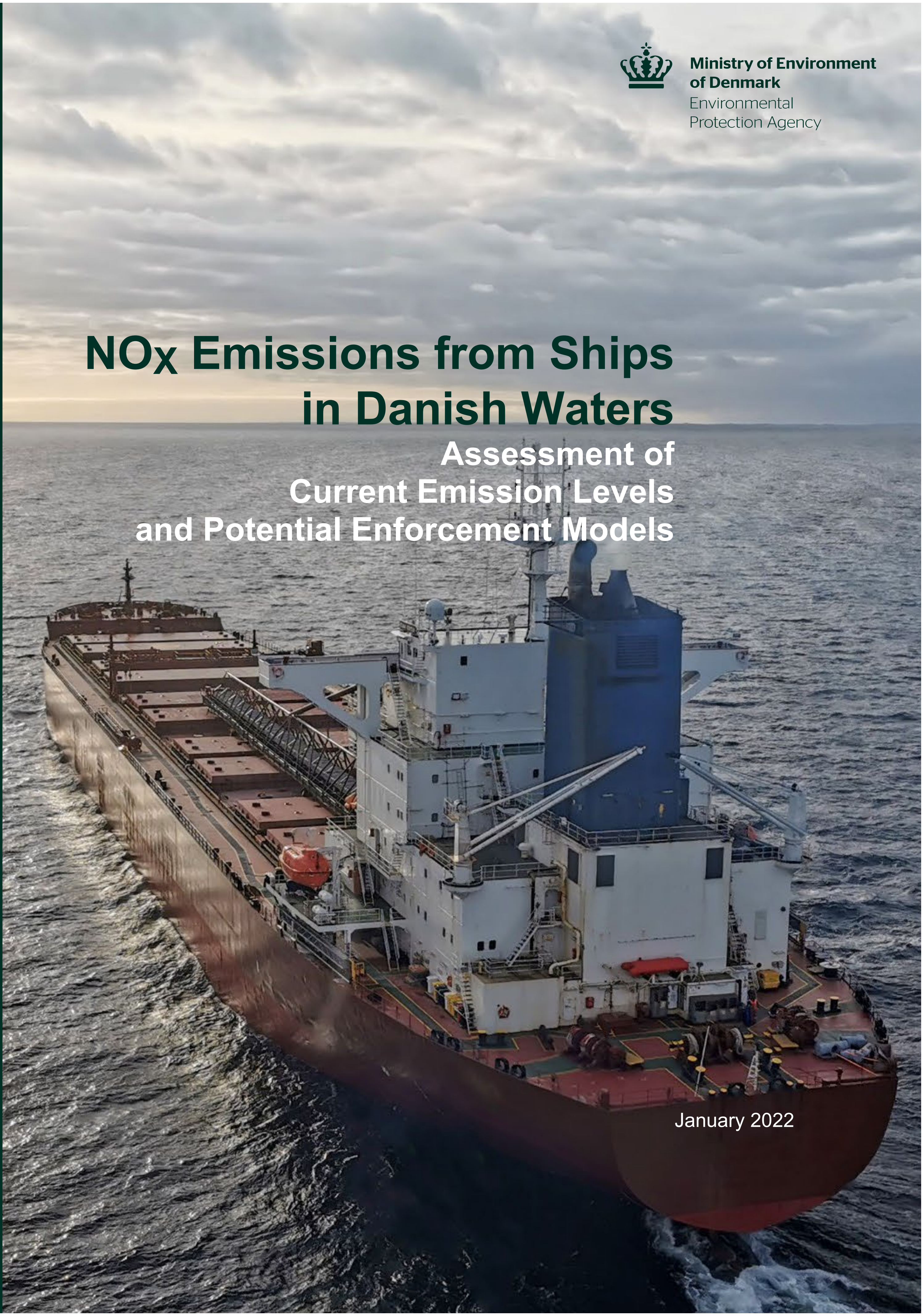
Ministry of Environment of Denmark
Environmental Protection Agency

NOx Emissions from Ships in Danish Waters

Assessment of Current Emission Levels and Potential Enforcement Models



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Acronyms and Abbreviations

AIS	Automatic identification systems
ANNEX VI	MARPOL Annex VI for the Prevention of Air Pollution from Ships
CASS	Combustion Air Saturation Systems
CO_2	Carbon dioxide
DEPA	Danish Environmental Protection Agency
DWI	Direct Water Injection
EGR	Exhaust gas recirculation
EIAPP	Engine International Air Pollution Prevention Certificate
Engine Rating	The crankshaft revolutions per minute at which the rated power occurs as specified on the nameplate and in the Technical File of a marine diesel engine. Also referred to as the engine's rated speed. Expressed in RPMs.
ECA	Emissions Control Area
FEW	Fuel-Water Emulsion
GPS	Global Positioning System
HSFO	High Sulphur Fuel Oil
ID	Identification
IMO	International Maritime Organization, a subsidiary body of the United Nations responsible for MARPOL Annex VI
IMO4GHG	4th IMO Greenhouse Gas Study: Final Report
kW	Kilowatt
LNG	Liquified natural gas
LSFO	Low Sulphur Bunker Fuel Oil
MARPOL	International Convention for the Prevention of Pollution from Ships
MCR	Maximum continuous rating, or the maximum power output an engine can produce while operating continuously
MDO	Marine Diesel Oil
MEPC	Marine Environment Protection Committee (MEPC)
NO_X	Nitrogen oxides, i.e. nitric oxide (NO) and nitrogen dioxide (NO_2).
NECA	NO_X Emission Control Area. When referenced as 'the NECA' this refers to the North European NECA, unless otherwise specified.
NTE	Not to exceed
Regulation 13	Regulation of nitrogen oxides (NO_X) under MARPOL Annex VI
RPM	Rotations per minute
RSE	Real sailing emissions
SCIPPER	Shipping Contributions to Inland Pollution Push for the Enforcement of Regulations. EU-funded research project under Horizon 2020.
SFC	Specific Fuel Consumption
SO_2	Sulphur dioxide
SRC	Selective Catalytic Reduction
ULSFO	Ultra-Low Sulphur Fuel Oil

Opsummering

Denne rapport er udarbejdet af Explicit ApS på vegne af Miljøstyrelsen. Rapporten har til hensigt at vurdere de nuværende udledningsniveauer af NO_X fra skibe i dansk farvand set i lyset af den gældende NO_X-regulering på skibsområdet samt at udforske mulige modeller for håndhævelse af det europæiske NECA ved brug af de samme overvågningsteknikker som i dag bruges til svovlovervågning til søs.

NO_X-dataene i rapporten er baseret på faktiske emissionsdata (RSE data = real sailing emissions data) indsamlet over en fire-årig periode og består af 2.249 skibsobservationer, hvor gasser i skibenes røgfaner er blevet målt ved brug af snifferteknologi monteret på enten helikoptere eller droner. På grund af dets store omfang giver datasættet et unikt indblik i de faktiske NO_X-emissioner til søs, som ikke tidligere har været kortlagt, inklusive emissionsforskelle i Tier-klasser, motor- og skibstyper.

I tillæg til de målte gasdata er der også blevet indhentet motordata for at afdække betydningen af sejlhastighed, motorstørrelse og brændstofeffektivitet på NO_X-udledningerne. For hvert skib er der således beregnet en individuel NO_X emissionsfaktor (g/kWh) med justeringer for motorbelastningen på måletidspunktet. Rapporten indeholder også en kort gennemgang af NO_X-dannelsen i skibsmotorer samt mulige reduktionsteknologier.

Med hensyn til udledningerne af NO_X fra skibe i dansk farvand finder rapporten følgende:

- Skibe i dansk farvand udleder i gennemsnit ca. 11 g/kWh NO_X.
- Gennemsnittet dækker over en stor spredning i NO_X emissionsfaktorer, hvilket også reflekterer variabiliteten i NO_X-udledningerne. Særligt ved lave motorbelastninger er emissionsfaktorerne høje (op til 35,6 g/kWh).
- Ud af de tre Tier-klasser, er det Tier II-skibene – den yngste gruppe i flåden – som udleder mest med 12,5 g/kWh i gennemsnit mod kun 11,5 g/kWh for Tier I og 10,7 g/kWh for Tier 0. Dette står i skarp kontrast til intentionen i NO_X-reguleringen (Regulation 13) om at reducere udledningen i yngre skibe.
- Motordriften ser også ud til at have betydning for NO_X-udledningen. Jo lavere motorbelastning, jo højere er den gennemsnitlige NO_X emissionsfaktor målt i g/kWh og jo større er spredningen i emissionsfaktorer. Denne tendens skyldes formentlig en kombination af flere forhold: Slow steaming / de-rating af motorer, optimering af brændstofforbruget gennem moderne motorteknologi samt den måde, hvorpå skibsmotorer certificeres på i henhold til NO_X Technical Code, hvor hovedmotorbelastninger under 25 % ikke er omfattet.
- Skibe i dansk farvand sejler i gennemsnit 12,1 knob, hvilket er langsommere end den typiske hastighed, skibene er designet til (service speed), og har en beregnet gennemsnitlig motorbelastning på ca. 49,2 %. Den relativt lave motorbelastning er bemærkelsesværdig, fordi den afviger fra den levetidsantagelse, som ligger implicit i NO_X Technical Code: At skibe bruger majoriteten af deres livstid (70 %) ved 70-100 % motorbelastning, hvorfor reguleringen vægter disse belastninger tungere i bestræbelsen på at reducere NO_X-udledningen. Men som dataene viser, så sejler skibe i dansk farvand typisk ikke med 70-100 % motorbelastning, hvilket potentielt kan have en formindskende effekt på NO_X-reduktionen indenfor NECA-området.
- Store motorer (≥40,000 kW) tegner sig desuden for bemærkelsesværdigt højere emissionfaktorer end gennemsnittet, mellem 16,4 – 20,1 g/kWh. Da disse motorer samtidig også er dem, der udleder mest i absolutte termer, er der tale om et betydeligt bidrag, også selvom den faktiske udledning i g/time er mindre ved lav motorbelastning.

- Analysen viser desuden, at visse undergrupper af skibe har en markant anderledes hældningsprofil i form af høje NO_X-udledninger ved lave motorbelastninger som aftager kraftigt i takt med stigende belastninger. Denne tendens er specielt udtalt for Tier II-skibe og motorstørrelser mellem 40,000-60,000 kW. Samme mønster ses også hos visse skibstyper, omend dette nok mest skyldes deres motorkarakteristika og ikke deres last.

Med hensyn til håndhævelsen af NO_X-reglerne (Regulation 13) til søs, finder rapporten flere udfordringer med den gældende lovgivning og den nuværende motorcertificering. Fraværet af NTE-grænser (not-to-exceed) for Tier I og Tier II samt brugen af et komplekst system af motorbelastninger med forskellige vægtninger, gør det umuligt i praksis direkte at overføre NO_X-reglerne til et håndhævelsesscenarie, hvor RSE-data indsamlet til søs kan bruges som direkte bevis på non-compliance. I det hele taget er det en svaghed i lovgivningen samt i NO_X Technical Code, at ingen af delene oprindelig er designet med uafhængig håndhævelse for øje, under faktiske driftsforhold til søs eller inden for særlige zoner med skærpede emissionskrav. Den begrænsede mulighed for at overføre metodikken til faktiske driftsforhold til søs vurderes således at hæmme muligheden for at dokumentere og sikre håndhævelse inden for NECA-området.

I stedet for at bruge RSE-data som direkte bevis, anbefaler rapporten, at NO_X-data indsamlet til søs bliver brugt til screening – analogt til måden svovlgrænserne håndhæves i dag – som en måde at identicere NO_X-outliere og målrette en videre indsats af havneinspektionen, herunder en revurdering af skibets motorgodkendelse. Med udgangspunkt i sådan en tilgang opridser rapporten to mulige overvågningsmodeller til håndhævelse:

(a) En **basismodel**, hvor overvågningen rettes mod alle skibe med en målt NO_X-emissionsfaktor på 50 % over den max-tilladte vægtede udledningsværdi for den pågældende Tier-klasse.

(b) En **udvidet model**, hvor overvågningen rettes mod skibe med en målt NO_X-emissionsfaktor på 50 % over den individuelle grænseværdi, som gælder for skibets Tier-klasse og motor-rating, undtagen i tilfælde hvor motorbelastningen er vurderet til at være under ≤ 25 %.

I begge modeller vurderes det, at NTE-grænser kan bruges effektivt som indikatorer på mulige overtrædelser.

Anvendt på RSE-dataene viser analysen desuden, at den udvidede model er bedre til at frasortere tilfælde med lave motorbelastninger end basismodellen samt mere præcist at identificere NO_X-outliere i tilfælde af skibe med højere motor-rating. Omvendt, så kræver den udvidede model flere tredjepartsdata end den mere simple, operationelle basismodel.

Begge modeller er i det hele taget afhængige af skibs- og motorinformationer, som ikke er inkluderet i AIS-strømmen i dag, og i visse tilfælde heller ikke lettilgængelige via tredjepartskilder i troværdig form. Det gælder f.eks. brændstofeffektiviteten og motorbelastningen. For yngre skibe vil disse data typisk kunne udtrækkes via skibets eksisterende motorrapporteringssystem, mens det for ældre skibe forventeligt vil kræve installation af fuel flow-metre, rapporteringssystemer osv. Manglende data og/eller data med dårlig kvalitet må derfor anses for at være en generel udfordring for en overvågningsindsats til søs, uanset model. Skulle de nødvendige data blive gjort obligatoriske at rapportere, og AIS-protokollen udvidet til at understøtte NO_X-håndhævelse, ville det kræve en tilføjelse af følgende datapunkter:

- Køllægningsdato, til bestemmelse af Tier-klasse.
- Motor-rating, til bestemmelse af den vægtede grænseværdi for det pågældende skib.
- Brændstofeffektivitet, for at kunne udtrykke NO_X-udledningen relativt til motoreffekten.

- Motorbelastning, til identifikation af lave motorbelastninger, såfremt håndhævelsesmodellen kræver, at der tages højde for motorbelastning i den målte NO_X-udledning.

Afslutningsvis finder rapporten, at både teknologier og metoder er til stede til at måle NO_X-udledningen til søs ved brug af fjernmåleteknikker samt at en inklusion af NO_X i den eksisterende overvågning som minimum vil kunne bidrage til en effektiv dokumentation af NO_X-reguleringens faktiske effekter generelt, samt særligt i forhold til grænseværdierne inden for NECA.

Summary

This report has been prepared by Explicit ApS on behalf of the Danish Environmental Protection Agency to assess current NO_X emission levels from ships in Danish waters and explore possible models for enforcement of the NECA using the same at-sea surveillance techniques currently used for sulphur emissions monitoring.

The NO_X data used in this report has been collected over a four-year period and consist of 2,249 ship observations in which ship exhaust plumes have been sampled using sniffer techniques deployed via airborne surveillance. Due to its magnitude, the dataset allows for a unique insight into the real sailing NO_X emissions – including differences in patterns between Tiers, engine and ship types – not seen before.

In addition to the gas sample data, external data has also been sourced on various engine parameters to understand impacts from speed, engine size, and fuel efficiency on the NO_X emissions. The RSE data is thus presented as a load-adjusted NO_X emission factor (g/kWh) for each ship observation. A brief introduction to NO_X formation in ship engines and possible abatement techniques is also presented.

From the analysis of the RSE data, the main findings concerning the current NO_X emission level in Danish waters are as follows:

- On average, ships in Danish waters are found to emit approx. 11 g/kWh of NO_X.
- In general, there is a substantial spread in NO_X emission factors, reflecting the variability of NO_X emissions, with the highest values (up to 35.6 g/kWh) found in ships running at low engine loads.
- Of the three Tiers, Tier II ships – the youngest section of the fleet[1] – appear to emit more NO_X in g/kWh than the older Tiers. On average, Tier II ships emit 12.5 g/kWh compared to only 11.5 and 10.7 g/kWh for Tiers 0 and I, respectively. This contrasts sharply with the intent of the international regulation of NO_X emissions from ships (Regulation 13) to reduce NO_X emissions from younger ships.
- Operational mode also appears to have an impact. The lower the engine load, the higher the average NO_X emission factor in g/kWh and the larger the spread in factors. This finding may be linked to a combination of slow steaming / engine de-rating, modern engine technology for fuel optimization, and how ships are certified under the NO_X Technical Code where main engine loads below 25 % are not addressed.
- Overall, ships have an average speed of 12.1 kn in Danish waters, below most service speeds, with a calculated average engine load of approx. 49.2 %. The relatively low average load is particularly noticeable since it deviates from the underlying assumption in the NO_X Technical Code that 70 % of a vessel's lifecycle operations are spent at 70-100 % engine loads, prompting the regulation to put its emphasis here as a means of achieving overall NO_X reduction. But as seen from the data, ships in Danish waters do not typically run at 70-100 % load, potentially diminishing the reducing effect of the NO_X regulation inside the NECA.
- Bigger engines (≥40,000 kW) are also found to have notably higher emission factors than the average, between 16.4 – 20.1 g/kWh. Given that these engines also emit the

[1] The study includes ships with keel-laying dates as young as 2020. However, given that the European NECA was only introduced on 1 January 2021, no ships are classified as Tier III.

most in absolute terms, this contribution is not negligible even if the actual emission in g/hour is smaller at low loads.
- Certain subgroups are also found to have distinctly different trendlines in the form of high NO_X emission factors at low loads that decline significantly as the loads increase. This is particularly notable for Tier II and engines sized 40,000-60,000 kW. The same can also be observed for certain ship types, although this is probably closer related to the engine size than the type of ship.

Investigating the applicability of Regulation 13 in a real sailing environment, the report finds several challenges with the existing regulation and engine certification scheme. The lack of NTE limits for Tiers I and II, and the existence of a complex load scheme with different weighted factors, makes it impossible to directly transfer the NO_X limits to a real-world compliance monitoring scenario with the intent to use RSE data to prove non-compliance. Indeed, it is a weakness of Regulation 13 and the NO_X Technical Code that it was never designed to be verified independently, in real sailing conditions, or in designated zones. The limited ability to translate the methodology to real world conditions thus hampers efforts to document and ensure compliance inside the NECA.

Instead, the report recommends using RSE data as a targeting mechanism – similar to the current approach used for sulphur emissions – to identify NO_X outliers for possible further follow-up action by Port State Control such as revalidation of the engine certification. In this context, the report outlines two potential compliance monitoring models that could be implemented:

(c) A **base model** in which the surveillance simply targets any ship with a NO_X emission factor 50 % above the highest permissible weighted values under Regulation 13 for each Tier.

(d) An **advanced model** in which the surveillance targets those ships with NO_X emission factors 50 % above the permitted Tier limit applicable to the specific engine rating of the ship, except in cases were the ship is assessed to operate ≤ 25 % load.

In both models, the NTE limits are found to function effectively as ‘flagging’ techniques.

Applied to the RSE data, the advanced model is found to better filter cases of low loads than the base model and to identify NO_X outliers more accurately in ships with higher engine ratings. Conversely, the advanced model requires more third-party engine data than the simpler, more operational, base model.

Both models require additional ship and engine data beyond what is available in the AIS stream today; in some cases, data that is not readily or reliably available from third-party sources such as the specific fuel consumption rate and current engine load. In the case of younger vessels, this data may be extractable from the existing engine setup; in the case of older vessels, it will require installation of fuel flow meters, reporting systems, etc. Missing data and/or poor-quality data is therefore a considerable challenge to any at-sea monitoring effort. If the data would be made mandatory to report, and AIS protocol expanded to support remote NO_X compliance verification, the following minimum data points would need to be added:

- Keel laying date, to determine Tier class
- Engine rating, to determine the applicable weighted compliance value.
- Specific fuel consumption, to express the NO_X emission relative to the power output.
- Engine load, to adjust for the impacts of low loads to the extent a load-dependent scheme is applied to RSE conditions

On a final note, the report concludes that technology and methods are in place to reliably measure NO_X using remote sensing techniques and that the inclusion of NO_X in the existing at-sea monitoring scheme would – as a minimum – allow for real-world tracking of the effectiveness of Regulation 13 generally and the impact of the NECA restrictions specifically.

Introduction

Emissions from shipping, including nitrous oxides (NO_X), contribute substantially to both environmental and human health risks, especially in coastal regions. The emissions contain greenhouse gases and substances contributing to eutrophication and acidification, as well as particles toxic to human health. NO_X are a group of these gases, formed by the combustion of fuel. NO_X acts as an indirect greenhouse gas by particle and ozone formation and contributes to nutrient pollution in coastal waters (US. EPA, 2020). It is also an irritant to the human respiratory system and can increase susceptibility to respiratory illnesses with long-term exposure (EEA, 2020).

Since the introduction of the European NECA on 1 January 2021, attention has grown around understanding and documenting real sailing emissions (RSE) of NO_X from ships as well as shaping effective enforcement strategies in the coastal states surrounding the European NECA. This includes Denmark which, due to its location at the entry to the Baltic Sea, is a hotspot for global maritime traffic.

To aid the understanding, the Danish Environmental Protection Agency (DEPA) has engaged with Explicit ApS – a Danish technology company specializing in collecting and analysing RSE data from ships – to further understand these emissions using RSE data on NO_X collected by Explicit via airborne surveillance in Danish waters. Explicit has been conducting regular monitoring of sulphur emissions from ships in Danish waters on behalf of DEPA since 2017 using airborne surveillance techniques and as a biproduct of this monitoring (for instrumentational and other analytical purposes) also collected thousands of RSE observations on NO_X.

The study has two objectives:

1. To establish how data on real sailing emissions of NO_X from ships in Danish waters can be used to assess the total NO_X emissions from shipping as well as identify emission patterns related to Tiers, engine types, ratings, ship types etc.
2. To investigate potential models for how remote sensing data can be used to assess if a ship is compliant with the NO_X regulation (all Tiers).

For two decades, the International Maritime Organization (IMO) has had in place regulation to curb the global emission of NO_X from shipping through the MARPOL convention Annex VI, Regulation 13 (Regulation 13). This regulation classifies ships into three Tiers according to their age, each Tier requiring compliance with ever decreasing NO_X emission limits – the newer the ship, the lower the limit. Tiers I and II apply on a global scale whereas an even stricter Tier III NO_X requirement on the newest ships apply inside the US and European Emission Control Areas (ECAs) effectively upgrading them to ‘NECAs’.

The intent of Regulation 13 is clear – to reduce the negative impacts of NO_X emissions from ships on humans and ecosystems, directly improving air and water quality while indirectly assisting in curbing climate change with each Tier class leading to progressively less NO_X impacts from shipping. The introduction of the two NECAs additionally aims to further reduce NO_X emissions by up to 80 % over time from Tier I levels in coastal regions where the impact of NO_X from shipping represents an increased threat to areas with high population density. The question is if the regulation is achieving it’s intended goal?

NO_X emission impacts and reduction potentials have been explored by several bodies in recent years (Transport & Environment, 2016). Common for these studies have been the limited access to RSE data on NO_X and the generally heavy reliance on atmospheric modelling. In order words, assumptions on NO_X are plentiful with little empirical data to confirm or deny values and projections. This study is in part an attempt to remedy this by offering an analysis of the largest empirical RSE dataset so far presented on NO_X.

By offering an empirical-based analysis, the goal of this study is to advance the understanding of real NO_X emissions from shipping in Danish waters and assess possible paths to compliance monitoring. As such, the report should be seen as part of DEPA's efforts to ensure effective and cost-efficient enforcement of MARPOL Annex VI.

1. Methodology

This chapter outlines the sources and methods used in this report to establish the independent NO_X emission factors for each ship observation and evaluate current compliance with Regulation 13.

The analysis relies on RSE data collected by Explicit as part of the regular airborne surveillance of maritime sulphur emissions conducted on behalf of DEPA throughout Danish waters.

1.1 Data Sourcing and Collection

The RSE data used in this report all stem from an original dataset of 2,448 observations measured from 1,867 ships in Danish waters between 1 July 2017 and 30 June 2021. The data was collected via airborne monitoring using either a manned helicopter or a drone equipped with sniffers comprising an array of sensors (SO_2, CO_2, NO and NO_2). To sample, the aircraft(s) would navigate the vessel exhaust plume to sample the emissions. The technology and sampling method are explained in detail in the DEPA 2018 publication on airborne surveillance of sulphur emissions in Danish waters (Explicit, 2018). In addition to data on NO_X and CO_2 emissions, timestamped GPS position and AIS data were also collected to couple emissions with specific vessel IDs.

In addition to the RSE data, other vessel-specific engine data was obtained using IHS database services including data on total kW of the main engine, maximum speed, service speed, ship type, date of construction / keelage, engine rating, fuel oil type and deadweight tonnage of the vessel.

Of the original dataset, 2,249 observations have been included in the analysis. The remaining data has been excluded for various reasons detailed in section 1.2 below.

1.2 Data Exclusions and Enhancements

The report focuses on main engine outputs from ships running on conventional low sulphur fuels under normal cruise conditions inside the NECA. Data not fitting these criteria, such as anchored or Liquified Natural Gas (LNG) vessels, were excluded from the analysis. In addition, some observations were marked as low quality (quality score < 3[2]) or otherwise – in the case of some of the IHS data – considered erroneous. These too were excluded.

[2] The Explicit Mini Sniffer Systems include systemic protocols for assessing the quality of each measurement based on the concentration levels and the sampling time spent in each plume. The quality score expresses the pilot's ability to successfully navigate the exhaust plume to capture a robust gas sample. For further, see the 2017 campaign report (Explicit, 2018).

In total, 199 observations were excluded from the gross dataset to improve data integrity. A breakdown of the exclusions can be found in TABLE 1.

TABLE 1. Data exclusions.

Exclusion criteria	Source	Number of observations
Gross dataset		2,448
Observations with a recorded AIS speed over ground <1 knot	Explicit	- 2
Observations on LNG-fuelled ships	IHS	- 16
Observations with a maximum speed < 1 knot	IHS	- 39
Observations with a sulphur content > 0.5%	Explicit	- 10
Observations with a quality score < 3	Explicit	- 53
Observations with missing engine rating data	IHS	- 43
Observations with a subsequent load factor > 100 %		-36
Total net ship observations analysed		**2,249**

In addition, to compensate for missing IHS data points, the following enhancements where made:

- For approx. 55.5 % of the observations, the maximum speed was not available. Instead, the missing maximum speeds were gap-filled using a regression model.
- For approx. 2.3 % of the observations, the keel-laid date was missing. Instead, the built date was used to determine the age of the vessel. Note, this did not influence the Tier classification of the vessel as no substitutions were aged close to a Tier threshold.

1.3 Establishing Individual NO_X Emission Factors

To establish the individual NO_X emission factor for each vessel, the analysis relies on a combination of methods in part to mitigate the lack of real-time engine data from the ships themselves. For this reason, the calculated factors should be considered conservative *estimates* of the NO_X output relative to the power consumption as opposed to absolute values.

The three methods used to calculate the emission factor estimates are as follows:

- Calculating the NO_X/CO2 ratio to determine the NO_X output in proportion to the overall engine output.
- Establishing a specific fuel consumption value to account for the amount of fuel being used at the time of monitoring.
- Calculating the individual load factor to account for the power performance of the engine at the time of monitoring.

In combination, these three steps allow for a load-adjusted expression of the individual NO_X emission factor in g/kWh. The details of each step are described below.

1.3.1 The base NO_X/CO_2 formula

To determine an individual NO_X emission factor in g/kWh for each ship a simple ratio between the measured NO_X and CO_2 concentrations in the exhaust plume (adjusted for background) was used. This approach, given by (Balzani Lööv, 2014) and presented in the formula *(1)* below, forms the backbone of the emission factor analysis:

$$EF\left(g\ \frac{NO_x}{kWh}\right) = \frac{NO_{X_{measured}}\,[ppm]}{CO_{2_{measured}} - CO_{2_{background}}\,[ppm]} \times 3.33 \times e \qquad (1)$$

$$Where: NO_x = NO + NO_2$$
$$EF = NO_x \text{ emission factor expressed in } g/kWh$$
$$e = \text{average specific fuel consumption expressed in } g/kWh$$

The unitless factor 3.33 is a combination of the molecular weight ratio between NO_2 and carbon and the percentage of carbon mass in the fuel[3]. In compliance with the IMO Technical Code MEPC 177(58), the ratio assumes complete conversion of all NO to NO_2 over time (IMO, 2008).

Once the NO_X/CO_2 ratio is established, the result is further multiplied with a specific fuel consumption value (*e*) to reach an individual emission factor for each ship.

1.3.2 Establishing the specific fuel consumption

As seen in equation 1, the specific fuel consumption of the ship is needed to calculate the NO_X emission factor. In an ideal world, this datapoint – along with the ship Tier class – would be part of the live AIS stream and thus readily available for authorities to conduct NO_X analysis 'on the fly'. Alternatively, an approximate specific fuel consumption can be calculated using a combination of IMO-established base values and independent load factors.

The specific fuel consumption is heavily dependent on the engine type (whether it is a slow-, medium-, or high-speed diesel engine), fuel type, and to some extent also on the engine load at the time of monitoring. The engine load also influences the fuel efficiency with lower efficiency at lower loads.

To establish the specific fuel consumption, adjusted for engine load, the following method prescribed by the 4th IMO Greenhouse Gas study (IMO4GHG, equation 10) was used (CE Delft, 2021).

$$SFC_{ME,i} = SFC_{base} \times \left(0.455 \times Load_i^2 - 0.710 \times Load_i + 1.280\right) \qquad (2)$$

$$Where\ Load_i = \text{is the hourly main engine load factor given as a proportion (from zero to one)}$$

The SFC formula *(2)* combines a SFC_{base} value with an individual load factor (LF = $Load_i$) to calculate the specific fuel consumption by the main engine at the time of monitoring. Once established, the $SFC_{ME,i}$ value substitutes the (*e*) in equation 1.

While the load must be calculated independently (see 1.4), the SFC_{base} can be found in the IMO4GHG report (table 19) and summarized as outlined in TABLE 2:

[3] Note, the carbon mass percentile of the fuel is determined to be 87 % ±1.5 % as described by Balzani Lööv et. al. (Balzani Lööv, 2014). While the actual carbon mass can vary with fuel type, the difference is considered to have immaterial impact on the 3.33 unitless factor. See also section 1.6 for further on measurement uncertainties.

TABLE 2. SFC_{base} in g/kWh for different engine/fuel types and year of build (CE Delft, 2021).

Engine type	Defined as having an engine rating of:	SFC_{base} (g/kWh) by year of build *		
		≤ 1983	1984 - 2000	2001 ≤
Slow Speed Diesel	≤300 RPM	190	175	165
Medium Speed Diesel	300-900 RPM	200	185	175
High Speed Diesel	>900 RPM	210	190	185

* Given that all ships were observed inside the NECA, where restrictions on sulphur content also apply, the SFC_{base} values all assume MDO fuel. To the extent that the original dataset contained observations of sulphur content values above >0.5 % these have been excluded.

It should be noted that the IMO4GHG report generally assumes a relatively high fuel efficiency, resulting in comparatively low(er) emission factors.

1.4 Establishing Individual Load Factors

To establish the individual load factors (LF) the below formula *(3)*, derived from propeller law, was used. It expresses the propulsion operating engine power (kW) (numerator) at the time of monitoring as a proportion of the total installed engine power (kW) (denominator):

$$LF = \frac{P_{ref} \times \left(\frac{V}{V_{ref}}\right)^3 \times SM}{P_{ref}} \qquad (3)$$

$$LF = propulsion\ engine\ load\ factor\ (unitless)$$
$$P_{ref} = vessel's\ total\ installed\ propulsion\ power\ (kW)$$
$$V = AIS\ reported\ speed\ (kn)$$
$$V_{ref} = vessel's\ maximum\ speed\ (kn)$$
$$SM = sea\ margin, assumed\ to\ be\ 1.10\ for\ coastal\ operations\ (unitless)$$

Once calculated the load factor (LF) replaces $Load_i$ in equation 2. With regards to the calculated loads, a few factors influence the general trend:

Most emission inventories for shipping are based on the propeller law. In this, the engine load factor (LF) is derived from a simple cubic ratio between the ship's speed (V) and a reference speed (V_{ref}) (MacKay, 2015) (P.S. Yau, 2012) (L. Goldsworthy, 2015). As such, the propeller law assumes that a vessel is running at maximum draught. Consequently, the calculated load factor should be considered an upper bound estimate of the actual engine load.

Furthermore, the addition of a conservative sea margin (SM) to account for average weather may also cause the load to trend high (MAN Energy Solutions, 2011).

Finally, AIS speeds are always reported as *speed over ground* whereas the maximum vessel speeds are given as *speed over water*. This discrepancy, including the inclusion of a fixed sea margin, introduces a degree of uncertainty in the calculated load factors which in some cases may result in factors exceeding 100 %. In such cases, the observation was excluded.

1.5 Tier Classification

All ships have been classified by Tier in compliance with Regulation 13. As Tier III[4] has only been in force from 1 January 2021, no Tier III vessels have been observed. The different Tier levels and their associated keelage and NO_X limits according to Regulation 13 are listed in TABLE 3. In cases where no keel-laying date was available, the built year was used instead to determine the Tier class. In no cases did this substitution affect the Tier.

TABLE 3. Tier levels and NOx limits according to Regulation 13.

Tier	Ship construction date (Keel laid)	Total weighted cycle emission limit (g/kWh)		
		n < 130	130 ≤ n < 2000	n ≥ 2000
Tier 0	< 1 January 2000	n/a	n/a	n/a
Tier I	≥ 1 January 2000	17.0	$45 \cdot n^{(-0.2)}$	9.8
Tier II	≥ 1 January 2011	14.4	$44 \cdot n^{(-0.23)}$	7.7
(Tier III)	(≥ 1 January 2021)	(3.4)	$(9 \cdot n^{(-0.2)})$	(2.0)

n = engine's rated speed (in RPM)

1.6 Uncertainties

The sniffer system used for the data collected has been validated by FORCE Technology, who has also established the measurement uncertainty according to ISO/IEC Guide 98-3 (GUM:1995).

The system has been validated to have a measurement uncertainty of ± 13.2 % at 1 x RSD in a dual configuration (two sensor systems operated in parallel).

For reference, no adjustments have been made to the RSE data on account of the instrument uncertainty or any other uncertainty parameters. However, it should be recognized that a range of uncertainties apply to the estimated NO_X emission factors. As stated earlier, in addition to the instrument uncertainty, the fuel type can influence the carbon mass, draught impacts power consumption as do the sea and weather conditions, etc. All of this has bearing on the individual factors calculated for each ship and should be considered when discussing individual ship monitoring as addressed in chapter 5. However, in a larger analytical context such individual discrepancies cancel each other out and do not affect the overall trend picture.

[4] Tier III for Baltic Sea and North Sea NECA.

2. NO_X Formation in Ships and Abatement Technologies

2.1 NO_X Formation in Ship Engines

NO_X – consisting of nitrogen oxide NO and nitrogen dioxide NO_2 – is formed during the combustion process of fuel sprays in the so called Zeldovich mechanism.

Key parameters contributing to NO_X formation are *temperature*, *residence time* and the *oxygen concentration* present. The longer the residence time and the higher the temperature, the more NO_X is formed. A critical period for NO_X formation is the beginning of combustion and shortly after the peak pressure, when temperatures are at their highest. During this period, the majority of NO is formed. Once the peak pressure and the temperature of the burnt gases start to decrease, NO formation stabilizes.

When it comes to oxygen concentration, the ratio between fuel and air is important. The maximum NO_X is produced during the period in which the fuel is burnt with the least amount of oxygen required for complete combustion. Therefore, the most NO_X is produced when the actual fuel/air ratio is closest to the stoichiometric ratio (Lloyd's Register, 2002).

The relationship between these three different parameters responsible for NO emissions is visualized in FIGURE 1 (De Nevers, 2000). As shown, *Prompt NO* represents the emission contribution through the interaction of oxygen and the fuel. *Fuel NO* represents the contribution from the fuel itself, but the biggest contributor is the *Thermal NO* during high combustion temperatures. This makes temperature by far the most important parameter for NO_X formation and therefore also the parameter most often considered in emission reduction techniques. How these three key parameters can be addressed to reduce NO_X emission is described in more detail in section 2.2.

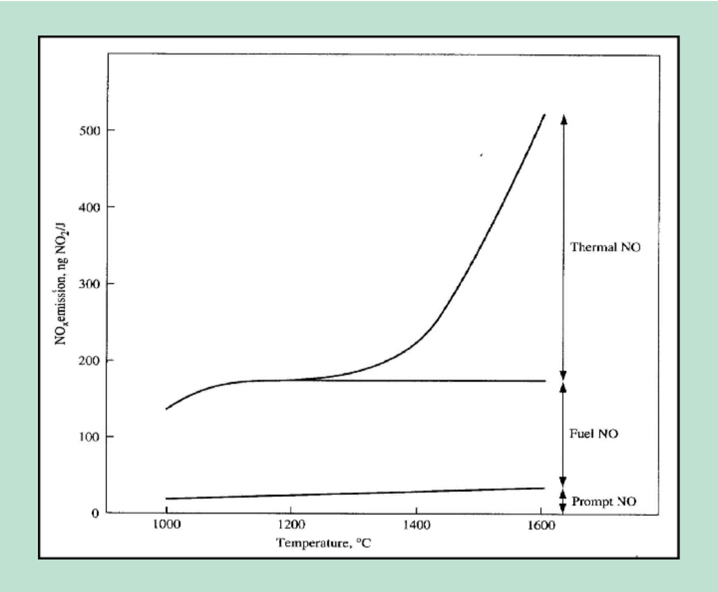

FIGURE 1. Temperature as a key parameter in NO_x emissions (De Nevers, 2000).

2.1.1 Engine features involved in NO_X formation

Several engine features contribute to the above-mentioned key parameter and therefore influence the NO_X formation. Features such as the injection and atomization equipment design, timing, pressure, as well as the geometry of the combustion chamber have a high influence on the combustion efficiency and thus an effect on the NO_X formation.

NO_X formation rates can be increased by:

- Moving fuel timing forward and raising the compression ratio. This leads to an increase of combustion pressure and temperature which have a direct effect on the NO_x formation.
- Increasing the residence time of the combustion gases due to lower rated engine speeds.
- Increasing the presence of organic nitrogen (N_2) in heavy fuel oil.

On the other hand, NO can be suppressed by a charge air cooler/pre-heater. Through an increase of the air humidity intake, peak combustion temperatures are reduced and therefore the NO formation diminished.

Over time, the technologies to modify internal engine parameters to adjust combustion parameters have developed, primarily with the objective to save fuel. In particular, the oil crisis in 1973 spurred an increased demand for improved fuel efficiency for low-speed diesel engines which led the market to develop engines with ever lower specific fuel consumption the countereffect of which was increased NO_X formation. This was the prevailing trend until 2000 when Regulation 13 was introduced as most of the NO_X reduction measures have the general effect of counteracting possible fuel oil savings. Since then – particularly since the introduction of Tier II – the general trend to achieve fuel efficiency while adhering to Regulation 13 has shifted to *de-rating* (Kristensen, 2015).

With the introduction of slow steaming, many ships have drastically lowered their actual transit speed from design levels to save fuel and reduce CO_2 emissions. This causes the vessel and its engines to operate at non-optimized load levels unless the engine is de-rated. By de-rating the engine, the vessel's top speed (maximum continuous rating (MCR)) is reduced by 10-15 % using various measures such as installation of shims, controlled cut-out of turbocharges and cylinders, and various other tuning methods. These adjustments enable the engine performance to be optimized at lower loads, resulting in higher fuel efficiency at the new optimum design point (GloMEEP, IMO). In the context of NO_X, however, de-rating has the effect of increasing the vessel's permissible NOx emission under Regulation 13 as seen in TABLE 3 and illustrated later in FIGURE 8 (chapter 4). In recent years, the introduction of advanced electronic (software) systems to control engine parameters more tightly have further increased the ability to optimize fuel performance at specific loads and speeds, effectively optimizing the individual vessel's NO_X emission curve within the boundaries of Regulation 13.

With the introduction of Tier III, however, de-rating is no longer sufficient to balance the need for fuel efficiency with Regulation 13 compliance. Instead, Tier III vessels will need to use various abatement techniques to achieve the 80 % emission reduction required under Regulation 13 from Tier I levels.The various abatement techniques currently available are presented below (Winnes F. Y., 2016).

2.2 Abatement Techniques – Strengths and Weaknesses

It is important to mention that when it comes to cleaning methods, all pollutants must be considered. As mentioned above, methods like lowering the peak combustion temperature will decrease NO_X formation effectively. On the other hand, other pollutants such as particulates and hydrocarbons are going to increase and additionally the efficiency of fuel consumption drop dramatically due to poor combustion (Lloyd's Register, 2002). Therefore, focus in this chapter is on optimised cleaning methods with regard to all pollutants.

2.2.1 Primary cleaning methods

Primary control methods are the key parameters targeting directly where the NO_X formation occurs to prevent their production in the first place. The following list explains the most important primary methods that are applied at present:

2.2.1.1 Exhaust gas recirculation (EGR)

EGR is a technology which aims to reduce the formation of NO by influencing the key parameters of temperature and oxygen concentration through recirculation and cooling of the exhaust gas. EGR systems have been around for a long-time on trucks but is relatively new to ships. EGRs do not use any catalyst and have lower initial costs than Selective Catalytic Reduction Systems (SRCs). Best performing EGR systems manage a NO_X removal rate of up to 60 %. On the other hand EGR systems are only available for a few engine brands, they tend to show an increased fuel consumption, and they tend to create high sulphur levels that can cause corrosion (Lloyd's Register, 2002) (The Scipper Project, 2020).

2.2.1.2 Water technologies

As well as EGR technologies, water technology addresses the same key parameter: combustion temperature. There are three different ways for how to add water into the combustion process to decrease combustion temperature and therefore reducing NO_X formation: (a) Direct Water Injection (DWI), (b) adding water vapor to the scavenging air with Combustion Air Saturation Systems (CASS), or (c) through the use of fuel-water emulsion (FEW).

Opinions of specialists on the performance of water technologies differ. Water technologies have the advantage that they can be initiated at low cost. On the other hand, they are also controversial, as water and fuel emulsions can be problematic for engines. It is also possible to combine various primary methods for NO_X reduction. Efficiencies vary between 10 to 60 % depending on method and engine type (Lloyd's Register, 2002).

2.2.1.3 Alternative fuels

LNG has increased in popularity recently due to its potential as a greener transition fuel (The Scipper Project, 2020). Through their engine design, the combustion peak temperatures and pressure of LNG engines are kept relatively low, which results in low NO_X emissions that reach Tier III levels without additional NO_X reduction technologies (Transport & Environment, 2016). On the other hand, a major disadvantage of this technology to date can be a significant methane slip. Slippage of up to 4% of fuel has been reported, peaking at low engine loads (Ushakov, 2019). Another disadvantage is extra space requirement for the cooled tanks. In terms of cost, it depends heavily on whether a marine engine was originally designed for an LNG vessel or whether an existing engine is being converted for LNG purposes. The latter is considerably pricier than the former (Transport & Environment, 2016).

2.2.2 Secondary NO_X reduction methods

Secondary reduction methods aim to reduce NO_X in the exhaust gas by downstream treatment. In other words, NO_X gases have already been produced and are now being prevented from entering the environment with the help of secondary treatment methods.

2.2.2.1 Selective catalytic reduction (SCR)

SCR is one of the most efficient NO_X reduction technologies, delivering a 98% reduction in NO_X emissions. NO_X formation is reduced by catalytic reduction with ammonia as the reding agent. This technology is considered state-of-the-art for lowering NO_X emissions below Tier III criteria, but also comes with large initial costs and space demand. If not managed properly, ammonia slip can occur, and SCRs are in general found to perform inefficiently during low engine loads and engine start-up where the required temperature for the catalytic reaction is not in place. Linking SCR and a scrubber also brings challenges such as activity loss of the scrubber or temperature loss. Furthermore, the catalysts can be damaged from poisoning and thermal degradation (Transport & Environment, 2016) (The Scipper Project, 2020) (Lloyd's Register, 2002).

3. Analysis of NO_X Emissions from Ships in Danish Waters

This chapter analyses the NO_X emissions from ships as they have been observed in Danish waters from 2017-2021. In particular, the analysis investigates how emissions relate to Tier class, engine size, ship type, and load.

Since July 2017, Explicit has been collecting data on NO_X emissions in Danish waters. The surveillance has focused principally on the international shipping lanes although local short-sea sailing traffic between Denmark and neighbouring countries has also been observed.

In accordance with the methodology described in chapter 1, this chapter seeks to use this RSE data to give a broad fleetwide assessment of the status of NO_X emissions in Danish waters. It also offers an assessment of the effectiveness of the overall NO_X regulation on real-world emissions. In a broader scientific context, this analysis is unique in that most studies so far investigating real NO_X emissions have been restricted to a single ship or a handful of ships. Here, the analysis extends to thousands of ships, making any fleet-wide patterns stand out more clearly.

Note, the use of linear trendlines have been applied throughout this analysis to illustrate the general trend of the data. Arguments could be made for the use of other trend methods; however, these would presumably not materially impact the findings.

3.1 General Observations

For this report a total of 2,249 observations have been analysed for NO_X emissions. All observations included in the analysis are taken from ships during cruise. While the airborne sampling technique is unable to distinguish between emission sources, the assumption is that all outputs stem from the main engines as opposed to auxiliary engines or boilers. This assumption is reasonable given the transit nature and gas concentration levels in the plume of the observed ships. While there may be some contribution from other sources to the measurements as well, this impact is assessed to be immaterial.

Given the period span of the data, some vessels were observed multiple times. This is a natural occurrence with ships often traveling the same routes and the high number of passenger ferries operating in the area. In total, the dataset includes 1,867 unique vessels.

The average speed observed in Danish waters is 12.1 kn with a range spread from 1.09 to 37.49 kn. The average is lower than the typical service speed of most ships and consistent with the slow steaming nature of ships operating inside the NECA. Relatedly, the average load factor is calculated to be 49.2 % which is notable given that the NO_X Technical Code assumes vessels to typically be running at higher loads. See section 4.1 for a further discussion of the real-world implications of this assumption.

Overall, the average specific fuel consumption is calculated to be 184.3 g/kWh, consistent with the 185 g/kWh currently applied as an internal generic consumption factor by Explicit.

Including all observations, the average NO_X emission factor is 11 g/kWh with values ranging from approx. 1.0 to 35.5 g/kWh.

3.2 NO_X Emissions by Tier

As introduced in section 1.5, Regulation 13 classifies all ships into Tiers by their keel-laying date with ever stricter NO_X limits applying as the ships get younger. Over time, the intent is for the varying limits to cause a significant reduction in the overall NO_X emissions with the pace of the fleet turnover. Between Tiers I and II the limit difference is ca. 8.5 % while there is a significant 80 % reduction in the limits between Tiers II and III.

Today, all three Tiers are in effect in Danish waters. However, since Tier III was only introduced in 2021, there are no observations yet of such ships in the dataset. In the below table and figures the impact of Tier on the load-adjusted emission factors are presented.

TABLE 4. Breakdown of load-adjusted NO_X emission factors by Tier.

Tier	Observations	Emission factors observed (in g/kWh)		
		Average	Minimum	Maximum
Tier 0	600	11.5	1.0	27.2
Tier I	1,192	10.7	1.2	33.5
Tier II	457	12.5	2.1	35.6

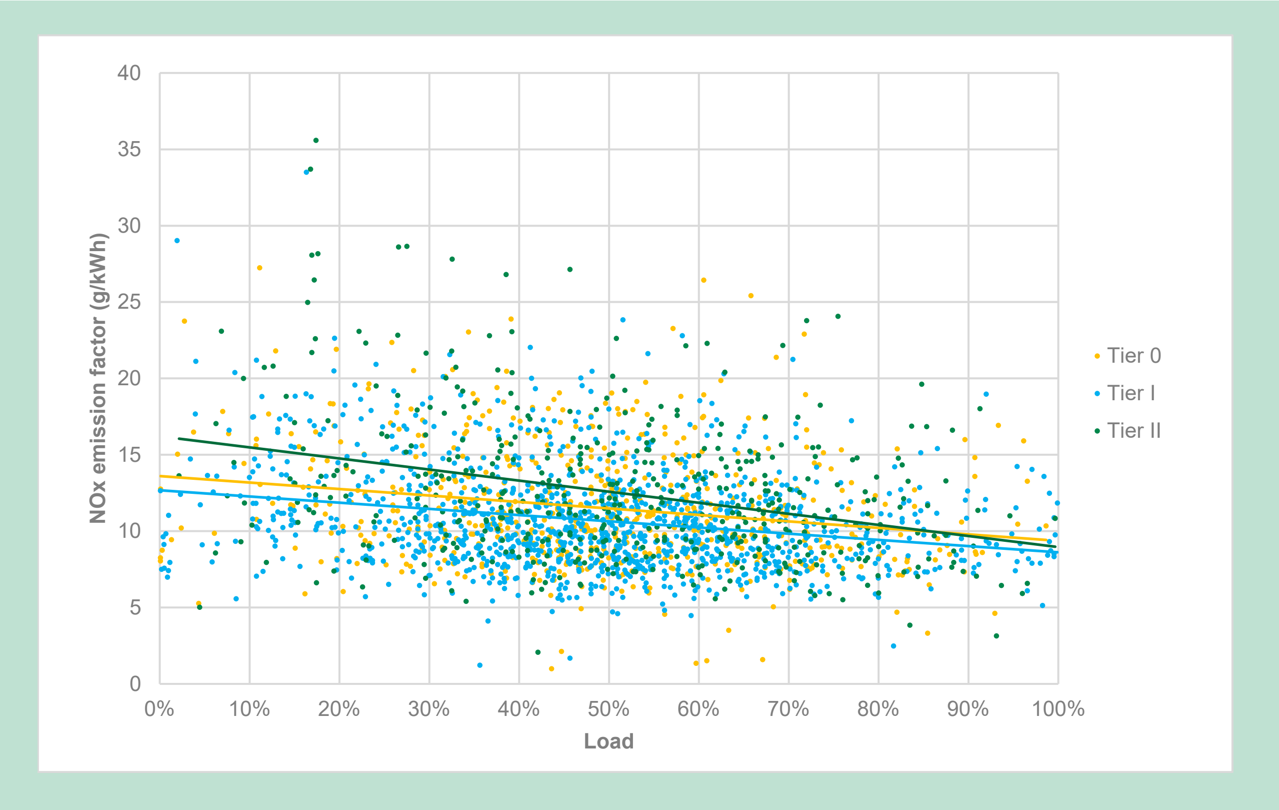

FIGURE 2. Load-adjusted NO_X emission factors by Tier (all Tiers).

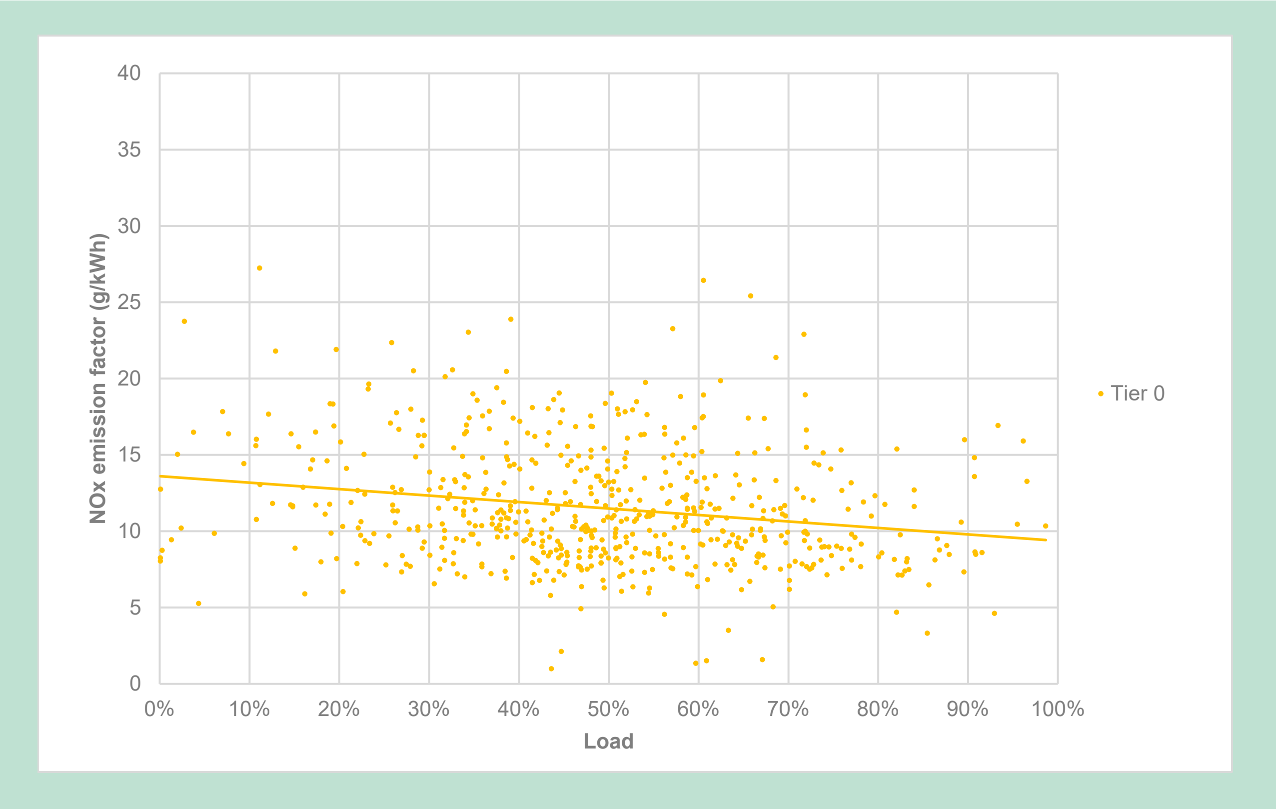

FIGURE 3. Load-adjusted NO_X emission factors by Tier (Tier 0 only).

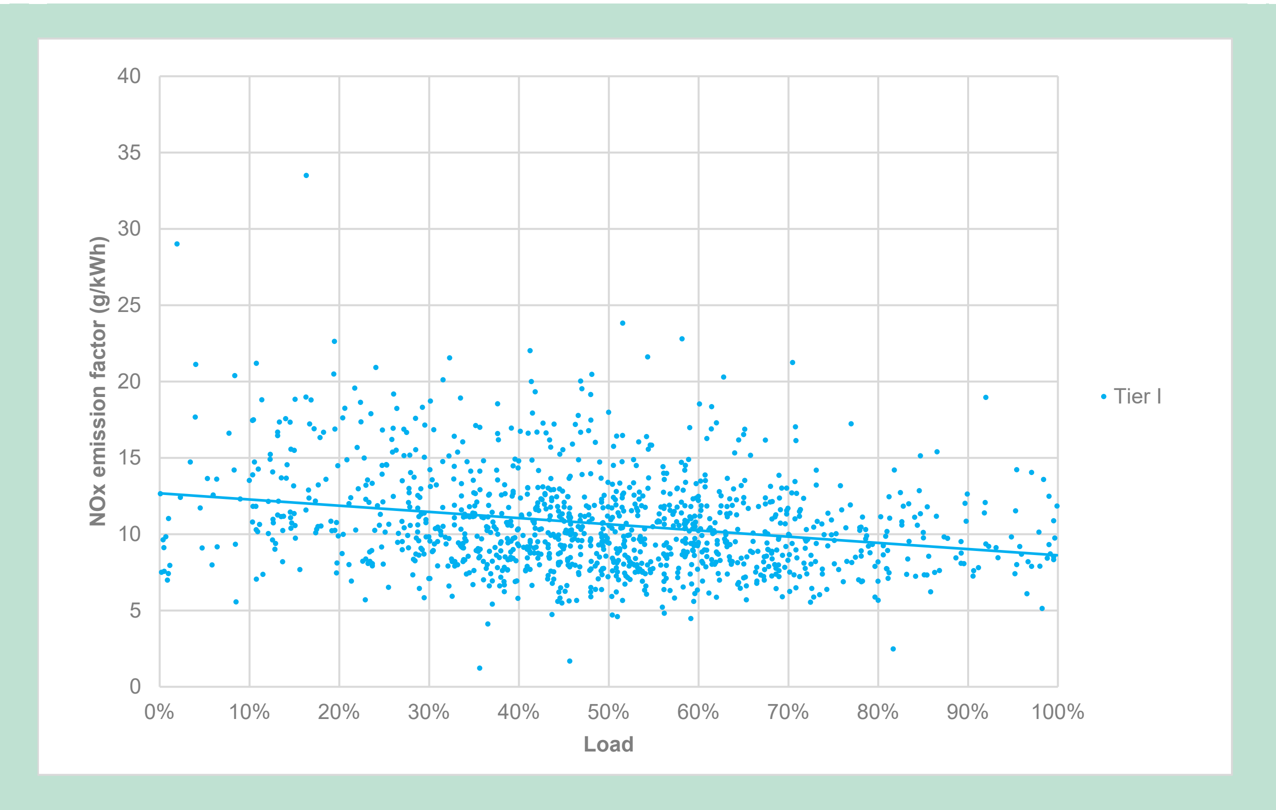

FIGURE 4. Load-adjusted NO_X emission factors by Tier (Tier I only).

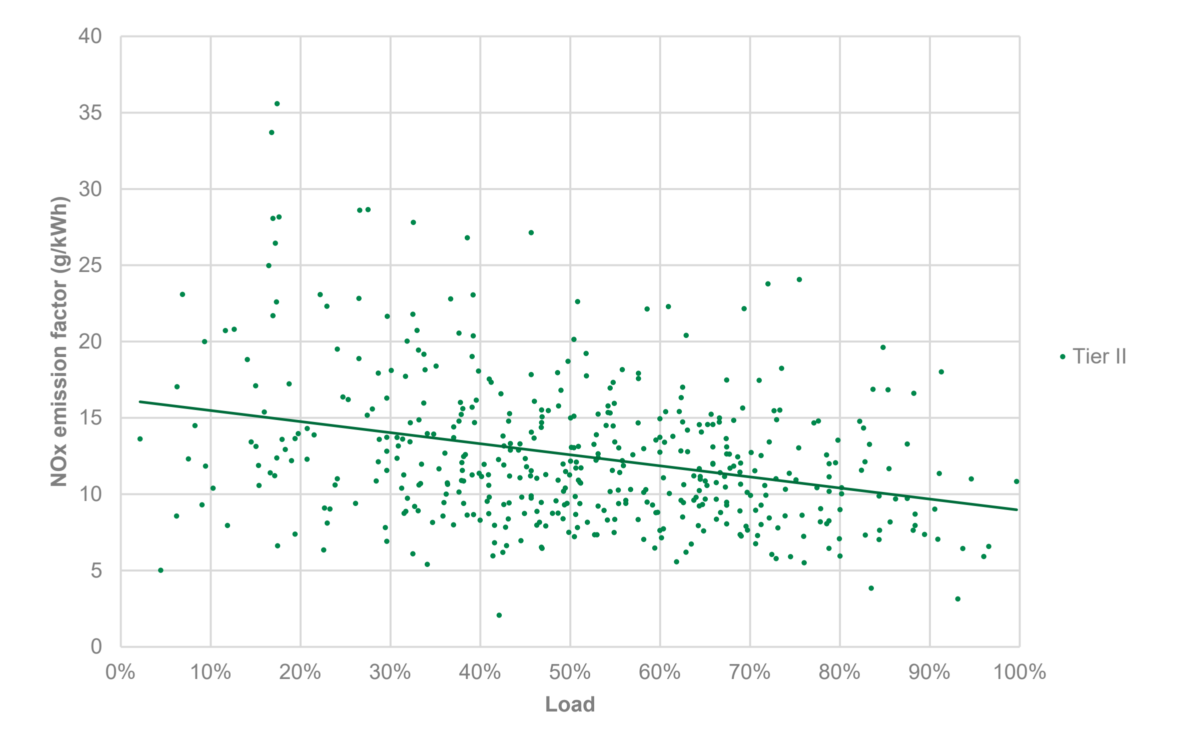

FIGURE 5. Load-adjusted NO_X emission factors by Tier (Tier II only).

Looking at the various Tier breakdowns, a few things are notable:

Firstly, age appears to have a clear impact on the average NO_X emission level. The highest NO_X emission factors are thus found in Tier II ships with an average emission factor of 12.5 g/kWh. This is 16.8 % higher than Tier I. Tier II ships also include the highest emission factors overall with a maximum value of 35.6 g/kWh. The higher average level of Tier II could in part be explained by lower engine ratings for Tier II ships (as illustrated in FIGUREs 12 and 13 in subsequent chapters) but may also involve other factors as discussed below.

Secondly, there appears to be a slight improvement in emissions from 11.5 g/kWh on average for Tier 0 to 10.7 g/kWh on average for Tier I. This finding is consistent with the intent of Regulation 13 when it was first introduced – to reduce the overall NO_X output by imposing (ever stricter) limits on younger ships.

Thirdly, however, this intent to reduce outputs appears to vanish with the Tier II ships. Here, the average NO_X emission factors are not only higher than the other Tiers; they have a steeper load profile with factors trending higher at low loads as demonstrated by the linear trendline. How much of this difference in trend that can be explained by the use of modern engine technology to optimize the individual engine NO_X curve, and what this means for the overall effectiveness of Regulation 13 and a potential compliance monitoring model, will be discussed further below and in chapter 5.

3.3 NO_X Emissions by Engine Size

When examining NO_X emission patterns, besides Tier, engine size (MCR) is another important parameter to study. The bigger the engines, the more NO_X a ship is emitting, simply because the overall engine output is higher. If the ship also has a high NO_X emission factor, even if there are only a few observations, the absolute impact from large ships can thus be significant on the environment.

In the TABLE 5 and FIGURE 6 below, a breakdown of the NO_X emission factors by MCR is presented with a focus on the largest ships:

TABLE 5. Breakdown of the load-adjusted emission factors by MCR.

MCR (kW)	**Observations**	**Emission factors observed** (g/kWh)		
		Average	**Minimum**	**Maximum**
0 – 9,999	1,637	10.8	1.0	29.0
10,000 – 19,999	452	12.1	4.8	35.6
20,000 – 29,999	82	13.8	2.1	26.4
30,000 – 39,999	36	11.9	6.4	17.8
40,000 – 49,999	17	16.4	7.6	28.6
50,000 – 59,999	11	20.1	13.0	33.7
60,000+	14	17.2	11.5	23.1

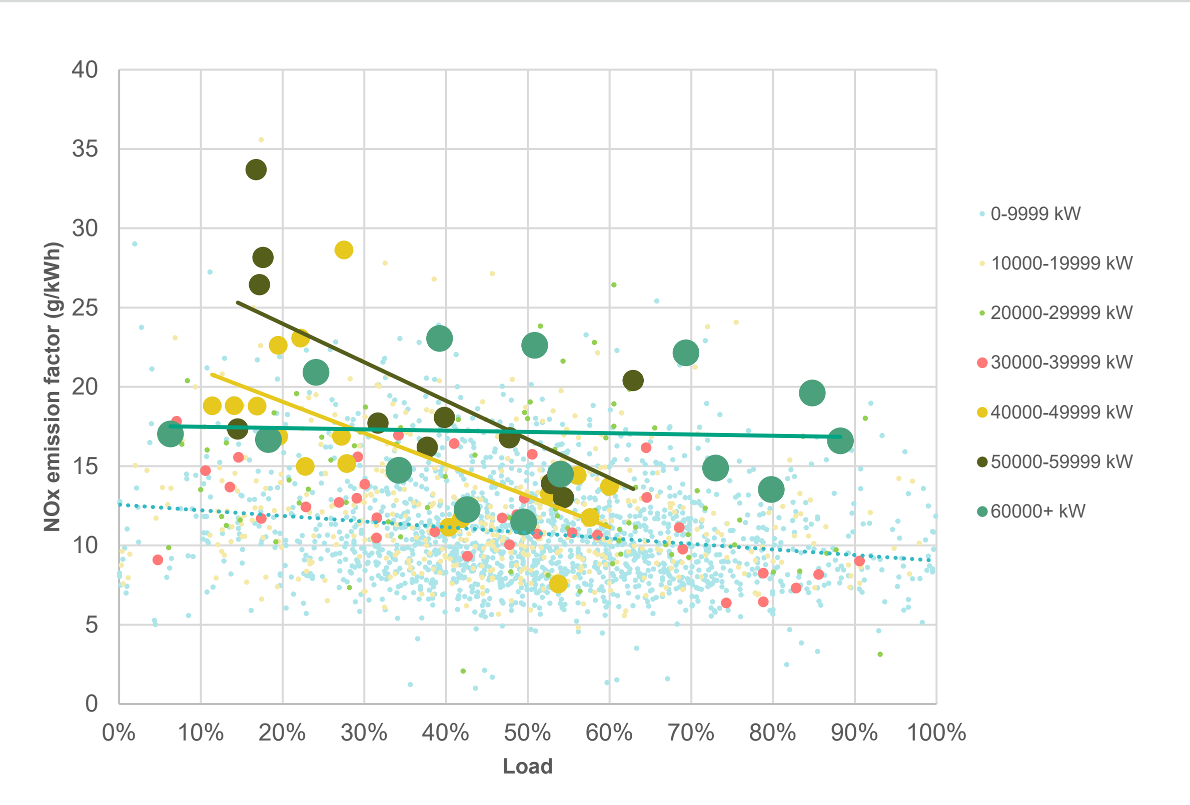

FIGURE 6. Load-adjusted NO_X emissions factors by engine size (MCR). Note, for easier reading the dotted blue trendline indicates all engines size below 30,000 kW.

As seen from the breakdown by MCR, there is a generally increasing trend in NO_X emissions with the increase in engine size, with factors peaking at 20.1 g/kWh on average for engines with an MCR of 50,000-59,999 kW, almost double the value of the smaller ships. Part of this trend may be linked to Tier with a progression towards bigger engines in younger ships. Tier 0 ships thus have an average total installed main engine power of 6,331 kW, whereas TierI ships have 9,189 kW with Tier II engines peaking at an average of 11,667 kW.

What can furthermore be discerned from the graph in FIGURE 6 is the lack of any recorded loads above 63 % for ships with engine sizes between 40,000-59,999 kW as well as a clear tendency for these ships to emit high emissions at loads below 30 %. Compared to the other engine sizes, this group also has a distinctly different trendline with sharply declining emission factors at increasing loads. Interestingly, this trend appears not to be linked to Tier as there are both Tier I and II ships represented in this group.

Conversely, mega engines with a power output of ≥60,000 kW do not display the same trend. While these ships are still observed to have above-average emission factors (at 17.2 g/kWh), the output appears to be unaffected by load. This group also includes both Tiers I and II ships.

One caveat which must be considered in this context is the relatively small sample of data on ships ≥30,000 kW. For this reason, some uncertainty must be assigned to the conclusions regarding large engines.

3.4 NO_X Emissions by Ship Type

An examination of NO_X emissions by different ship types can also help to illustrate what is happening at sea. Although conclusions can be drawn about the ship types from the analysis, it should be noted that these conclusions point mostly to an indication of engine size, which is the more significant parameter indicator of NO_X emission than what a vessel carries. As explored above, Tier class may also play a role.

The ranges and averages for each ship type are presented in TABLE 6 and the spread is displayed in FIGURE 7 below.

TABLE 6. Breakdown of the load-adjusted emission factors by ship type.

Ship Type	Observations	Emission factors observed (g/kWh)		
		Average	Minimum	Maximum
Auto Carrier	69	10.1	1.0	18.7
Bulk	421	11.4	3.8	29.0
Container	233	14.1	4.7	35.6
General Cargo	657	10.2	2.1	27.2
Other	13	9.4	2.1	16.9
Passenger	134	12.6	6.4	22.6
Reefer	45	12.4	5.8	20.7
Tanker	677	11.1	1.2	27.1

FIGURE 7. Load-adjusted NO_X emissions factors by Ship Type.

Note, only trendlines for the two highest average emitting ship types (containers and passenger ships) and the two lowest average emitting ships (tankers and general cargo) have been added.

3.5 Use of Abatement Technologies

Unfortunately, the IHS data available to this study does not provide information on the installation of any abatement systems onboard vessels and so we cannot see, if any of such systems have historically had an impact. The use of SCRs etc. would in any case have been voluntary given that no such technologies are necessary to comply with Tier I or II (and Tier III has had no impact yet in Baltic Sea and North Sea NECA).

However, it would appear from FIGURE 2 that a small sample of vessels have low enough emission factors to indicate the possible use of abatement techniques, but they are very few and cannot be confirmed. Further analysis of the use of NO_X cleaning technologies would require access to other data sources.

3.6 Implications of the RSE Data Analysis

From the RSE analysis some immediate implications can be drawn:

Firstly, as the data in FIGURE 2 shows, there is a substantial spread in NO_X emission factors across the fleet reflecting the variability associated with NO_X emissions. NO_X is dynamic by nature which poses the first challenge to enforcement efforts.

Secondly, as was observed in section 3.2, there is a clear difference in the NO_X emission patterns between the various Tiers. While Tier I appears to be a simple downward improvement over Tier 0, Tier II is distinctly different. Not only does it appear to be associated with a generally higher average NO_X emission factor; there also appears to be an overrepresentation of high values at low loads compared to the other Tiers and a distinctly steeper decreasing linear progression in factors from low to high loads. Jointly, this causes Tier II to perform worse than the other Tiers overall. As discussed later in chapter 4.3, one possible explanation behind these differences could be the weighting scheme in the NO_X Technical Code but also de-rating may play a role.

Thirdly, it is clear from the data that the operational mode of the engine affects the output. Regardless of Tier, the lower the load the higher the average emission factors and the bigger the spread, with the most significant differences recorded below 25 % load. This too can be important in an enforcement context since the NO_X Technical Code does not provide any guidance on how to interpret compliance at load points below 25 % (see chapter 4.3 for further discussion).

Fourthly, the significant number of high emissions at low loads highlights the potential negative consequences of a combination of slow steaming and fuel optimization inside the NECA. As the ships rightfully try to limit their consumption to save on costs and reduce their CO_2 footprint, the adverse effect may be an increase in NO_X emissions. With 11.7 % of all ships in the dataset assessed to be run below 25 % load, this effect is not negligible.

Finally, as can be drawn from the graph in FIGURE 6, engine size also appears to matter, with engines between 40,000-60,000 kW operating principally below 60 % with a much sharper tilted linear trend than any of the other sizes. Why this particular size range stands out is unclear.

4. Enforcing Regulation 13

This chapter explores options and challenges for enforcing Regulation 13 at sea using existing methods of surveillance of ship exhaust plumes currently applied by DEPA.

As described in chapter 2, NO_X emissions are a result primarily of engine design and operation and to a lesser extent fuel choice. It is uniquely dynamic and deviates from other pollutants such as sulphur and CO_2 by not being linked solely to the fuel. Instead, its formation depends predominantly on the specific sailing and engine conditions. For this reason, it also presents a unique monitoring challenge since NO_X emission levels cannot be retroactively verified. They exist only in the 'now'.

If one wants to know whether a ship complies with a certain NO_X emission level, it is necessary to either measure it in real time or test the engine under controlled conditions to understand its performance in different operating scenarios. The current Regulation 13 relies heavily on the latter by requiring all diesel engines to be tested and certified according to the NO_X Technical Code 2008[5]. Once verified in testbed, the engine is equipped with an Engine International Air Pollution Prevention (EIAPP) Certificate. This certificate documents the engine's compliance with Regulation 13 and will only need to be updated in case the engine undergoes a major conversion.

Regulation 13 implicitly assumes (a) that the current test regime set out in the NO_X Technical Code adequately reflects the actual life cycle emissions at sea and (b) that emissions are unaffected by deteriorating engine performance over time. Both assumptions have been proven to be weak in multiple studies (Winnes, et al., 2019), however, there are no alternative methods of compliance verification currently prescribed by the IMO.

To explore how Regulation 13 can be monitored and potentially enforced via at-sea surveillance, it is therefore important to understand how the current testbed regime works and how it may extend (or not) to emissions sampled under operational conditions.

4.1 The NO_X Limits and the E3 Test Cycle

As presented in section 1.5, according to Regulation 13 ships are classified according to their keel-laying date into three Tiers. Each Tier has its own permitted 'NO_X limit' expressed as a curve with varying values depending on the engine rating of the ship. In general, the lower the engine rating, the higher the permitted NO_X level.

While the actual formulas for establishing the NO_X limits at different engine ratings can be found in section 1.3, FIGURE 8 illustrates the same in graph form:

[5] Resolution MEPC.177(58) as amended by resolution MEPC.251.(66).

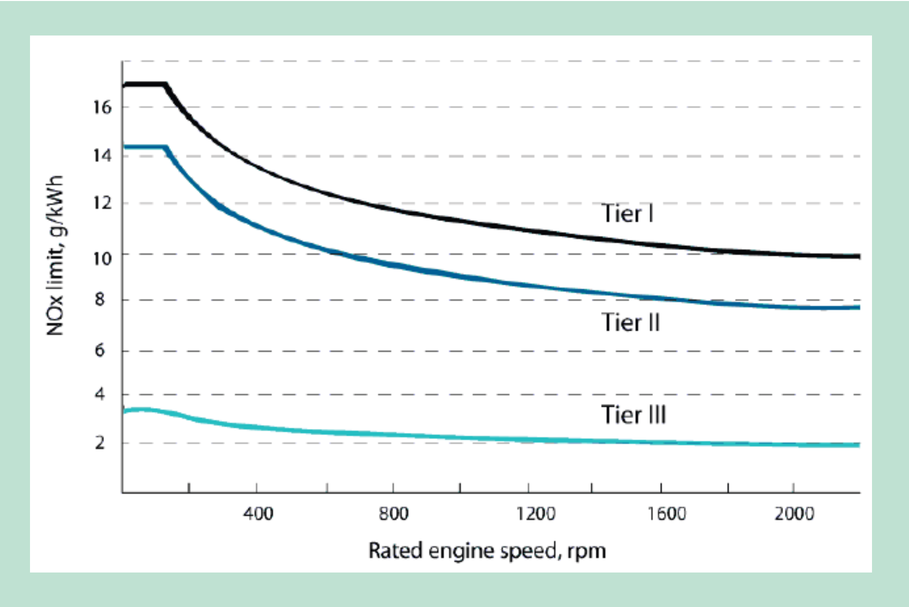

FIGURE 8. NO_X limits by Tier according to Regulation 13.

As can be seen from FIGURE 8, there is approx. 40-45 % difference between the highest and the lowest point on any NO_X Tier curve, meaning ships with a low engine rating have a considerable 'advantage' over ships with high engine ratings in the amount of NO_X, they are allowed to emit.

The Tier curves express a total weighted cycle emission limit, not a max value. Engines are tested at different load points (= power settings), the weighted average of which must not exceed the applicable Tier limit. In other words, so long as the consolidated emission result of the full test cycle is below the limit, the individual load value(s) can be higher. Only for Tier III does the NO_X Technical Code apply a not-to-exceed (NTE) limit of 50 % above the applicable weighted NO_X emissions limit for any of the individual load points in the main engine test cycle (Regulation 13, 3.1.4).

The main test cycle designed to verify emissions performance at sea is known as E3 (Regulation 13, section 3.2.4). It applies to propeller law operated main and auxiliary engines and tests NO_X emission levels at four engine load points: 25, 50, 75 and 100 % load. It further applies weighting factors to each load point from 0.15 to 0.5. The E3 cycle is presented in TABLE 7.

TABLE 7. Test cycle type E3 as presented in Table 2, section 3.2 of the NO_X Technical Code.

Test E3	Settings and factors			
Speed	63 %	80 %	91 %	100 %
Load point (power)	25 %	50 %	75 %	100 %
Weighting factor	0.15	0.15	0.50	0.20

The intent of the weighting scheme is to capture the life-cycle operation of a ship engine, albeit under testbed conditions. It does not take area of operation into consideration and, as seen in TABLE 7, it puts emphasis on high loads.

The E3 test cycle implicitly assumes that any engine will spend half its life at 75 % load (close to the service speed, it was designed for), and a combined 70 % of the time at or above 75 % load. The weighted factors are also designed to recognize the expected higher outputs of NO_X

at low loads when the engines are running below their service speed. How well these assumptions match real-life and the consequences they have for the NO_X emissions inside the NECA is further discussed below.

In FIGURE 9 is an example of how the weighted E3 test cycle can translate into different load-dependent NO_X curves for a compliant Tier I ship with an engine rating below 130 RPM. Here, the weighted total cycle emissions value is 17 g/kWh in all four cases (ship D represents the weighted limit. Here all four loads are set at 17 g/kWh).

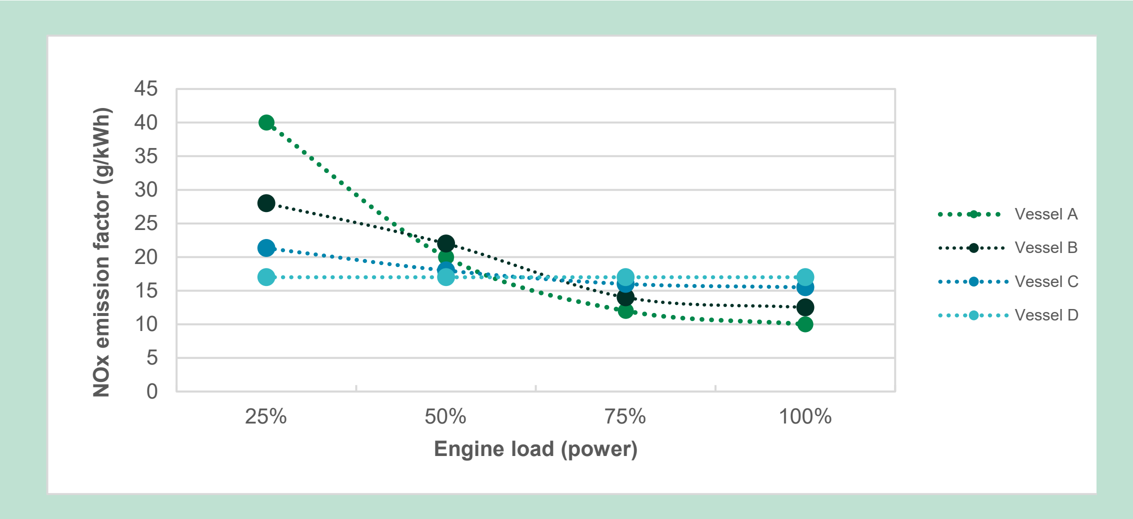

FIGURE 9. Examples of different load-dependent NO_X curves as applicable to a compliant Tier I ship under the E3 test cycle.

As illustrated, particularly the 25 % load point can sustain high levels of NO_X emission without compromising the overall compliance of the engine. Furthermore, note how only small adjustments to the 75 % and 100 % load points can facilitate a large spread in emissions at the 25 % load point without affecting the weighted compliance value.

This is an important observation with implications for the NECA and any potential options for at-sea compliance monitoring.

Firstly, it allows ships to optimize their fuel consumption considerably at low loads without compromising compliance, and from the data presented in chapter 3 this appears to be happening. In fact, it would appear from the findings in chapter 3 that there is a lot of operational activity at lower loads (below 50 %), particularly in younger vessels, driving higher NO_X emission factors inside the NECA.

If this observation is universally true, it is not only a problem in Danish waters but everywhere speeds are reduced which is typically in near-coastal areas where traffic density and the risk of various collisions are highest. This study thus appears to confirm one of the concerns related to the real-world implications of the life-cycle assumption behind the weighting scheme in the NO_X Technical Code; that it may inadvertently incentivize ships to lower their NO_X emissions in the high seas while driving up emissions in areas where the risk of NO_X to humans and ecosystems is higher.

Secondly, it raises questions about how to handle low loads when monitoring for compliance, particularly at load points ≤25 % where there are no limits. (0-25 % load is effectively a legislative ‘grey zone’).

Thirdly, Regulation 13 is in fact effectively silent on the issue of compliance on any other load point than the four included in the test cycle(s) opening a legal void which may be exploited to further optimize engines in the search for additional fuel savings or (at least in principle) for national or regional authority actors to 'interpret the space' in between load points.

4.2 Use of Test Fuel Oils

When engines are tested, the NO_X Technical Code specifies that the selection of fuel oil for testing must *"fit the purpose of the test"* (chapter 5, section 5.3.2). However, there are no requirements that engines are tested on the actual fuels the ship will eventually use. In fact, where reference fuel oils are not available, the NO_X Technical Code recommends the use of distillates (DM-grade marine fuel as specified in ISO 8217:2005) over fuel oils. Distillates are distinctly different from the LSFO, ULSFO and HSFO fuel oil products most often used in operation, particularly by ocean-going vessels, in that they contain hardly any nitrogen. This may lead to differences in NO_X emissions between testbed and real-life operations (IMO, 2008).

As explained in section2.1, fuel characteristics can influence NO_X formation through the increased presence of organic nitrogen (N_2). This means there is a risk of a discrepancy in the emissions between the test regime and real-life in cases where the test fuel differs from the operational fuel which cannot subsequently be easily verified, even if this difference may be minor.

4.3 Implications of the NO_X Technical Code on the Enforcement of Regulation 13 at Sea

From the descriptions above, there are several implications involved in trying to apply the principles of Regulation 13 and the NO_X Technical Code in a real sailing environment. Most notably are the following conditions and challenges essential to a potential compliance monitoring strategy outside testbed:

1. **Tier class:** Observations must take ship Tier class into account. Tier class is not currently part of the AIS data stream and must therefore be sourced elsewhere.

2. **Engine rating:** Observations should ideally take ship engine rating into account. Without it the individual observations cannot be related to the correct limit value on the applicable NO_X Tier curve. Engine rating is not currently part of the AIS data stream and must therefore be sourced elsewhere, or the monitoring can take a max approach applying only the max NO_X limit for each Tier to all ships (i.e., 17 g/kWh for all Tier I ships etc.) to ensure no one is falsely targeted. The latter approach of course also carries the converse risk of letting some ships with higher engine ratings 'off the hook'.

3. **Loads:** Observations should ideally take into consideration the load of the ship at the time of monitoring. Especially at low loads (≤ 25 % load) there is a risk of flagging ships for potential non-compliance when in fact they may be perfectly within their weighted limit as illustrated in FIGURE 6. It is also worth noting, that the NO_X Technical Code doesn't stipulate anything about compliance in between the load points in the test cycle. How to address compliance at any other load point than the four specified in E3 is thus an open question. On the other hand, the lack of direction in the NO_X Technical Code concerning these other load points can also provide an opening for national interpretation.

4. **Fuels:** Not knowing the test fuel oil used to certify the engine or the fuel the ship is operating on also presents a challenge to any at-sea compliance monitoring scheme. This is not data that can be attained from any other source and the uncertainty can only be overcome by designing wide enough compliance margins to mitigate the issue. How wide is also an open question.

In general, the real test to the applicability of any compliance monitoring scheme outside testbed will come when measurements are weighed by the court system. In this context, the heavy burden of proof lies with the authorities who must prove that a given measured NO_X emission factor documented at sea – far away from testbed – does in fact constitute a violation of Regulation 13. This is a heavy burden to lift given the structure of the current regulation.

For this reason, it is difficult to see that any at-sea compliance monitoring scheme can be legally successful as anything but a *targeting mechanism* similar to the current screening done for sulphur emissions.

The at-sea emissions surveillance today is based on a simple spot check approach: Ships are checked regularly at various locations throughout Danish waters through a single gas sample of their exhaust plumes against a compliance threshold, without preference towards the operational mode of the vessel. This contrasts with the approach prescribed in the NO_X Technical Code where compliance is validated through multiple gas samples at several specific operational modes against a consolidated weighted average. If possible, guidelines from IMO would be helpful in order to manage the difference between the two methods. Only in the case of Tier III is it possible that the 50 % NTE limit may be reasonably transferred to an RSE scheme as direct evidence but even this comes with some legal uncertainty.

However, even if a practical enforcement response is limited to a targeting regime, such a scheme can still provide an effective way to identify NO_X outliers that can subsequently be followed up by other Port State Control actions. It also does not in any way diminish the value of RSE data as a means to (a) track impacts from NO_X ship emissions on the environment and (b) enable the continued evaluation of the general effectiveness of the NO_X regulation.

5. Monitoring NO_X Compliance at Sea, Two Models

On the assumption that the current surveillance of ship emissions in Danish waters was extended to include compliance monitoring of NO_X emissions, this chapter explores two models for how NO_X outliers could be identified.

As assessed in chapter 4, the current structure of the NO_X regulation and Technical Code only supports a targeting model. In such a model, the object is not to document direct violations but to identify outliers the emission patterns of which fall sufficiently far from the compliance thresholds, given their operational mode, to merit further investigation.

Two such possible models are presented here and tested against the RSE data:

(a) A **base model** in which the surveillance simply targets any ship with a NO_X emission factor 50 % above the highest point on the applicable Tier curve.

(b) An **advanced model** in which the surveillance targets those ships with NO_X emission factors 50 % above the permitted Tier limit applicable to the specific engine rating of the ship, except in cases where the ship is assessed to operate ≤ 25 % load.

In both cases, the model relies on the basic NO_X/CO_2 ratio measured in the ship exhaust plume to establish an individual NO_X emission factor (equation 1, section 1.3.1) corrected as well for fuel efficiency to express the result relative to the power consumption (g/kWh). The fuel efficiency at the time of monitoring can either be verified by direct contact with the vessel itself or by engine data calculations as presented in equation 2 (1.3.2). Either way, both models are dependent on third-party data sources to confirm Tier class and engine parameters.

The 50 % limit is inspired by the NTE level applicable to Tier III and thus grounded in the existing regulation. However, this limit is used purely as an illustration here to demonstrate how the two compliance monitoring models behave when applied to the RSE data. Arguments could be made for both a higher and a lower flagging threshold.

Note, a variant of the base model has recently been developed by the Royal Belgian Institute of Natural Science (MUMM) and implemented as part of the Belgian airborne surveillance programme for ship emissions. The Belgian model incorporates more details and protocols than the base model presented here.

5.1 Base Compliance Monitoring Model

As the data shows, the basic technology and capability to monitor NO_X is already in place. In the most basic of cases, the ideal scenario for compliance monitoring would be to simply leverage the existing infrastructure and methodology without adding too much more to it. This would make the monitoring of NO_X emissions as cost-efficient as possible.

In the *base model*, the calculation of the individual emission factors is done using only the ratio formula (equation 1, section 1.3.1) with the SFC value initially replaced by a generic 185 g/kWh value (average of all data) and subsequently verified via (a) direct radio communication with the ship or (b) via the methodology described in 1.3.2.

To identify outliers, the base model would apply a 50 % NTE limit above the highest point on each Tier curve (17 g/kWh and 14.4 g/kWh respectively for Tiers I and II) over which a vessel would be flagged for potential non-compliance.

In FIGURE 10 and FIGURE 11 below, the base model is applied to the two Tiers as described above with red dots indicating potential non-compliance:

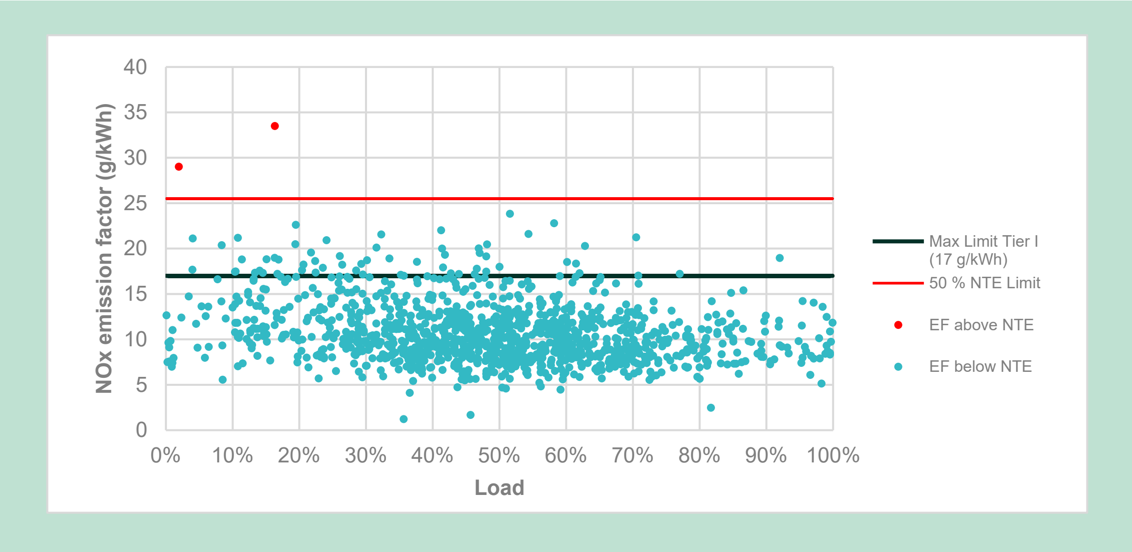

FIGURE 10. Base model applied to Tier I (NTE = 50 % above 17 g/kWh = 25.5 g/kWh).

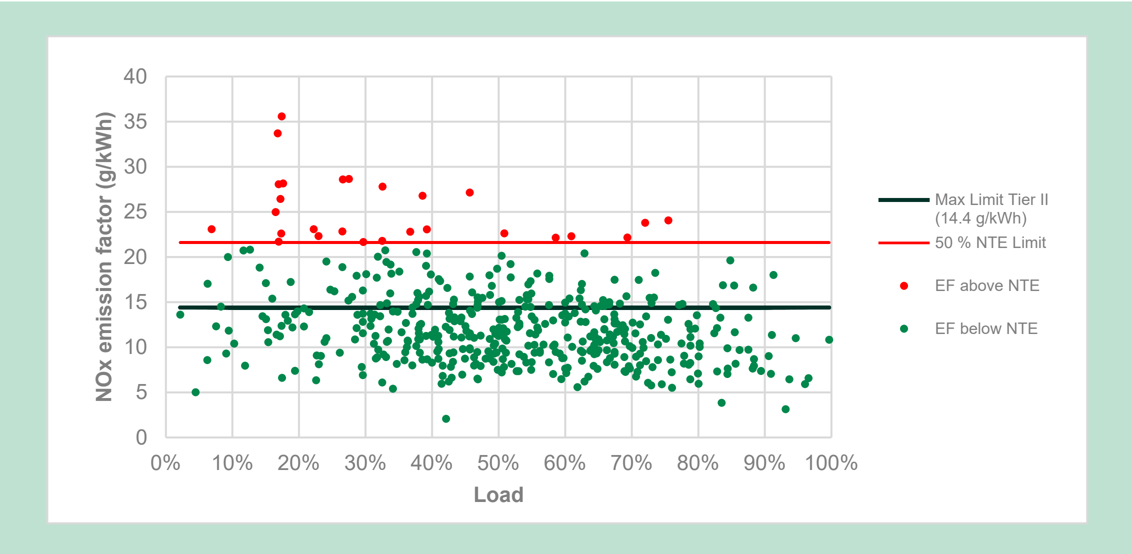

FIGURE 11. Base model applied to Tier II (NTE = 50 % above 14.4 g/kWH = 21.6 g/kWh).

In an applied scenario only 2 Tier I ships would have been flagged (0.2 % of the total) versus 27 Tier II ships (5.9 % of the total). This corresponds to the findings in section 3.2 where Tier II was found to have the highest average NO_X emission factor despite the stricter NO_X limits for these younger ships.

5.2 Impact of Engine Rating on the Base Model

As described, the base model does not take engine rating into account. This is to keep the model as operational as possible since engine rating is not a readily available data point. However, not taking engine power into account creates the risk that ships with an engine power of more than 130 RPM will not be appropriately flagged as potentially non-compliant.

The effect of a potential negative bias towards low-rated engines is illustrated in FIGURE 12 and FIGURE 13 where the base model has been applied as before but with the data and NO_X curve limits sorted according to engine rating:

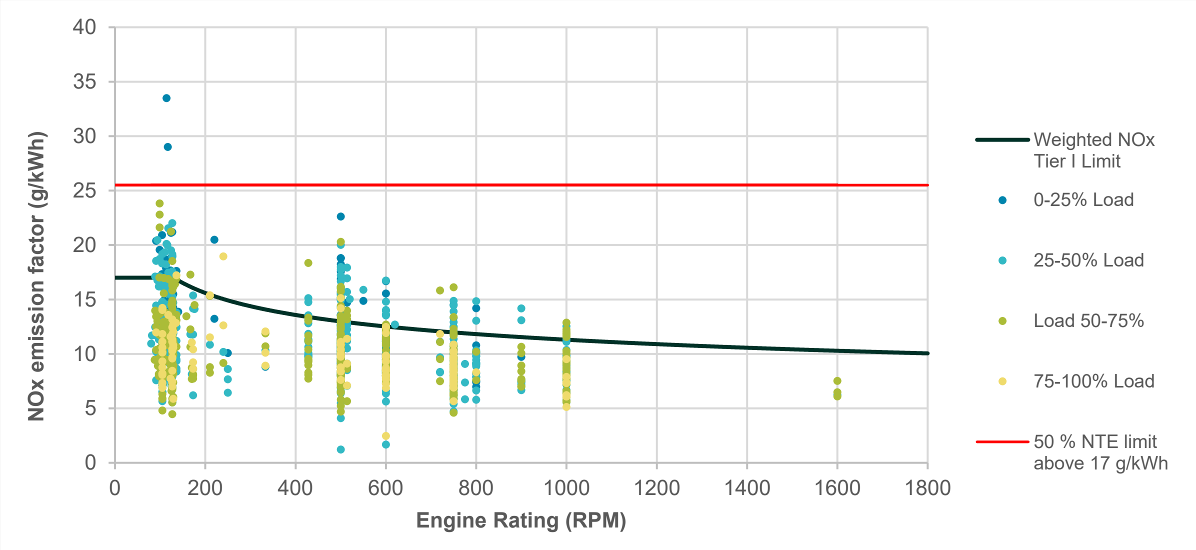

FIGURE 12. Base model applied to Tier I, sorted by ship engine rating.

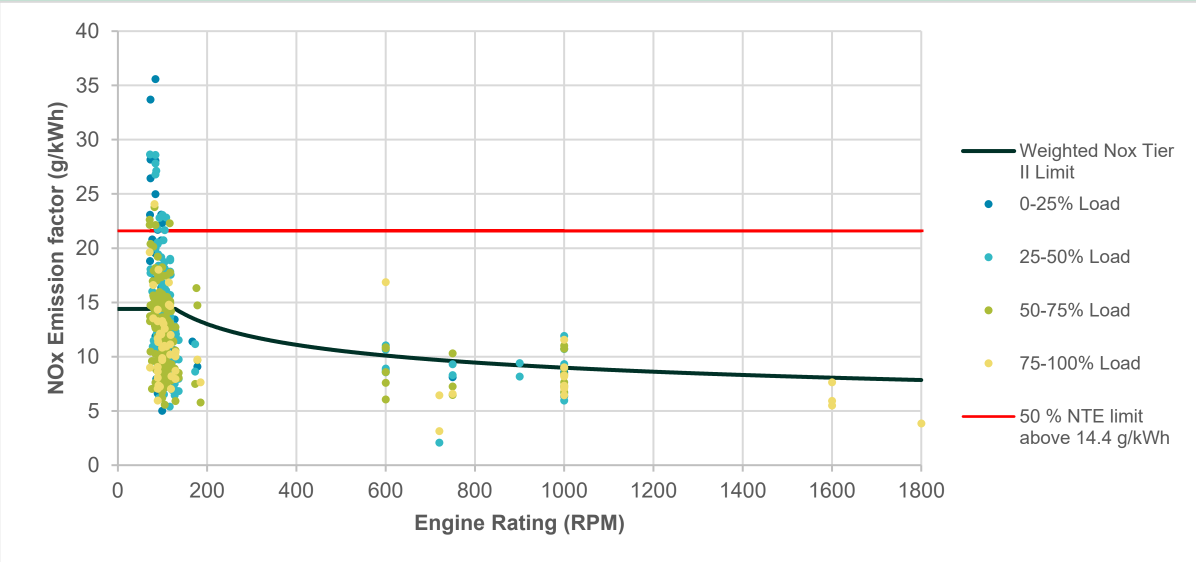

FIGURE 13. Base model applied to Tier II, sorted by ship engine rating.

As marked in FIGURE 12, the base model effectively allows a 96 % exceedance for ships with a rated engine speed of 500 RPM. However, it also appears that the bias is mostly a problem for Tier I given the relative absence of ships rated above 130 RPM for Tier II.

From the figures above the impact of load is also starting to show. With a few exceptions, almost all observations above the NTE limits are associated with loads below 50 % (blue dots) which is the main weakness of the base model.

Recalling the example in FIGURE 9 (section 4.1), high NO_X emission factors may not always be indicative of non-compliance. In some cases, they are simply a result of low engine loads. A potential advancement of the base model would thus look to incorporate a way of screening for low loads, particularly ≤ 25 %, to avoid flagging compliant ships.

5.3 Speed as an Indicator of Low Load

One of the ways to try to avoid flagging low loads could be to use (AIS) speed as an indicator of low load. This approach could be an easy screening technique which would enhance the base model.

However, as can be seen from FIGURE 14 speed is not a strong indicator of low loads. In the graph, a speed limit of 10 knots has been applied. If the aim was to avoid loads ≤ 25 % such an approach would still leave a substantial number of ships open for targeting (red box).

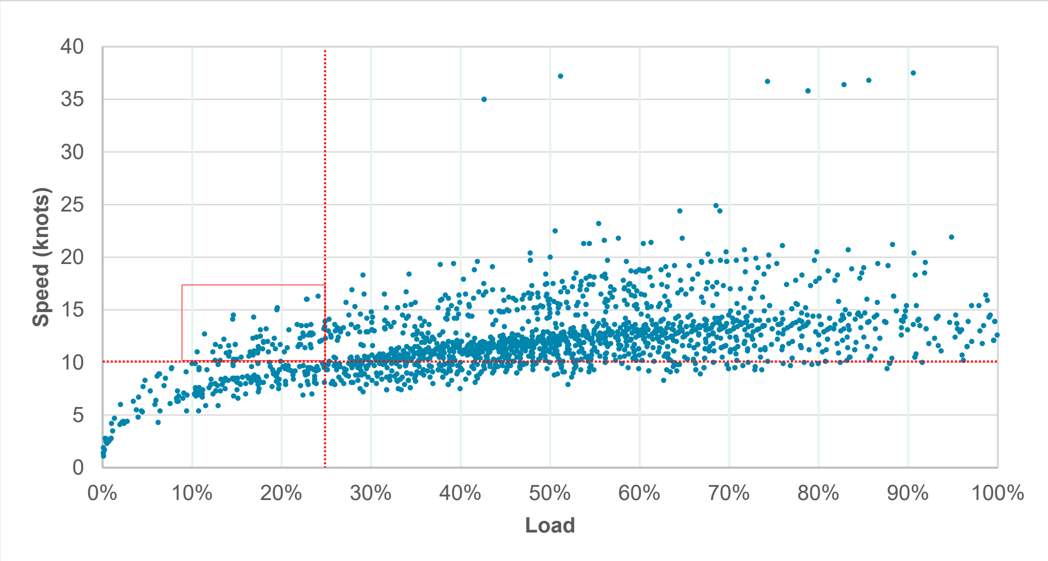

FIGURE 14. Correlation between AIS speed and estimated load.

5.4 Advanced Compliance Monitoring Model

An alternative to the base model would be the *advanced model* where both the engine rating and the low load issue it considered. In this model the same data is used as in the base model but with additional information on engine rating and engine max speed incorporated.

In the advanced model, the objective is to ensure that compliance it evaluated against the correct individual threshold for each ship (no bias) and that ≤ 25 % loads are filtered out to avoid flagging ships with high emission factors caused by low loads.

In FIGURE 15 the advanced model is applied to both Tiers. The baseline (zero) represents the weighted NO_X emission factor (g/kWh) applicable to each ship under Regulation 13. The percentage difference (y-axis) expresses the ratio between the measured NO_X emission factor and the weighted factor. Similar to the base model, a 50 % NTE has been applied but only to estimated loads above 25 %. Potential non-compliance is indicated by dots with red outlines.

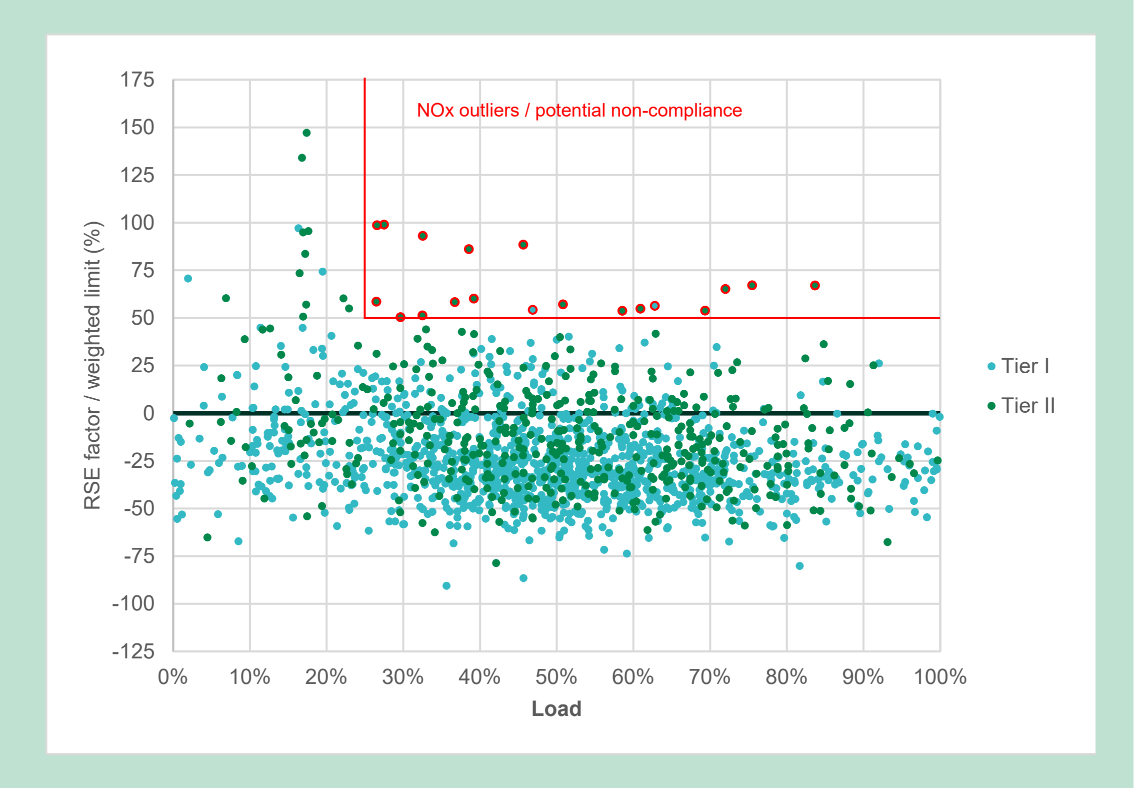

FIGURE 15. Advanced model applied.

When applied the advanced model identifies 19 NO_X outliers (red box) – two Tier I ships and 17 Tier II ships. 3 of these were ships not flagged by the base model. The net total result is 10 ships fewer than the simple model. The principal difference lies in the low loads.

In FIGURE 16 the difference is compared. Here the results from the base model are marked according to their position in the advanced model (red circles). As can be seen, 11 ships fall outside the red 'outlier box' because of their loads while the advanced model flags three ships (orange circles) as potential non-compliant that the base model did not identify because of their higher engine rating.

FIGURE 16. Advanced model and base model compared. Red outlined dots indicate non-compliance according to the base model, whereas only dots inside the red box indicate non-compliance according to the advanced model. The three dots with a yellow outline indicate cases only identified by the advanced model.

5.5 Strengths and Weaknesses of the Models

While the advanced model is a closer reflection of the NO_X Technical Code it also has weaknesses, principally in its dependence on additional engine data points that are difficult to source and of potential poor quality. When compiling data for the RSE analysis, more than half the ships were missing information on max speed, which subsequently had to be gap filled to complete the analysis. Several ships were also missing engine ratings and thus had to be excluded. This is okay for a broader fleet analysis and to identify trends but is highly problematic when evaluating individual compliance.

The high level of data dependency is in general a weakness. In both models, the compliance evaluation is highly dependent on third-party sources and data the quality of which is hard to verify. As highlighted already in section 4.3, there is not much support to be found in the current AIS stream. If the AIS protocol were to be expanded to support remote NO_X compliance verification, the following minimum data points would need to be added:

- **Keel laying date**, to determine Tier class
- **Engine rating**, to determine the applicable weighted compliance value.
- **Specific fuel consumption**, to express the NOX emission relative to the power output
- **Engine load**, to adjust for the impacts of low loads to the extent a load-dependent scheme is applied to RSE conditions.

The first two data points should be simple enough to add. The last two points would require older vessels to installation fuel flow meters and additional engine reporting features, something which may be burdensome for some ships.

Regardless, either model cannot stand alone but must be supported by other measures to follow-up on ships with reportedly elevated NO_X emission factors. The NO_X Technical Code currently provides for three methods for onboard NO_X verification by Port State Control or others accredited inspectors (Regulation 13, section 2.4.3) (IMO, 2008):

- Engine Parameter Checks to verify that an engine's component, setting and operating values have not deviated from the specifications of the engine's Technical File;
- Simplified onboard measurements according to section 6.3; or
- Direct measurement and monitoring in accordance with 6.4.

6. Perspectives

As a matter of final reflection, this study has described a potential pathway to operational enforcement of Regulation 13 but also exposed key weaknesses in the existing regulation that may dilute its NO_X reduction potential where it matters most – close to shore and densely populated areas.

By emphasizing higher engine loads, the NO_x weighting scheme may inadvertently expose humans and ecosystems to higher NO_X emissions from shipping than intended. The distinctly different emission profile for Tier II vessels, the trend towards ever bigger engines and ships, and the prevalence of slow steaming and low-load operations in NECAs are all observations that point to this, raising the question if the weights could be more effectively applied?

In addition, with the increased ability for modern engine technologies to 'tailor' their load curves, the space between the four main load points could conceivably be exploited. This is particularly true for any operations below > 25 % load and may help explain why we see a large spread in NO_X emission factors at low loads. This is also where the empirical data suggests a different reality than what was originally assumed.

When the atmospheric impact models were made that informed the decisions to implement Tiers I, II and III respectively, the assumption was that the real-life emission patterns would follow the NO_X Tier curves as prescribed by Regulation 13. Non-compliance was not accounted for, nor was the response from industry to try and mitigate the cost effects of the regulation through derating, early keel-laying, engine load optimization, etc.

The RSE data thus raise concerns that the model assumptions may not hold true. Instead, the regulation may unintentionally incentivize behaviours which lead to higher NO_X emissions, particularly in coastal areas. The consequence of this is two-fold:

1) That the current atmospheric models may be underestimating the NO_X contribution from shipping; but also
2) that the future projected reduction value may be overstated, particularly as we look to harvesting the benefits of Tier III and multiple NECAs.

As illustrated in this study, the complex nature of the NO_X testing regime is a fundamental challenge to enforcement. It was never designed to be verified independently, in real sailing conditions, or in designated zones, making the structure of the NO_X Technical Code the Achilles heel of Regulation 13. The limited ability to translate the methodology to real-world conditions hampers efforts to document and ensure compliance inside the NECA. This observation has been made before, most recently by the EU-funded SCIPPER research project in its study of gaps in current maritime emission enforcement regulations and their impacts on real-world emissions (Winnes, et al., 2019).

With the introduction of Tier III and yet another NECA, there is a growing need for further guidance from the IMO/MEPC on how to build a credible bridge between testbed and operational compliance on NO_X. In particular, we need to understand how the NO_X limits should be interpreted in a real-world scenario? Can we transfer the cycle concepts from the NO_X Technical Code, or do we need to develop a separate set of compliance guidelines for real sailing conditions?

We know from road transport that there can be a significant discrepancy between emissions measured in testbed and under real-operational conditions, not just because of nefarious software but because testbed tends to only capture a sliver of the actual stress and wear an engine can experience. There are multiple factors that impact engine operations and thus NO_X formation at sea that testbeds cannot mimic with the risk that the results become disconnected from reality. This is also why other transport sectors are increasingly modifying their test and certification schemes to real-world operations and emission curves that have been verified in operational environments. A similar consideration could be made for shipping.

On the positive side, the ability to measure NO_X reliably in the exhaust plume has now been proven in multiple studies and through real-world surveillance operations for several years using multiple platforms, both airborne and stationary. The simple ratio of NO_X/CO_2 is a reliable methodology for expressing NO_X impacts relative to the overall emissions output used in many other emissions monitoring contexts.

As proven here, when applied right, guiding NTE limits may also function relatively effectively as a screening technique to alert authorities to potential issues with compliance. What happens after a ship is flagged, is then a matter of follow-up strategy which may ultimately culminate in a need for the ship to undergo recertification. Exactly how that might play out, is another area for further investigation, beyond the scope of this project.

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NOx Emissions from Ships in Danish Waters - Assessment of Current Emission Levels and Potential Enforcement Models

Resume
Denne rapport er udarbejdet af Explicit ApS på vegne af Miljøstyrelsen. På baggrund af en analyse af faktiske udledningsdata fra mere end 2.200 luftprøver indsamlet fra skibe i dansk farvand over en fireårig periode fremsættes en vurdering af de nuværende udledningsniveauer af NOX set i lyset af den gældende NOx-regulering på skibsområdet. Rapporten finder, at der på flere områder er en manglende overensstemmelse imellem intentionerne i NOX-reguleringen og de faktiske udledningsniveauer til søs. Dette gælder særligt for Tier II-skibe. Herudover identificerer rapporten flere udfordringer med håndhævelse af den gældende NOX-lovgivning til søs. Endelig udforsker rapporten to mulige modeller for håndhævelse af det europæiske NECA-område ved brug af de samme overvågningsteknikker som i dag bruges til svovlovervågning til søs inklusive en vurdering af modellernes styrker og svagheder.

Abstract
This report has been prepared by Explicit ApS on behalf of the Danish Environmental Protection Agency. The report presents an assessment of NOX emission levels from ships in Danish waters considering the current NOX regulation for shipping. The report finds several instances where the intentions of the NOX regulation do not align with the actual real sailing emissions at sea. This is particularly prevalent for Tier II ships. The report further identifies several challenges with enforcing the existing NOX regulation at sea. Finally, the report explores two possible models for enforcement of the NECA using the same at-sea surveillance techniques currently used for sulphur emissions monitoring, including an assessment of strengths and weaknesses of the models.

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