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Real-world NO_X emissions from ships and implications for future regulations

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Summary

This study utilizes real-world measurements of ship exhaust plumes to estimate emissions of nitrogen oxides (NO_x). We analyze samples of real-world NO_x emissions from ships operating in Danish waters between the North Sea and the Baltic Sea in 2019. In total, 615 measurements from 545 unique ships were obtained using exhaust gas sampling devices (sniffers) attached to helicopters that were flown into the exhaust plumes of ships as they sailed. The data include measurements from ships covering all engine tiers, although ships with Tier III engines were only required to comply with Tier II limits in the Baltic in 2019.

We used a modified version of the approach in Balzani Lööv et al. (2014), to estimate NO_X emission rates in grams per kilowatt hour (g/kWh) based on the measured ratio of NO_X (nitrogen dioxide and nitrogen oxide) to carbon dioxide (CO_2) in the plume and assumptions about the specific fuel consumption of the main engines, which vary based on engine type, fuel type, and engine load. We discuss the implications for regulating NO_X from ships and recommend ways to make regulations more effective by setting not-to-exceed (NTE) standards, implementing a next-generation Tier IV standard, establishing additional emissions control areas (ECAs), facilitating the use of remote measuring systems, and building up port incentive programs to reduce emissions.

Newer Tier II engines had significantly higher NO_X emission rates than older Tier I engines (Figure S1). Moreover, there was no statistical difference in NO_X emission rates between unregulated Tier 0 engines and Tier II engines. This suggests that NO_X regulations could be revised to make them more effective at reducing air pollution.

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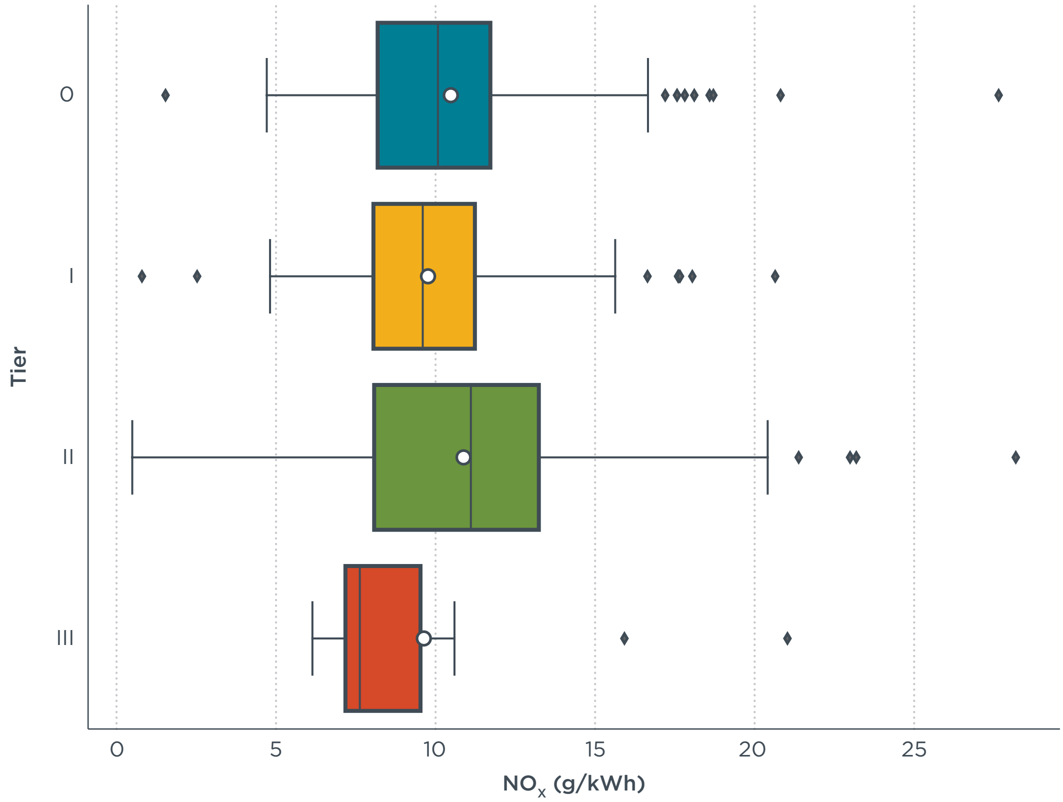


Note: white dots show mean; vertical bars show median; error bars show interquartile range; diamonds show outliers.

Figure S1. Boxplot showing distribution of observed NO_x emission rates by engine tier.

Across all vessel types and engine tiers, the data show the greatest mean NO_x emission rates at main engine loads below 25% with mean emissions of 12 g/kWh. Emission rates decrease as main engine loads increase, with mean emission rates of 8.1 g/kWh at loads greater than 75%. Existing NO_x test cycles assume that marine engines most often operate at higher engine loads; however, our research shows that engines typically operate at lower engine loads.

The tendency for emission rates to be higher at lower engine loads, paired with the finding that ships frequently operate at lower engine loads than those assumed in NO_x test cycles, highlights the need to consider and control NO_x emission rates at lower loads (<25% maximum continuous rating). For vessels operating near shores, where lower speeds and engine loads are prevalent, the potential for higher NO_x emission rates amplifies the impact on air quality for communities near shorelines and ports. Furthermore, Tier III NO_x control technologies, such as Selective Catalytic Reduction (SCR), cannot effectively operate at low loads due to low engine temperatures [International Maritime Organization (IMO), 2013].

The results of this study suggest the need to address and control NO_x emission rates at low load operation (<25%). Rather than relying solely on weighted emission limits, the IMO could consider implementing NTE standards for new and existing ships, particularly focusing on operations at low loads, and including a test point below a 25% load (e.g., 10%). This would result in more complete emissions profiles for ships, especially during low load operations where we observed emission rates higher than would be expected by the regulations.

Introduction

Nitrogen oxides (NO_x) are gaseous compounds which can be produced by fossil fuel combustion. They are significant agents in the formation of ozone, photochemical smog, and acid rain (Crutzen, 1970; Prather & Sausen, 1999; Skalska et al., 2010). Furthermore, risk assessments of high outdoor concentrations of nitrogen dioxide (NO_2) in residential areas reveal increased respiratory and cardiovascular diseases and mortality (Chaloulakou et al., 2008).

Reducing NO_x emissions could alleviate the health burdens associated with the shipping industry. Globally, in 2020, there were up to an estimated 266,000 premature deaths from lung cancer and cardiovascular disease caused by ship-source air pollution accounting for the combined impacts of NO_x, sulfur oxides (SO_x), and particulate matter and accounting for the impacts of the global sulfur rule that reduced the maximum allowable sulfur content of marine fuels from 3.5% to 0.50% in 2020 (Sofiev et al., 2018).

In the global maritime shipping sector, NO_x emissions are estimated to have increased by 3.8% between 2012 and 2018, growing to 23 million tonnes in 2018, even in the presence of NO_x emission regulations (Faber et al., 2020). Researchers have estimated that national-level implementation of Tier III regulation could prevent around 42% of premature deaths caused by shipping, especially for countries with high levels of domestic shipping (Zhang et al., 2021). This refers to the established International Maritime Organization (IMO) NO_x standards in Regulation 13 of MARPOL Annex VI known as Tier I, Tier II, and Tier III (of which Tier III are the most stringent). Despite the implementation of a tiered NO_x regulation by the IMO, previous studies have observed NO_x emission rates higher for Tier II vessels compared to the least demanding Tier I vessel standards (Fridell et al., 2023; Manjamäki & Jalkanen, 2021; SCIPPER, 2023; Van Roy et al., 2023a).

Background

IMO regulates NO_x for engines with rated power greater than 130 kilowatts (kW), which includes most engines on international ships.[1] The NO_x Technical Code 2008 (NTC) describes how to certify marine engines for NO_x compliance. Engines that pass are issued an Engine International Air Pollution Prevention (EIAPP) certificate (IMO, 2014). The IMO NO_x limits for most engines are established based on the NTC's E2/E3 test cycle, which weights emissions as follows: 0.15 at 25% engine load; 0.15 at 50% engine load; 0.50 at 75% engine load; and 0.20 at 100% engine load. Only Tier III defines a not-to-exceed (NTE) NO_x limit; the weighted emissions limit for an engine cannot be exceeded by more than 50% for any individual test load point. Note that this is not the same as an NTE zone that would apply to off-cycle emissions.

The IMO regulates engine NO_x emissions based on the date a ship was constructed, which is most often defined by a ship's keel laid date. NO_x emission limits are set for engines depending on their rated speed (rpm). For ships built prior to 2000, NO_x emissions are unregulated, referred to as Tier 0. Tier I limits apply to engines on ships constructed 2000–2010. Tier II limits apply to vessels built beginning in 2011 and they are set at approximately 15–20% below Tier I. Tier III is set at 80% below Tier I (or approximately 75% below Tier II). Tier III applies to engines on ships constructed in 2016 or later when operating in the North American or U.S. Caribbean Sea Emission Control Areas (ECAs) or ships constructed 2021 or later when operating in the Baltic or North Sea ECAs.

1 See Regulation 13 of Annex VI of the International Convention on the Prevention of Pollution from Ships (MARPOL). https://www.imo.org/en/OurWork/Environment/Pages/Nitrogen-oxides-(NOx)-–-Regulation-13.aspx.

Unlike SO_x, NO_x is formed regardless of the fuel type used, and the reduction choices for NO_x are primarily focused on engine parameters or exhaust aftertreatment technologies. Except for low-pressure injection dual-fuel liquefied natural gas (LNG) engines, which can typically comply without aftertreatment, complying with Tier III usually requires installing and operating exhaust gas aftertreatment technologies such as selective catalytic reduction (SCR) or exhaust gas recirculation (EGR).

Researchers, including the authors, have identified two main issues with how the IMO has regulated NO_x emissions. First, using the keel laid date as the construction date allows shipowners to pre-buy and stockpile keels ahead of new NO_x regulations.[2] The average age of the global fleet is around 22 years and increasing (UNCTAD, 2022). Moreover, the average time between keel laid dates and build years increased from about approximately one year in 2015 to four years in 2023 (Van Roy et al., 2023b).

The second issue relates to the test cycle on which NO_x emissions are measured and engines are certified. Changes in international shipping practices, especially slow steaming in the wake of the 2008 global financial crisis, and slower speeds induced by IMO's energy efficiency regulation, mean that weighted test cycle assumptions may not align with current operational practices (UNCTAD, 2022). We investigate this issue as part of this study.

Methods

Measurements

NO_x concentrations were sampled in the exhaust plumes of ships sailing in the Danish Straits in 2019 (Figure 1 maps testing locations). A helicopter equipped with gas sensors was used to detect NO_x (nitrogen dioxide and nitrogen oxide) and carbon dioxide (CO_2) by navigating the sensors into each plume to sample emissions.[3]

2 The U.S. Coast Guard identified issues with "undefined structural members" being placed in a shipyard and used as evidence of the keel laid date without vessel construction plans in place or intent to build to act as a regulatory placeholder. This was addressed in 2019 by a guidance document CVC-WI-015(2), but this guidance is not legally binding. The U.S. Environmental Protection Agency similarly identified keels being laid by builders to circumvent regulation and sell lesser tier vessels at later dates (this was addressed in 2020, Docket ID No. EPA-HQ-OAR-2018-0638). Moreover, Environment and Climate Change Canada stated that many ships had keels laid just prior to the December 31, 2015, cut-off date that would allow Tier II ships to continue calling in North America (https://aeic-iaac.gc.ca/050/documents/p80054/130072E.pdf).

3 For further context on sampling methods using airborne technology, see Explicit ApS's (2018) report on airborne surveillance of sulfur emissions in Danish waters.

Figure 1. Map of in-plume NO_x measurement locations, 2019.

Calculating NO_x emission rates from measurements

Based on the sampled concentration of NO_x and CO_2 in each ship plume, the observed NO_x emission rate was calculated by comparing the ratio of NO_x to CO_2 measured in the plume against background levels, as described by Balzani Lööv et al. (2014). The emission rate is calculated by multiplying the observed ratio of NO_x to CO_2 by the molar mass ratio of NO_x to carbon and then by the fuel carbon content (*FCC*). Per Balzani Lööv et al. (2014), these estimates can be further adjusted to provide an engine power weighted NO_x emission rate based on the power-weighted specific fuel consumption (SFC_{ME}) in grams of fuel per kilowatt-hour (g/kWh).

$$ER_{NO_x} = \frac{NO_{X\,measured} - NO_{X\,background}}{CO_{2\,measured} - CO_{2\,background}} \times \frac{46\ gNO_X\ mol^{-1}}{12\ gC\ mol^{-1}} \times FCC \times SFC_{ME}$$

In that equation, ER_{NO_x} is the NO_x emission rate in units of g NO_x/kWh. $NO_{X\,measured}$ is the concentration of NO_x in the plume and $NO_{X\,background}$ is the background concentration of NO_x. $CO_{2\,measured}$ is the concentration of CO_2 in the plume, while $CO_{2\,background}$ is the background CO_2 concentration in ppm outside of the plume. For most ships, we assume FCC to be 0.87 grams of carbon per gram of fuel, equivalent to the FCC of distillate fuel, the fuel type we assume is used to comply with sulfur regulations in the Baltic and North Sea ECAs in 2019. For the 41 ships that had scrubbers installed, we assume their FCC is 0.85, reflecting residual fuel usage.[4] For the 18 LNG-fueled ships, the FCC is set to 0.75. Finally, we multiply by the main engine power-weighted specific fuel consumption (SFC_{ME}) in grams of fuel per kilowatt hour based on the SFC assumptions in the Fourth IMO GHG Study (Faber et al. 2020), which vary with engine load.[5] For ships with scrubbers, we increase SFC by 2% to account for the extra fuel consumption associated with the parasitic load of the scrubber (Astrom et al., 2014; Campling et al., 2013; Comer et al., 2020; Reynolds et al., 2011).

The NO_x emissions measured in the plume were likely produced by a combination of a ship's main engines, auxiliary engines, and boilers. Each has a different SFC. Auxiliary engines and boilers are generally less efficient than main engines and, therefore, have greater SFCs, except when the main engine is operating at low engine loads, when the main engine SFC can be greater than the auxiliary engine SFC, for example. While underway, most fuel consumption and emissions are associated with main engines, supplemented by auxiliary engines (see, for example, Table 17 in Faber et al., 2020). We use only the main engine SFC, noting that the actual weighted SFC could be different because of fuel consumption from auxiliary engines and boilers when they are in use. As the equation shows, as SFC increases, the calculated NO_x emission rate also increases, and vice-versa (i.e., SFC and calculated NO_x emissions rate are directly proportional). However, when we calculated results accounting for both main engine and auxiliary engine SFC and compared them to results using only the engine-load-adjusted main engine SFC, the differences in calculated NO_x emission rates were typically between 1–2%, and the average difference across all samples was zero. Therefore, we opted for a simplified approach by using only the engine-load-adjusted main engine SFC.

Results

Overview

There were 545 unique vessels measured in the 2019 campaign, yielding 607 measurements after removing observations of vessels that were stationary (n=6) or otherwise traveling at speeds below 3 knots (n=2). Approximately 50% of the unique vessels and measurements were from ships with Tier I engines; approximately 25% were Tier 0, 20% were Tier II, and 2% were Tier III (see Table 1). Mean engine power increases with tier.

Of the ships sampled, general cargo ships represented 26% of observations, followed by chemical tankers at 21%, bulk carriers at 16%, oil tankers at 11%, and container ships at 10%, followed by a few measurements of ferries, liquefied gas tankers, and others.

Tiers

Considering all values observed at speeds greater than 3 knots, we observed a mean of 10.2 g NO_x/kWh, standard deviation of 3.3 g/kWh, median of 9.8 g/kWh, maximum of 28.2 g/kWh and a minimum of 0.5 g/kWh (see Table 1 and Figure 2). NO_x emission rates from Tier II engines in the sample are statistically significantly greater than mean Tier I emission rates (T-test, $p < 0.01$), and do not differ significantly from Tier 0, the unregulated group ($p = 0.32$). Tier III vessels in the sample were operating in Tier II mode, and, therefore, do not significantly differ from Tier II ($p = 0.38$).

4 Eight of the 41 had scrubbers retrofitted in the year 2019.

5 For this study, engine load was calculated using the Propellor Law, i.e., by dividing the observed speed over ground by the ship's maximum speed and raising to the third power. Observed speed was reported by Explicit ApS based on Automatic Identification System (AIS) data. Maximum speed was taken from the ICCT's Systematic Assessment of Vessel Emissions (SAVE) model, which is based on IHS Markit data.

Table 1. Statistical summary of NO_x emission rates, reported by tier.

	Unique Vessels	Measurements	NO_x g/kWh				
			Mean	Std. Dev.	Median	Max	Min
Tier 0	138	161	10.5	3.3	10.1	27.6	1.5
Tier I	283	311	9.8	2.6	9.6	20.6	0.8
Tier II	115	124	10.9	4.5	11.1	28.2	0.5
Tier III	9	11	9.6	4.7	7.6	21.0	6.1
All Tiers	**545**	**607**	**10.2**	**3.3**	**9.8**	**28.2**	**0.5**

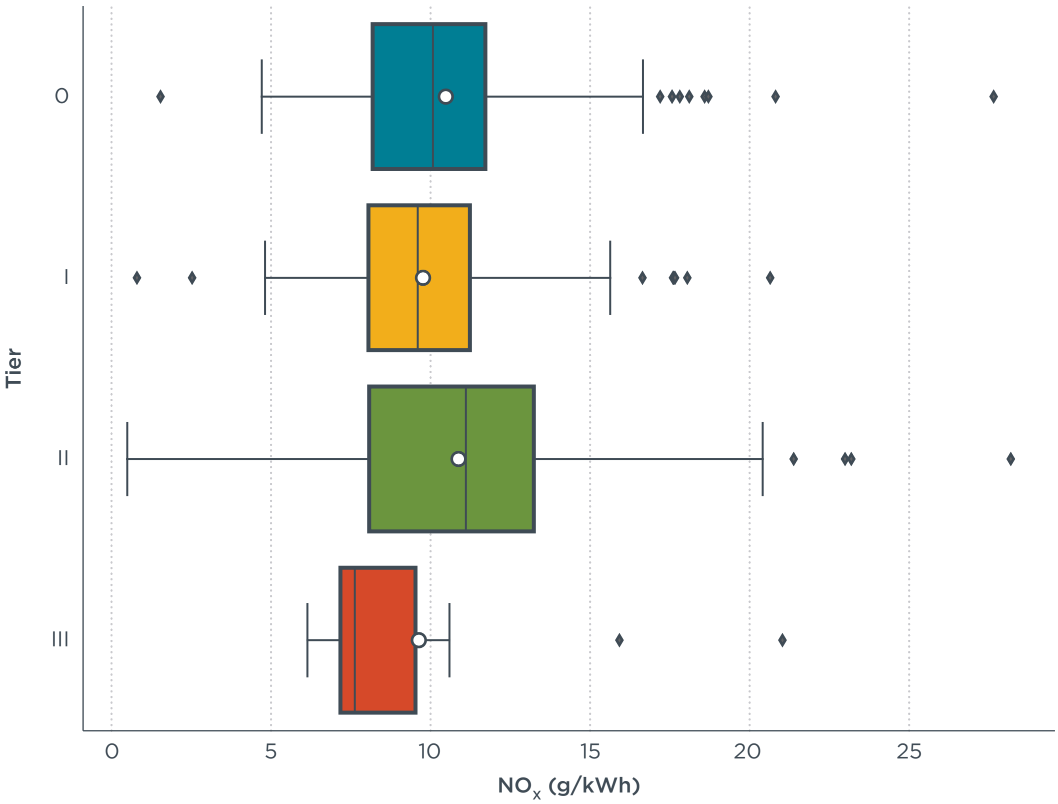


Figure 2. Boxplot showing distribution of observed NO_x emission rates by engine tier.

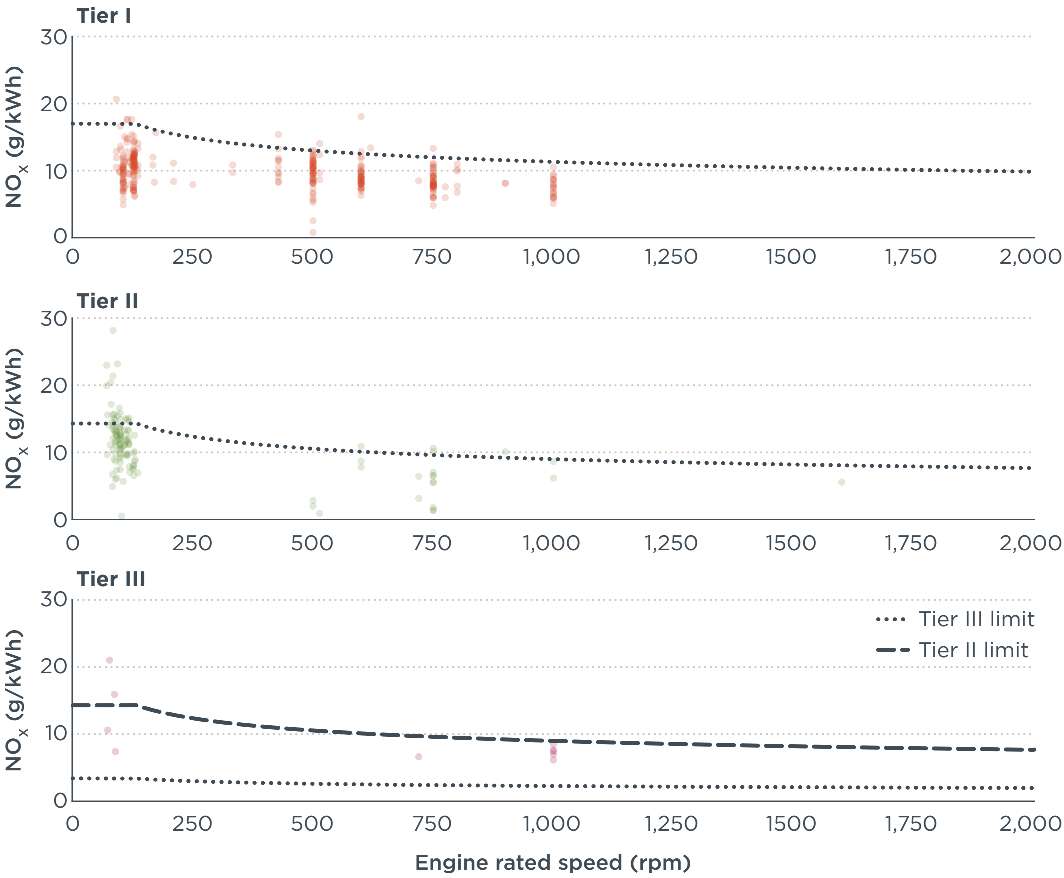
Figure 3 shows NO_x emission rates by tier compared to regulatory limits. Individual values above their respective lines do not necessarily mean that an engine is out of compliance with the NO_x regulation because of the NTC weighting scheme previously discussed.

As shown in Figure 3, 92% of measured emission rates were at or below the respective weighted emissions curves.[6] Moreover, 74% of measured NO_x emission rates fell below the Tier II weighted emissions curve, regardless of engine tier. Only 1.8% of measurements were also below the Tier III limit, although none of those observations were from any of the nine ships with Tier III engines, which were only required to operate in Tier II mode. Of these Tier III-compliant measurements, 9 of 11 were from LNG-fueled ships.

For Tier 0 ships, which are unregulated, most emissions inventories assume an emission factor of 18.1 g/kWh for engines <130 rpm, compared to the average emission rate in this study of 10.5 g/kWh, 42% lower than the assumption. For Tier I engines,

6 For Tier 0 engines, we compared measured emission rates against 18.1 g/kWh, which is the emission factor assumed in the Fourth IMO GHG Study and several other emissions inventories.

observations were 31% below the weighted regulatory limit for Tier I engines. For Tier II engines, the mean sampled emission rate was 21% below the limit for Tier II, and measured values for Tier III engines were on average 14% below the Tier II regulatory limit they were operating under.



Note: Tier III is only required to be operating in Tier II mode

Figure 3. NO_x emission rates (g/kWh) by engine rpm and tier (points) compared with weighted test cycle limits (lines).

Main engine loads

NO_x emission limits must be achieved by an engine when it is measured on a test cycle comprising several engine load points as prescribed in the IMO's NTC. For all engines, mean NO_x emissions are highest in the <25% engine load range. Mean NO_x emissions across all vessels at loads below 25% were 12.0 g/kWh, trending downward as shown in Table 2. Above 75% engine load, the mean NO_x emission rate was lowest, at 8.1 g/kWh.

Table 2. Mean NO_x emission rates by engine tier and load (g/kWh).

	< 25%	25 - 50%	50 - 75%	> 75%
Tier 0	11.2	11.0	9.5	8.9
Tier I	11.6	9.6	9.3	8.2
Tier II	13.5	11.8	9.4	7.2
Tier III [7]	21.0	7.6	9.2	7.3
All tiers	**12.0**	**10.5**	**9.4**	**8.1**

7 Note that n=11 for Tier III vessels, operating in Tier II mode, and so descriptive statistics may be impacted by low sample sizes; n=1 below 25% engine load.

Figure 4 shows that emission rates are highest at lower loads, trending downward as loads increase. Across all tiers, emission rates below 25% (mean = 12.0 g/kWh) are significantly higher than loads between 25–50% (T-test, mean = 10.5 g/kWh, p = 0.001), which are in turn higher than emission rates at loads between 50--75% (mean = 9.4 g/kWh, p < 0.001), which are again higher than emission rates at loads between 75–100% (mean = 8.1 g/kWh, p = 0.005).

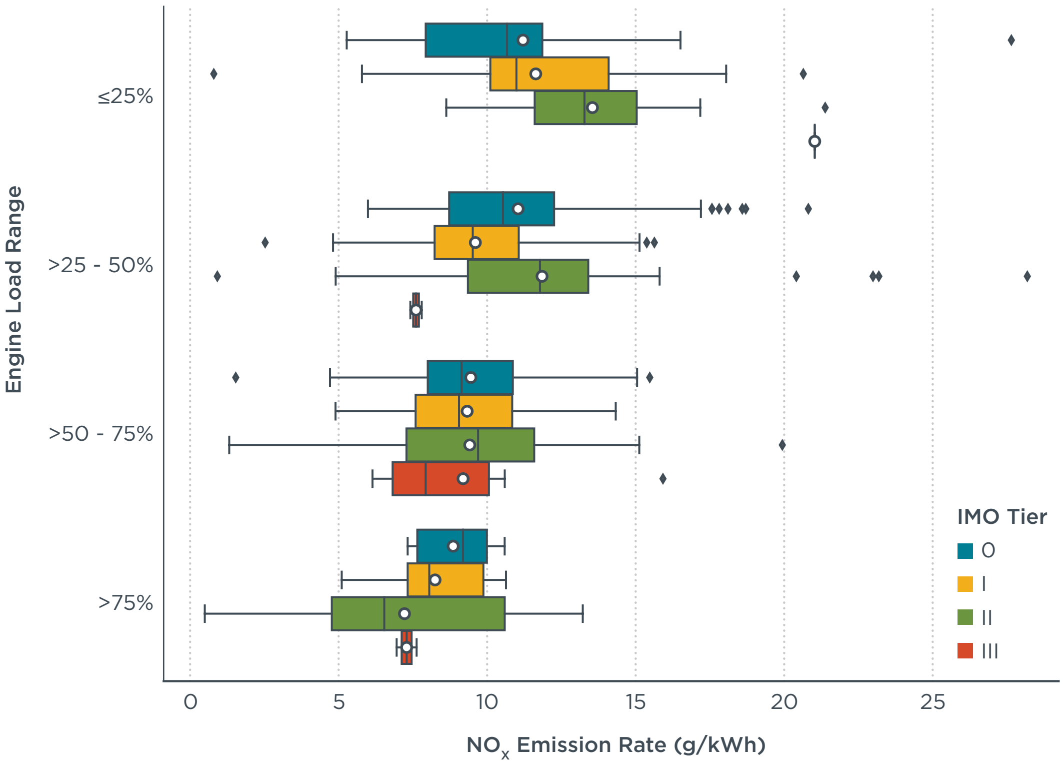
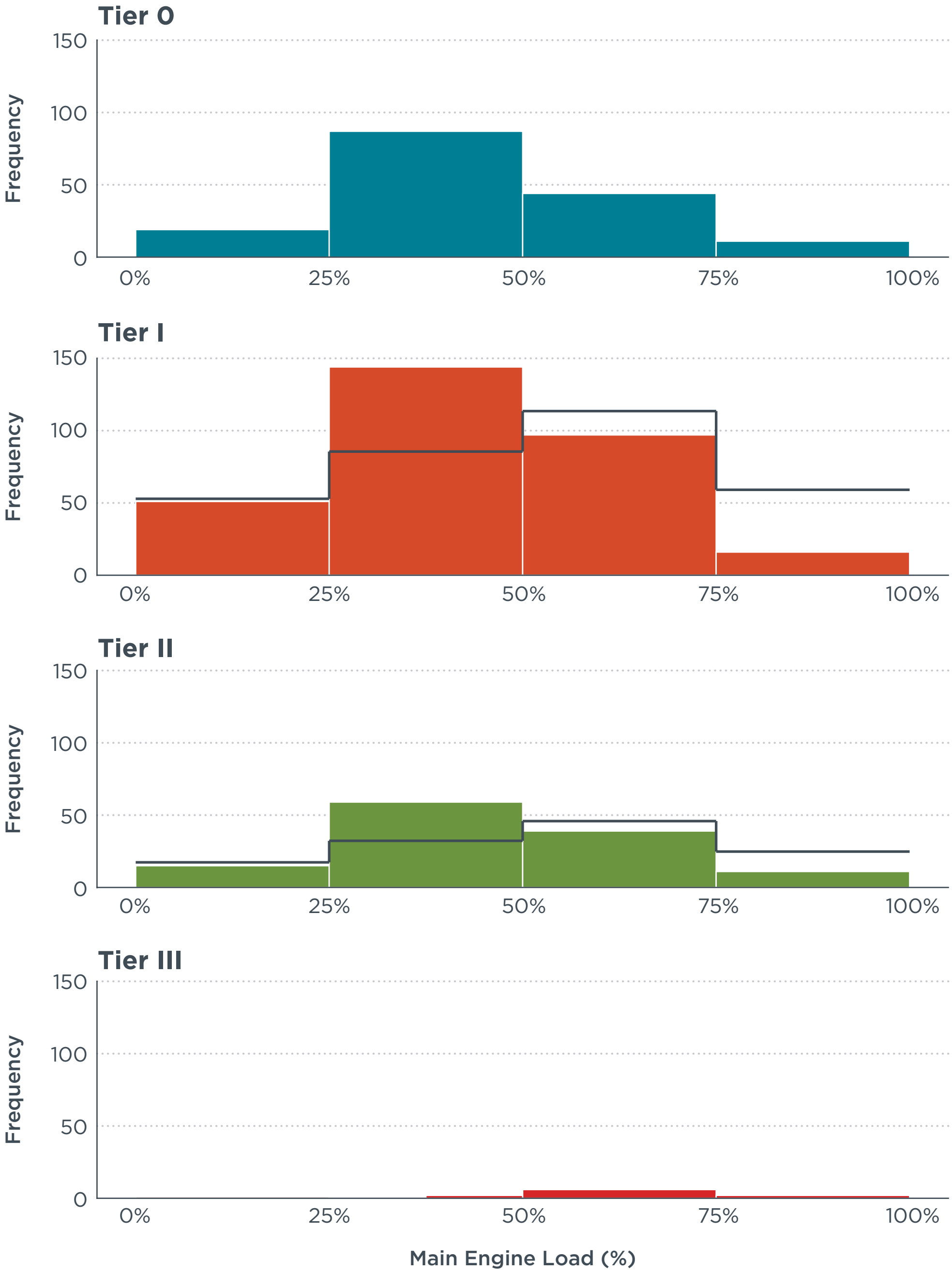


Figure 4. Boxplot showing the distribution of NO_x emission rates by engine load and IMO tier.

Though mean values indicate compliance with NO_x tier limits, results show that 3.5% of Tier I observations are higher than the weighted Tier I limit for all engines sampled, 20.2% of Tier II observations exceed the weighted Tier II limit, and 18.2% of Tier III observations exceed the weighted limit for Tier II, which is the NO_x standard they were operating under in the Baltic at the time of observation.

As shown in Figure 5, at the time of measurement, 7% of sampled vessels were operating at or above 75% engine load. In total, 48% of samples were operating at loads between 25% and 50%, and 14% were at loads below 25%. Based on main engine load, we estimate that 16% of samples at <25% exceeded the weighted regulatory limit, followed by 7.5% of samples at 25%–50%, and 3.8% of samples above 50%.

These results reflect operations inside the ECA. To determine how the load distribution in the ECA compares to annual load profiles of the ships, we estimated the engine load distribution of these same ships globally over the full course of 2019 using ICCT's SAVE model (Olmer et al., 2017) for Tier I and Tier II, as shown by the black lines in Figure 5. This estimation reveals that these ships spent approximately 20% of their global annual operating hours at or above 75% engine load, and around 37% of their global operating hours at loads between 50% and 75%. The data show that vessels sampled in this analysis are generally operating at loads below their global annual activity profile.



Note: Black lines show the relative distribution of engine loads based on annual global observations for Tier I and Tier II.

Figure 5. Engine load distribution, by tier, at time of sampling.

While changes in engine load only explain approximately 7–12% of the variance in measured NO_x values for Tier I and Tier II ships according to the R^2 values shown in Figure 6, we observe a significant trend for all Tiers in Figure 6 that NO_x emission rates tend to increase as main engine load decreases. For ships with Tier I engines, every 10 percentage point reduction in engine load increases NO_x emissions by 0.39 g/kWh, and 0.81 g/kWh for ships with Tier II engines. In addition, Tier II ships demonstrate a much larger spread in emission rates, regardless of load, compared to Tier I ships.

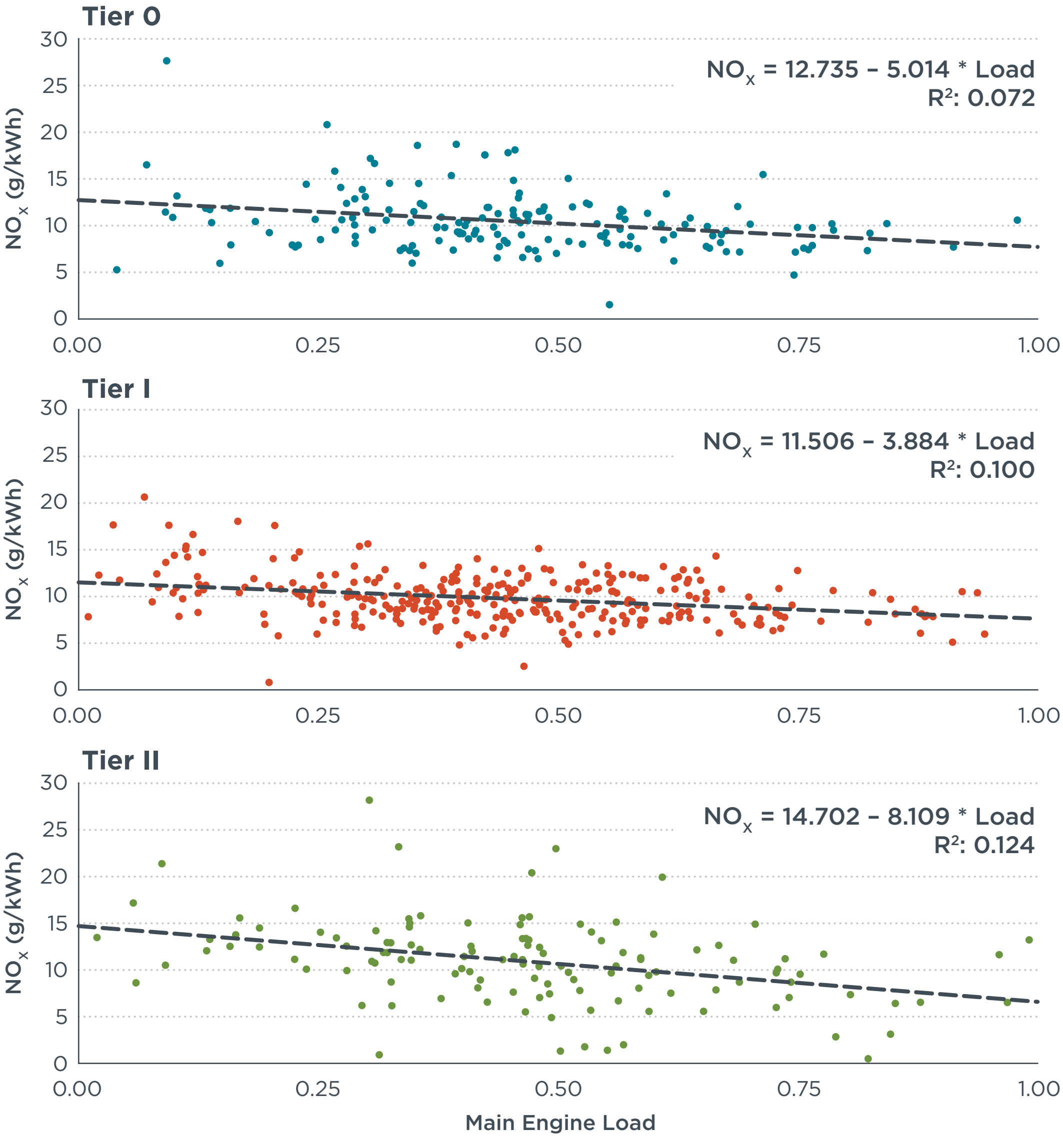


Figure 6. Relationship between main engine load and NO_x emission rates by tier.

Discussion & policy implications

Measured NO_x emission rates for ships operating in Danish waters in 2019 fell below regulatory limits in 92.4% of observations. This is important because many ship emissions inventories use the weighted regulatory limits as the NO_x emission factors, owing to a lack of empirical data on real world NO_x emissions (Comer et al. 2017; Faber et al., 2020; Grigoriadis et al., 2021; Office of Transportation and Air Quality, 2022; Olmer et al. 2017; Starcrest Consulting Group, 2022). These results show that those inventories may not be accurately estimating NO_x emission rates.

We find evidence that NO_x emissions are significantly higher at lower loads (average emission rates are 1.5 g/kWh higher at loads <25% than at loads 25%–50%), and that ships are operating at lower loads than are covered by the NTC, as has been widely discussed (IMO, 2023).

Observed NO_x emission rates are typically below regulatory limits, no matter the age of an engine or whether an engine is regulated for NO_x (Tier 0 compared to Tier I). We observed that ships are operating at engine load cycles different from those for which their engines are being certified, and they exceed weighted regulatory limits in 16% of samples below 25% main engine load. The NO_x Technical Code was finalized in

2008, just before the global financial crisis. Since 2008, ships have tended to operate at speeds slower than they were designed to sail. This has resulted in ships using less of their installed engine power and operating at lower engine loads ("slow steaming"). When measured, Tier I and Tier II ships were operating at or above 75% engine load 2.6% and 1.8% of the time, respectively. When we investigated their engine loads over the course of the year, that increased to about 20% of the time for both tiers.

At lower loads, we see a shift toward higher NO_x emissions, with potentially important implications for Tier III NO_x control technologies. The evidence suggests that SCR, a common technology used to control NO_x emissions to meet Tier III standards, cannot operate effectively below 25% engine load. This means that not only are Tier 0, Tier I, and Tier II emission rates generally higher in near shore areas, Tier III control technologies may not be operational while vessels are operating close to shore. Moreover, newer Tier II engines sampled are, on average, emitting pollution at statistically significant higher rates than the older engines. These newer Tier II engines are larger, on average, than Tier I engines, meaning that their higher average NO_x emission rates per kilowatt-hour also result in higher total NO_x emissions per hour.

Regulating NO_x will continue to be an important task, even as the sector works to decarbonize. This is because the fuels that could be used to achieve low life-cycle GHG emissions, such as green versions of methanol, ammonia, hydrogen, and biofuels, will continue to emit NO_x if used in internal combustion engines (Karvounis et al., 2022). NO_x mitigation measures will mainly rely on the implementation of exhaust technologies (e.g., SCR) and/or engine-design modifications by manufacturers (Fortich et al., 2021; Seddiek & Elgohary, 2014).

Updating the NTC could be a complex and time consuming process requiring coordination between the IMO and the International Organization for Standardization. Setting straightforward NTE limits at low load points for new and existing ships could be an effective regulatory option to ensure low-NO_x operations at points in the load profile outside the current test cycle, and to ensure that the intended effects of Tier III technologies persist in near-coast areas. An NTE standard would help reduce emissions at low loads and clarify emission standards for alternative fuels. Moreover, an NTE limit for all tiers would promote continuous emissions monitoring systems (CEMS) for enforcement and compliance verification.

Additionally, an established international maximum time limit for the duration between keel laid date and the year of construction could be considered. Presently, Belgium is the only flag state with a 5-year maximum keel date requirement (Koninklijk Besluit Inzake Milieuvriendelijke Scheepvaart, 2020); it could be adopted globally and the 5-year limit could also be reduced.

Emission control areas are helpful in reducing emissions from new ships. However, as highlighted, there are limitations in controlling NO_x emissions below a 25% engine load, which is often associated with ships operating near shore. ECAs are considered one of "the most far-reaching policies at the global/regional scale" (Gössling et al., 2021); however, the multiyear timelines to implement additional measures of this scale are inconsistent with the need for timely action (Winnes et al., 2016). Port-level restrictions and incentives could, theoretically, be introduced and tightened faster than national- or global-level regulations. Through collaboration between ports and governments, the swift implementation of broad-reaching guidelines by ports could accelerate the timeline relative to the NTC, ECAs, or IMO NO_x action.

Incentives differ from regulations; their purpose is to motivate actors to modify their behaviors through rewards or penalties. These programs can set standards for all flag states that call to their ports. With evidence that NO_x emission rates are higher at low loads, paired with the harmful health impacts of NO_x emissions for coastal communities, ports could be central to NO_x mitigation. The reach of NO_x mitigation at port is affected by the volume of traffic at individual ports, as well as the cooperative efforts among ports within a given region or along shared routes. Ports could incentivize emissions abatement with adjusted fees on emissions, shore power installations, and investment in alternative fuel bunkering (Ahl et al., 2017; Daniel et al., 2022; Gössling et al., 2021; Klopott et al., 2023; Winnes et al., 2015). Ports could influence actions to reduce NO_x pollution with tiered costs for polluters and early-adopters, particularly if 'polluter-pay' schemes fund incentives for early-adopters of pollution reducing technologies (Alamoush et al., 2022). Small environmental tariffs can be more effective motivators than larger incentives at ports, but a combination strategy would likely be most effective (Molavi, Shi, & Lim, 2020). Therefore, governments and other stakeholders should consider funding and other strategies for port incentives to reduce NO_x emissions while developing long-term policy solutions.

Conclusions

We analyzed samples of NO_x emissions from ships sailing in Danish waters in 2019 that were obtained using sensors on helicopters and compared them across tiers (ages) and against the IMO's regulatory limits. More than 90% of measured emission rates for Tier I, II, and III engines fell below their respective limits. Moreover, 74% of measured NO_x emission rates fell below the Tier II weighted emissions curve, regardless of engine tier, suggesting that vessels are largely already over-complying with IMO's NO_x regulations. Alternatively, this could be interpreted to mean that regulations are too lax, making compliance straightforward and consequently failing to reach maximum emissions abatement potential. In fact, we found that newer Tier II engines had significantly higher NO_x emission rates than older Tier I engines; there was no statistical difference in NO_x emission rates between unregulated Tier 0 engines and Tier II engines. This suggests that the NO_x regulations could be revised to make them more effective at reducing air pollution.

Ships are spending more time operating at lower engine loads than covered by the NTC weighting factors. The lack of an NTC test point below 25% load for these engines, combined with inefficient or non-functioning NO_x control technologies at these low loads has implications for human health. Ships tend to operate at lower engine loads closer to shore, thereby impacting local populations. Future work should focus on determining if ships are complying with Tier III standards in relevant ECAs to ensure these ships are operating in low-NO_x mode, especially when engine loads are lower than 25%.

Efforts to improve the NTC to better reflect real-world operations are justified despite the expected transition to new fuels such as ammonia, methanol, and hydrogen because burning them in an internal combustion engine will still result in NO_x emissions. Rather than relying solely on weighted emission limits, the IMO could consider implementing NTE standards for new and existing ships, particularly focusing on operations at low loads, and including a test point below 25% load (e.g., 10%). This would result in more complete emissions profiles for ships, especially during low load operations where we observed emission rates that are higher than would be expected by the regulations.

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