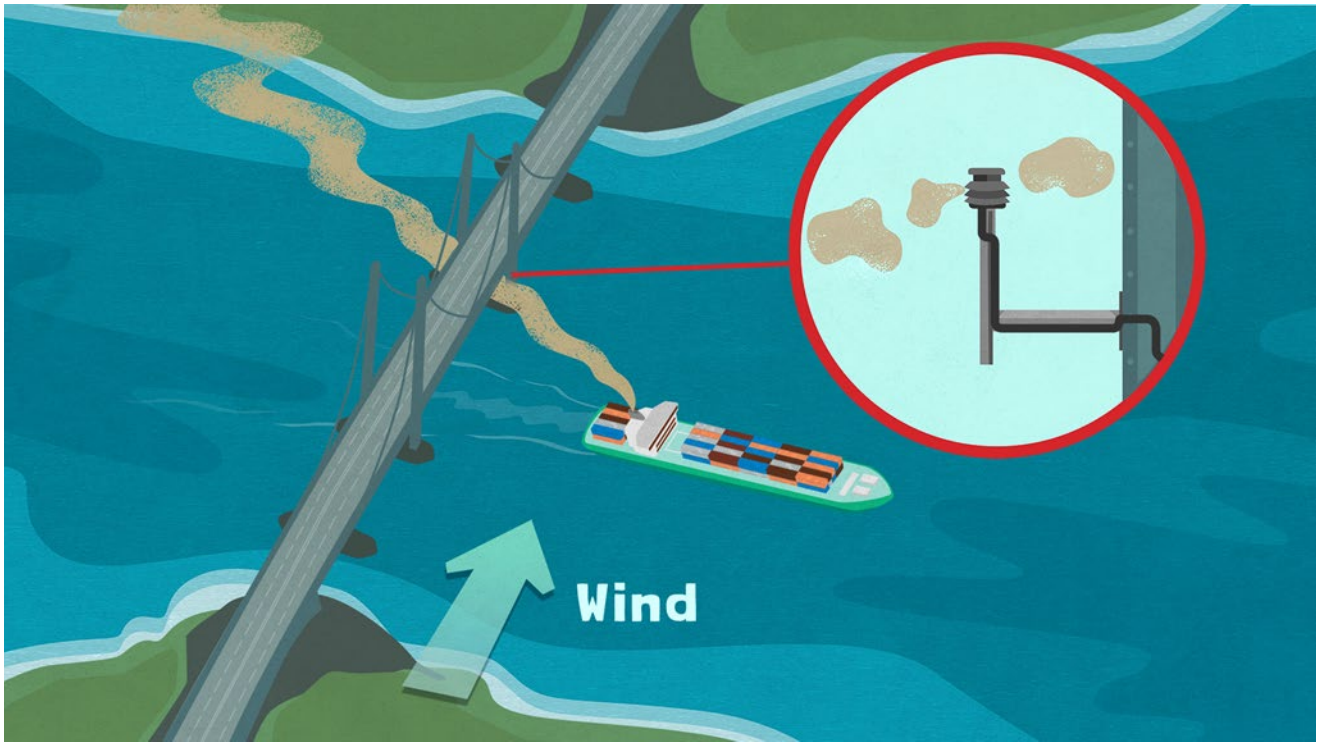
CHALMERS

July 5 2023

Technical memorandum:



Results from exploratory project on NOx emissions from Ocean Going Vessels (OGV) using remote sniffer measurements

Johan Mellqvist[1,2], Vladimir Conde[1]

[1]Chalmers University of Technology, Gothenburg Sweden,
[2]FluxSense Inc, San Diego

Extended Summary

The NO_x emissions from ships are governed by the International Maritime Organization (IMO) through MARPOL's Annex VI. This annex is part of the International Convention for the Prevention of Pollution from Ships. It establishes emission limits in the form of Tiers, which vary depending on the construction date of the ships and their engines. Our study concentrates on ships classified under Tiers 0 to II, as these are currently the most common vessels navigating the waters.

In the study, mass- and brake-specific emissions of NO_x at different ship engine loads were determined from six years of remote sniffer measurements at the Great Belt Bridge in Denmark. This bridge is situated over the main shipping channel connecting the Baltic Sea and the North Sea, with over 25,000 ships passing through annually. The analyzed data predominantly corresponds to 721 container ships, 425 RoRo vessels, 127 Reefers (refrigerated cargo), and 892 crude oil tankers, which are highly relevant for the ship types traversing Southern California waters to call Port of Los Angeles and the Port of Long Beach. Additionally, since vessels tend to reduce speed when approaching the Great Belt Bridge, the operational profiles of these ships are also very relevant for specific areas like Southern California, where multiple federal and local programs exist to encourage ships to voluntarily adopt reduced speeds as a strategy to either avoid whale strikes or decrease total emissions by reducing fuel consumption for the same distance travelled.

The findings, as shown in Figure ES 1 below, reveal that Tier II container ships have the highest brake-specific NO_x emissions among all ship types and tiers and that they display a different emission load dependency. The Tier II engines are tuned to minimize emissions at higher engine loads. However, emissions significantly increase at lower loads, being 30 % higher compared to those at 70 % engine load. This is unlike the older Tier 0 and Tier I engines. Noteworthy is that the requirement in the IMO technical code is based on a weighted average which is heavily weighted against higher loads, typically 80 %, and therefore Tier II container vessels are still in compliance with the IMO rules when being measured on a test bed. It should also be noted that the emissions at engine loads below 25 % are not included for any of the tiers in the IMO rules.

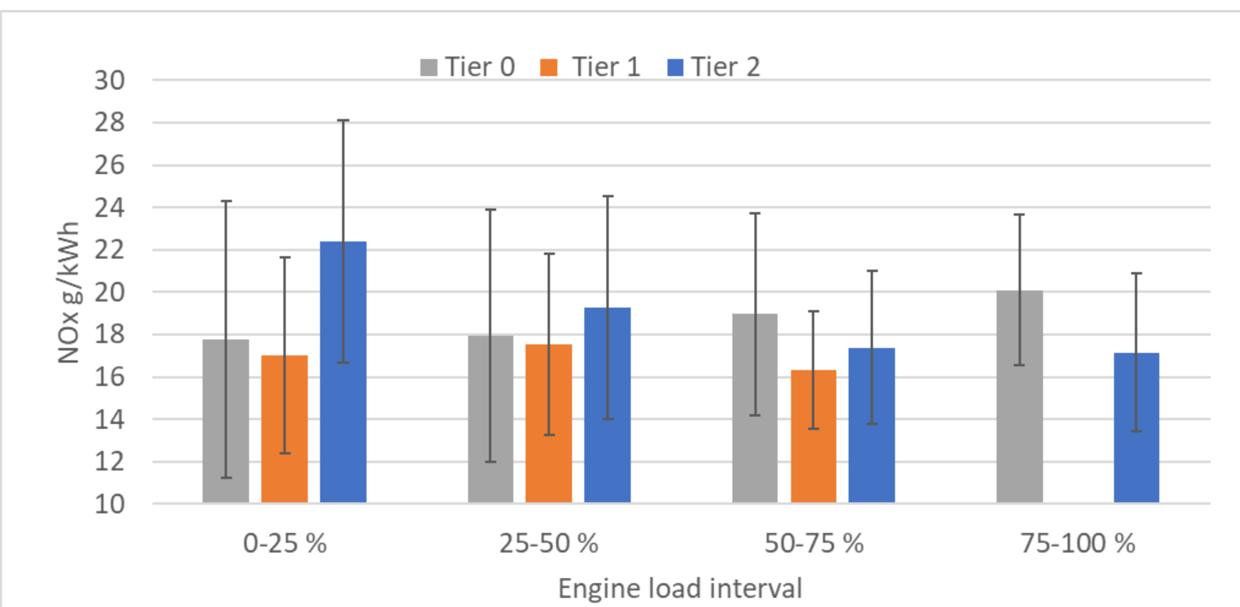


Figure ES I Brake specific NO_x measurements versus engine load of Tier 0, Tier I and Tier II container ships, by an automatic sniffer at the Great Belt bridge Denmark between 2018-2023. This bridge is situated over the main shipping channel connecting the Baltic Sea and the North Sea, with over 25000 ships passing through annually.

An observation from the study is that the obtained average emission factor (E_{avg}) for Tier II container ships was 17.7 g/kWh. While this is considerably lower than the 19.2 g/kWh observed for Tier 0 ships, it is significantly higher when compared to the NO_x emission limit of 14.4 g/kWh as outlined in the NO_x technical code. Part of this discrepancy might be attributed to uncertainties in the calculation of Specific Fuel Oil Consumption (SFOC) for the container ships and differences in the calculation of the weighted average, necessitating further investigation. It is noteworthy that the average emission factor (E_{avg}) for other ship types such as Reefers, RoRo, and crude oil tankers is significantly lower than that of container ships and are generally consistent with the requirement of being below 14.4 g/kWh.

In conclusion, Tier II container ships, despite being optimized for reduced emissions at higher engine loads, display substantially increased emissions at lower engine loads compared to Tier I and Tier 0 container ships. Notably, ships have low engine loads when they navigate through nearshore shipping lanes to enter or exit a port. This is of concern for Vessel Speed Reduction (VSR) programs in areas like Southern California, since the elevated NO_x emissions at lower loads could neutralize or even surpass the emission reductions these programs aim to achieve. We suggest that it would be beneficial if Tier II emissions could be abated through modifications in engine design or optimization, or potentially through retrofitting. This could be achieved through amendments to the IMO regulations and updates to the associated engine certification procedures. For example, this might involve giving more weight to emissions at low engine loads when calculating the emission limit, and including emissions below 25% engine load in the assessment.

Contents

1. Background

The NOx emissions from ships are governed by the International Maritime Organization (IMO) through MARPOL's Annex VI. This annex, part of the International Convention for the Prevention of Pollution from Ships, establishes emission limits in the form of Tiers, which vary depending on the construction date of the ships and their engines. Our study concentrates on ships classified under Tiers 0 to II, as these are currently the most common vessels navigating the waters. In addition, in some areas such as Southern California, ships are running reduced speed as a strategy for the dual purposes of reducing whale strikes and reducing air pollutant and greenhouse gas emissions by reducing fuel consumption. Multiple voluntary programs exist that encourage participating ships to sail at reduced speeds. The Vessel Speed Reduction (VSR) program implemented by the San Pedro Bay Ports has a year-round speed limit of 12 knots, with more than 90 percent of the vessels complying with the speed limit. The seasonal Blue Whales and Blue Skies program implemented by multiple California air districts encourages vessels to reduce speed to no-more-than 10 knots when sailing within portions of California waters including a large area in Southern California.

During the last 10 years remote “sniffer” measurements of ship emissions have been carried out by various actors analyzing ship smoke a few hundred meters downwind the ships, without stepping on board of the ship, Figure 1. The fuel specific emission of NO_x is obtained from measuring the NO_x to CO_2 ratio, and to convert this to the brake specific emission (g/kWh). FluxSense Inc. and Chalmers University of Technology did a collaboration project in 2015, funded by South Coast AQMD, in which remote sniffer measurements were carried out in the Port of Long Beach (POLB) and Port of Los Angeles (POLA), (Mellqvist 2017a). FluxSense and Chalmers have also built a flight system for the Belgian Coast Guard (Mellqvist, 2017c). During the last 5 years Chalmers have carried out fixed sniffer measurements at the Great Belt bridge (20,000 ships, Mellqvist 2020) (see illustration on the front page and Figure 1). In addition, campaign measurements have been carried out by European Union projects (CompMon, EnviSum, CSHIPP, SCIPPER) in various parts of Europe from patrol vessels and surveillance aircraft (Mellqvist 2021), as well as fixed measurements from Öresund Bridge (5,000 ships, Mellqvist 2017b).

In this project, we have calculated mass and brake-specific emissions of NO_x at various loads using remote sniffer measurements taken at the Great Belt Bridge. The data have mainly been analyzed with respect to specific ship types of relevance for POLA and POLB, corresponding to container, reefer, RoRo, and crude oil tanker vessels. The bridge is 2 km long and spans the Great Belt strait between the Danish islands Zealand and Funen. This bridge is situated over the main shipping channel connecting the Baltic Sea and the North Sea, with over 25,000 ships passing through annually. There is no fixed speed limit for ships passing under the bridge, however, larger ships, especially those with high air draft or those that are carrying hazardous cargo, often reduce their speed for navigational safety while transiting under the bridge.

Figure 1 Automatic Sniffer measurements at the Great Belt bridge are conducted from the eastern Pylon (marked in red). Here 25000 ships are passing annually to reach or leave the Baltic Sea. Chalmers has measured more than 20,000 ships at this site since 2015 (Mellqvist 2018).

2. Methods

Emissions from ships can be measured 1 - 2 km downwind of the vessel using sniffer systems based on equipment for air quality monitoring and research, i.e. cavity ring down spectroscopy for CO_2 and chemiluminescence for NO_x (see Mellqvist 2021). The systems have a detection limit of around 0.5 parts per billion (ppb) for NO_x and 200 ppb for CO_2 and a time response of around 1 second ($t_{10\text{-}90}$).

The ***mass*** fuel specific emission (emission factor) of NO_x is obtained from the NO_x to CO_2 ratio, according to Eq. 1 and here CO_2 is given in parts per million (ppm) while NO_x is given in ppb. To calculate the emission factor (EF) the molecular weight of NO_2 is used, in accordance with the IMO NOx technical code ((MEPC.177(58).

$$EF_{NOx}\left(\frac{g}{kg\ fuel}\right) = \frac{\mathrm{M(NO2)}\frac{g}{mol}\times\int[NO_x]_{ppb}-[NO_{x,bgd}]_{ppb}dt}{\frac{\mathrm{M(C)}\frac{g}{mol}}{0.87}\times\int[CO_2]_{ppm}-[CO_{2,bgd}]_{ppm}dt} = 3.333\times\frac{\int[NO_x]_{ppb}-[NO_{x,bgd}]_{ppb}dt}{\int[CO_2]_{ppm}-[CO_{2,bgd}]_{ppm}dt} \quad \text{Eq. 1}$$

The mass fuel specific emission measurements are then converted to ***brake*** specific emissions in g/kWh using Eq. 2 below.

Here the brake specific fuel oil consumption (SFOC) is calculated from Eq. 3, in accordance with the recommendations outlined in the 4th Greenhouse Gas (GHG) Study by the International Maritime Organization (IMO). This study also provides the baseline SFOC ($SFOC_{base}$) based on the age of the ship.

In this study it was assumed that all ships run on Marine Diesel Oil (MDO fuel) and the Tier classification was obtained from the year the ship was manufactured (keel laying date), which was obtained from the database IHS Fairplay. The engine load (EL) was calculated from the actual ship speed over ground at the time of monitoring, as reported by the Automatic Identification System (AIS) and using the STEAM2 model (Jalkanen 2012). This model calculates engine loads during voyages based on the ratio of the ship's speed to the calculated resistance that the ship is required to overcome at a specified speed, based on Hollenbach (1998). This is more sophisticated and provides better results than using the simple assumption that the engine load is proportional to the cube of the speed relative to the design speed, as used in the STEAM 1 model (Jalkanen et al., 2009), or relative to the maximum speed as used by others.

$$EF_{NOx}\left(\frac{\mathrm{g}}{\mathrm{kWh}}\right) = SFOC \cdot EF_{NOx}\left(\frac{g}{kg\ fuel}\right) \quad \text{Eq.2}$$

$$SFOC = SFOC_{base} \cdot (0.455 \cdot EL^2 - 0.710 \cdot EL + 1.280) \quad \text{Eq.3}$$

It is relatively straightforward to automate the sniffer measurements for real-time evaluation of fuel specific emission of NO_x using Eq. 1 to Eq. 3. In addition, from AIS data and wind measurements it is possible to identify the ships, calculate the emissions, and send data to a database in near real-time. The data is usually sorted in quality classes (high, medium, or poor). The measurement uncertainty for the sniffer measurements depends on the distance to the ships, size of ships and wind conditions (speed and direction), but typically correspond to 10-20 %.

The International Maritime Organization (IMO) NO_x Technical Code, as per resolutions MEPC.177(58) and MEPC.251(66), mandates that the nitrogen oxides (NOx) emissions of marine diesel engines with an output power above 130 kW must be limited, as shown in Figure 2. This regulation stipulates different engine emission limits based on the keel-laying date and engine type. The engine type is determined according to its rated speed, measured in crankshaft revolutions per minute (RPM). The emission level (EF_{avg}) that is regulated corresponds to a weighted average of the emissions at different engine loads and is expressed in terms of brake specific emissions, with the unit being grams of NO_x (expressed as NO_2) per kilowatt-hour (kWh) of axial power. This weighted average emission value is calculated using Eq. 4 based on the emission factors (EF_i) obtained at four different engine operation modes (i) with varying relative engine loads ($P_{rel,i}$) and weighting factors (wf_i), as detailed in PROMINENT D5.8, 2017. In general, the ships that are being monitored follow the E3 test cycle, which is typical for propulsion engines. The weighting factors for this test cycle correspond to 0.15, 0.15, 0.5, and 0.2 for engine load points at 25%, 50%, 75%, and 100% respectively
.

$$\boldsymbol{E_{avg}\left(\frac{g}{kWh}\right) = \frac{\sum_{i=1}^{n} EF_i\left(\frac{g}{kWh}\right) \cdot P_{rel,i}(kW) \cdot wf_i}{\sum_{i=1}^{n} P_{rel,i}(kW) \cdot wf_i}} \quad \text{Eq. 4}$$

As part of the IMO NO_x Technical Code, different levels (Tiers) of control apply, based on the ship's keel-laying date and the engine's rated speed, which is given in crankshaft revolutions per minute. Tier I applies to ships built (keel laid) between 2000 and 2010, Tier II applies to ships with a keel-laying date after 2011, and Tier III applies to ships operating in special emission control areas (Northern Europe and North America). In more detail, Tier III applies to engines that are installed on ships with a keel-laying date after December 31, 2015, for ships operating in the North American ECA (Emission Control Area) and the United States Caribbean Sea ECA, and after December 31, 2020, for ships operating in the Baltic Sea ECA or the North Sea ECA. As shown in Figure 2, the limits for slow-speed ships, with a rated engine speed below 130 rpm, correspond to 17, 14.4, and 3.4 g/kWh for Tier I, Tier II, and Tier III, respectively.

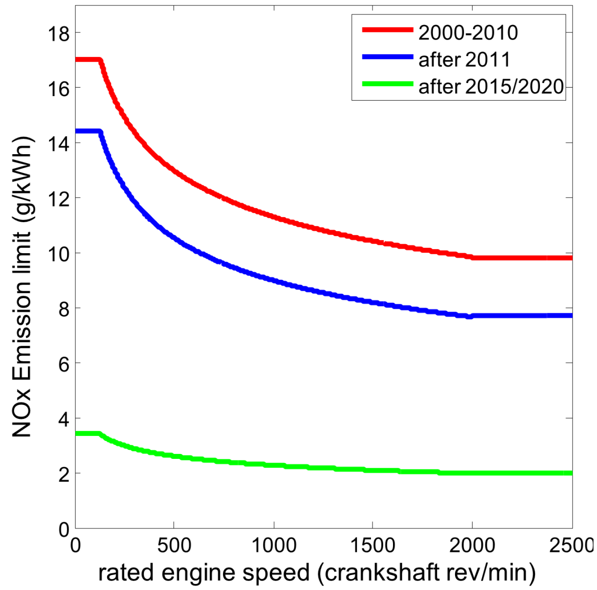


Figure 2 The IMO annex VI NO_x emission limits for ship engines. The emission levels depend on ship build year, divided int three tiers, and engine type. The engine type is defined according to the corresponding rated engine speed. The emission corresponds to g NO_x per axial power in kWh, corresponding to a weighted average of several engine loads. Tier III applies in ECAs in North America (ships built in or after 2016) and northern Europe (ships built in or after 2021).

3. Results

At the Great Belt bridge, approximately 12300 ship measurements of 5900 individual ships were conducted during the period 2018 to 2023. In Figure 3 these data are shown, as a function of main engine load for each ship. The latter was derived using the STEAM2 model (Jalkanen 2012) as illustrated in Figure 4. Note that the ship data correspond to different ship types, tiers, ship lengths and engines. The data are shown both as brake specific emission and fuel-mass specific emissions. In this study we focused on the larger ocean-going vessels corresponding to 721 container ships, 425 RoRo vessels, 127 Reefers (refrigerated cargo) and 892 Crude oil tankers. The data were converted to brake specific emissions by multiplying with the Specific fuel oil consumption as outlined in section 2 and as illustrated in Figure 5 for some of the studied ships.

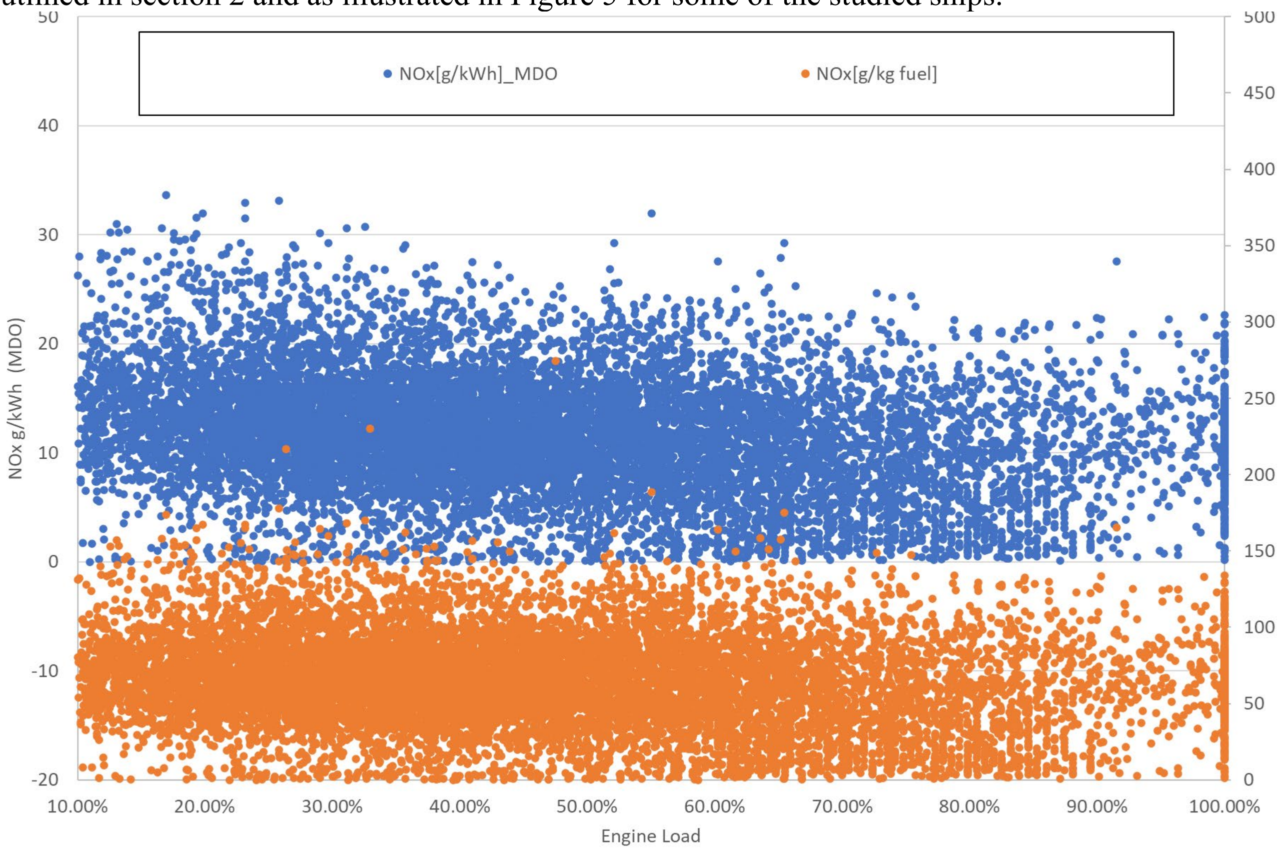


Figure 3 NO_x measurements versus load by an automatic sniffer at the Great Belt bridge Denmark between 2018-2023. The data set includes 12,300 ship observations, and this corresponds to 5,300 individual ships.

In Figures 6 to 9, examples of the obtained NOx emissions (both brake-specific and mass-specific) versus engine load are displayed for the analyzed ship types (container, reefer, RoRo, and crude oil tankers), with data filtered according to Tier, ship length, and rated engine power. Additional plots for other categories can be found in the appendix. The ships studied generally have slow speed two-stroke engines (with speeds less than 130 RPM), which means that their emission limits are among the highest in the IMO NO_x regulation curves (see Figure 2). Furthermore, we have processed statistics for the data, divided into four engine load intervals (0-25 %, 25-50 %, 50-75 %, and 75-100 %), as illustrated in Table 1, Table 2, Table 3, and Table 4 for various ship types and tiers. The statistics in the tables are plotted and further elaborated on in the discussion section. Average data from the engine load intervals were used to calculate a weighted NO_x emission factor (EF_{avg}) based on Equation 4. While this is not identical to the engine loads specified for the E3 cycle in the IMO NOx technical code ((MEPC.177(58) and MEPC.251.(66)), since we include also engine loads below 25 % we believe it offers a reasonable approximation of this value, making it feasible to compare the results to the IMO curves in Figure 2. In instances where the emission factors of the ships were not measured in the highest engine load interval (75-100%), we made the assumption that the emission factors for this range were the same as those in the 50-75% range. This applies to the following categories, i.e. RoRo Tier 0, Reefer Tier 0, and Container Tier I. Since the emission factors vary relatively little above 50%, we believe this approximation introduces minor uncertainties. However, for one ship type, i.e., Reefer Tier I, only the two lower engine loads were measured. In this case, the two intervals above 50% engine load were assumed to be the same as the 25-50% range, leading to larger uncertainties for this category. In Figures 6 to 9, examples of the obtained NO_x emissions (brake specific and mass specific) versus engine load are displayed for the ship types studied (container, Reefer, RoRo, and Crude oil tankers), filtered by Tier, ship length, and rated engine power. Additional plots for other categories are provided in the appendix.

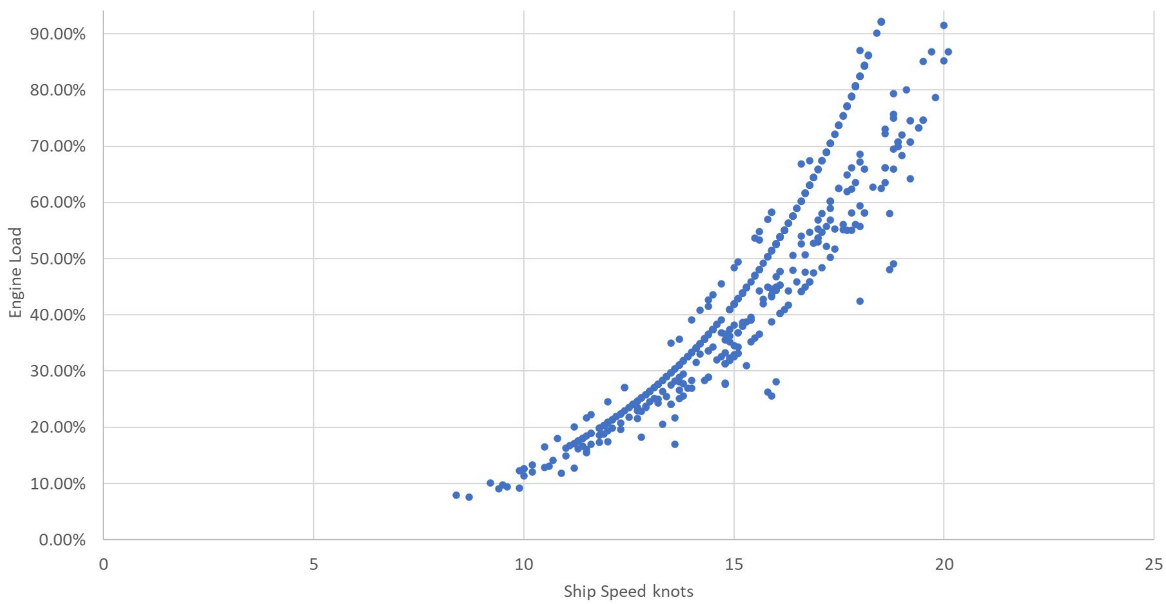


Figure 4 Engine load vs. speed for Tier II container ships at the Great Belt site, derived using the STEAM2 model (Jalkanen et al, 2012). Note that the IMO regulations don't apply below 25 % engine load. For context, ships in Southern California's VSR program slow down to 12 knots or less.

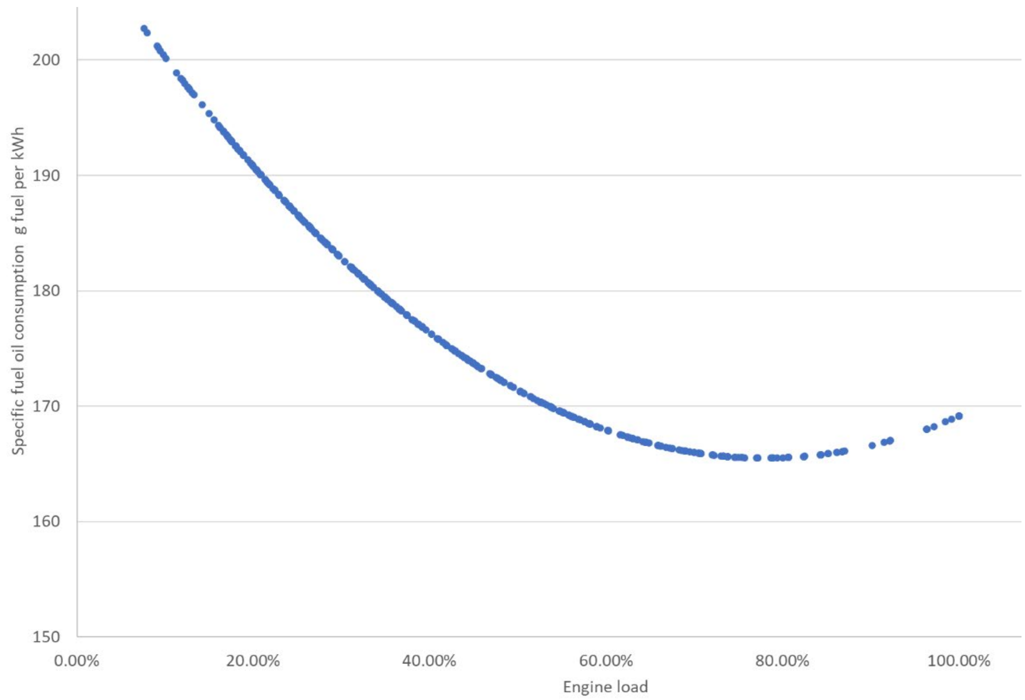


Figure 5 Specific fuel oil consumption versus engine load for the Tier II container ship data shown in Figure 4, as calculated from Eq 3 and engine load calculated by the STEAM 2 model form the ship speed.

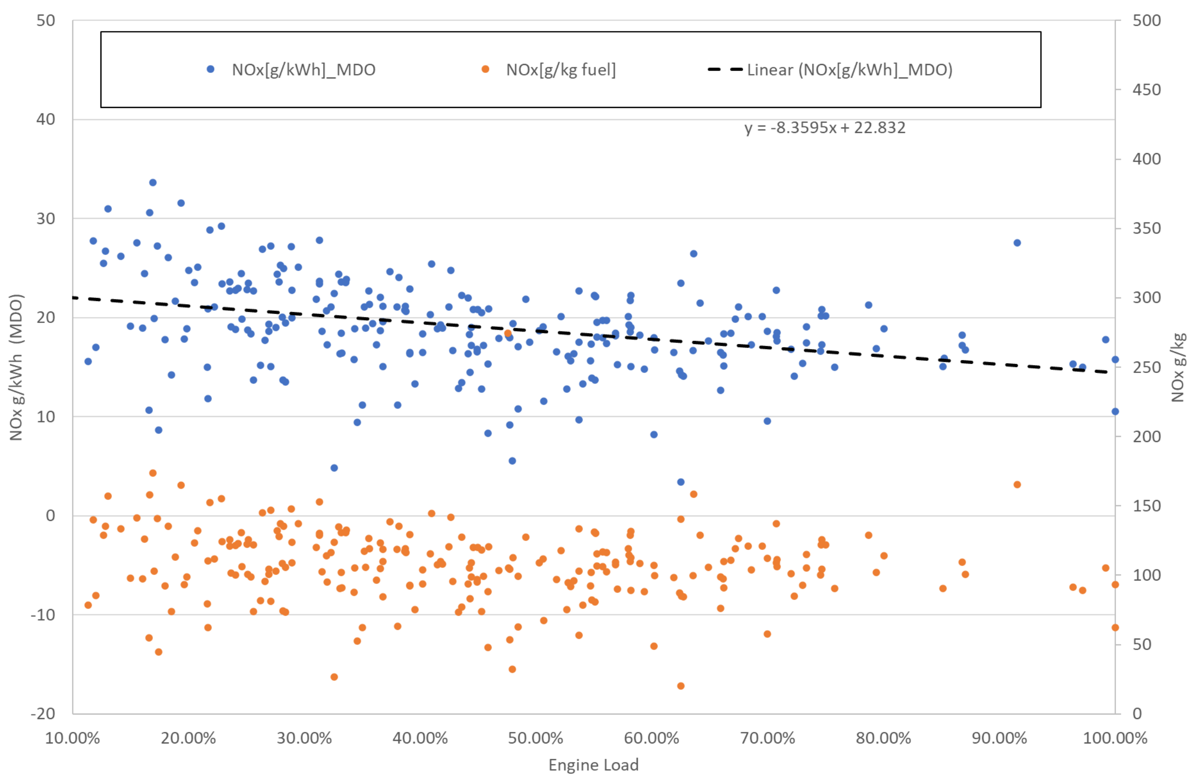


Figure 6 NO_x measurements of Tier II container ships by an automatic sniffer at the Great Belt bridge Denmark between 2018-2023. A linear fit is also shown to the brake specific NOx emission. The Ship engine power was above 20,000 kW and ship lengths were longer than 200 m. The data set includes 248 ships. Note that the Tier II limit for ships with slow speed two-stroke engines is 14.4. g/kWh.

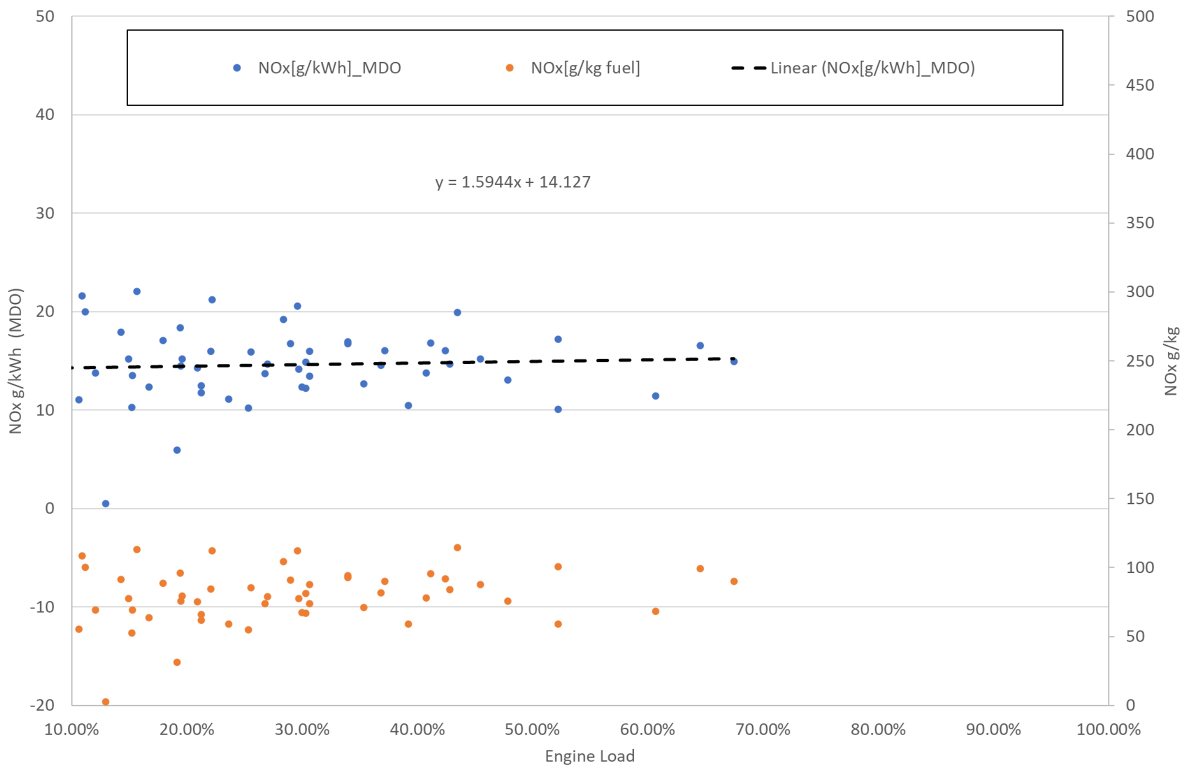


Figure 7 NO_x measurements of Tier II Reefers by an automatic sniffer at the Great Belt bridge Denmark between 2018-2023. A linear fit is also shown. The data corresponds to 56 ships with ship lengths 100-150 m and rated engine power 3000-9000 kW.

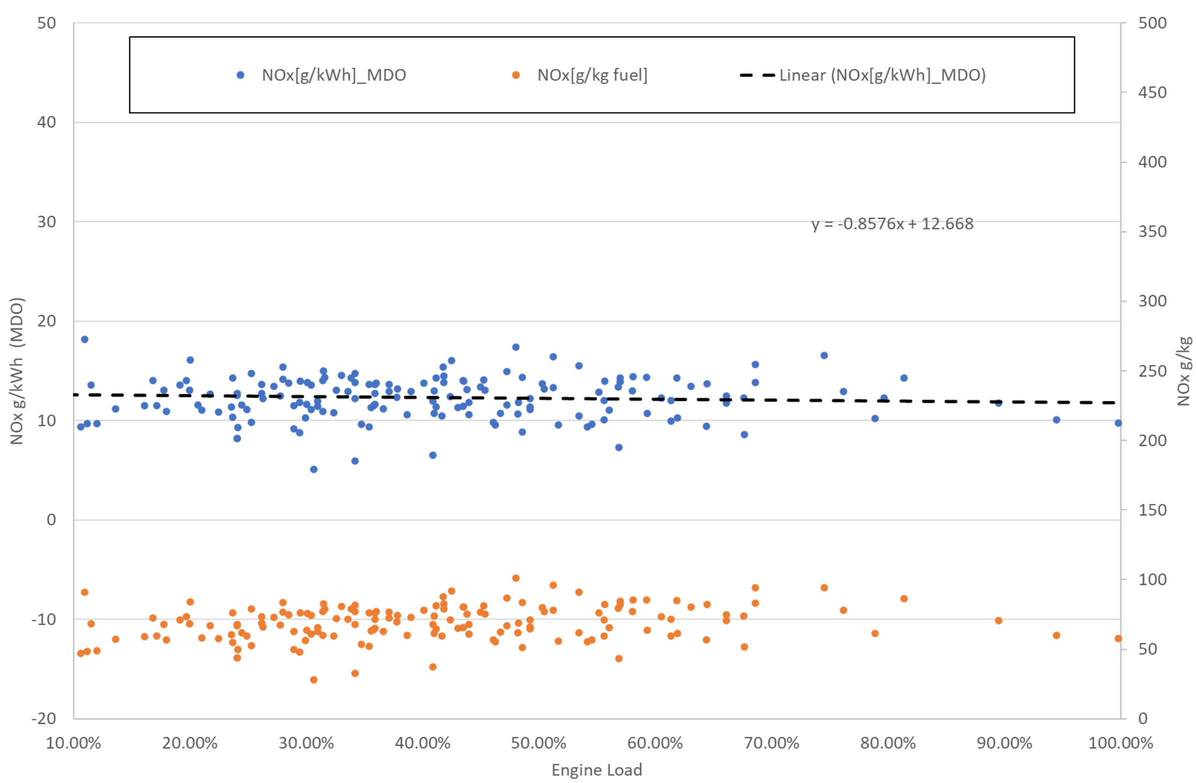


Figure 8 NO_x measurements of Tier I Roro ships by an automatic sniffer at the Great Belt bridge Denmark between 2018-2023. A linear fit is also shown. The data corresponds to 171 ships with ship lengths 150-190 m and rated engine powers 11000-25000 kW.

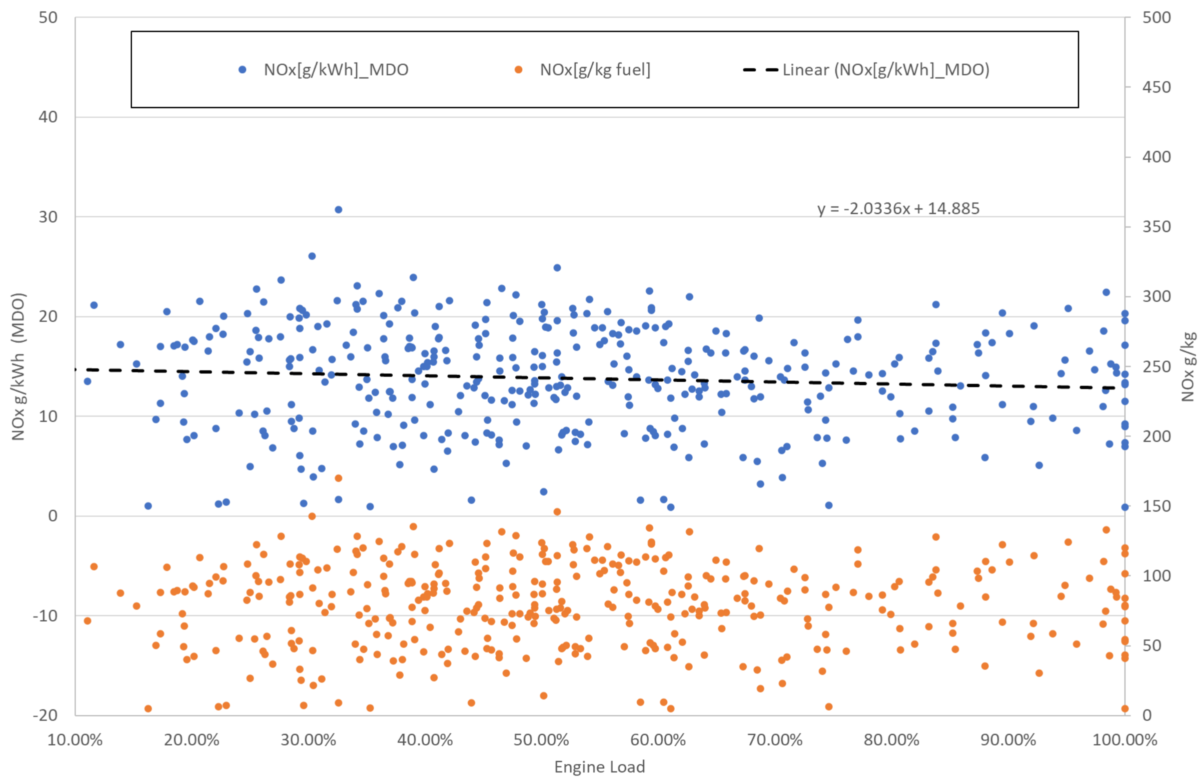


Figure 9 NO_x measurements of Tier II Crude Oil tankers by an automatic sniffer at the Great Belt bridge Denmark between 2018-2023. A linear fit is also shown. The data corresponds to 440 ships with ship lengths 200-300 m and rated engine powers 10000-21000 kW.

Table 1 Statistics from NO_x measurements of 721 container ships by an automatic sniffer at the Great Belt bridge Denmark between 2018-2023. The data has been filtered for ship length and rated engine power above 200 m and 20000 kW, respectively. N corresponds to number of ship measurements.

Engine Load	N	EF_i	Std	25th perc	50th perc	75th perc	EF_i	Std	25th perc	50th perc	75th perc
		g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	g/kg	g/kg	g/kg	g/kg	g/kg
Tier 0											
0-25 %	76	17.8	6.5	13.1	16.3	23.3	86.9	32.4	65.0	78.2	115.4
25-50 %	145	18.0	6.0	13.6	18.2	22.5	94.9	31.2	72.4	97.2	119.6
50-75 %	69	19.0	4.8	15.2	20.5	22.5	106.2	26.8	85.0	113.6	126.1
75-100 %	9	20.1	3.6	20.0	20.8	22.3	113.9	20.1	113.7	116.9	125.0
EF_{avg}		***19.2***									
Tier I											
0-25 %	95	17.0	4.6	13.9	17.0	19.4	88.1	24.4	72.1	88.1	100.2
25-50 %	70	17.5	4.3	14.4	16.9	20.1	97.1	24.1	78.8	95.6	112.1
50-75 %	10	16.3	2.8	15.5	16.0	18.1	96.4	16.4	91.9	94.2	107.0
75-100 %	0										
EF_{avg}		***16.45***									
Tier II											
0-25 %	47	22.4	5.7	18.9	22.7	26.1	116.0	29.4	97.8	120.9	134.6
25-50 %	109	19.3	5.2	16.5	19.3	22.2	107.8	29.3	95.2	108.3	124.0
50-75 %	77	17.4	3.6	15.6	17.7	19.7	103.6	21.7	92.2	106.1	116.5
75-100 %	14	17.1	3.7	15.2	16.7	18.0	102.8	22.6	91.0	100.7	107.5
EF_{avg}		**17.7**									

Table 2 Statistics from NO_x measurements of 127 Reefers by an automatic sniffer at the Great Belt bridge Denmark between 2018-2023. The ranges of ship length and rated engine power correspond to 100-150 m and 3000-9000 kW, respectively. Tier I ship are not presented since only few such ships were observed. A weighted average has been calculated based on Eq 4 and using the average engine loads for each interval which can be compared to the IMO curves in Figure 2. *N corresponds to number of ship measurements.*

Engine Load	N	EF_i	Std	25^{th} perc	50^{th} perc	75^{th} perc	EF_i	Std	25^{th} perc	50^{th} perc	75^{th} perc
		g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	g/kg	g/kg	g/kg	g/kg	g/kg
Tier 0											
0-25 %	73	13.7	4.9	10.2	13.3	17.5	67.1	24.1	49.5	65.7	86.0
25-50 %	77	12.4	3.7	10.5	12.2	14.6	65.3	19.2	54.2	64.2	75.7
50-75 %	14	12.8	5.2	9.1	12.9	15.6	71.7	28.8	51.5	71.9	86.4
75-100 %	0										
EF_{avg*}		***12.8***									
Tier I	<20										
Tier II											
0-25 %	26	14.2	5.2	11.9	14.4	17.9	72.9	26.7	62.5	75.5	88.3
25-50 %	28	14.9	2.7	13.3	14.8	16.7	83.3	15.0	74.0	82.8	92.0
EF_{avg*}		**14.9**									

* Highest engine load interval is assumed to have same EF_i as the next highest.

Table 3 Statistics from NO_x measurements *of 425 RoRo ships by an automatic sniffer at the Great Belt bridge Denmark between 2018-2023. The ranges of ship length and rated engine power correspond to 150-190 m and 11,000-20,000 kW, respectively.* N corresponds to number of ship measurements.

Engine Load	N	EF_i	Std	25^{th} perc	50^{th} perc	75^{th} perc	EF_i	Std	25^{th} perc	50^{th} perc	75^{th} Perc
		g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	g/kg	g/kg	g/kg	g/kg	g/kg
Tier 0											
0-25 %	20	12.4	4.7	9.7	12.2	15.0	61.4	23.4	48.0	59.4	75.6
25-50 %	166	14.7	3.0	12.9	15.2	16.7	78.1	15.7	68.9	80.9	88.7
50-75 %	67	14.6	2.5	13.6	15.2	16.0	81.9	13.7	75.8	85.3	89.0
75-100 %	0										
EF_{avg} *		**14.56**									
Tier I											
0-25 %	40	12.4	2.5	11.0	11.9	13.7	63.9	12.1	56.9	61.4	71.4
25-50 %	88	12.3	2.1	11.2	12.4	13.9	69.0	12.0	62.8	70.3	76.9
50-75 %	37	12.4	2.2	10.5	12.9	13.9	73.5	13.1	61.7	76.0	82.3
75-100 %	7	11.6	1.7	10.1	11.8	12.6	69.8	10.5	60.9	70.6	76.1
EF_{avg}		**12.2**									

* Highest engine load interval is assumed to have same EFi as the next highest.

Table 4 Statistics from NO_x measurements of 892 Crude Oil tankers by an automatic sniffer at the Great Belt bridge Denmark between 2018-2023. The ranges of ship length and rated engine power *correspond to 200-300 m and 10,000-21,000 kW, respectively.* N corresponds to number of ship measurements.

Engine Load	N	EF_i	Std	25th perc	50th perc	75th perc	EF_i	Std	25th perc	50th perc	75th perc
		g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	g/kg	g/kg	g/kg	g/kg	g/kg
Tier I											
0-25 %	58	12.6	4.1	9.9	11.7	14.7	66.0	21.1	50.5	61.2	76.2
25-50 %	250	11.0	3.9	8.6	11.0	13.0	61.9	22.1	48.2	61.4	73.2
50-75 %	128	10.0	3.1	7.8	9.6	11.6	59.4	18.5	46.5	57.6	69.6
75-100 %	64	9.7	3.5	7.9	9.5	11.4	58.2	21.2	47.7	56.6	68.8
EF_{avg}		**10**									
Tier II											
0-25 %	35	13.9	5.7	10.0	16.5	17.6	72.4	30.0	52.6	82.7	92.3
25-50 %	157	14.2	5.5	10.2	14.9	17.9	79.8	30.7	55.4	84.0	102.1
50-75 %	135	13.5	5.1	9.7	13.6	17.3	79.9	30.1	58.3	81.4	103.0
75-100 %	65	13.6	4.5	10.3	14.3	17.2	81.5	27.1	62.1	85.3	101.5
EF_{avg}		**13.6**									

4. Discussion

In Figure 10, the relationship between engine load and NO_x emission factors for the measured Tier II container ships is shown, with the data sourced from Table 1. The graph illustrates that Tier II engines have been fine-tuned to achieve the lowest emissions when operating at higher loads. However, there is a distinct contrast in their performance at lower engine loads, where emissions are found to be 30 % higher compared to when they are at 70 % engine load. This type of engine tuning is not observed in the older Tier 0 and Tier I container ships, as highlighted in Figure 11.

Figure 12 compares the emission factors across different ship types and tiers, measured at the Great Belt Bridge. It becomes evident that container ships have the highest brake specific NO_x emissions compared to other ship types. Additionally, Tier II container ships exhibit a different emission load dependency compared to other ship types. The calculation of the average emission factor (E_{avg}), according to Eq. 2 and shown in Table 1, yields a value of 17.7 g/kWh. This value is lower than the Tier 0 value of 19.2 g/kWh but is considerably higher when compared to the NO_x emission limit of 14.4 g/kWh as stipulated in the NO_x technical code and shown in Figure 2. Part of this discrepancy could be attributed to uncertainties in the calculation of Specific Fuel Oil Consumption (SFOC) according to Eq. 3, and this aspect requires further investigation and assessment. In the calculation of the weighted emission average (E_{avg}), we also included engine loads below 25%, which may bias the results upwards. Nevertheless, it is clear from the data in Table 1 that even the emission factors at the higher engine loads above 50 % are considerably higher than the required value, and therefore the latter is not likely the reason. Nevertheless, it is important to investigate the observed discrepancy further.

It is also noteworthy that the average emission factor (E_{avg}) for other ship types such as Reefers, RoRo, and crude oil tankers is considerably lower than that of container ships, and generally meets the requirements of being below 14.4 g/kWh, even for Tier 0 and Tier I ships, as shown in Table 1 to Table 4 and Figure 12.

This study provides critical insights into the performance of Tier II container ships. Although these ships are designed for reduced emissions at high engine loads, their emissions significantly increase at lower loads. Moreover, IMO limits for any of the Tiers do not include the b emissions below 25 % engine load. Notably, ships often operate at low engine loads when navigating nearshore shipping lanes to enter or leave ports. This poses a concern for Vessel Speed Reduction (VSR) programs in regions like Southern California, as increased NO_x emissions at lower engine loads might offset or even exceed the reductions targeted by these programs. We propose that mitigating Tier II emissions through engine design modifications, optimization, or possibly retrofitting could be advantageous. This could be achieved through amendments to the IMO regulations and updates to the associated engine certification procedures. For example, this might involve giving more weight to emissions at low engine loads when calculating the emission limit, and including emissions below 25% engine load in the assessment.

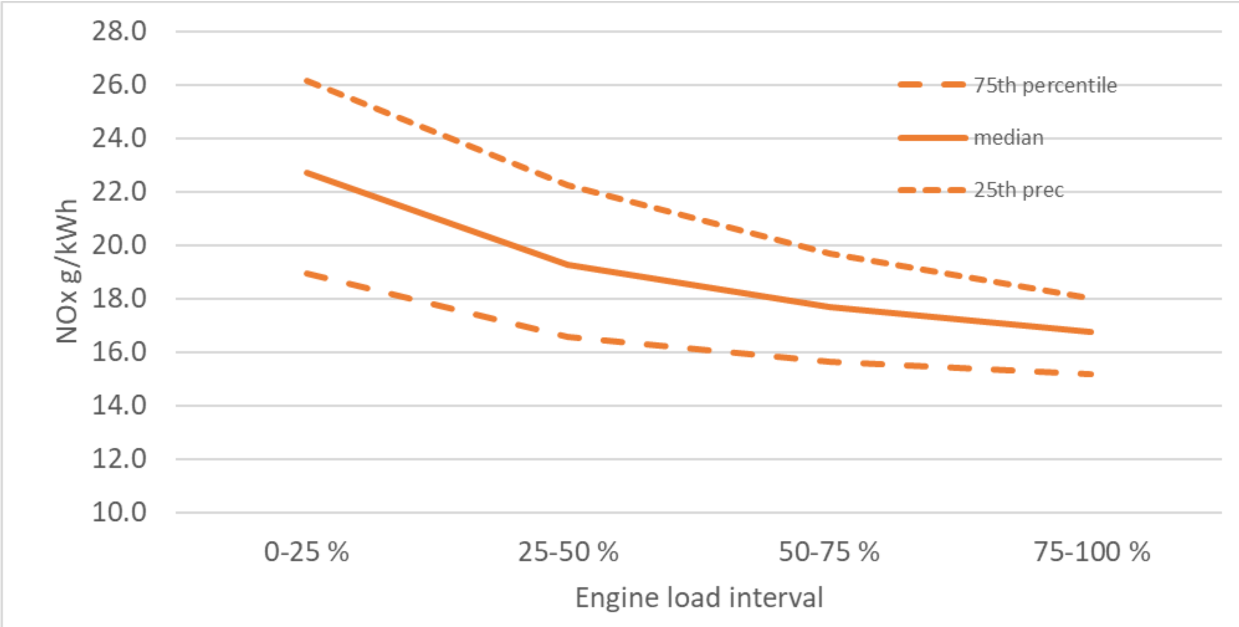


Figure 10 Statistics (25th, 50th and 75th percentile) from NO_x measurements of Tier II container ships by an automatic sniffer at the Great Belt bridge Denmark between 2018-2023. The rated ship engine power was above 20,000 kW and ship length were longer than 200 m. Data set includes 249 ships.

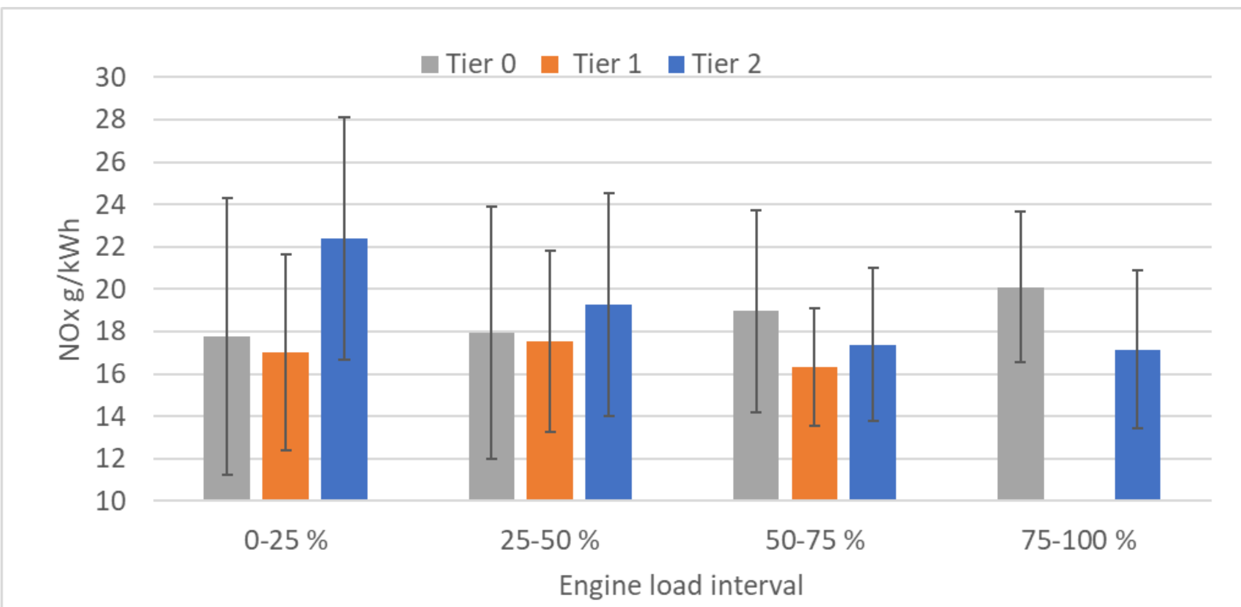


Figure 11 NO_x measurements versus engine load of Tier 0, Tier I and Tier II container ships, by an automatic sniffer at the Great Belt bridge Denmark between 2018-2023. The average and standard deviation is shown.

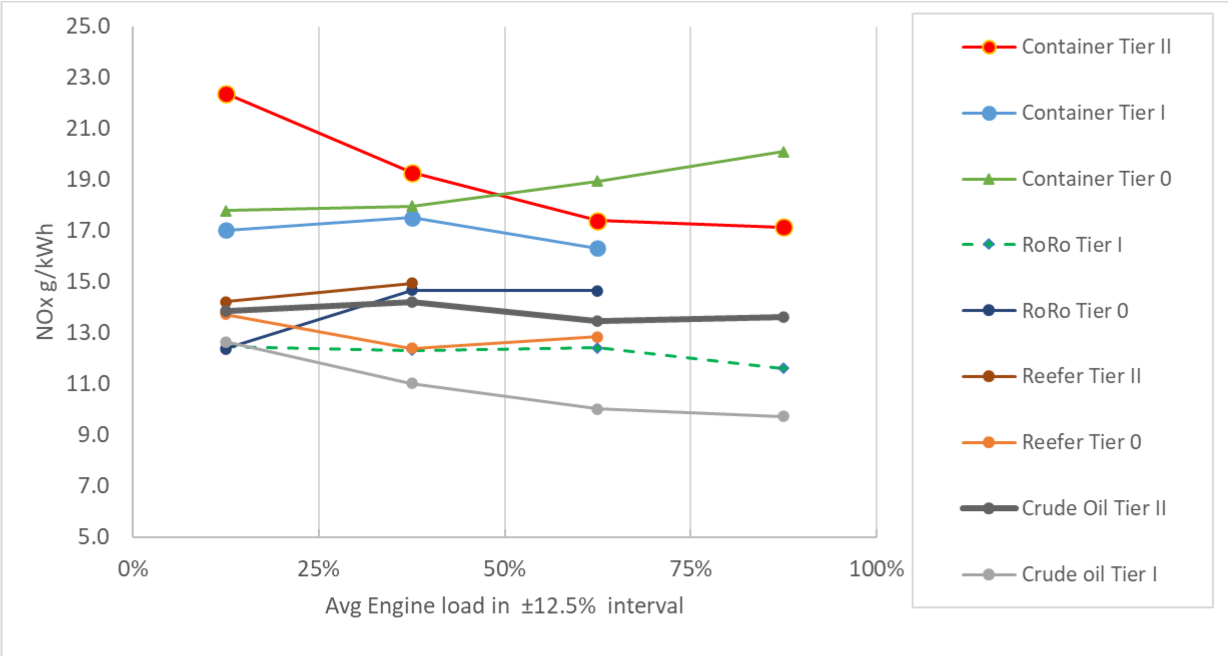


Figure 12 NO_x measurements of different ships against engine load by an automatic sniffer at the Great Belt bridge Denmark between 2018-2023.

5. Acknowledgement

We thank Jukka-Pekka Jalkanen with the Finnish Meteorological Institute for providing STEAM2 data, South Coast Air Quality Management District (CA) for providing funding to analyze the NO_x data, Elaine Shen with the South Coast AQMD for providing advice and ship information data, and Danish EPA and Belmont for providing funding for performing the measurements.

6. References

1. Goldsworthy,L-.et al., (2015). Modelling of ship engine exhaust emissions in ports and extensive coastal waters based on terrestrial AIS data – An Australian case study.Environmental Modelling & Software, 45-60.
2. Jalkanen, J.-P., Brink, A., Kalli, J., Pettersson, H., Kukkonen, J., and Stipa, T.: A modelling system for the exhaust emissions of marine traffic and its application in the Baltic Sea area, Atmos. Chem. Phys., 9, 9209–9223, doi:10.5194/acp-9-9209-2009, 2009
3. Jalkanen, J.-P, Johansson, L., Kukkonen, J., Brink, A., Kalli, J. and Stipa, T., Extension of an assessment model of ship traffic exhaust emissions for particulate matter and carbon monoxide.Atmos. Chem. Phys., 12, 2641–2659, 2012, www.atmos-chem-phys.net/12/2641/2012/
4. Mellqvist, J., Beecken, J., Ekholm, J., Samuelsson, J., Ericsson, M., Tisopulos, L., Apolidari, A., & Pikelnaya, O. (2016). Remote Quantification of Stack Emissions from Marine Vessels. A&WMA's 109th Annual Conference & Exhibition, New Orleans, Louisiana, June 2016, 1, 579–583.
5. Mellqvist, J., Beecken, J., Ekholm, J., Samuelsson, J., Ericsson, M., Tisopulos, L., Polidori, A., & Pikelnaya, O. (2016). Quantification of stack emissions from marine vessels. Air and Waste Management Association - Air Quality Measurement Methods and Technology Conference 2016, 416–421
6. Mellqvist et al., (2017a) Remote Quantification of Stack Emissions from Marine Vessels in the South Coast Air Basin, Report to SCAQMD. http://www.aqmd.gov/ors-study/project-3

7. Mellqvist et al., 2017b, Fixed remote surveillance of fuel sulfur content in ships from fixed sites in Göteborg ship channel and Öresund bridge, report to Danish Environmental Protection Agency, DOI: 10.17196/CompMon.001, http://dx.doi.org/10.17196/CompMon.001
8. Mellqvist et al., 2017c, Certification of an aircraft and airborne surveillance of fuel sulfur content in ships at the SECA border, CompMon final report to European Commission , DOI: 10.17196/CompMon.002 , http://dx.doi.org/10.17196/CompMon.002
9. Mellqvist et al., 2018, Surveillance of Sulfur Emissions from Ships in Danish Waters, final report to Danish Environmental Protection agency , DOI: 10.17196/DEPA.001,http://dx.doi.org/10.17196/DEPA.001
10. Mellqvist, J., & Conde Jacobo, A. V. (2021). Best practice report on compliance monitoring of ships with respect to current and future IMO regulation. https://research.chalmers.se/publication/523049
11. PROMINENT D5.8, 2017 D5.7 Technical recommendations on options for specifications of monitoring equipment and database set-up. TNO, TÜV Nord, SGS, IMST. PROMINENT WP5 report, grand agreement 633929, Dec 2017.

7. Appendix

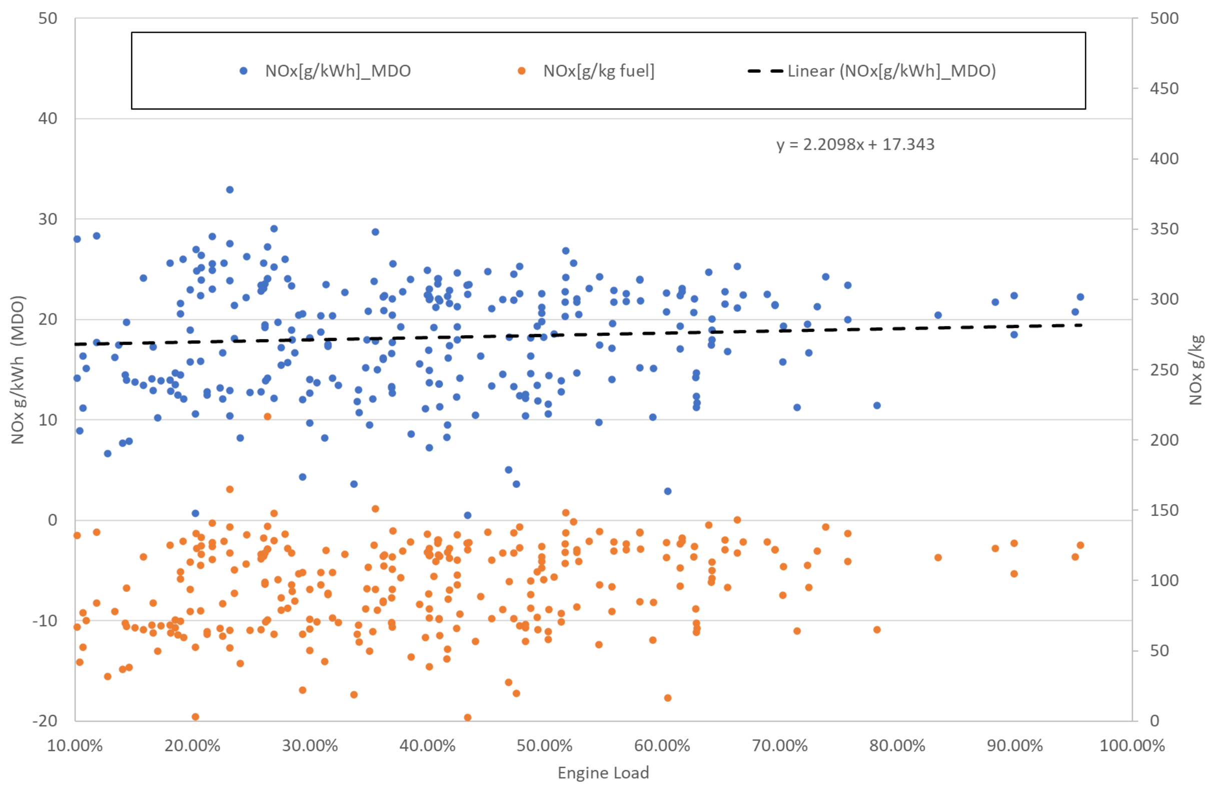


Figure 13 NO_x measurements of Tier 0 container ships by an automatic sniffer at the Great Belt bridge Denmark between 2018-2023. A linear fit is also shown to the brake specific NOx emission. The rated ship engine power was above 20,000 kW and ship length were longer than 200 m. The data set includes 300 ships.

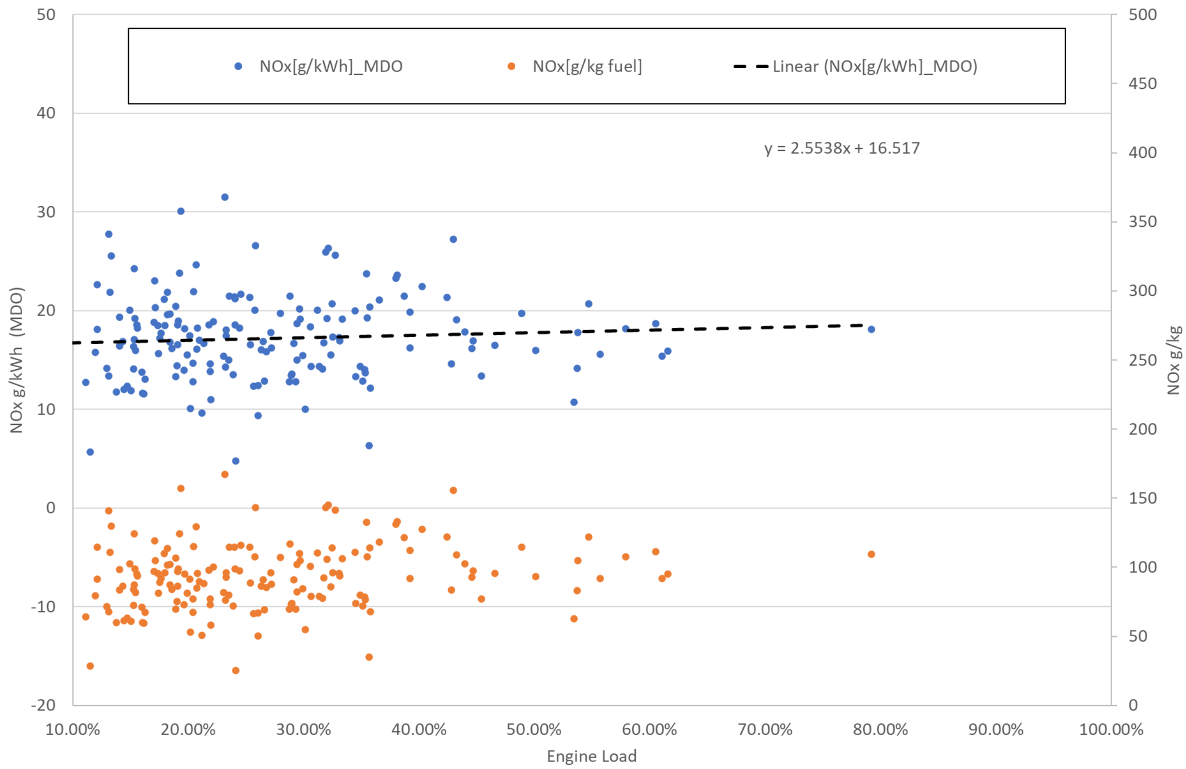


Figure 14 NO_x measurements of Tier I container ships by an automatic sniffer at the Great Belt bridge Denmark between 2018-2023. A linear fit is also shown to the brake specific NOx emission. The rated ship engine power was above 20000 kW and ship length were longer than 200 m. The data set includes 177 ships.

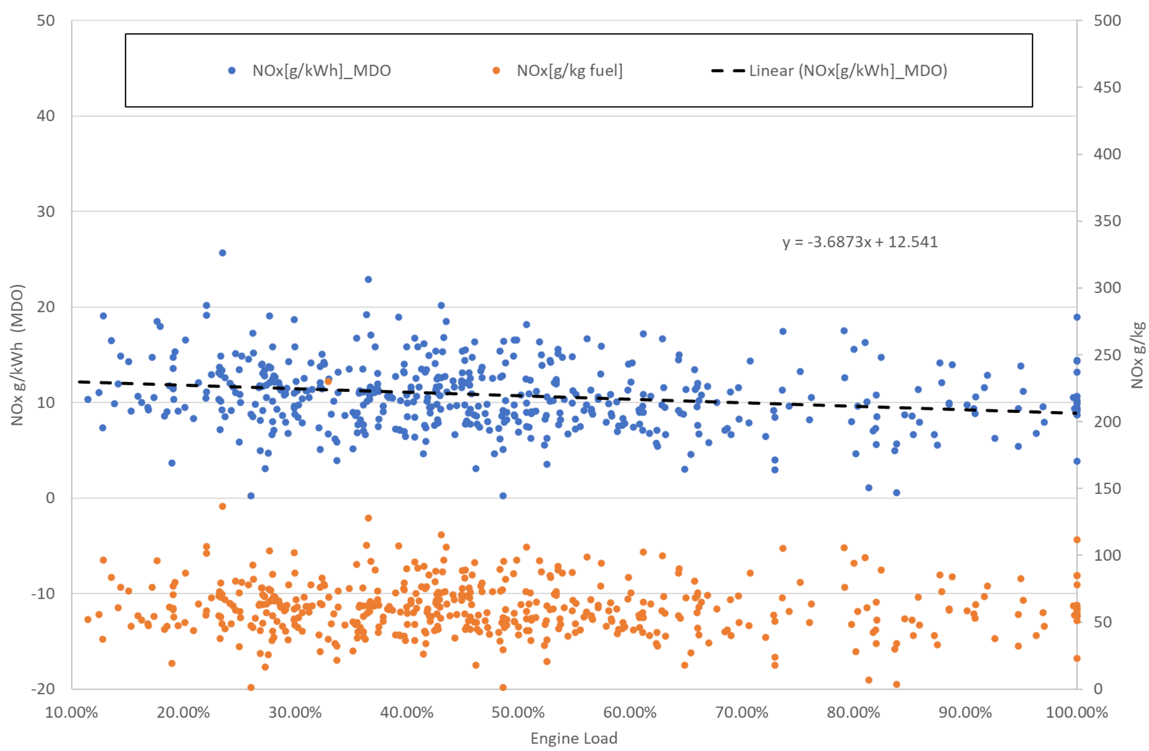


Figure 15 NO_x measurements of Tier I Crude Oil tankers by an automatic sniffer at the Great Belt bridge Denmark between 2018-2023. A linear fit is also shown. The data corresponds to 500 ships with sizes, 200-300 m, , and rated engine power,10000-21000 kW. .

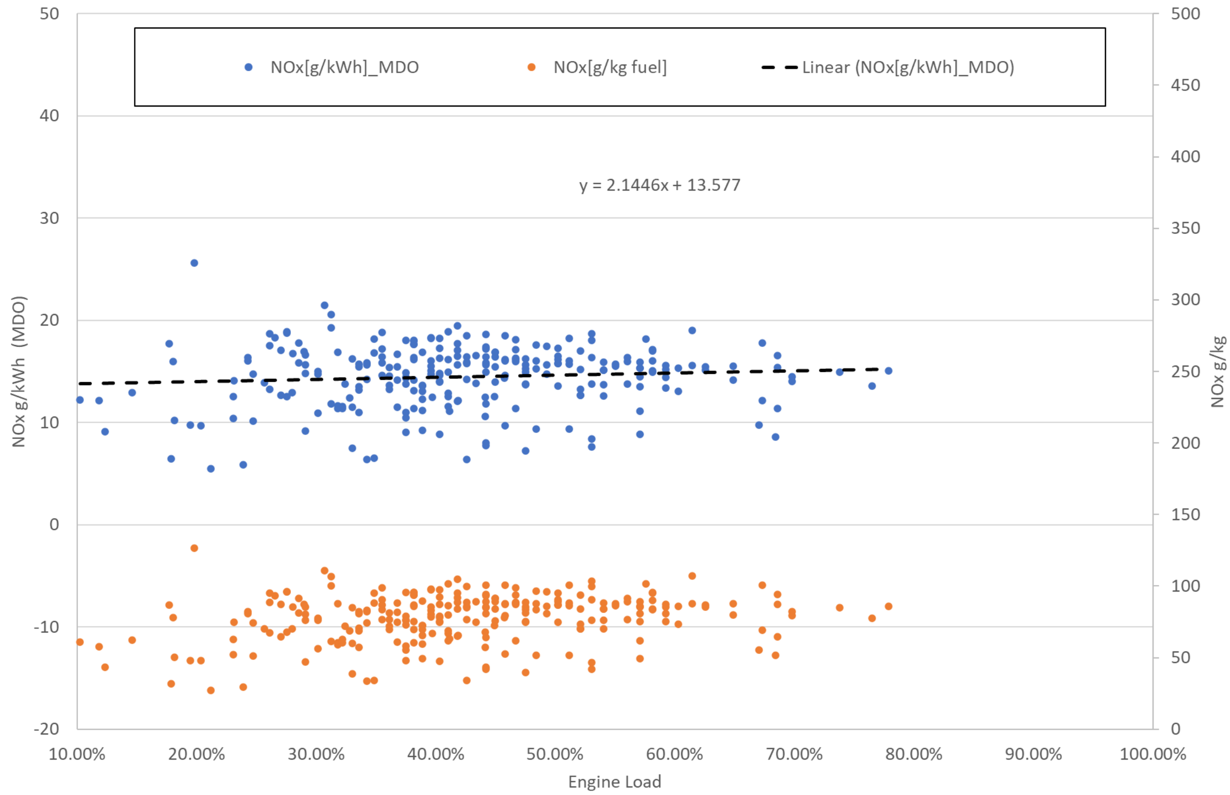


Figure 16 NOx measurements of Tier 0 RoRo ships by an automatic sniffer at the Great Belt bridge Denmark between 2018-2023. A linear fit is also shown. The data corresponds to 254 ships with sizes 150-190 m and rated engine powers 11000-25000 kW..

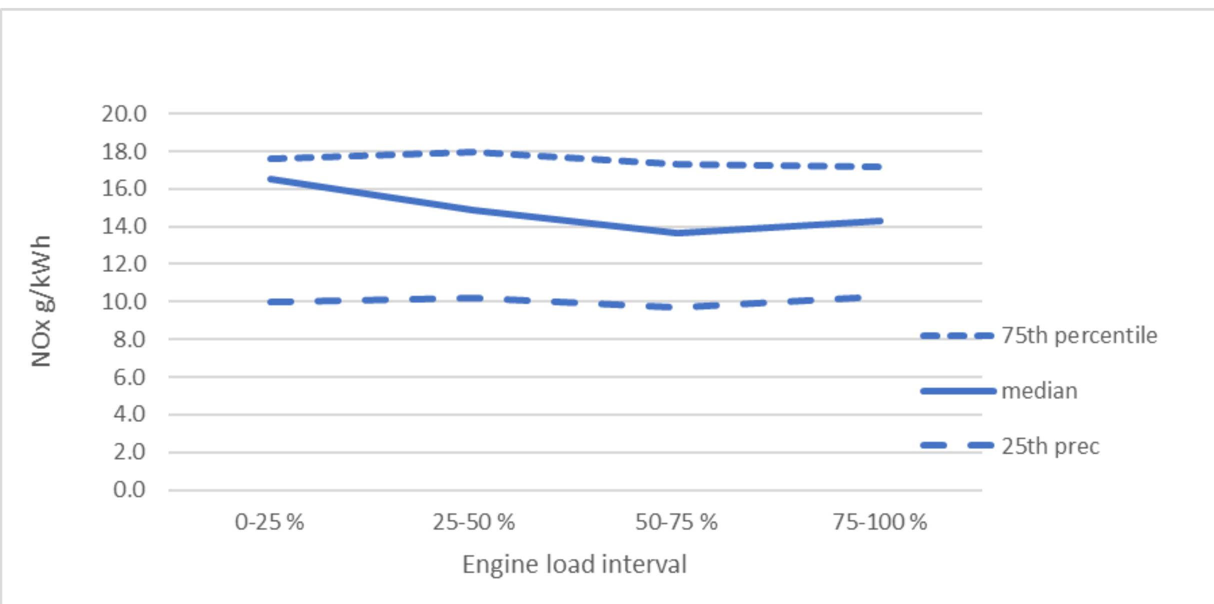


Figure 17 Statistics (25th, 50th and 75th percentile) from NO_x measurements of Tier II crude oil tanker s by an automatic sniffer at the Great Belt bridge Denmark between 2018-2023. The ship lengths were longer than 200 m. Data set includes 393 ships.