loads. Particularly these days, this kind of optimization has a lot of value to shipowners since any path to lower fuel consumption, via slow steaming and engine optimizations, will not only reduce costs but also improve a vessel's overall CO_2 footprint.

Although this engine optimization practice is arguably reflected in the load-dependent NOx curves currently used in the OGV emission inventory, our analysis identifies some very high NOx

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[1] For the San Pedro Bay Ports Emissions Inventory, for example, the Engine NOx Emission Value recorded on a vessel's EIAPP would be used instead of the higher default NOx emission factor.

[2] The load adjustment factors were applied to reflect the load-dependent variations of specific NOx emission rates (in g/kWh), which are assumed to increase with decreasing engine loads.

observations well above the current load curves. Specifically, when compared to Tier 0-I vessels, the Tier II SSD vessels included in this analysis exhibit markedly larger spread with high emission factors below 50 % main engine loads. Particularly, *large* SSD vessels with massive deadweight and big engines (most of which are container ships), display an entirely different load and emissions pattern from other ships. Although our RSE measurements were taken in nearshore waters, with the prevalent practice of slow steaming, large SSD vessels such as post-Panamax [Malaccamax] or even larger container ships were also found to cruise on open sea at main engine loads far below 75 %, therefore rendering any test-bed NOx emission reductions achieved at higher loads irrelevant under real sailing conditions (Cheng et al., 2018). Therefore, our findings are pertinent for both nearshore and open sea operations.

The findings indicate potentially different engine optimization patterns between IMO engine tiers, size classes and potentially even ship types. To estimate NOx emissions from OGVs, the same set of load adjustment factors are currently either applied across OGVs of all engine tiers, sizes, and types, or they are applied uniformly to a subset of SSD vessels (with main engine of 130 or lower RPM) with no low load adjustments for other vessels. These adjustment factors were developed largely to reflect decreasing fuel efficiency for diesel-cycle engines (U.S. EPA, 2009) and for unregulated (i.e., Tier 0) OGV fleet, sometimes supplemented by lab testing of a rather limited number of Tier 0-I propulsion engines (Starcrest, 2019), therefore not reflective of varying engine optimization strategies especially for meeting the Tier II standards. The study's empirically derived NOx emission rates suggest room for improvement in the current emissions inventory methodology. The findings also point to the potential use of a large number of cross-sectional observations, enabled by recent advancement of remote measurements, to assist in updating shipping emissions estimation under real-world sailing conditions.

2 Methodology

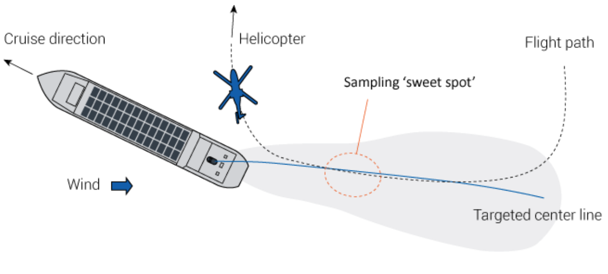
This chapter outlines the methodology used in this report to establish the load-dependent NOx emission factors for the individual ship observations and the applied load-curves.

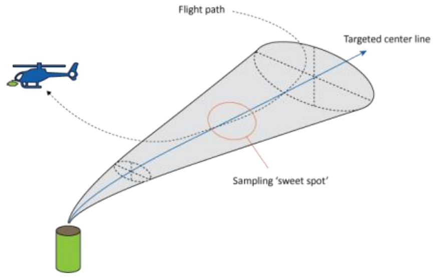
2.1 Data Sourcing

All RSE data was collected from ships sailing in Dutch or Danish waters. A total of 929 ship observations were included in the gross dataset. Data from Dutch waters were collected in September 2016 while data from Danish waters were collected throughout the year 2020. They constitute a representative selection of the fleet operating in those waters.

The observations of NOx and CO_2 emissions from individual ships were all collected using the Explicit Mini Sniffer System mounted on a light helicopter such as an AS355 or AS350. When sampling, the helicopter flies into the plume at a safe distance of typically 25-100 meters from the vessel stern to sample the exhaust gasses ca. 20-70 meters above sea level. Each measurement takes only a couple of minutes to complete after which the helicopter breaks off to clear the sensors in free air before the next target approach. The exact distance of each measurement to the ship depends on the vessel design and size.

Because sampling is always done upwind with the air inlet in an extended position in front of the helicopter, sampling is not disturbed by the downwash nor impacted by the helicopter exhaust. During sampling, the pilot navigates using a combination of wind data to estimate the rough location of the plume vis-à-vis the vessel, and live sensor feedback to locate the optimal sampling position inside the exhaust plume (‘sweet spot’) where gas concentrations are sufficiently high to satisfy the sensors. The sampling principal is illustrated below.





Details of the instrumentation and sampling technique can be found in the 2018 report on airborne surveillance in Danish waters published by the Danish EPA (Explicit, 2018). See also images in section 3.1.

During sampling, the emissions data was paired in real-time using GPS position data and UTC time stamps with data obtained from the AIS signals of the observed vessels, including but not limited to MMSI and IMO numbers, name, and speed over ground (knots).

All observations were subsequently scored according to quality on a scale of 0-10 using the quality assurance (QA) protocol in the Explicit Mini Sniffer System (Explicit, 2018). The quality score expresses the pilot’s ability to successfully navigate the exhaust plume to position the sensor for optimal performance when sampling. The quality score allows Explicit to evaluate when a sample is robust enough to be considered valid and give guidance to the pilots when flying. Measurements with a quality score below 1.0 are disregarded as failed attempts at measuring. Indicative quality ranges are as follows: 1-3 = low quality; 3-6 = medium quality, 6-10 = high quality. For details of the systemic quality scoring protocol, please see the Danish EPA report (Explicit, 2018).

The Explicit Mini Sniffer System has been independently validated by FORCE Technology to have an uncertainty of 13 % on the estimated NOx emission factors.

Further vessel-specific data was sourced using IHS database services including data on total main engine KW, maximum speed, service speed, ship type, built/keel-laid date, engine speed (RPM), oil engine type, and deadweight tonnage.

2.2 Exclusions and Data Enhancements

Not all observations in the gross dataset were relevant to the analysis of NOx emissions from conventional propulsion engines, such as anchored and LNG-fueled vessels, and some IHS data points were judged to be erroneous. To enhance data integrity, the following exclusions were made to the gross dataset:

- Observations with a quality score <1.
- Observations with a recorded AIS speed over ground <1 kn.
- LNG-fueled ships.
- Observations with reported zero values for maximum speed and/or maximum engine speed, indicating erroneous IHS data.
- Observations with a subsequent load factor >100 %. See section 2.3 for further discussion.

In total, 46 observations were excluded, leaving a net dataset of 883 ship observations.

Additionally, to compensate for missing data points, principally in data sourced from IHS, the following enhancements were made:

- For 54 % of vessels, the maximum speed was not available. Instead, the missing maximum speeds were gap filled using linearly fitted values, as provided by the South Coast AQMD based on maximum and service speeds data for approximately 3,200 OGVs.
- In some cases, the keel-laid date was missing from IHS. Instead, the built date was used to determine the age of a vessel. In no cases did the substitution affect the tier classification of the vessel (none of the substitutions were aged close to a tier threshold).

2.3 Establishing Individual Load Factors

The individual load factors at the time of monitoring were established using propeller law as laid out in the U.S. EPA’s Port Emissions Inventory Guidance (U.S. EPA, Sep 2020):

$$P_p = P_{ref} \times \left(\frac{V}{V_{ref}}\right)^3 \times SM \qquad \textbf{Equation 1}$$

Where P_p = propulsion engine operating power (kW)
P_{ref} = vessel’s total installed propulsion power (kW)
V = AIS-reported speed before the record interval (kn)
V_{ref} = vessel’s maximum speed (kn)
SM = sea margin, which accounts for average weather conditions, assumed to be 1.10 for coastal operations and 1.15 for at-sea operations (unitless)

Since all observations were made in near-coastal areas, a sea-margin of 1.10 was applied as prescribed by the US EPA PEIG Guide.

The load factor (LF) was subsequently calculated using the same guidance:

$$LF = \frac{P_p}{P_{ref}}$$ **Equation 2**

Where $LF =$ propulsion engine load factor (unitless)
$P_p =$ propulsion engine operating power for each AIS record (kW)
$P_{ref} =$ vessel's total installed propulsion power (kW)

Note, propeller law assumes a vessel is operating under maximum draft. Consequently, the calculated load factor expresses a conservative (upper bound) estimate of the actual engine load factor.

Additionally, AIS speeds are reported as *speed over ground* which means the operating speeds at the time of sampling are impacted by weather conditions in addition to engine operation speeds, whereas vessel maximum speeds are reported as *speed over water* and are directly derived from an engine's maximum continuous rating (MCR). This difference, including the addition of a fixed sea margin, introduces an uncertainty to the calculated load factors compared to the actual engine loads. In some cases, it results in factors above 100 %. In such cases, the observation has been excluded.

In general, because of the sea margin, the calculated load factors trend high.

2.4 Establishing Individual Load-adjusted NOx Emission Factors

To establish an individual load-adjusted NOx emission factor in g/kWh for each ship observation, the function prescribed by Balzani Lööv et al. (2014) was used, including a ratio of the measured NOx/CO_2 in the exhaust plume adjusted for background concentrations of CO_2:

$$E\left(\frac{g_{NOx}}{kWh}\right) = \frac{(NOx_{measured} - NOx_{background})}{(CO2_{measured} - CO2_{background})} \times 3{,}33 \times e$$ **Equation 3**

Where $NOx = NO + NO2$ (ppm)
$E =$ NOx emission expressed (g/kWh)
$e =$ specific fuel consumption expressed (g/kWh)

The unitless 3.33 factor denotes a combination of the molecular weight ratio between NO_2 and carbon and the carbon mass percent in the fuel. Note, in compliance with the IMO Technical Code MEPC 177(58), NO is counted as NO_2 for the purpose of the molecular weight, implicitly assuming a complete conversion of all NO to NO_2 over time.

For the specific fuel consumption (*e*) at the time of sampling, given the lack of access to onboard data, a load-adjusted consumption value was subsequently calculated for each ship using a base specific fuel consumption (SFC) assumption and load-adjustment function as prescribed by the IMO4GHG (CE Delft, 2020):

$$e\left(\frac{g_{fuel}}{kWh}\right) = SFC_{base} \times (0.455 \times LF^2 - 0.710 \times LF + 1.280)$$ **Equation 4**

Given that all observations were made inside the North European ECA (NE-ECA), for the purpose of this analysis only MDO fuel use was assumed with a carbon content factor of 0.87. This is the dominant bunker fuel inside the NE-ECA. For those vessels potentially running on other fuels the carbon content factor may deviate slightly. However, this impact is not assessed to be material. More detail on the base SFC value assumptions and the function for estimating the load-adjusted specific fuel consumption is presented in Appendix C.

Note, the IMO4GHG generally assumes higher fuel efficiency than that applied by the U.S EPA (and presumably also by SPBPEI).[3] This means the calculated specific fuel consumption for each vessel (e) is trending low leading to comparatively lower emission factors.

Note also, the methodology assumes a basic functional relationship between the fuel efficiency and the calculated NOx emission factor which, when adjusted for load as prescribed by the IMO4GHG, implies a higher NOx emission factors per energy unit (kWh) at lower loads. However, as will be shown in the ensuing chapters, the rate of increase in the calculated NOx emission factor is much higher than implied by the load-dependent SFC alone.[4]

For the sake of consistency, the definition of engine type (SSD, MSD, and HSD) in this report further follows the definitions prescribed by IMO4GHG:

- SSD is defined as having an engine speed ≤300 RPM.
- MSD is defined as having an engine speed between 300-900 RPM.
- HSD is defined as having an engine speed >900 RPM.

These definitions vary from those currently used in the San Pedro Bay Ports Emissions Inventory Methodology Report (Starcrest, 2019) and in the U.S. EPA’s Port Emissions Inventory Guidance (U.S. EPA, Sep 2020). For further discussion see chapter 4.

Note, because nearly all SSD vessels in the dataset are 2-stroke engines, while nearly all MSD and HSD vessels are 4-stroke engines, no separate analysis has been made with regards to stroke number.

2.5 Tier Classification

All ships were classified by Tier in accordance with IMO MARPOL Annex VI regulation 13 on NOx emissions. Note, given that the Tier III NOx limits only recently (from 1 January 2021) became effective in the North Sea and the Baltic Sea ECAs in North European, no vessels are classified beyond Tier II even though a number of vessels in the dataset were identified as capable of operating in Tier III mode.

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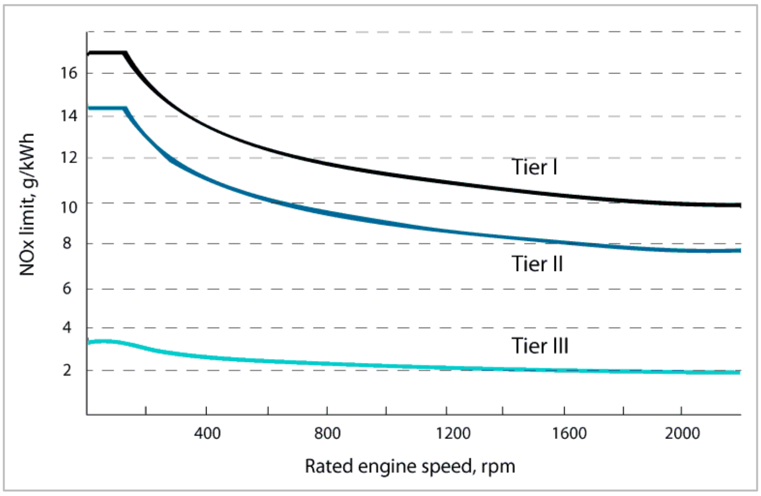
[3] For SSD vessel observations in this study, for example, the SFC at or above 20 % main engine load would be 185 g/kWh under the assumption recommended in the U.S. EPA’s emissions inventory guidance. In contrast, the load-dependent e averages 175 g/kWh when the IMO4GHG method is applied to all observations with main engine load ≥20 %.

[4] At 10 % main engine load, Equation 4 implies that the load-dependent NOx emission factor would be approximately 5 % higher than at 20 % main engine load due to worsening SFC. At 2 % main engine load, the difference becomes approximately 9.5 %.

For the sake of a full overview, the various Tier levels and their associated keel-laid dates and NOx limits as per Regulation 13 are included in the below table and graph[5]:

Tier	**Ship construction date**	**NOx Limit (g/kWh)**		
		n < 130	**130 ≤ n < 2000**	**n ≥ 2000**
0	< 1 January 2000	n/a	n/a	n/a
I	≥ 1 January 2000	17.0	$45 \cdot n^{(-0.2)}$	9.8
II	≥ 1 January 2011	14.4	$44 \cdot n^{(-0.23)}$	7.7
(III)	(≥ 1 January 2021)	3.4	$9 \cdot n^{(-0.2)}$	1.96



2.6 Load-Dependent NOx Curves

To replicate the load-dependent curves used in the current OGV emissions inventory for the San Pedro Bay Ports area (SPBPEI), the default NOx EF values for 0.1 % MGO were used in combination with the applicable load adjustment factors, as documented in the SPBPEI (Starcrest, 2019) and compiled and transmitted by the South Coast AQMD staff. SPBPEI applies 3 different sets of load adjustment factors to SSD vessels with 2-stroke main engine RPM less than 130, including one for MAN diesel engines with conventional valve, another for MAN diesel engines with slide valve, and the third set for non-MAN engines. For propulsion engines with RPM ≥ 130, no load adjustment factors are applied, meaning NOx emission rates stay constant across the entire engine load range for these vessels and are not assumed to increase at lower loads. Notice that the non-MAN load adjustment factors are also utilized by U.S. EPA and the IMO4GHG; unlike SPBPEI, however, they are applied to all OGVs.

2.7 Uncertainties

As indicated above, a certain level of instrument uncertainty applies to the individually measured NOx values. The methodology also relies on assumptions on factors like fuel efficiency and

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[5] Source: IMO Regulation 13.

estimated engine power for each ship which may cause the individual NOx emission factors to deviate from actual emissions.

Similarly, another potential source of uncertainty is the mix between main and auxiliary engine emissions, particularly at low load (<25 %). The analysis only assumes main engine operations given that most of the observations are from ships in transit mode[6] where main engines are expected to dominate emissions, even as the sampling technique measures on the combined emissions. At low main engine load, it can however be argued that auxiliary engine outputs start to play a role in the emissions, although this impact is hard to assess and highly dependent on the design and operation of the individual ship.

However, when considering the full dataset, any such individual uncertainties are assessed to have no material impact on the correct observation of trends such as emission level differences between Tiers, load dependencies, etc. For instance, had we excluded low load observations (<25 %), we would see no material difference in trendlines. While this study is not able to quantify the influence of emissions from auxiliary engine due to data limitations, future research utilizing concurrent remote and onboard (in-stack) emissions measurements may help shed light on the extent of influence from the auxiliary engines.

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[6] Transit mode is defined as operations in which a ship is sailing in open water and traveling at a cruising speed above 8 knots (Starcrest, 2019). In this operational mode, according to U.S. EPA Port Emissions Inventory Guidance, auxiliary engine usage is low (U.S. EPA, Sep 2020).

3 Analysis of the load-dependent NOx Emission Factors using RSE data

This chapter analyzes the emission patterns of the load-dependent NOx emission factors derived from the RSE data according to the methodology described in chapter 2.

As a matter of context, when investigating maritime emissions, it is important to note that only a few fleet-wide studies of the overall NOx emission patterns at sea have been conducted. This analysis differs by its breath using RSE data from remote sensing across a significant fleet of different vessels sampled over longer periods. As such, its unique perspective may contribute to new understandings about maritime NOx emissions.

3.1 General Observations

The full dataset analyzed consists of 883 ship observations. 305 of these were collected in September of 2016 in Dutch waters, many from vessels coming to/from Rotterdam Port. The remaining 578 observations were collected from vessels in Danish waters in 2020. By the nature of these waters, all observations were collected inside the NE-ECA in near-shore locations along the Dutch and Danish coasts.

The quality of the RSE data is generally very high with 94 % of all observations achieving a 'high' quality score ≥ 6 and 83 % of all observations achieving the top score of 10, meaning the pilot was able to fully optimize the position in the exhaust plume at the time of sampling to satisfy the gas sensors.

The average quality score for observations with different engine loads are as follows:

- Average quality score for loads <25 %: Score 8.8
- Average quality score for loads 25-50 %: Score 9.5
- Average quality score for loads >50 %: Score 9.6

As shown, the quality of the air samples is unaffected by engine load. Instead, it is very much tied to the skills of the pilot and the specific wind conditions at the time of sampling, which may sometimes create turbulence which affects the integrity of the plume.

Images of the system and how the samples were taken are shown below. Further details about this sampling technique can be found in the 2018 report on airborne surveillance in Danish waters published by the Danish EPA (Explicit, 2018).

As discussed previously, the sampling approach is unable to distinguish between ship emission sources (main engines, auxiliary engines, and boilers) implying a potentially increasing influence on the remote measurements coming from auxiliary engine and boiler emissions as main engine loads decrease. Without further information on the operations of auxiliary engines and boilers, it is not possible to quantify the extent of such influence. However, most of the observations in this study are consistent with transit mode operations (>8 knots). As stated in the U.S. EPA Port Emissions Inventory Guidance (U.S. EPA, Sep 2020): "Auxiliary engine usage is generally low in [transit] operating mode, and boilers are typically not running in this operating mode for most ship types. Instead, auxiliary power is pulled of the main engine." If most vessels in our study sample indeed operated as such, we can reasonably expect that the extent of influence from auxiliary engines and boilers on the measured NOx emissions would be rather limited.

The Explicit Mini Sniffer System mounted on an AS355 helicopter, and a scrubber vessel being sampled in Danish waters. Photos: Explicit ApS / Charlie 9 Helicopters ApS.

Some vessels were observed multiple times due to their repeat operations in the area (with one single vessel observed 6 times). This is a normal pattern for any sea area where the same ships often travel the same routes. The total number of unique vessels in the dataset is 748.

While many of the vessels are OGVs, the dataset also includes short-sea sailing vessels that only operate within the NE-ECA. The latter are typically smaller 'handy sized' vessels, passenger vessels, and HSD ships.

The average AIS speed is 12.2 kn, which is typical for operations inside the NE-ECA, with speeds ranging from just above 1 kn to high-speed vessels sailing at 37.5 kn.

The dataset covers the full spectrum of estimated load factors from near-zero to almost 100 % with an average load of 47.1 %. (See Section 2.3 for a discussion on the uncertainty associated with estimating load factors.)

Of the full dataset, 31 observations were made on ships that have also called at the Los Angeles, Long Beach, or El Segundo Ports during 2016-2019. Of these most were bulk and general cargo (12), tanker (10), and container (6) vessels, and most of them were smaller in size with a DWT <80,000. This is not surprising since many of the e.g., big (container) vessels operate (and are designed to operate) on fixed transit routes between either Asia and North America or Europe and Asia.

Note, the overall analysis assumes vessels are using fuels with a 0.1 % sulfur content. This assumption is well-supported by the general rate of sulfur non-compliance reported to be 2-3 % in Danish waters in 2020 (Explicit, 2021).

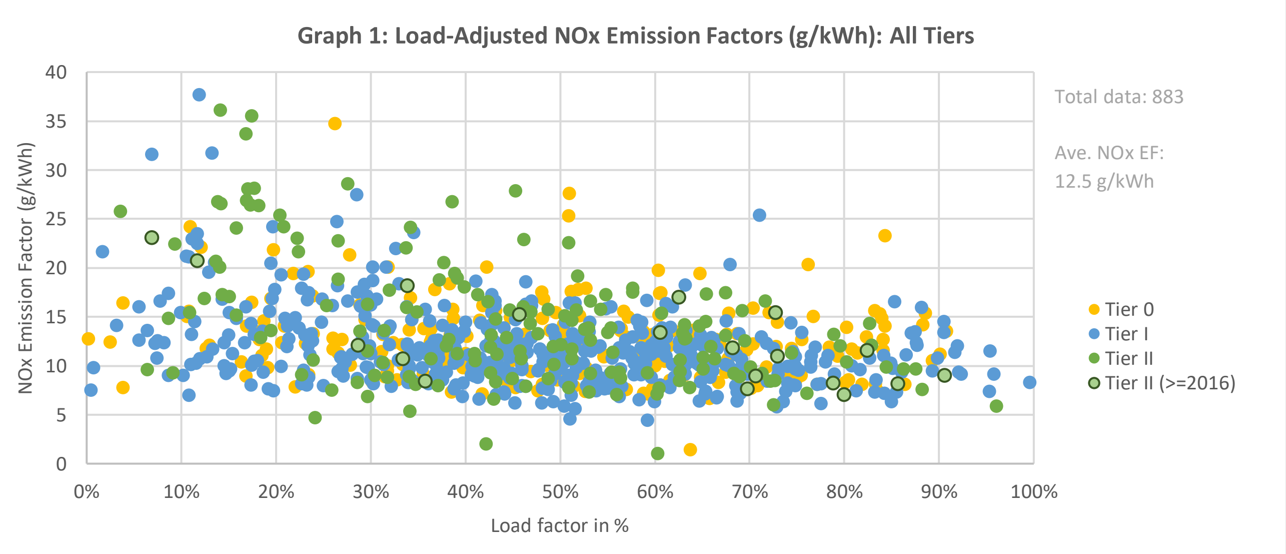
In the following sections, the observations are broken down in greater detail on various parameters with main findings summarized after each breakdown.

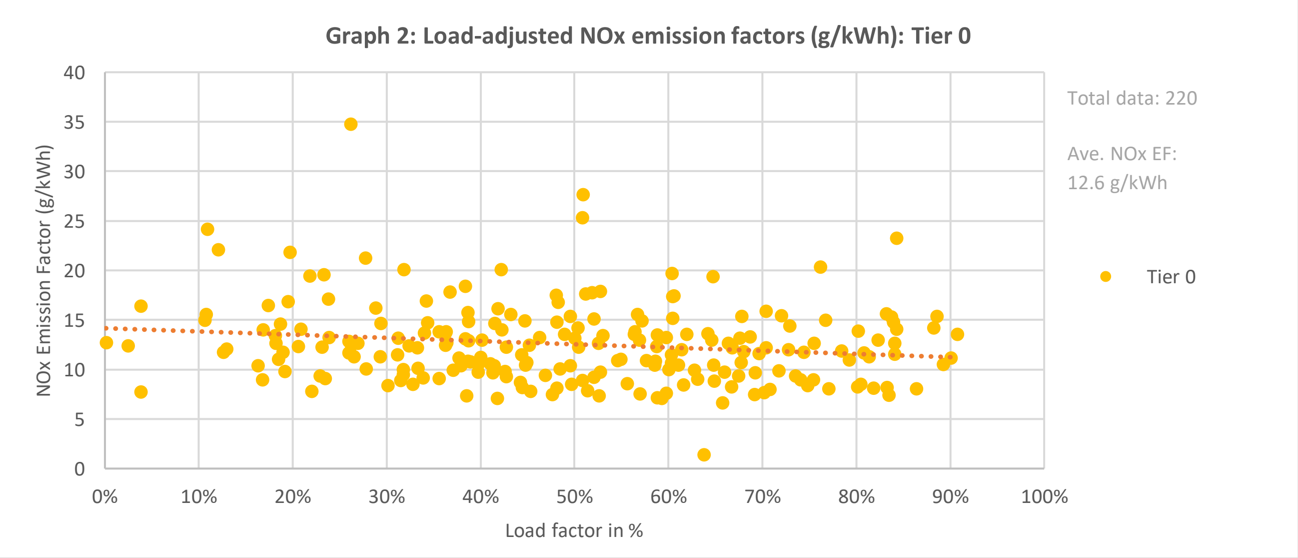
The total number of observations and the average NOx emission factor for each graph is noted in grey in the top righthand corner. Linear (dotted) trendlines have also been added to indicate the general data progression from 0 → 100 % load.

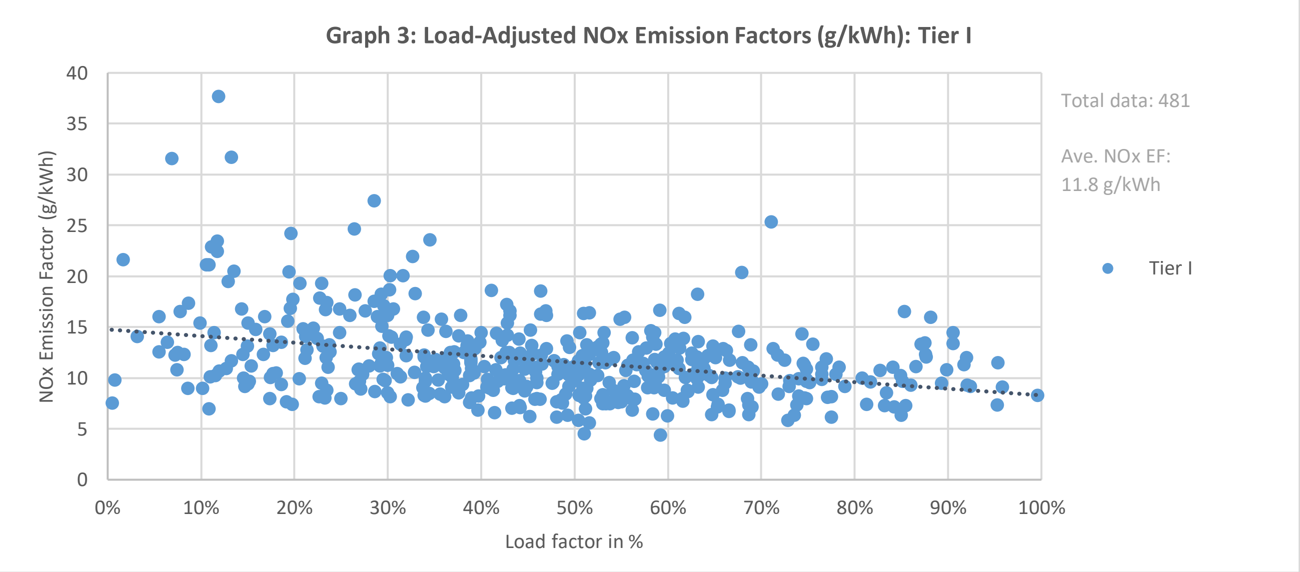
3.2 Load-dependent NOx Emission Factors by Tiers

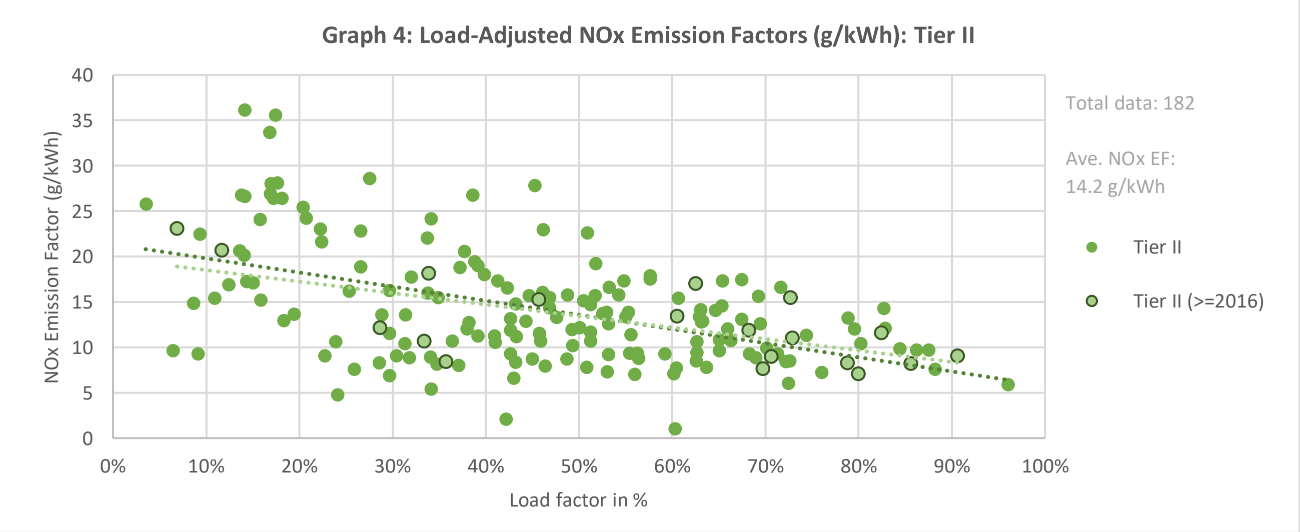
Note, while there are no Tier III vessels in the dataset, ships aged 2016 or younger have been plotted as "Tier II (≥2016)" consistent with the Tier III age threshold applicable to the North American ECA. This is to identify younger vessels more easily and should not be confused with the Tier III NOx limits under IMO MARPOL Annex VI Regulation 13 for NOx emissions (Regulation 13).

220 observations are of ships classified as Tier 0 meaning they are older than 1 January 2000. These ships are not regulated under Regulation 13.









Main tier findings:

From the analysis of the emission patterns, engine tier appears to be an important factor in understanding potential sources of high(er) NOx emissions. Tier II vessels systematically exhibit a significantly steeper linear trend than older tiers, with high NOx emission rates at low loads and lower emission rates at high loads. Across all estimated engine loads, the average NOx emission factor for Tier II vessels (at 14.2 g/kWh) is higher than for older tiers, likely correlated with the fact that vessels, especially those types with higher maximum design speeds such as container and reefer vessels, tend to operate at lower loads during nearshore operations.

Moreover, as the tiers progress towards Tier II, the spread of NOx emission factors expands significantly, particularly at the lower end of the load spectrum (<25 %) where observations range from ca. 5-38 g/kWh. While the assumed deterioration in fuel efficiency at lower loads is a contributing factor, the increased emission rates at the low load range—as shown in Graph 4—

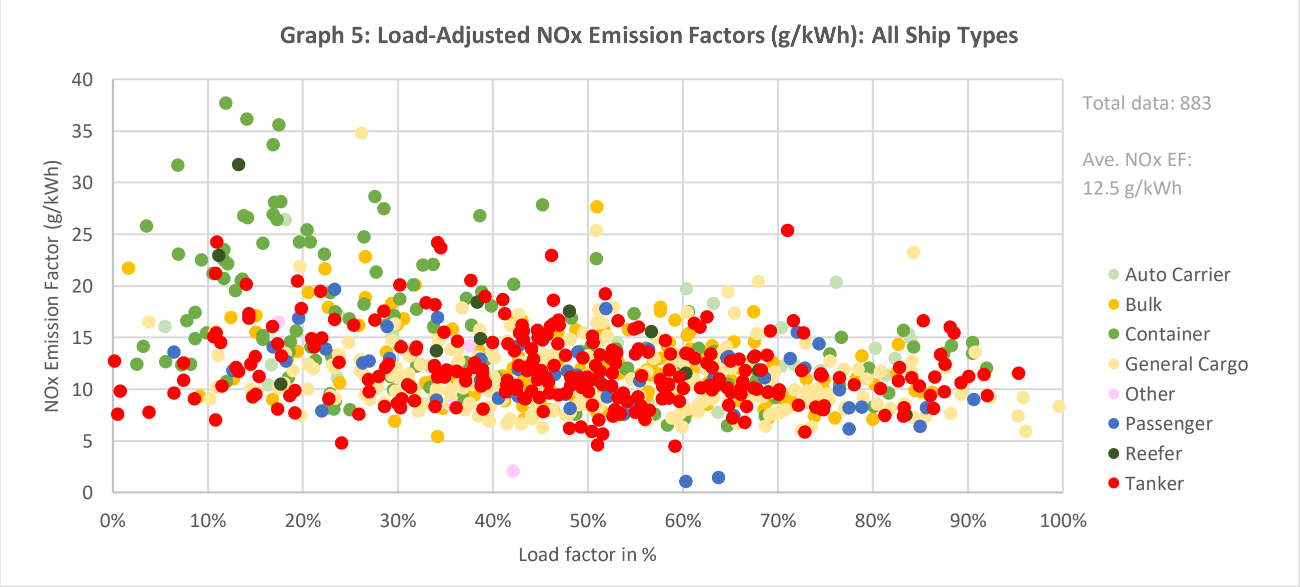
are largely driven by higher NOx measurements.[7] It should further be noted that even if we excluded observations <25 % load, to mitigate uncertain impacts from auxiliaries, the trendline progressions would remain the same. This is true for all the breakdowns.

3.3 Load-dependent NOx Emission Factors by Ship Type

In the breakdown by ship type, 5 observations are noted as ‘other’ covering pusher tugs, suction hopper dredgers, and one pipe laying vessel. Due to the insignificant number of these observations, they are only included in the initial summary graph.

Passenger vessels are almost exclusively made up of Ro/Ro ferries with space for both vehicles and passengers (also known as “RoPax” vessels), with only 3 observed cruise ships.

The breakdown by ship type has been simplified from the original 29 ship types as per IHS to 8. By example, all vessels with the denomination ‘tanker’ in the IHS type classification name has been grouped together.



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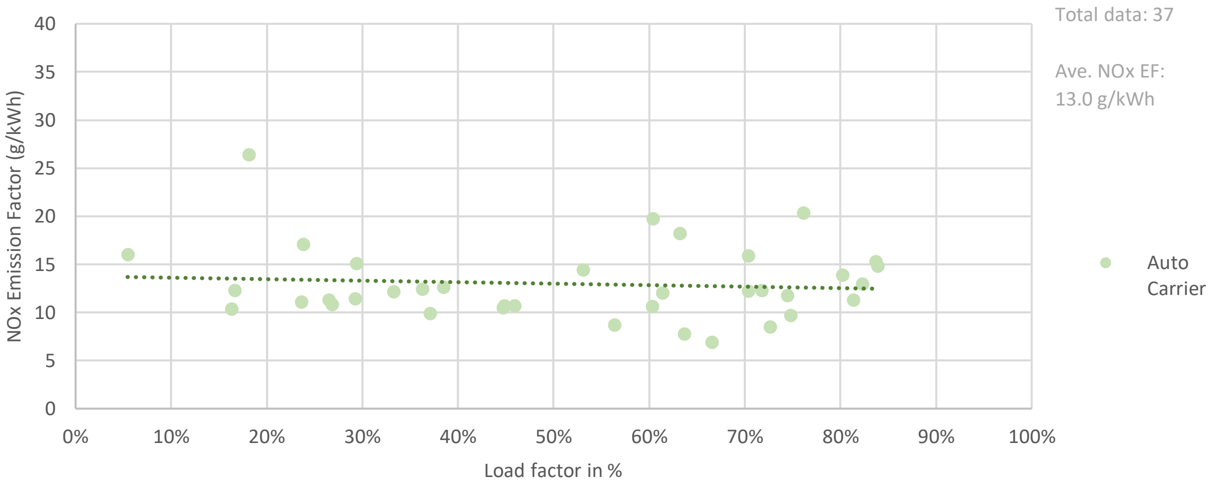
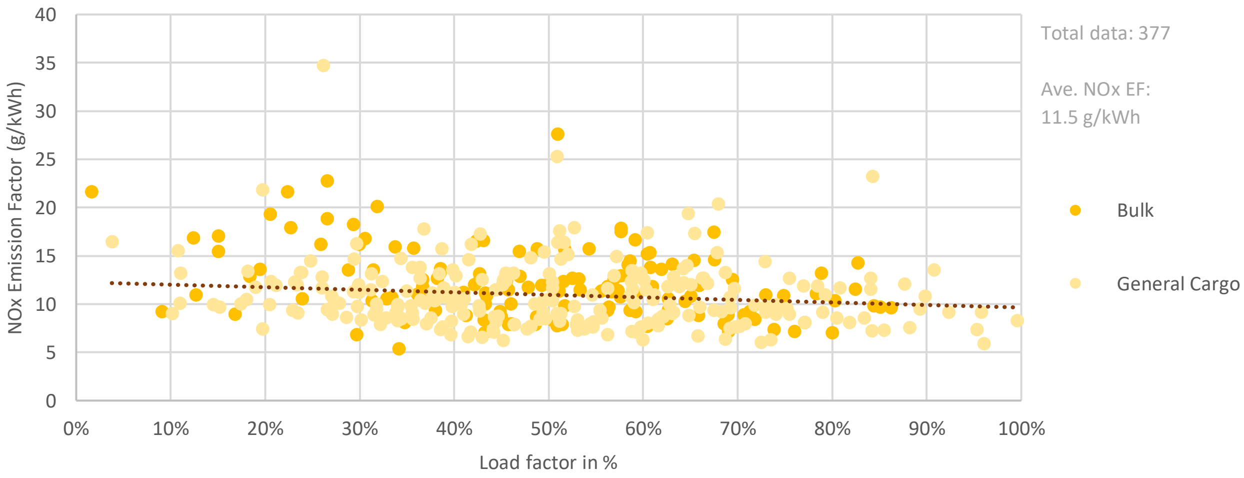
[7] If we assume conservatively that, at 75 % load, a main engine emits NOx at the IMO Tier II limit of 14.4 g/kWh, then the assumed decline in fuel efficiency would increase NOx emission rates to up to 17.9 g/kWh only at the lowest engine loads.

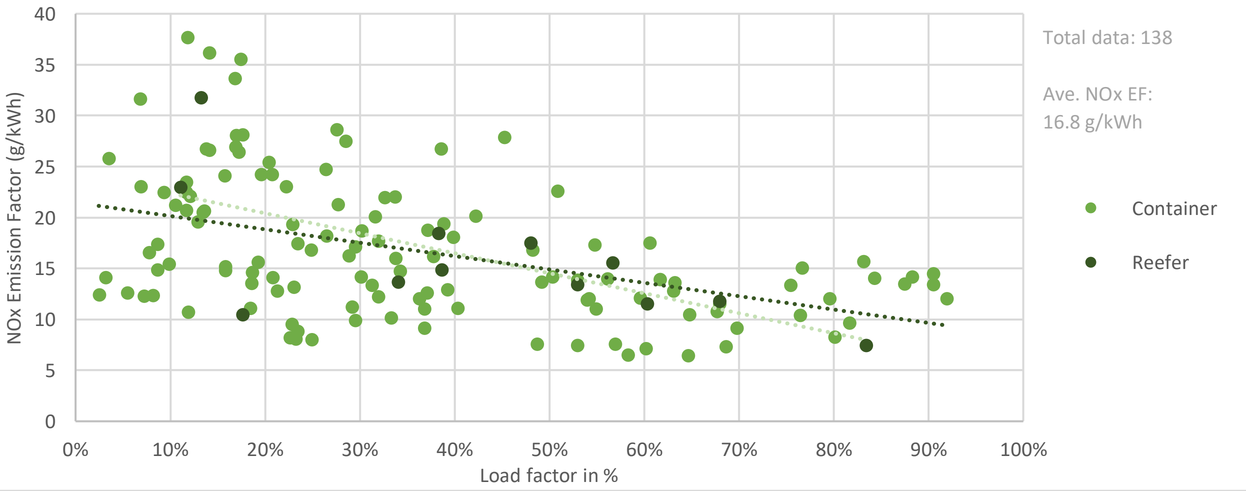
Graph 6: Load-Adjusted NOx Emission Factors (g/kWh): Auto Carriers

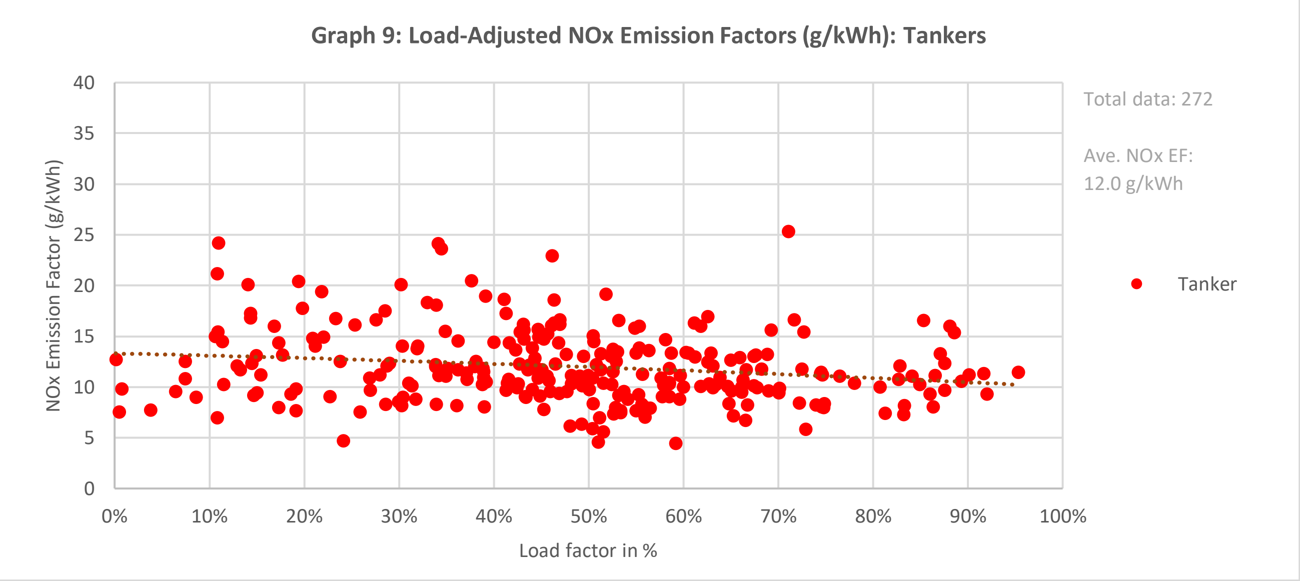


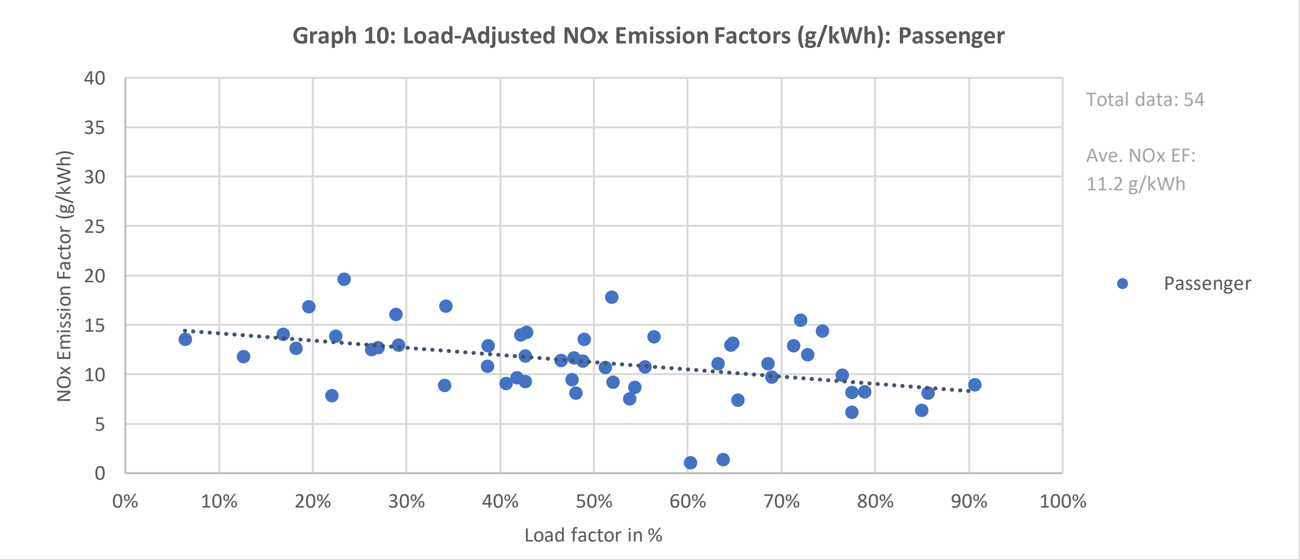
Graph 7: Load-Adjusted NOx Emission Factors (g/kWh): Bulk and General Cargo



Graph 8: Load-Adjusted NOx Emission Factors (g/kWh): Containers and Reefers







Main ship type findings:

As shown in Graph 8, containers and reefers present a significantly different NOx emission pattern than other vessel types. While all other ship types, except auto carriers, contribute to lowering the average NOx emission factor across the dataset, containers and reefers have an above-average NOx emission rate of 16.8 g/kWh. Part of this difference in average emission may be driven by a downshift in average load, with containerships and reefers having an average load of ca. 36-44 % compared to ca. 50 % for the rest.

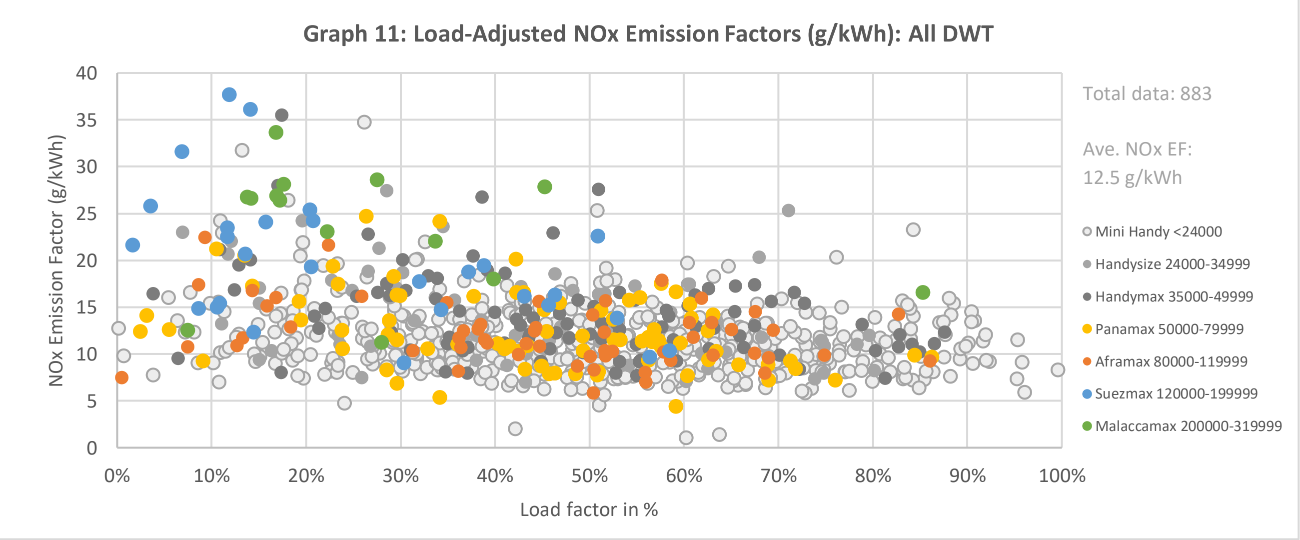
In addition, these vessels are also observed to have significantly elevated NOx emission factors below 50 % load with values rising significantly as the load factor decreases. Below 25 % load, the average NOx emission rate increases to 19.7 g/kWh (58 % above the average).

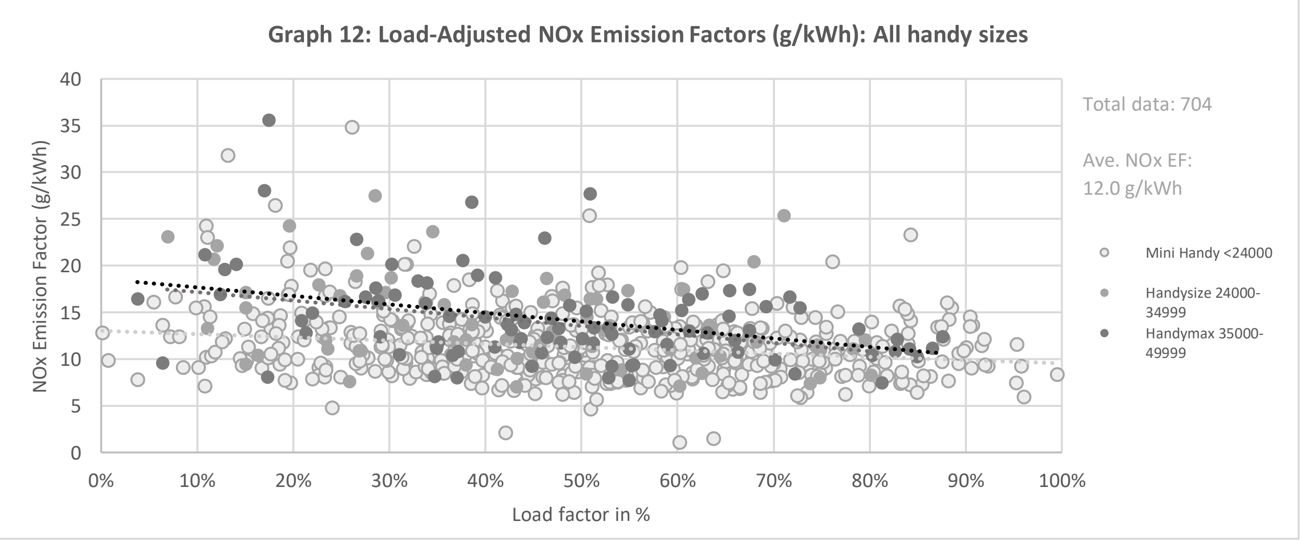
The general linear trend is also clearly steeper than for any of the other ship types, as is the spread in emission factors, particularly at low loads (<25 %) where factors range from ca. 8-38 g/kWh. In general, the very scattered pattern also appears to be unique to container ships.

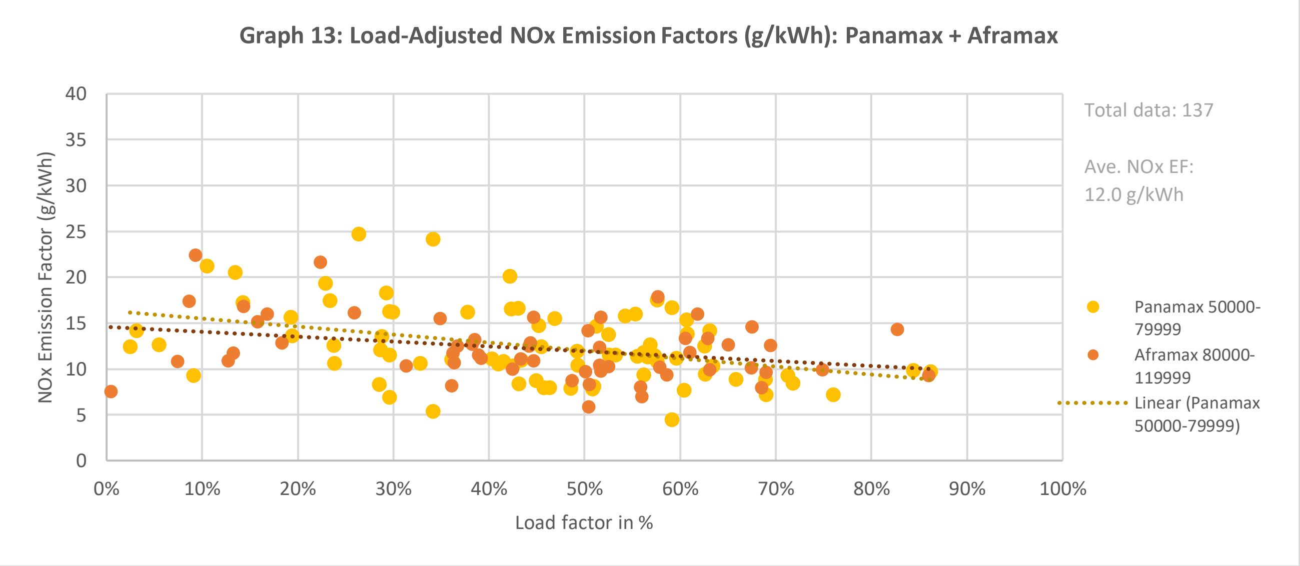
Note, for passenger vessels auxiliary engine emissions are generally higher than for other vessel types due to the nature of the onboard operations and so it is fair to consider this impact at low load. However, even if we disregarded low load observations to avoid this impact, it would not change the trajectory in the emission factors.

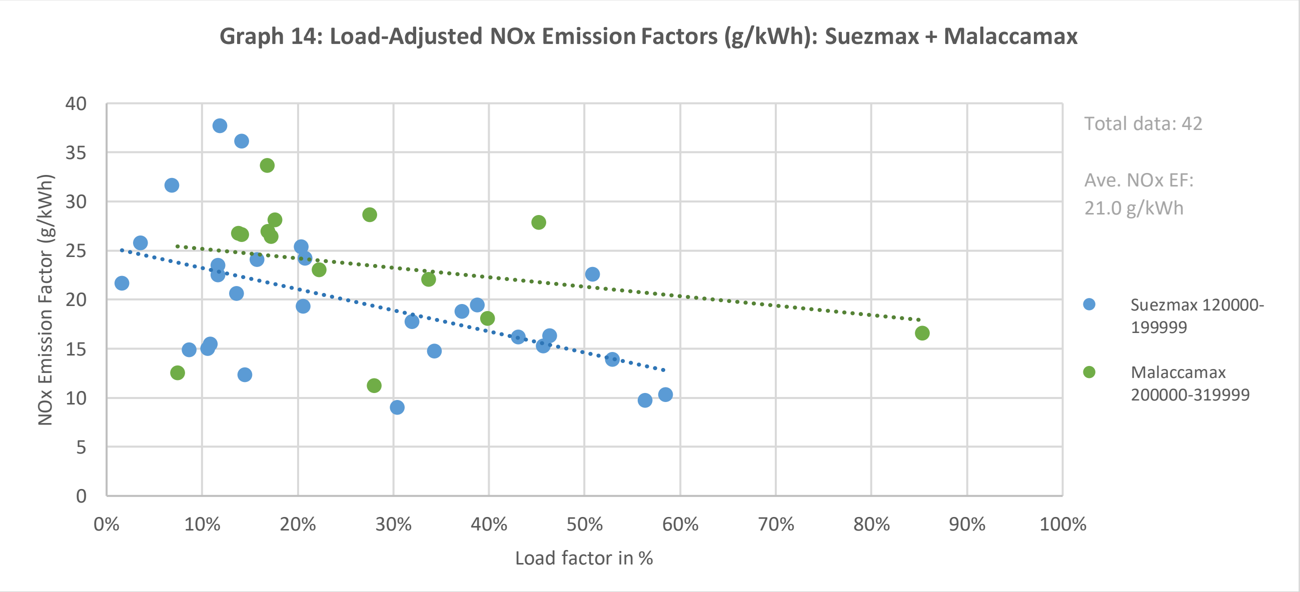
3.4 Load-dependent NOx Emission Factors by DWT

Due to a lack of a uniform classification of DWT across all ship types, observations by DWT have been grouped and labelled with an approach inspired by the DWT classification used for tankers.









Main DWT findings:

As shown in Graph 14, deadweight appears to contribute significantly towards explaining higher NOx emission rates. Not only do Suezmax and VLCC ships with ≥120,000 DWT have a 68 % higher recorded average NOx emission rate (21 g/kWh) than the overall average; except for a single VLCC ship, but all of these vessels also appear to operate below 60 % load. None of the other breakdowns presented so far display the same lack of high(er) loads, making this pattern particularly noticeable.

Also noteworthy are the number of observations at very low loads. 57 % of the observations in Graph 14 have load factors below 25 %. Again, the data appears more scattered than for lighter vessels.

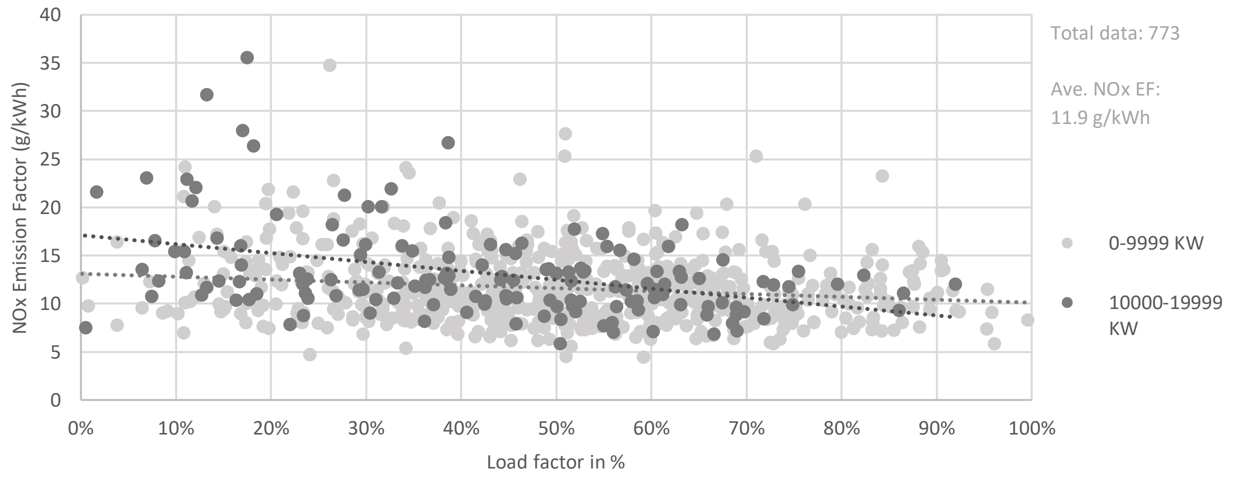
Without knowing the correct draft, it is difficult to pinpoint the exact cause of DWT pattern. However, assuming the amount of weight these ships were carrying at the time of monitoring was not unusually low (causing a reduced demand for power from the engines), the only other main parameter that may influence the load factor is the operating AIS speed.

With an average service speed of 19.1 kn, Suezmax and VLCC ships are designed for higher normal speeds than ships with a lower DWT. By comparison, the average service speed of the full dataset is 15.3 kn. At an average AIS speed of 12.6 kn, the observed Suezmax and VLCC ships are operating significantly below their designed service speeds.

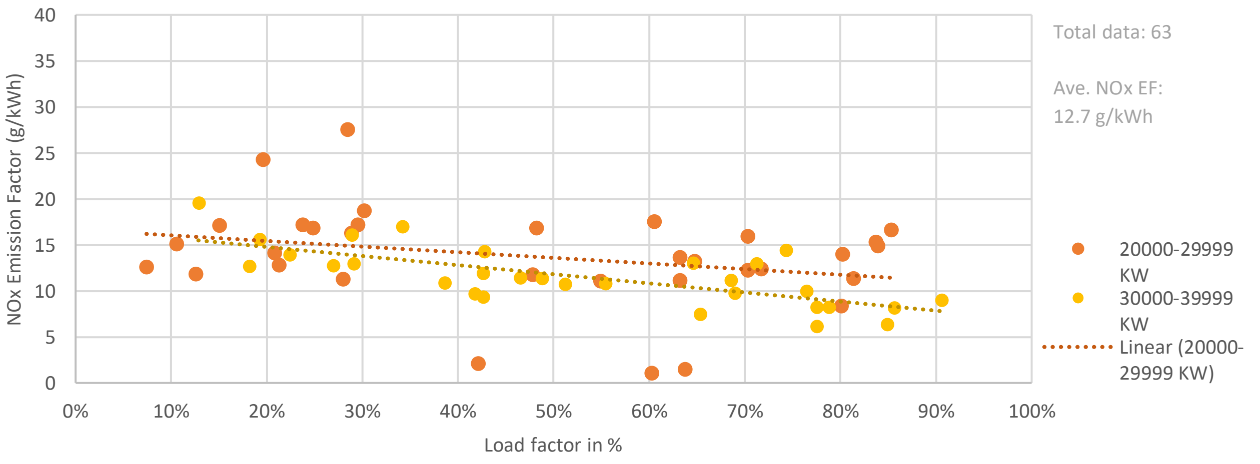
3.5 NOx Emission Factors by MCR

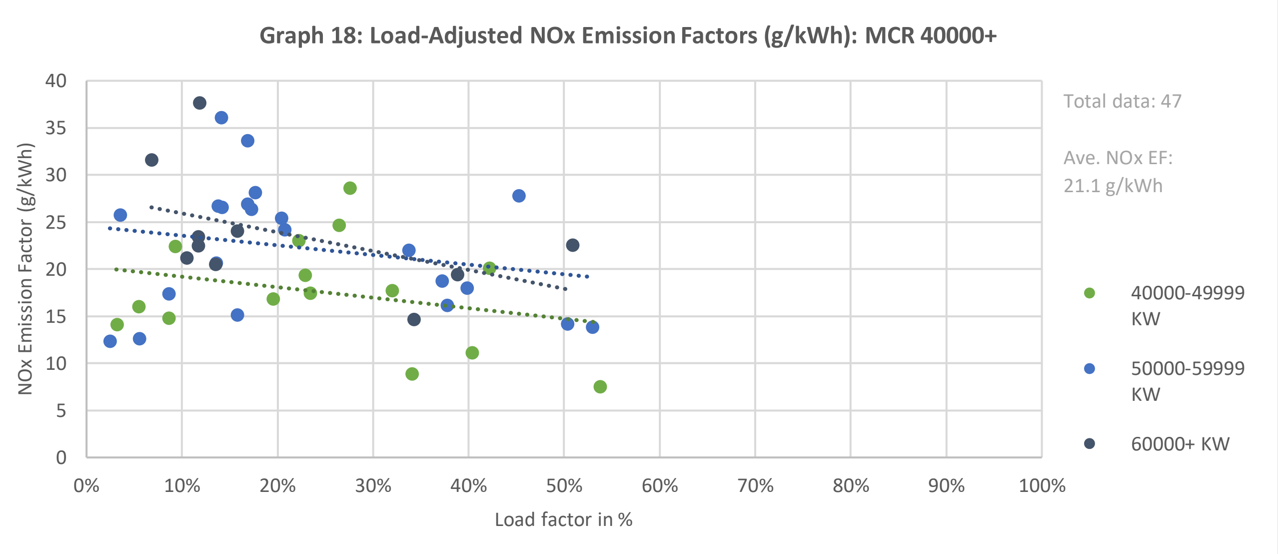
Due to the lack of a standard classification of vessels by MCR, observations have simply been grouped by order of tens of thousands of kW, see graphs 16-18.

Graph 16: Load-Adjusted NOx Emission Factors (g/kWh): MCR 0-19999 KW



Graph 17: Load-Adjusted NOx Emission Factors (g/kWh): MCR 20000-39999





Main MCR findings:

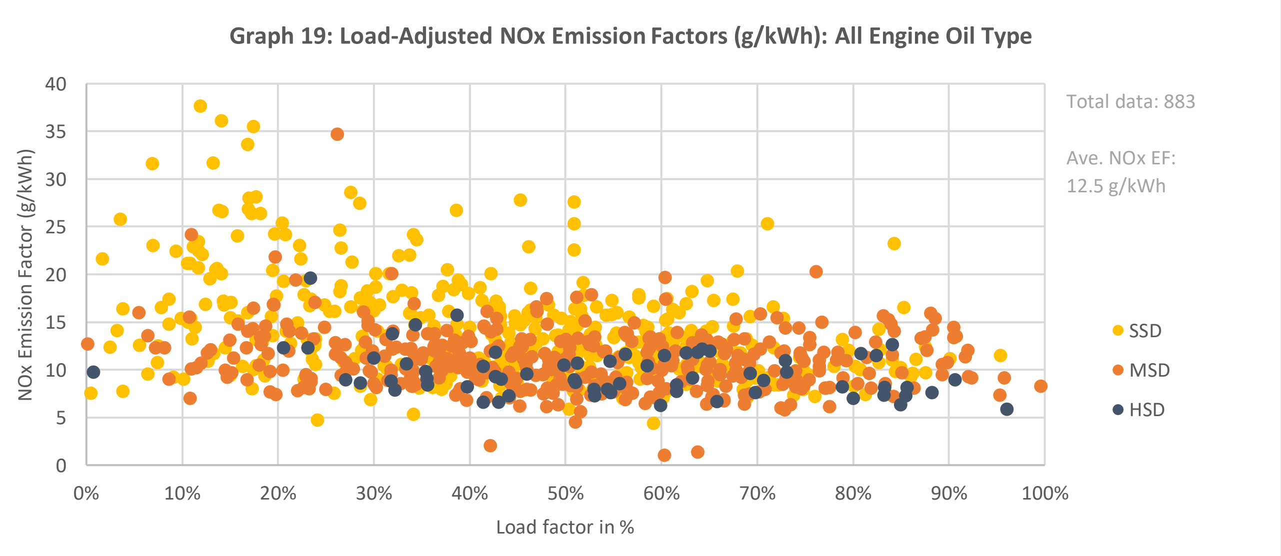
As with DWT – not surprisingly, as the two are closely related – the size of the engine also appears to play a significant role in explaining the high NOx emission rates at low loads.

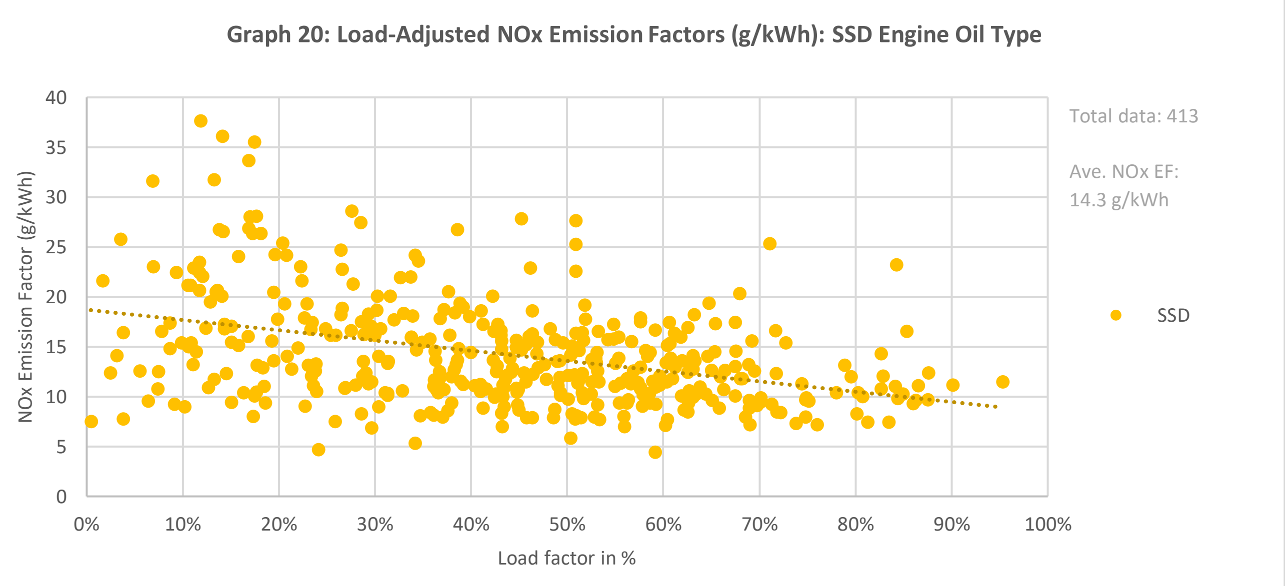
As shown in Table 18, vessels with engines ≥40,000 KW are observed to have an average NOx emission rate of 21.1 g/kWh (68 % above the average). Again, the breakdown is also distinct by its lack of observations above 55 % load and its scattered pattern.

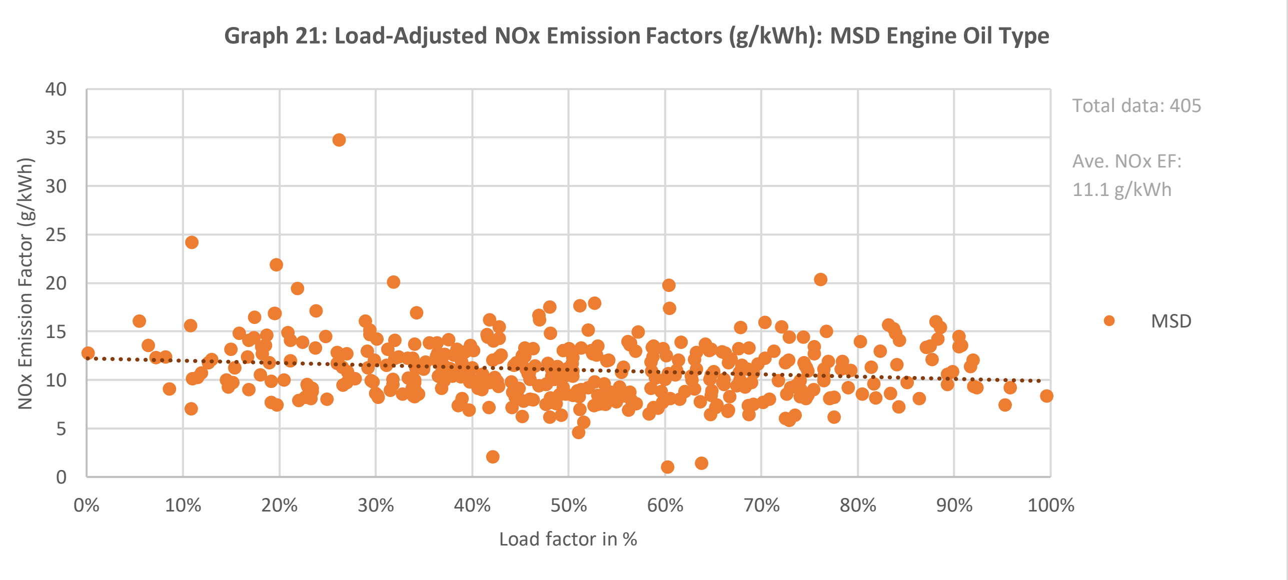
64 % of the observations are associated with loads below 25 %.

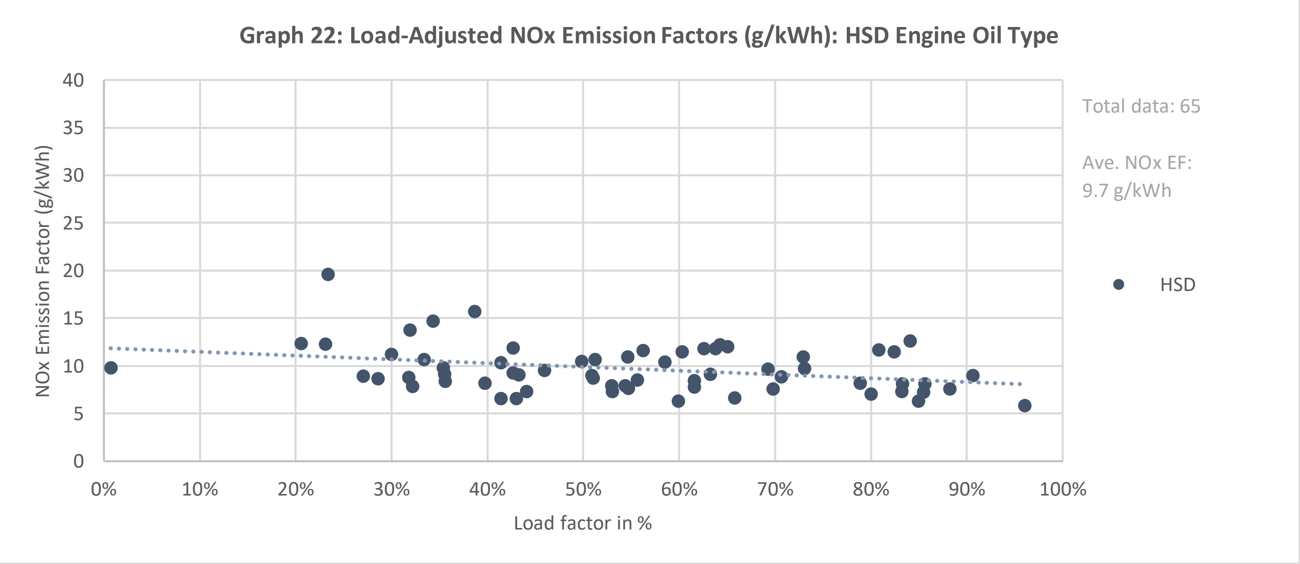
3.6 Load-dependent NOx Emission Factors by Engine type

As previously referenced, the classification by engine type (SSD, MSD, and HSD) follows the definitions prescribed by IMO4GHG. See section 2.4 for further.




Graph 20: Load-Adjusted NOx Emission Factors (g/kWh): SSD Engine Oil Type
NOx Emission Factor (g/kWh)
40
35
30
25
20
15
10
5
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Load factor in %
Total data: 413
Ave. NOx EF: 14.3 g/kWh
SSD


Graph 21: Load-Adjusted NOx Emission Factors (g/kWh): MSD Engine Oil Type
NOx Emission Factor (g/kWh)
40
35
30
25
20
15
10
5
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Load factor in %
Total data: 405
Ave. NOx EF: 11.1 g/kWh
MSD



Main engine type findings:

With regards to the engine type, a clear pattern may also be observed. While the load factor does not seem to significantly impact the NOx emission rates for medium-speed (MSD) vessels, slow-speed (SSD) vessels appear to emit significantly more NOx at low loads as illustrated by the linear trend progression in Graph 20.

Given that there are hardly any observations below 20 % load, the same conclusion cannot be made for HSD vessels, although they appear to resemble the pattern of the MSD vessels more closely.

The SSD vessels also have a higher average NOx emission rate (14.3 g/kWh) than the overall average.

3.7 An Observation About Speed

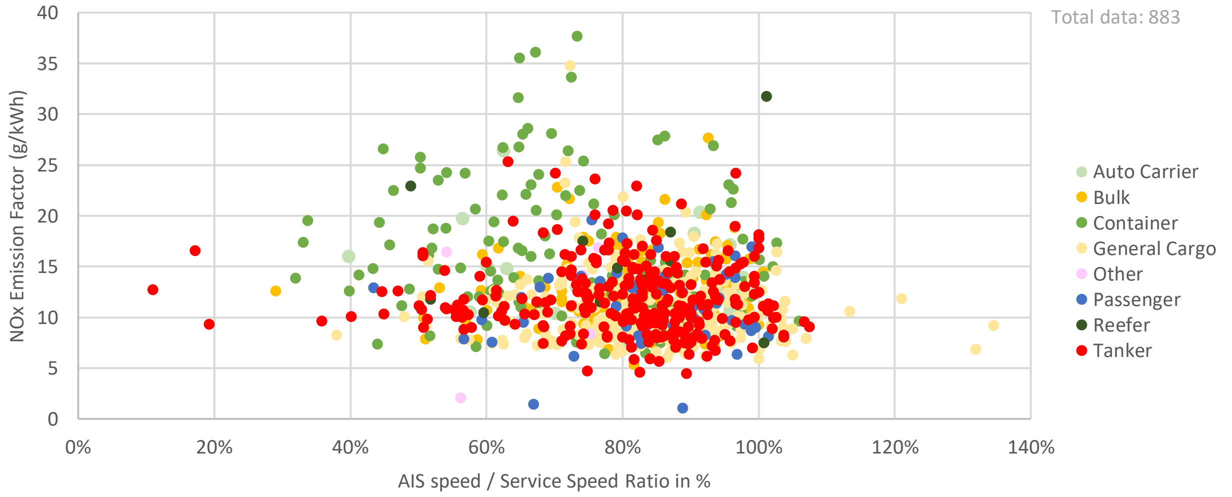
As mentioned in section 3.4 concerning deadweight tonnage, the correlation between speeds also appears to play a role in the NOx output, in particular, the difference between the service speed (i.e., the average intended speed maintained by a ship under normal load and weather conditions in open sea) and the recorded AIS speed at the time of sampling.

When calculating a *speed ratio*, i.e., the ratio between the AIS speed and service speed calculated for the individual ship and averaged for each ship type, and comparing this to the corresponding NOx emission factors, the same pattern as previously detected may be observed: The lower the recorded AIS speed vs the intended service speed, the higher the NOx emission factor with the exception of tankers and a few ‘others’.

The correlation between speed ratios and average NOx emission factors is illustrated in the below table and graph:

Ship Type	# Observ.	Average AIS speed (kn)	Average Service Sp. (kn)	Speed ratio (%)	Average NOx EFs (g/kWh)
Container	126	14.05	19.99	71.5 %	16.75
Reefer	12	14.79	19.30	77.7 %	15.81
Auto Carrier	37	15.61	19.17	81.8 %	12.97
Bulk	140	11.55	14.07	82.1 %	12.13
Tanker	272	11.25	14.04	80.3 %	11.99
Other	5	9.97	14.82	67.2 %	11.61
Passenger	54	19.41	22.91	83.5 %	11.24
General Cargo	237	10.51	12.59	84.1 %	10.95

Graph 23: Speed Ratio (%) vs. NOx Emission Factors (g/kWh): All Ship Types



Again, the container ships and their sister type, reefers, which have a relatively low speed ratio (below 80 %) and correspondingly a low average load, are also observed to have higher average NOx emission factors (above 15 g/kWh) than other ship types.

While this speed observation is not necessarily conclusive – speed in shipping is a murky concept with many definitions and a mix between measurements over ground and water – it is worth considering further how slower levels of steaming than a ship is principally 'designed' for may impact the NOx output.

3.8 Characterization of the Top NOx Emitters

The average NOx emission factor is 12.46 g/kWh with a slightly lower median value of 11.56 g/kWh. However, these values cover a significant spread of factors ranging from 1.06 to 37.71 g/kWh.

Approaching the data from "the top", the following characteristics can be made of the vessels with the highest NOx emission factors:

Of the top 10 % recorded NOx emission factors (consisting of 88 observations with an average quality score of 8.6) the average NOx emission factor is a notable 22.9 g/kWh – almost double the average NOx value of the total dataset.

These top 10 % observations share the following common characteristics:

- 79 % are SSD vessels.
- 84 % are operating at loads ≤50 %.
- 50 % are container vessels.
- 40 % are Tier II vessels.
- 34 % are vessels with engines ≥40,000 KW.
- 30 % are vessels with ≥120.000 DWT.

As the NOx EF values increase, the pattern crystallizes to include mainly large, SSD, Tier II container vessels with big engines operating at very low loads, as illustrated by the Top 10 and Top 25 tables below:

Top 10 Highest NOx EF Observations	
Share of total:	1.1 %
Average NOx EF:	32.61 g/kWh
Average AIS speed:	11.61 kn
Characteristics: • 90 % SSD vessels • 80 % container vessels • 80 % operating at ≤25 % loads • 60 % Tier II • 60 % with engines ≥40,000 kW • 60 % with ≥120.000 DWT	

Top 25 Highest NOx EF Observations	
Share of total:	2.8 %
Average NOx EF:	28.81 g/kWh
Average AIS speed:	12.44 kn
Characteristics: • 96 % SSD vessels • 76 % Container vessels • 64 % operating at ≤25 % loads • 60 % Tier II • 56 % with engines ≥40,000 kW • 52 % with ≥120.000 DWT	

4 Evaluating the Load-Adjustment Factors in the OGV Emissions Inventory

As stated in the introduction, part of the objective of this Memorandum is to use the RSE data to evaluate the current NOx EFs and load adjustment factors used in various OGV emissions inventories. The study uses the emissions inventory for the San Pedro Bay Ports area (SPBPEI) as the benchmark, but the adjustments are similarly applied in the U.S. EPA's Port Emissions Inventory Guidance (U.S. EPA, Sep 2020) and the IMO 4th GHG Study (CE Delft, 2020).

While the objective of this evaluation is to examine the correlation between the load-dependent NOx curves and the RSE data, it is not the objective of this Memorandum to offer specific recommendations as to the possible adjustments of the current curves.

Given that the NOx curves in the SPBPEI are used as conservative default factors in cases where authorities do not have access to a ship's engine certification data, it is a fair assumption to consider them as 'upper limits' as opposed to averages and are considered as such for this analysis.

4.1 Use of Definitions

As indicated in section 2.4 there is a discrepancy between how engine type is defined in the IMO4GHG and the SPBPEI. In particular, the SPBPEI has a much broader definition of MSD vessels (range: 130 – 2000 rpms) than the IMO4GHG (range: 300-900 rpm) and no HSD category for OGV main engines.

To overcome this misalignment in definitions in the evaluation of the default factors utilized in the SPBPEI, a band of upper and lower load-dependent NOx curves have been applied to the comparative analysis based on the default NOx emission factors for 0.1 % MGO fuel-use prescribed in the SPBPEI.

The default NOx EF factors (before load adjustments) and load curve labels are presented below:

IMO4GHG Def.	**SPBPEI Def.**	**RPM(n)**	**SPBP NOx EF when using 0.1 % MGO ***				**Load Curve label**
			Tier 0	**Tier I**	**Tier II**	**Tier III**	
SSD	SSD	n < 130	17.01	15.98	14.38 **	3.38 **	SSD High
	MSD	300 ≥ n ≥ 130	13.16	12.22	10.53	2.63	SSD Low
MSD		900 ≥ n > 300	13.16	12.22	10.53 **	2.63 **	MSD
HSD		2000 > n > 900	13.16	12.22	10.53	2.63	HSD High
	HSD	n ≥ 2000	10.90	9.78 **	7.71 **	1.97 **	HSD Low

* NOX EF for n ≥ 2000 are based on the EFs used in SPBPEI for auxiliary engines.
** Denotes consistency between the NOx EFs used by SPBPEI and the IMO4GHG.

Three types of load curves have been plotted for each combined engine type / Tier using the default NOx EFs and load adjustment factors utilized by the SPBPEI:

- A curve type based on a MAN Diesel conventional valve engine design, typically seen in Tier 0-I MAN engines;
- A curve type based on a MAN Diesel slide valve engine design, typically seen in Tier II MAN engines, and;
- A curve type based on a non-MAN Diesel engine design.

While these curves (load adjustment factors) are only applied to 2-stroke diesel engines with RPM below 130 in SPBPEI, the U.S. EPA Guidance and the IMO4GHG use only the non-MAN curve but apply it uniformly across all OGVs.[8] For the sake of simplicity, this study compares RSE NOx emission factors against each NOx curve for all vessels in the dataset. If no adjustment factors are applied, as is the case for all OGVs other than those with RPM < 130 in SPBPEI, NOx emission rates are then implicitly assumed to not increase with lower loads (i.e., a flat NOx curve), leading to overall lower estimated NOx emitted from OGVs with RPM at or greater than 130.

As stated above, high/low versions of each of these curve types are applied where the engine oil definitions of the SPBPEI do not match the IMO4GHG definitions. This is the case for the SSD and HSD categories, but not MSD where the narrow IMO4GHG definition matches the SPBPEI.

Example: For SSD Tier I vessels both High and Low curves have been plotted using the default SSD and MSD NOx EF values for Tier I from the SPBPEI (15.98 and 12.22 g/kWh respectively).

For those wishing to see the same analysis using the SPBPEI definitions instead, please see Appendix B.[9]

As with the previous chapter, the total number of observations and the average NOx emission factor for each graph is noted in grey in the top righthand corner. For this analysis, to avoid any confusion with the load-dependent NOx curves, linear trendlines have been omitted. Additionally, the y axis has been capped with a maximum of 40 g/kWh for comparative purposes, even if the non-MAN load curves start out higher than this.

4.2 Load curves for SSD vessels

Note, graphs 24, 25 and 26 are a further breakdown of the data previously presented in graph 20. For legends SSD high and SSD low, refer to table above.

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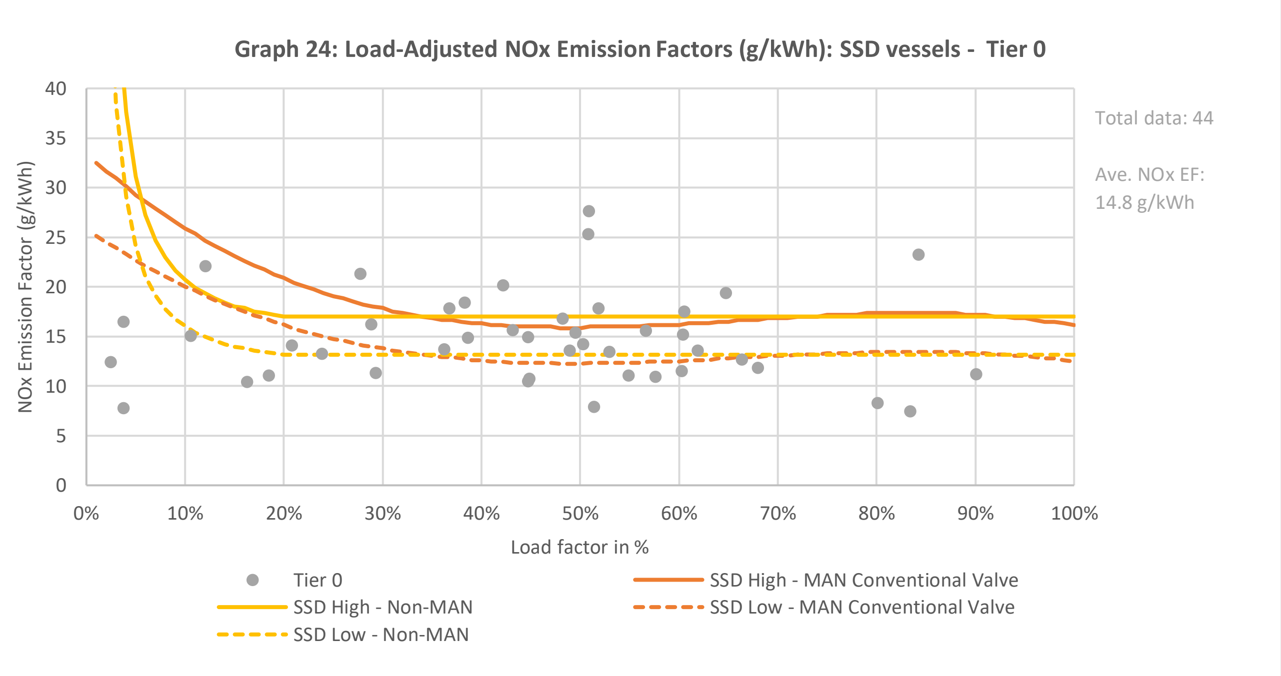
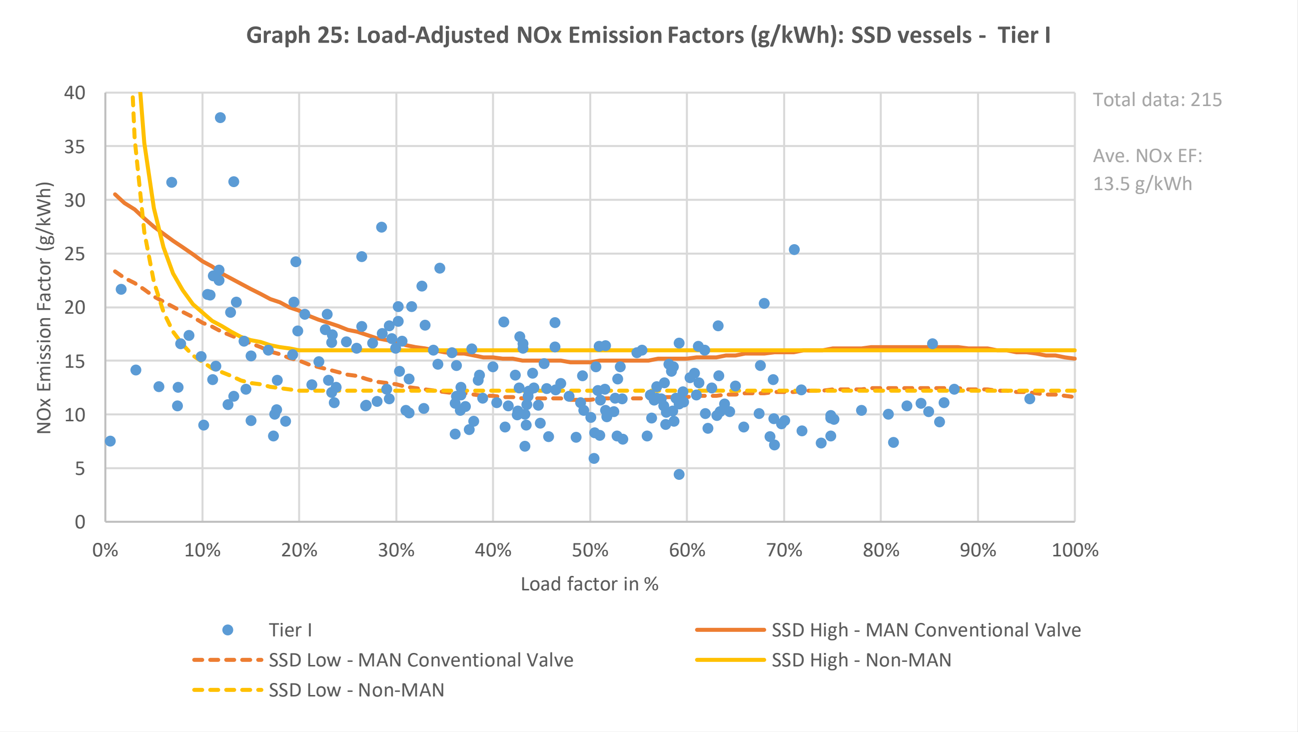
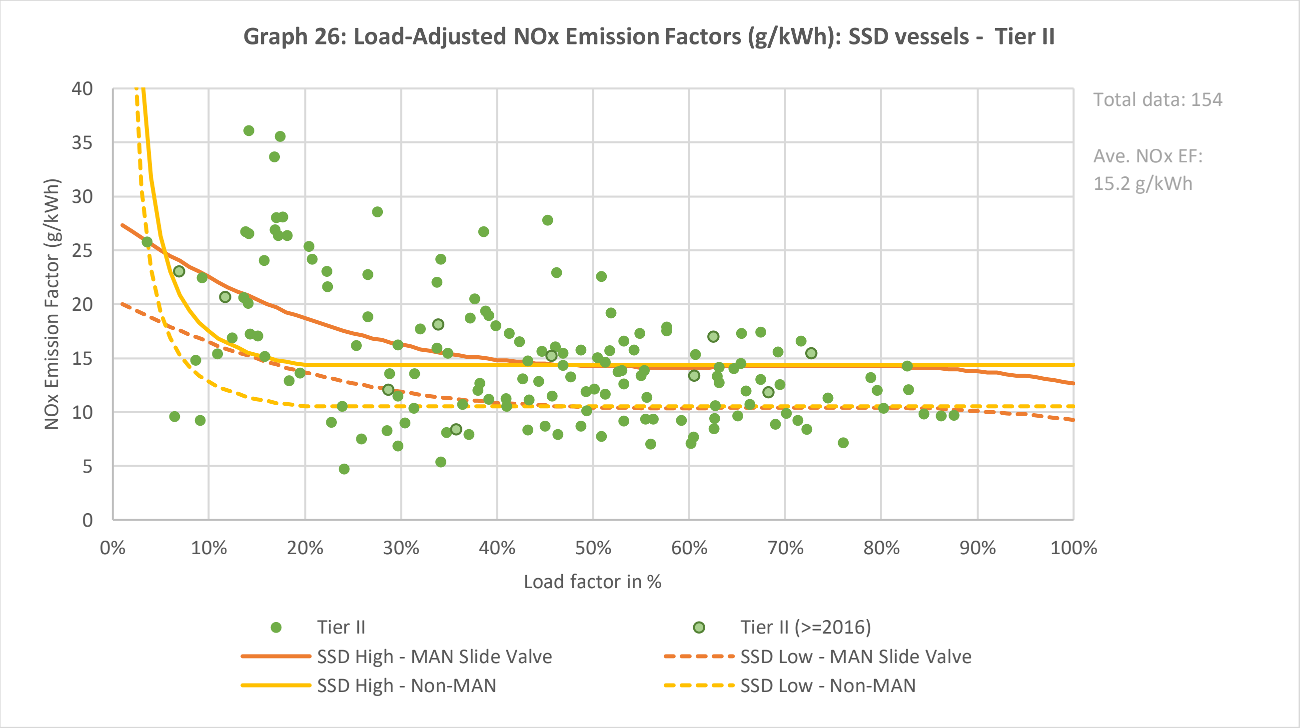
[8] NOx emission factors along the non-MAN increase exponentially at very low loads. This may be unrealistic, and therefore, the model used in IMO4GHG does not report emissions for the main engine below 7 % load. In comparison, both the U.S. EPA Guidance and SPBPEI apply low load adjust factors to all low loads.

[9] Only the engine oil type categorization is changed in Appendix B. The calculation of the NOx EFs is still based on the IMO4GHG methodology for calculating the specific fuel consumption.


Graph 24: Load-Adjusted NOx Emission Factors (g/kWh): SSD vessels - Tier 0
Total data: 44
Ave. NOx EF: 14.8 g/kWh
NOx Emission Factor (g/kWh)
40
35
30
25
20
15
10
5
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Load factor in %
Tier 0
SSD High - MAN Conventional Valve
SSD High - Non-MAN
SSD Low - MAN Conventional Valve
SSD Low - Non-MAN


Graph 25: Load-Adjusted NOx Emission Factors (g/kWh): SSD vessels - Tier I
Total data: 215
Ave. NOx EF: 13.5 g/kWh
NOx Emission Factor (g/kWh)
40
35
30
25
20
15
10
5
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Load factor in %
Tier I
SSD High - MAN Conventional Valve
SSD Low - MAN Conventional Valve
SSD High - Non-MAN
SSD Low - Non-MAN



Graph 26: Load-Adjusted NOx Emission Factors (g/kWh): SSD vessels - Tier II

Main SSD load-dependent NOx curve findings:

As displayed in graph 20 and broken down here in graphs 24, 25 and 26, SSD vessels can be characterized by generally higher NOx emissions than that of MSD or HSD vessels. At the same time, the SSD data is noticeable for its considerable spread in emission factors, with observations up to 38 g/kWh.

For the Tier I vessels ca. 13-46 % of the observations are positioned above one of the load-dependent NOx curves. For Tier II this pattern is even more distinct with 35-76 % of observations located above one of the curves while Tier 0 is somewhere in between with 23-59 %. This finding is significant.

If the intent of the load-dependent NOx curves are to serve as conservative near-upper limits for NOx emission estimation, none of them seem to fully achieve this. This is particularly true for Tier II vessels. Similarly, none of the load-dependent curves seem to fully capture the slight downward trend in the data as the loads increase. In fact, the non-MAN curves are flat at engine loads at or above 20 %.

That the SSD vessels present a more scattered pattern in NOx emission factors with many high observations – particularly at low loads and in younger vessels – is not unsurprising when considering recent decades' incentive to optimize fuel consumption and the way NOx emissions from main engines are tested and certified under the NOx Technical Code (MEPC.177(58)).

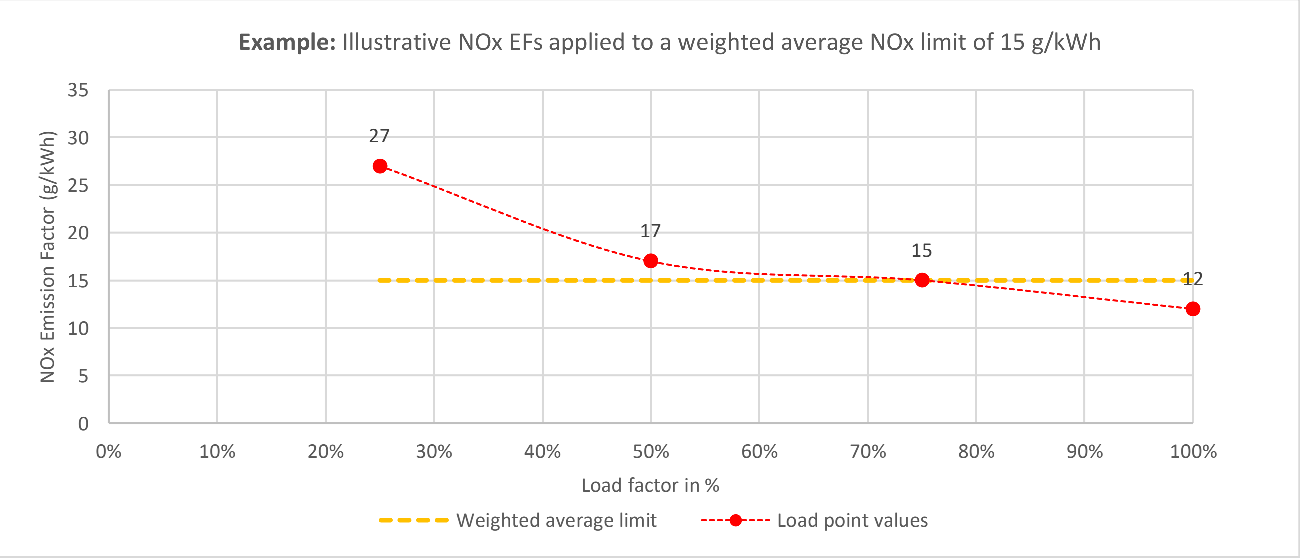
Under test cycles E2 and E3 for main engines, NOx emissions are measured at four different engine load points (25, 50, 75, and 100 %). However, when calculating the total NOx emissions, each load point is given different weight. Under the Code's test scheme, the lower load points (at 25 and 50 %) are only given a combined 30 % weight while the higher load points (at 75 and 100 %) collectively weigh 70 %. This imbalance means small reductions at higher loads can be matched by relatively higher increases at the low end while still maintaining the same weighted average. In addition, except for Tier III standards, Regulation 13 does not impose legal restrictions on how much the specific NOx emission rate at each test cycle load point may deviate from the applicable NOx emission limit. It only looks at the total weighted NOx emissions across all four load points.

In other words, the current weighted test structure under Regulation 13 leaves an opportunity for vessels to optimize fuel consumption at low loads while still being compliant which could help explain the large spread in emission factors and high values below 50 % load.

The relation between fuel consumption and NOx emissions is important. In general, there are several ways to improve the fuel efficiency of an engine, the main one being controlling the phasing of the heat release and the air-fuel ratio to achieve a higher thermodynamic efficiency. However, as combustion temperatures increase so does the formation of NOx when the molecular nitrogen and oxygen from air brake apart and recombine to form NO molecules. For this reason, there is a natural dichotomy between wanting to reduce fuel consumption (and with this also CO_2 emission) and limiting NOx emissions, also known as the fuel efficiency / NOx trade-off.

If a ship has the option to reduce its fuel consumption by steaming slow and additionally optimize the engine for low NOx at high load (and less so at low load), then the effect is a compounded fuel save which, in the case of large vessels, can be of significant nominal value.

The mathematical effect of the weighted structure implemented in the NOx Technical Code (MEPC.177(58)) is illustrated in the graph example below. Here the weighted limit is set at 15 g/kWh but each of the four load points are optimized to reduce the fuel consumption at low loads. As illustrated, by reducing the NOx emissions at the highest load point by 20 %, NOx emissions at the lowest load point may be increased by 80 % above the weighted limit.



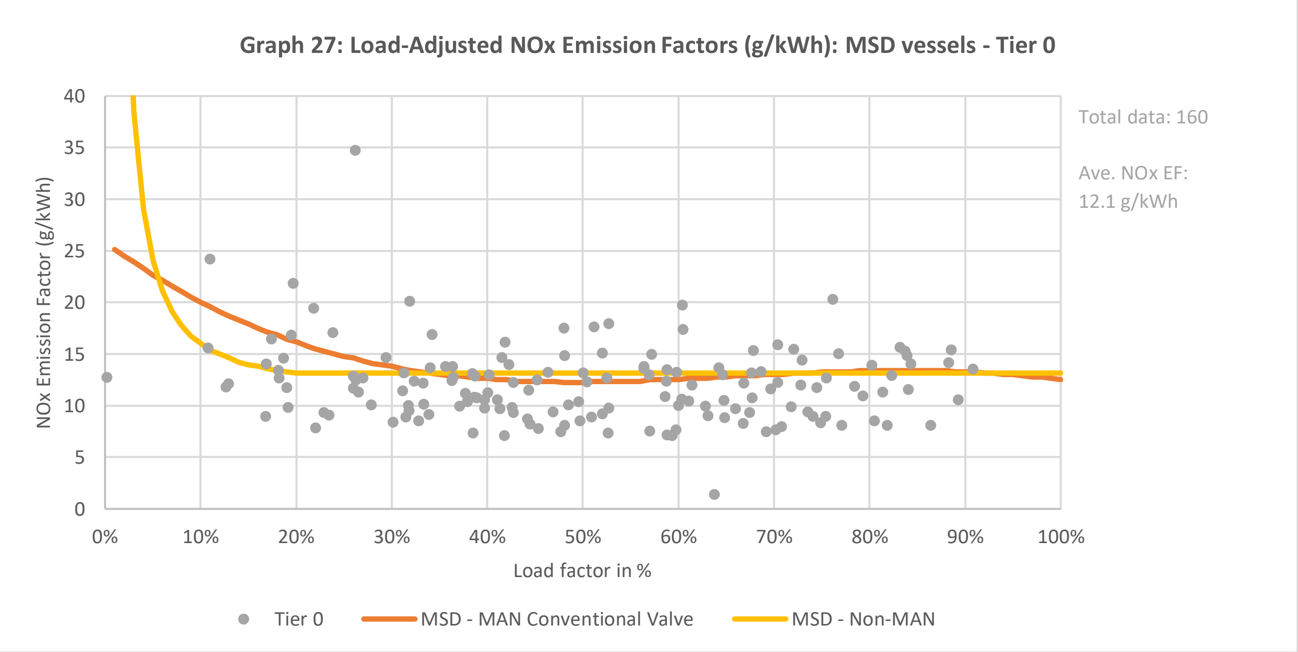
Note: According to the NOx Technical Code (section 5.12.6.1, MEPC.177(58)), the weighted average is applied to the g/h value per load point and not the g/kWh, effectively factoring in how diminishing power creates a lower quantity emission overall. This difference has been accounted for in the emission factors presented in the example above.

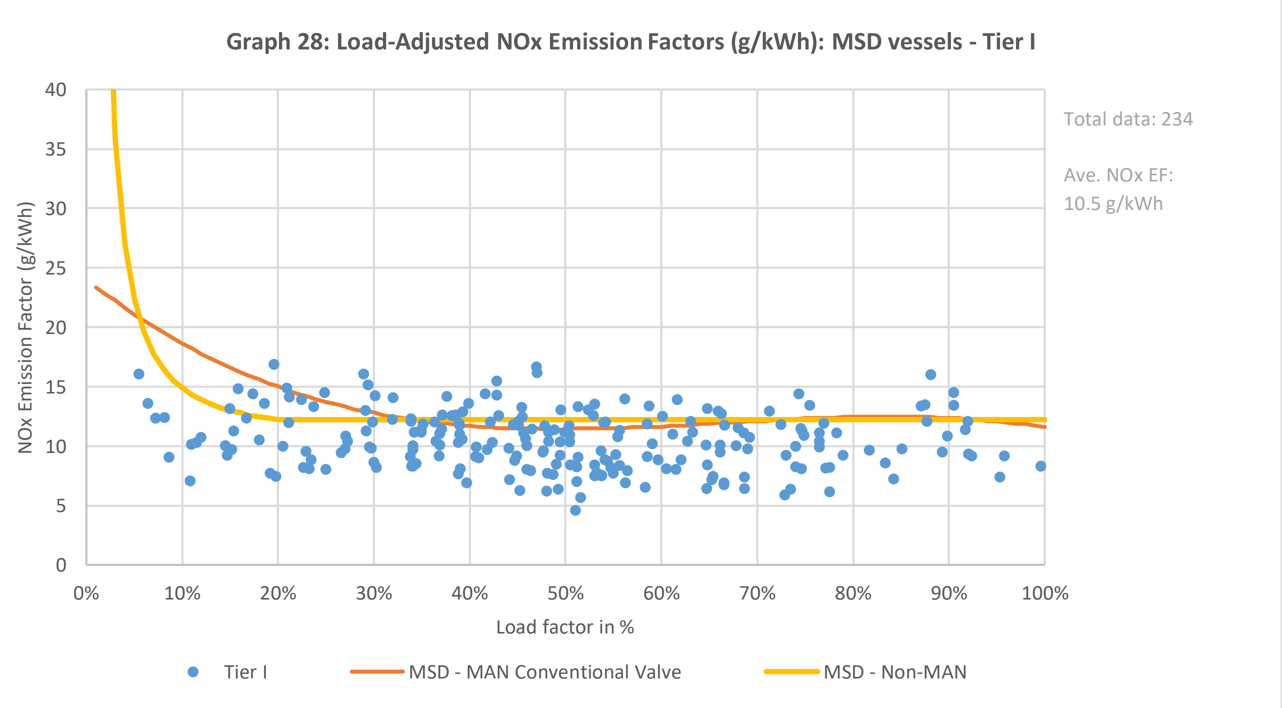
It should also be noted that the NOx Technical Code (MEPC.177(58)) does not test emission factors below 25 % load for main engines where several of the highest NOx emission factors are observed.

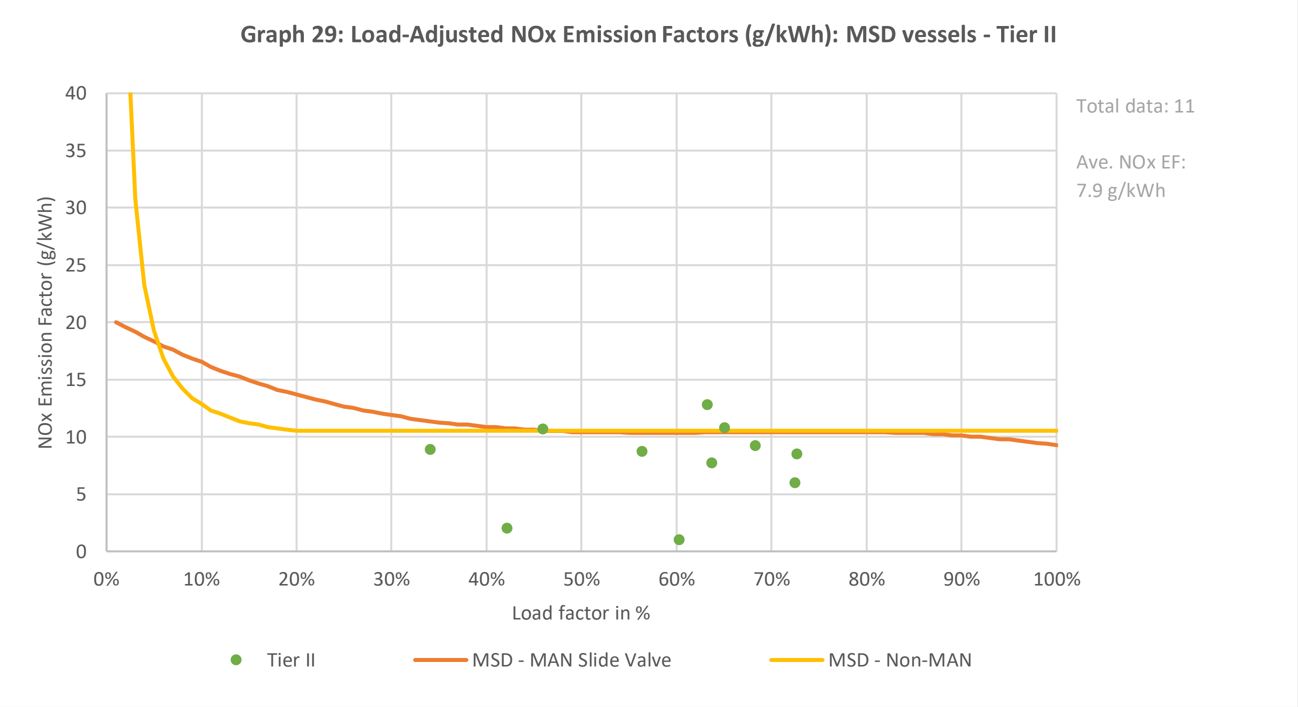
The inability of the existing NOx Technical Code (MEPC.177(58)) to fully capture the actual engine emission performance at sea under operational conditions, and the options for modern engines to ‘beat the cycles’, has most recently been noted by the SCIPPER Project, a current research project funded by the EU Commission investigating emissions contributions from shipping, monitoring techniques, and gaps in the current regulation and enforcement (Winnes et.al (2019)).

4.3 Load curves for MSD vessels

Note, graphs 27, 28 and 29 are a further breakdown of the data previously presented in graph 21.







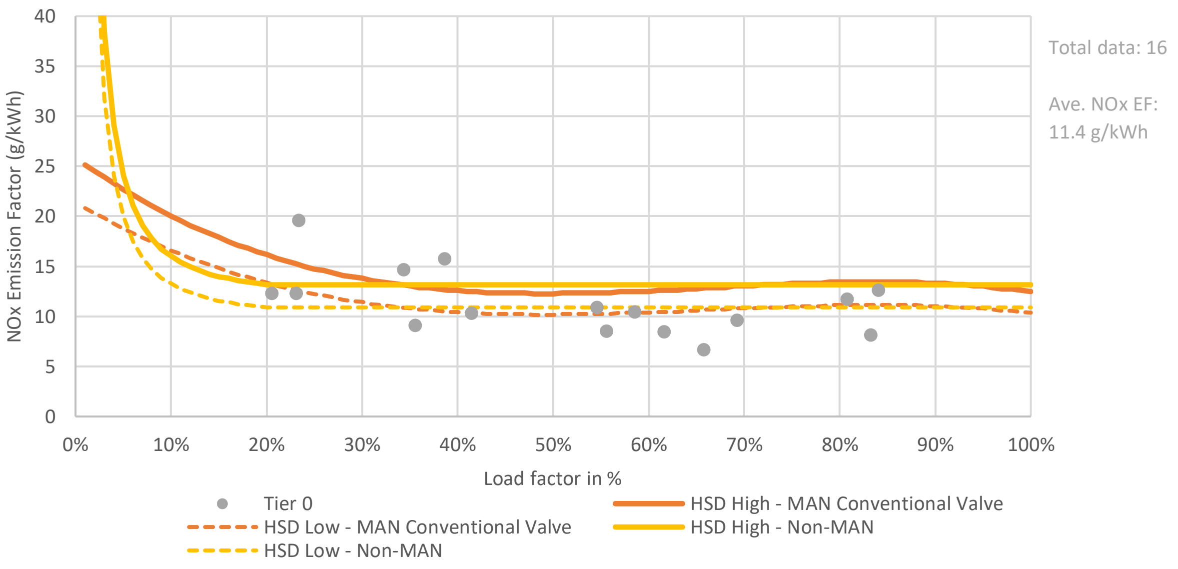
Main MSD load curve findings:

Unlike with the SSD vessels, the load curves for the MSD segment appears to fit better with the RSE data albeit still with a tendency to underreport the actual emissions factors. While there are still ca. 26 % of Tier 0 observations and 15 % of Tier I observations above the curves, the difference is less pronounced than that for SSD vessels with no apparent issue at lower loads. The limited number of MSD Tier II observations makes it impossible to reach any broad conclusions for this segment.

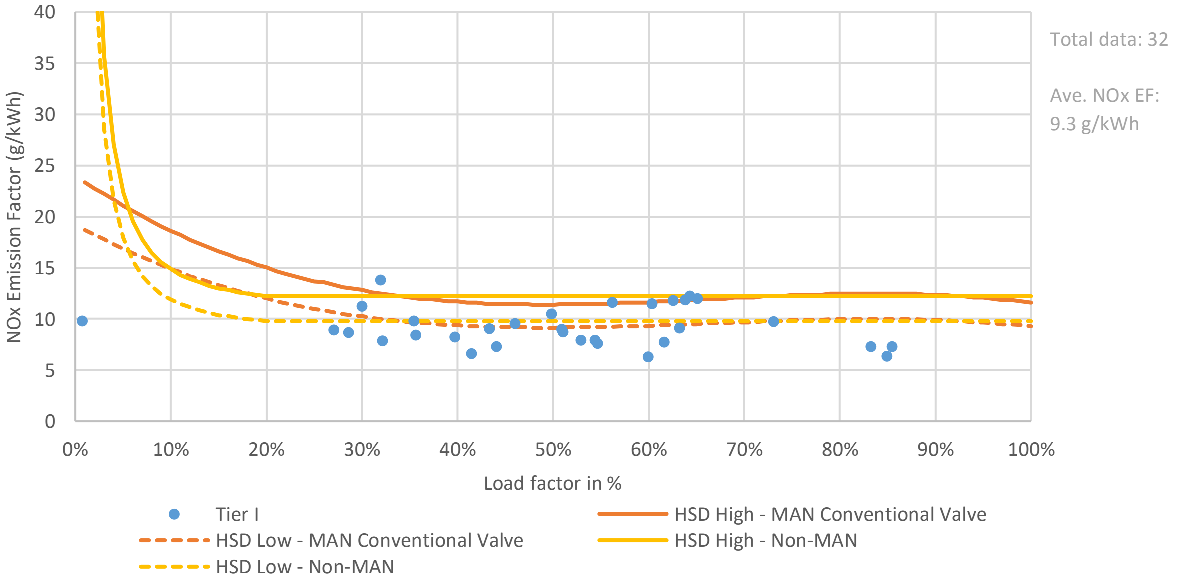
The average NOx emission factors for all three tiers are lower than the overall average, with Tier II producing the lowest average of any of the breakdowns (7.9 g/kWh).

4.4 Load curves for HSD vessels

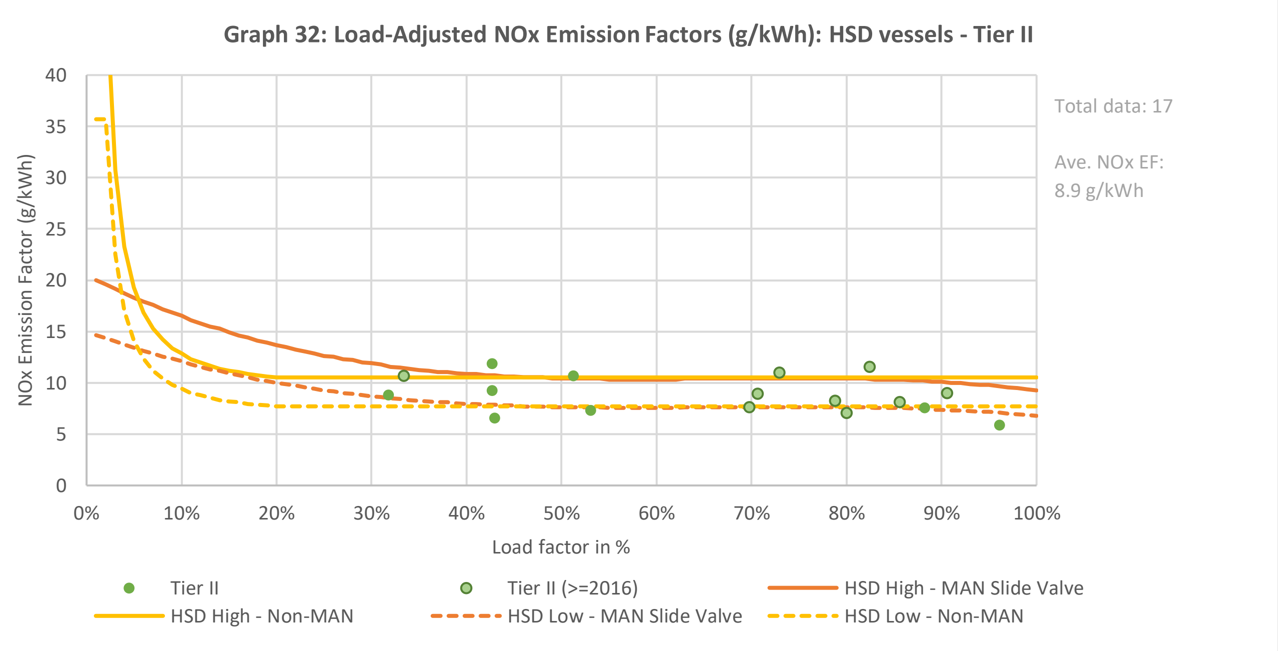
Note, graphs 30, 31 and 32 are a further breakdown of the data previously presented in graph 22.



Graph 30: Load-Adjusted NOx Emission Factors (g/kWh): HSD vessels - Tier 0



Graph 31: Load-Adjusted NOx Emission Factors (g/kWh): HSD vessels - Tier I



Main HSD load curve findings:

For all three tiers, the HSD curves appear to fit well with the RSE data. However, the limited number of data points makes it hard to reach any robust conclusions.

4.5 Concluding remarks and potential implications to the OGV emissions inventory

As mentioned in the introduction to this chapter, it is not the intent of this Memorandum to prescribe specific changes to the OGV emissions inventory. However, in conclusion, the analysis offers several important take-aways with potential implications for the inventory going forward:

From the comparison with the RSE patterns it is clear that:

- For SSD vessels, the load-dependent curves currently applied for each engine tier are generally underestimating the NOx emission factors estimated in this study that are based on RSE measurements. This finding applies to all tiers:
    - For Tier 0 on average ca. 41 % of the observations are above the corresponding curves;
    - For Tier I the average is 30 %;
    - For Tier II an average of 56 % of all observations are found above the corresponding curves.
- This finding is significant and means there is a risk of a general underestimation of the NOx contribution from SSD OGVs in further atmospheric modelling.
- In particular at lower loads (between 10 and 50 %), the load-dependent curves appear to significantly underestimate the NOx emission factors for SSD vessels.
- For MSD vessels there also appears to be a tendency towards underestimation in the current load-dependent curves, however not at the level found with SSD ships.
- In HSD vessels no such immediate discrepancy can be found, although there are few observations to base a conclusion on.
- These findings not only accentuate the spreads identified for SSD's but also speaks to the overall quality of the measurements and the methodology used in this analysis. If the data and approach had suffered from systemic measurement errors and/or methodological problems, these would have been apparent for all engine types.

- Drawing also on the conclusions in chapter 3, the high NOx emission factors are not only related to the engine type and tier class but also to the size of the ships, both in terms of DWT and MCR, and to a certain degree ship type. To capture the material differences in emissions patterns across ships of varying tiers, sizes, and types, changing the best practice to instead apply a more segmented approach to the load adjustment factors in the inventory could be considered to ensure a more accurate representation of the fleet.
- Furthermore, the analysis highlights a need to further investigate the NOx emission factors for the segments with the highest factors, many of which are container ships similar to those frequently calling into the San Pedro Bay ports.

Furthermore, it is worth noting that the NOx emission rates are empirically based estimates only. This being said, the distinctly different presentation of Tier II SSD vessels – with a larger rate spread and higher values at lower loads (< 50 %) – is indication that it could be problematic to simply assume that the NOx curve for each tier is just a downward shift from older tiers. Indeed, Tier II (and perhaps III) may have an altogether steeper profile that may explain the higher observations at lower loads to the extent that these are not significantly impacted by auxiliary engine outputs.

As a final comment to the overall analysis, it should be noted that several of the observations made here concerning NOx emissions and load patterns are not necessarily new. They have been noted in other studies. The difference is that this analysis is based on a uniquely large set of real sailing emissions data across a broad section of the commercial fleet, collected along dense shipping lanes outside highly populated coastal areas. Its empirical scale makes it hard to discount.

With regards to the existing regulation of maritime NOx emissions, the analysis indicates that coastal areas hoping to combat NOx emissions from shipping, may find little support in Regulation 13 as implemented via the NOx Technical Code (MEPC.177(58)). There are still only very few Tier III ships around and the existing test regime for Tier I and II may not sufficiently capture real emission patterns as they play out in coastal areas.

For a complete summary of all the findings in this Memorandum, please see chapter 1.

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Appendix A: Summary Tables

The following presents various summary tables of the composition of the ship observations used in this analysis:

Ship Observations	**#**
Total # of ship observations in the full dataset	929
Total # of excluded ship observations *	46
Total # of ship observations used in the analysis	883
Total # of unique ship observations in the analysis	748

* For details on the grounds for exclusion of some observations, see section 2.2.

Observations by Quality	**#**	**%**
Ship observations with a high-quality score (6-10)	728	93.5
Ship observations with a medium quality score (3-6)	40	4.5
Ship observations with a low-quality score (1-3)	18	2.0
Total # of ship observations	**883**	**100.0**

Speed Analysis	**Kts**
Average speed	12.22
Median speed	11.70
Minimum speed	1.09
Maximum speed	37.49

Observations by Tiers	**#**	**%**
Tier 0	220	24.9
Tier I	481	54.5
Tier II	182	20.5
*Tier II ≥ 2016 **	*19*	*2.1*
Total # of ship observations	**883**	**100.0**

Note, onwards observations of Tier II vessels aged 2016 or younger will be marked *Tier II+*. These observations form a subset of the Tier II category and for this reason do not count towards the sum totals.

Observations by Ship Type	**Total**	**Tier 0**	**Tier I**	**Tier II**	***Tier II+***
Tanker	272	28	192	52	*7*
Bulk	140	7	66	67	*5*
Container	126	21	71	34	*2*
General Cargo	237	113	110	14	*1*
Passenger	54	20	26	8	*3*
Reefer	12	9	3	0	*0*
Auto Carrier	37	20	12	5	*0*
Other	5	2	1	2	*1*
Total # of observations	**883**	**220**	**481**	**182**	***19***

Observations by DWT	**Total**	**Tier 0**	**Tier I**	**Tier II**	***Tier II+***
Mini Handy <24000	541	203	298	40	*10*
Handysize 24000-34999	65	7	44	14	*3*
Handymax 35000-49999	98	6	45	47	*3*
Panamax 50000-79999	80	2	43	35	*1*
Aframax 80000-119999	57	1	36	20	*1*
Suezmax 120000-199999	28	1	12	15	*1*
Malaccamax 200000-319999	14	0	3	11	*0*
Total # of observations	**883**	**220**	**481**	**182**	***19***

Observations by MCR	**Total**	**Tier 0**	**Tier I**	**Tier II**	***Tier II+***
0-9999 KW	624	167	335	122	*12*
10000-19999 KW	149	29	95	25	*4*
20000-29999 KW	33	16	14	3	*0*
30000-39999 KW	30	5	19	6	*3*
40000-49999 KW	15	1	8	6	*0*
50000-59999 KW	22	2	3	17	*0*
60000+ KW	10	0	7	3	*0*
Total # of observations	**883**	**220**	**481**	**182**	***19***

Observations by Engine type	**Total**	**Tier 0**	**Tier I**	**Tier II**	***Tier II+***
SSD	413	44	215	154	*10*
MSD	405	160	234	11	*0*
HSD	65	16	32	17	*9*
Total # of observations	**883**	**220**	**481**	**182**	***19***

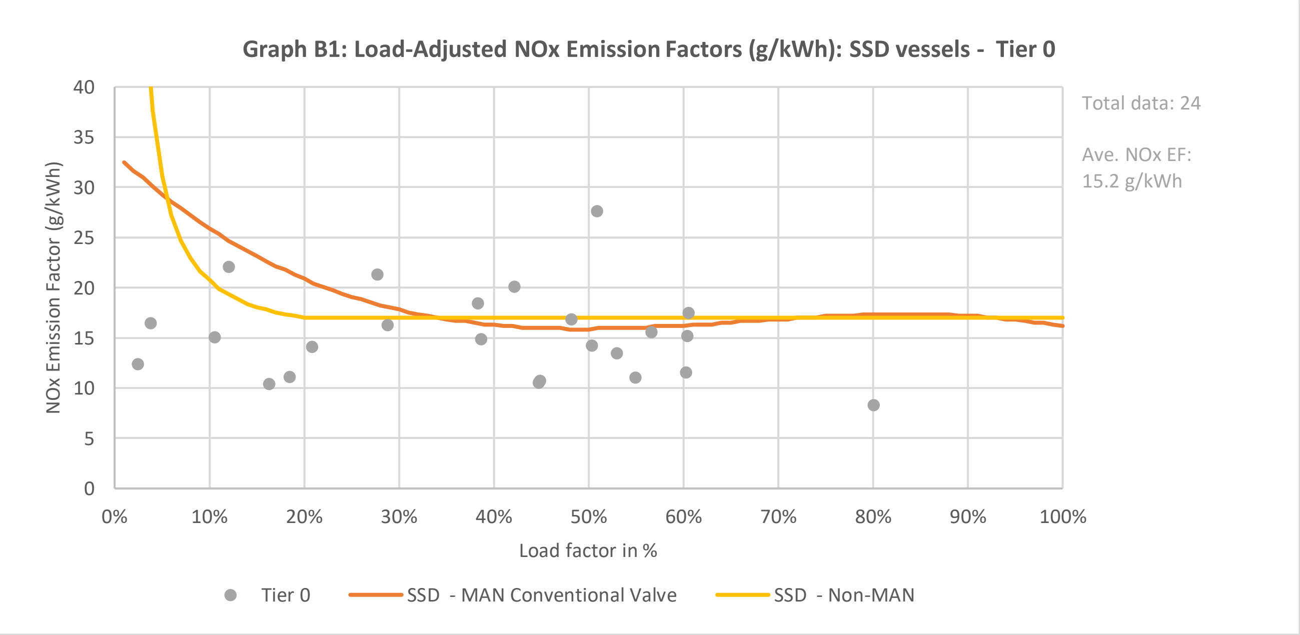
Appendix B: Load Curves Using SPBPEI Definitions

This appendix presents the same graph analysis as presented in Chapter 4, however using the engine type definitions applied in the SPBPEI. The calculation of the NOx EFs is still based on the IMO4GHG methodology for calculating the specific fuel consumption.

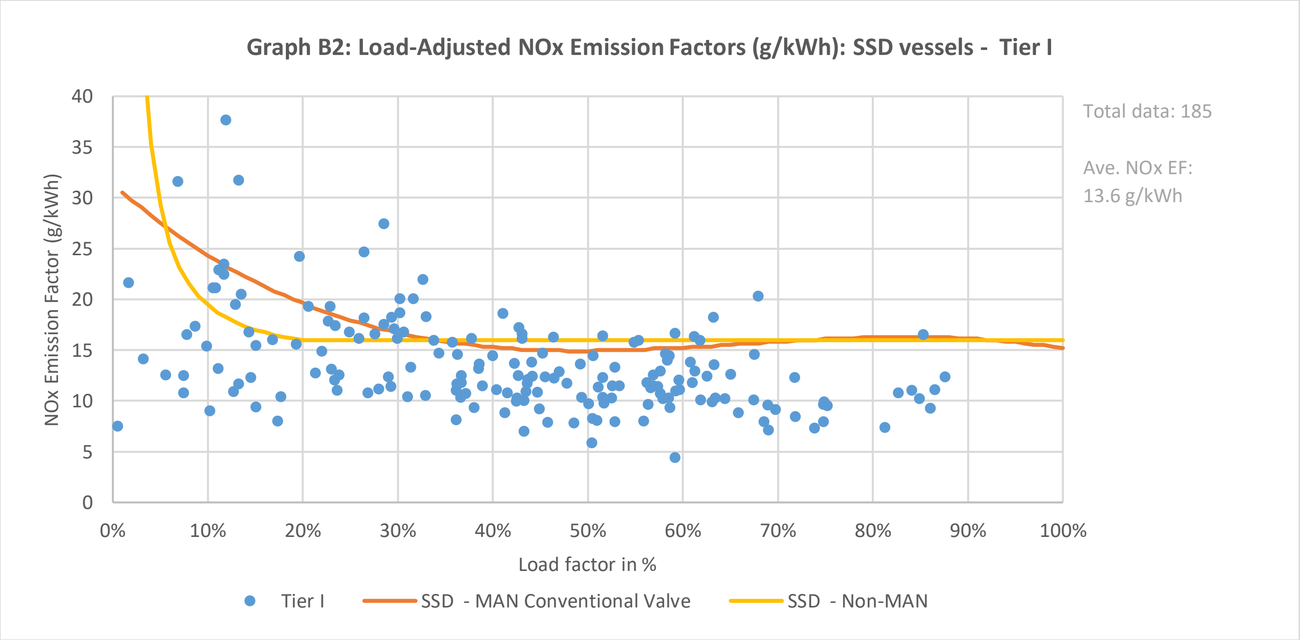
Note, the SPBPEI only includes SSD and MSD categories.

For each graph, the percentages of observations exceeding any of the curves is noted in percentages spreads.

SSD vessels by tier:



Observations above the curves: 25 %

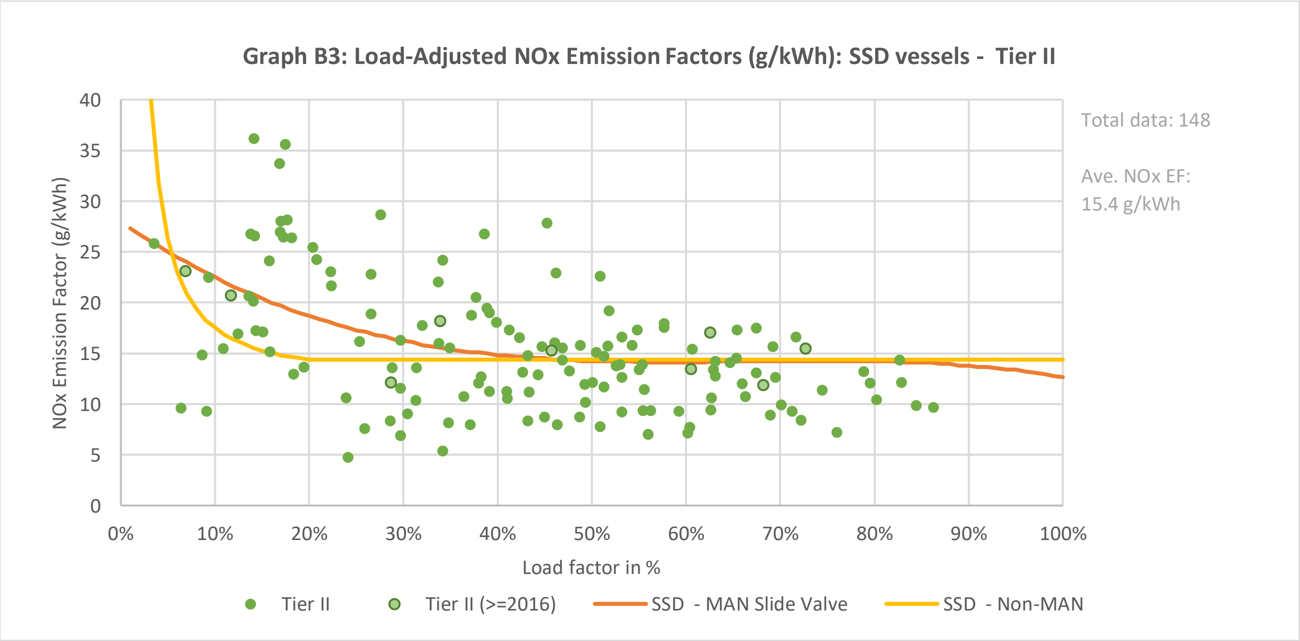


Graph B2: Load-Adjusted NOx Emission Factors (g/kWh): SSD vessels - Tier I

Total data: 185

Ave. NOx EF: 13.6 g/kWh

Observations above the curves: 16-21 %



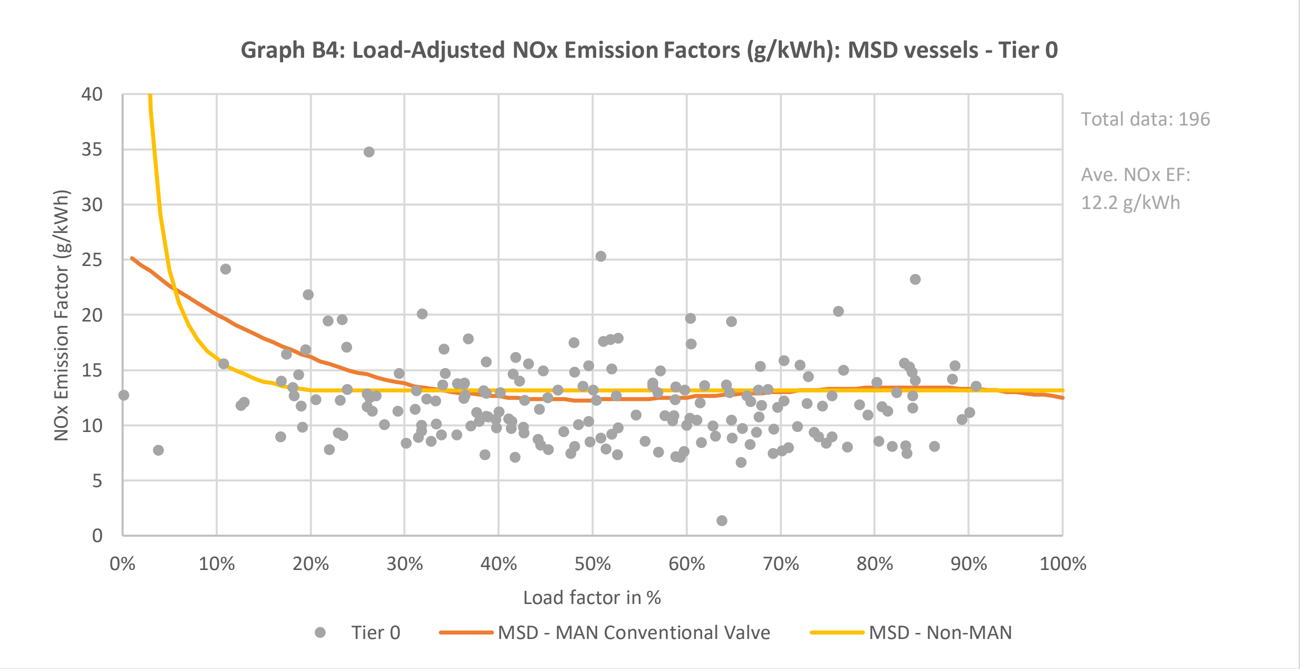
Graph B3: Load-Adjusted NOx Emission Factors (g/kWh): SSD vessels - Tier II

Total data: 148

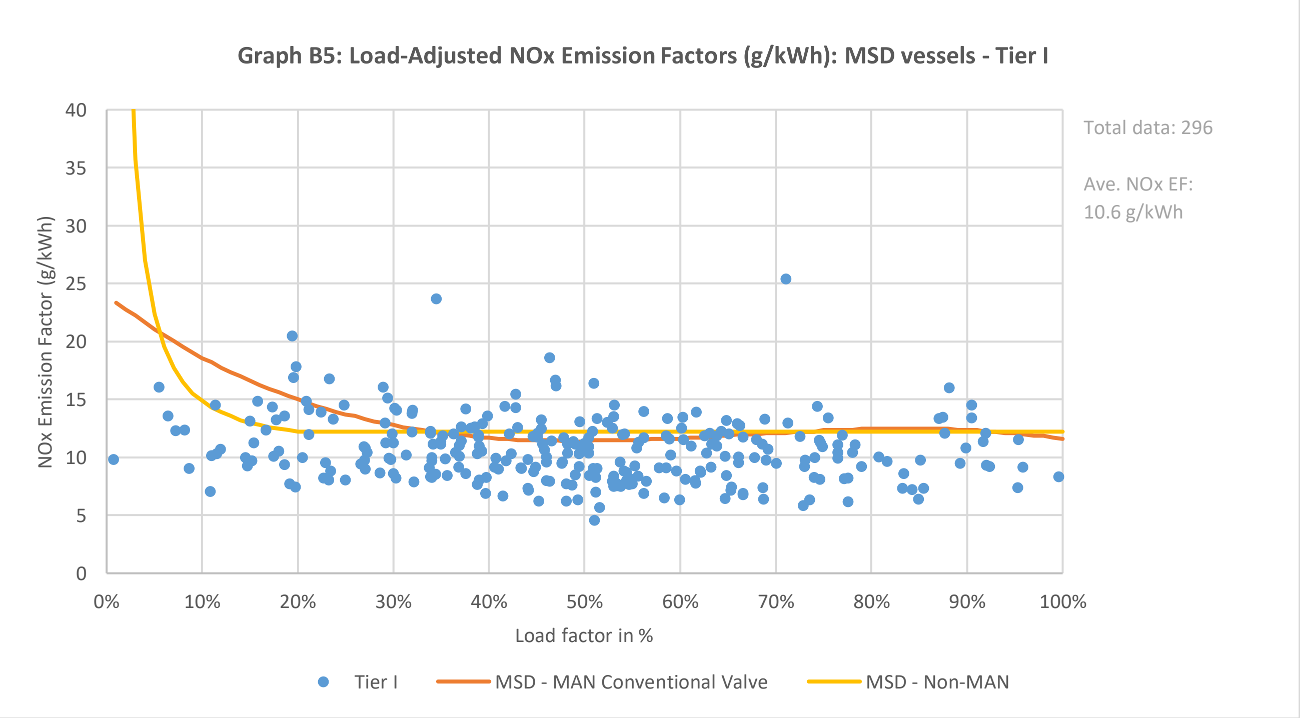
Ave. NOx EF: 15.4 g/kWh

Observations above the curves: 40-46 %

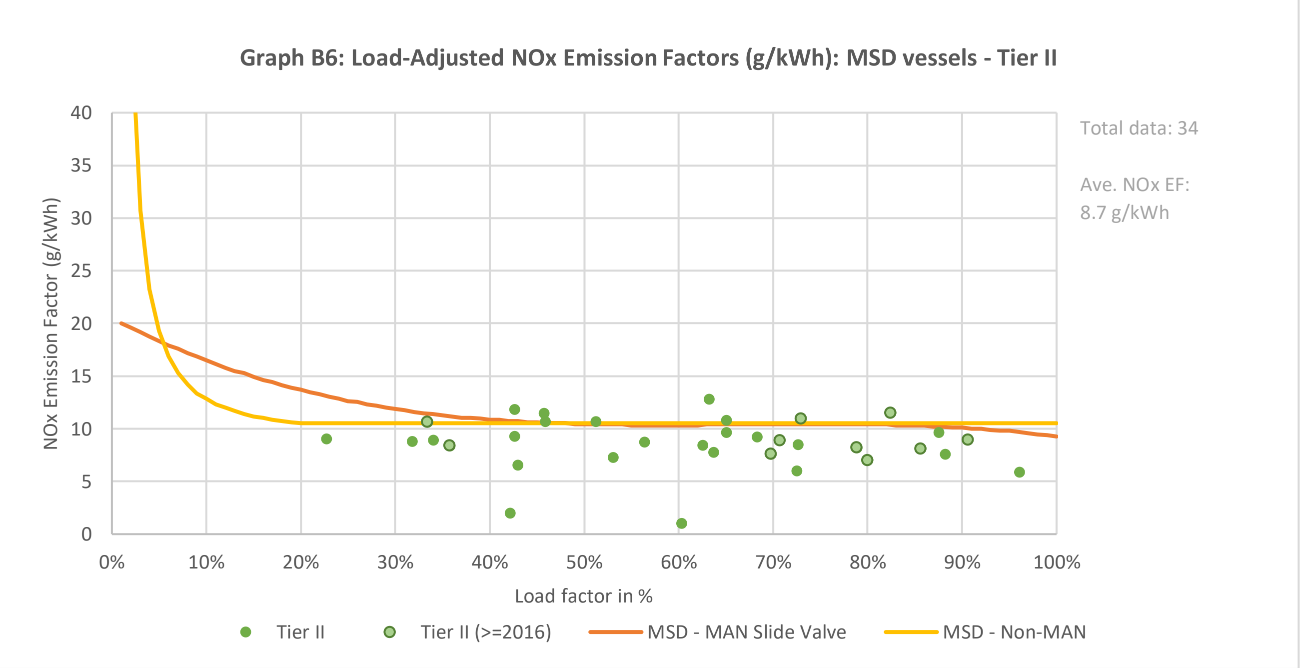
MSD vessels by tier:



Observations above the curves: 30-32 %



Observations above the curves: 23 %



Observations above the curves: 29-32 %

Appendix C: SFC_{base} Values

This appendix presents the base specific fuel consumption (SFC) values used to determine the load-adjusted fuel efficiency of the individual ships. The values are derived from the IMO4GHG (page 70-71) and given in g/kWh for each combination of engine type, fuel type, and year built.

Engine Type	Fuel Type	Before 1983	1984-2000	2001+
SSD	HFO	205	185	175
	MDO	190*	175*	165*
	MeOH**	N/A	N/A	350*
MSD	HFO	215	195	185
	MDO	200*	185*	175*
	MeOH**	N/A	N/A	370*
HSD	HFO	225	205	195
	MDO	210*	190*	185*

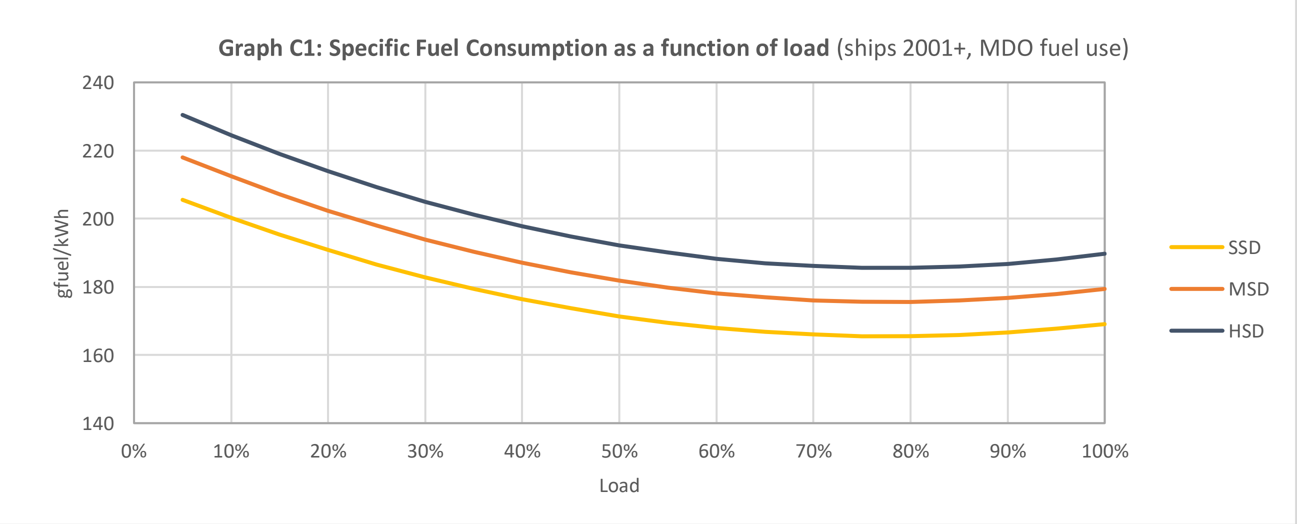
* Refer to a change from the Third IMO GHG Study 2004.

** The conversion of SFC_{base} between fuels was done using the following assumed energy densities: For HFO is 40,200 kJ/kg; MDO uses 42,700 kJ/kg; and Methanol is assigned 19,900 kJ/kg (International Maritime Organization, 2018).

As outlined in the IMO4GHG, the main engine specific fuel consumption (e) is assumed to vary as a function of its load as follows (CE Delft 2020, equation 10, page 71):

$$e\left(\frac{g_{fuel}}{kWh}\right) = SFC_{base} \times (0.455 \times LF^2 - 0.710 \times LF + 1.280)$$

This functional relationship between fuel consumption and load can also be illustrated in graphic form as follows using the above base values for MDO fuel use for ships aged 2001+:



As illustrated in graph C1, the main engine is assumed to be most fuel efficient around 75-80 % load with the specific fuel consumption at its highest level at low loads.