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TNO report

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Measurements of emission factors of nitrogen oxides of seagoing vessels in the port of Rotterdam

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Summary

In order to improve air quality and to lower nitrogen deposition, nitrogen oxide emissions from vessel engines must respect certain Tier norms to obtain the required Engine International Air Pollution Prevention (EIAPP) certificate for sailing. In this study emissions factors of nitrogen oxides (NO_x) of vessels in the port of Rotterdam region were determined, using a so-called sniffer system. Over the time period 10-10-2019 till 1-11-2021 the data of the sniffer system were taken into account in this study. The NO_x emissions in gNO_x/kg fuel, were calculated from the concentrations of nitric oxide (NO) (based on the assumption that 80% of the NO_x is NO and 20% is NO_2) and carbon dioxide (CO_2). To compare to IMO Tier norms the ships keeling date, rated engine speed and service speed have to be known. The fuel specific oil consumption (*SFOC*) is used to convert the NO_x emission in g/kg fuel to g/kWhr (the unit used in the IMO norm). In the period considered, the emission factors of 13 000 individual plumes were determined from almost 3 500 different ships. General statistics of the NOx emission (assuming a constant *SFOC*) showed that, as expected, the higher the speed over ground, the higher the NO_x emissions. The 23 vessels which passed by the station most often (we excluded dredgers and tuggers for the analysis) were analysed in more detail using a load specific *SFOC* given the speed over ground of the vessel at the time of the measurement. This analysis showed that 22 ships, using the average of the observed plume, lie within the IMO norm (when the uncertainty in the average NO_x emission is taken into account). Only one Tier I vessel seems outside the IMO norm, though direct non-compliancy monitoring is not possible since not all engine loads can be considered. The average uncertainty in the NO_x estimate of these vessels is in general low with only 4.2% on average. Taken into account the effect of the tides on load can further improve the *SFOC* estimate and thus the NOx emission estimate. On average Tier II had higher NO_x emission factors than Tier I ships. This is probably, because close to the port the power on the engine is low and Tier II engines are tuned to have low NOx emissions at high powers.

Contents

1 Introduction

In order to limit the hazards related to sulphur oxide (SO_X) and nitrogen oxide (NO_X[1]) emissions from ships, the International Maritime Organization (IMO), prepared an international agreement, adopted in 1997, known as the 1997 MARPOL Protocol, which includes the Annex VI ‘Regulations for Prevention of Air Pollution from Ships’. These regulations entered into force in 2005, after being received by appropriate laws by the signatory States (at European level it was received with the directives 1999/32/EC and 2005/33/EC) and introduces limits to marine fuel sulphur content and engine performance to reduce SO_X and NO_x. Under contract with the Dutch authorities, represented by ILT[2], TNO has been monitoring fuel sulphur content at the entry of the port of Rotterdam (Duyzer and Weststrate, 2015) continuously in the last five years. A remote monitoring method (the sniffer method) is used to determine the sulphur content. This method is based on the measurement of both sulphur (sulphur dioxide) and carbon dioxide concentrations in the ships exhaust plume as the ships passes the monitoring site. These concentrations are then used to derive the fuel sulphur content of the ship. The results of these measurements are used by ILT in the process of selecting ships that will be visited for further inspection. Fuel samples can be taken onboard by ILT as a formal step in the process of enforcement of IMO rules. The sniffer measurements make it possible to better target ships which might be non-compliant.

Emissions of nitrogen oxides (NOx) are important as well. In the Netherlands especially they play an important role in nitrogen deposition and air quality issues. International shipping is an important source for nitrogen deposition. In 2018 its contribution to nitrogen deposition was with 3% half of the contribution by road traffic[3]. In regions near the important ports this contribution is larger. Especially in these regions the contribution of international shipping to air pollution such as nitrogen dioxide (NO_2) is significant. The contribution of international shipping varies across the country between 6% in the middle of the country to 13-15% in cities in the Netherlands (with large road transport contributions) [4]. Contributions near major waterway, with inland shipping may be much larger.
In order to improve air quality and to lower nitrogen deposition, nitrogen oxide emissions from vessel engines must respect certain Tier norms to obtain the required Engine International Air Pollution Prevention (EIAPP) certificate for sailing. The emissions can be reduced through modifications of the engine design or through specific abatement systems (e.g. Selective Catalytic Reduction, Humid Air Motor). The different tiers depend on several factors such as the construction year of the ship and engine characteristics.

The aforementioned sniffer method can also be used to determine the NOx emissions, in addition to the fuel sulphur content already reported to ILT. However, remote sensing of NOx emissions in Rotterdam has only been used on a non-continuous basis (Duyzer et al., 2006, Duyzer and Weststrate, 2015). End of the

[1] NOx= the sum of (the concentrations of) nitric oxide (NO) and nitrogen dioxide (NO_2)
[2] Human Environment and Transport Inspectorate of the Netherlands (in Dutch Inspectie Leefomgeving en Transport; ILT)
[3] Herkomst stikstofdepositie, 2018 | Compendium voor de Leefomgeving (clo.nl) (in Dutch)
[4] Bronnen per component van luchtverontreiniging | RIVM (in Dutch)

year 2021, ILT has asked TNO to start a project to investigate the options to monitor NOx emissions. The goal of the project was therefore:

- To derive emission factors of NOx of individual vessels by remote sensing using the current sniffer equipment mounted at the port entrance in Rotterdam.
- To investigate the options and limitations to use these emission factors in the process of enforcing emission norms for NOx.

The second part of the project was carried out in close collaboration with ILT staff.

2 Methods

Below the instrumentation and data treatment is described in short. Appendix A provides more detail.

2.1 Measurements

The sniffer system is mounted in the tower and its location indicated on the map (see Figure 1) The sniffer system draws air from ten meters above the ground of the island to the instruments in the tower (Figure 2). At the same time wind speed and direction are measured at approximately 10 m above ground. The SO_2 (used to determine the fuel sulphur content), NO and CO_2 monitor measure the concentrations in the outside air continuously. The presence of a plume is detected from the sudden rise in the NO concentration (Figure 3). At the same time the AIS receives information (such as GPS location) of ships sailing in the direct vicinity of the tower. When a plume is detected, the software uses the wind direction and windspeed and AIS information to find which ship is responsible for the plume. In most cases this works fine. Only in a few cases (for example when there is more than one vessel upwind of the tower) it is difficult to attribute the plume to a specific vessel, then these measurements are not taken into account. The whole system is schematically depicted in Figure 3. Note that, given the fact that the current experimental setup is focused on the determination of the fuel sulphur content, we measure NO and not NO_x. In order to measure both NO and NO_2 two monitors would be needed, or one monitor with two separate measurement cells. In this study we assume that a 20% correction is needed to convert the NO concentration to the NOx concentration (i.e. the measured NO concentration is multiplied by a factor of 1.25). This contribution of 20% NO_2 was found during a measurement campaign of the EU-project SCIPPER[5] in Wedel, Germany. Because conditions in the port of Rotterdam may differ from the Wedel campaign, and may actually vary throughout the year, this adds uncertainty to the NO_x emission factors.

Figure 1 The tower and its location on the map at the port of Rotterdam.

[5] Shipping Contributions to Inland Pollution Push for the Enforcement of Regulations.

Figure 2 Measurement instruments in the tower.

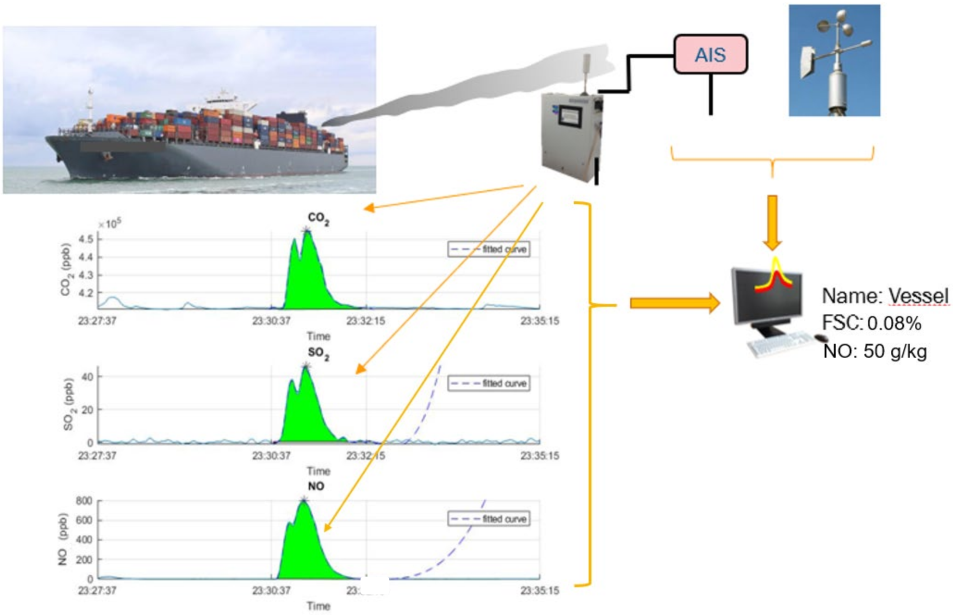

Figure 3 Schematic of the sniffer system for monitoring. The instruments detect a peak (in green) and uses wind speed and direction and AIS information to couple the peak to a vessel. The software then calculates the NO emission rate in g/kg fuel from the ratio of the peak-areas of NO and CO_2. Traditionally the fuel sulphur content (FSC) is calculated from the SO_2 and CO_2 concentrations.

The results of this combination of monitoring and intelligent software yields an NOx emission factor in g NOx/kg fuel. The following equation is used to derived the emission rate in g/kWhr from the measurements (MEPC, 2008)*:*

$$\frac{E}{P} = \frac{c(NO_x)}{c(CO_2)} \cdot \frac{46}{12} \cdot 0.87 \cdot SFOC = 3.33 \cdot \frac{c(NO_x)}{c(CO_2)} \cdot SFOC,$$

where *E/P* is the emission rate in g/kWh, and *c* (NOx or CO_2) are the measured net mixing ratios of the components in ppb, while *SFOC* [g/kWh] is the specific fuel efficiency. Appropriate corrections for the background concentrations were made. The specific fuel consumption parameter is discussed in the next section.

2.2 Data treatment

For NO_x the IMO emission standards are referred to as Tier I, Tier II and Tier III norms. These IMO standards are shown in Figure 4 and

Table 1. The Tier norms are all given in g/kWhr and depend rated engine speed (RPM). Tier III ships, that have a keeling date starting from 1 January 2021, are not yet present in the dataset used in this study.

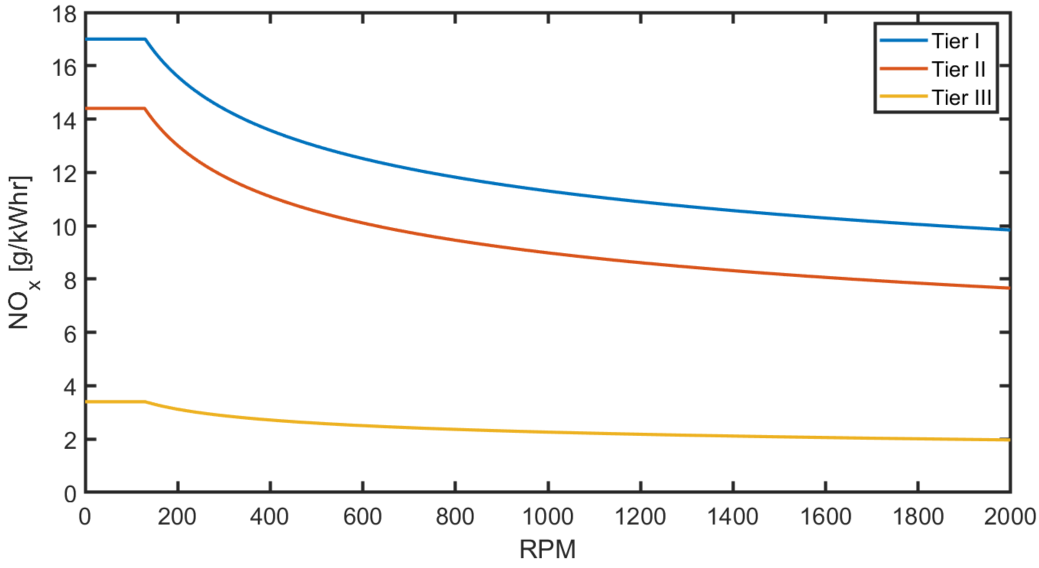

Figure 4 IMO standards for NOx emissions as a function of Rated engine speed.

Table 1 IMO standards for NOx emissions as a function of Rated engine speed (RPM).

Tier	Keel laying date	NOx Limit (g/kWh)		
		RPM<130	130≤RPM<2000	RPM≥2000
I	≥ 1 January 2000	17.0	45 x $RPM^{-0.2}$	9.80
II	≥ 1 January 2011	14.4	44 x $RPM^{-0.23}$	7.70
III	≥ 1 January 2021	3.4	9 x $RPM^{-0.2}$	1.96

The results of our measurements are derived from the ratio of the NOx and CO_2 concentrations in g/kg fuel the emission rate derived from our measurements is first calculated in g/kg fuel and then converted to g/kWhr using a value for *SFOC*. This number depends on engine type and characteristics and varies between 160 and 210 kg fuel/kWhr (Balzani Lööv *et al.*, 2014). The *SFOC* is load depended. In this study, it is calculated using the guidelines of the fourth IMO Greenhouse Gas Study (Faber *et al.*, 2020), which states:

$$SFOC = SFC_{base} \cdot (0.455 \cdot Load_i^2 - 0.710 \cdot Load_i + 1.280),$$

where SFC_{base} is the lowest *SFOC* seen in the vessels loading curve and $Load_i$ the hourly main engine loading given as a proportion (from 0 to 1).
The load of the ship is calculated using (Kauffman and Hulskotte, 2021):

$$Load_i = \frac{\frac{SOG}{V_{service}}^{3.2} + 0.1}{1.1} \cdot 0.85,$$

where *SOG* is the speed over ground of the ship (in knots) and $V_{service}$ is the service speed of the ship.

To compare our NO_x emission estimates with IMO standards some more information is needed. This includes:

- The ships keel laying date (in the absence of this date *the built year* was used)
- Rated engine speed
- Servicing speed
- Lowest *SFOC* in the vessels loading curve (SFC_{base})

The information can be found on the internet or in specific commercial databases (Bespoke Maritime Data Services | IHS Markit and others), and can be looked up by using the AIS transmitted IMO number of the vessels. In this study, the more in depth analysis with load specific *SFOC* is undertaken for ships that passed the measurement station frequently (more information is given in Ch. 3.2). Note that in the analysis only the main engine is taken into account, so not the auxiliary engines. Close to the harbour these auxiliary engines are probably also on and thus emitting NO_x. However, without additional information we cannot separate NOx emission from the main and auxiliary engines.
In addition, some general statistics on NO_x emission are given for the complete dataset. For these general statistics, a constant *SFOC*-value of 200 kg fuel/kWhr is assumed. This value is rather high, but in accordance with the value used by Belgian researchers monitoring ships using aircraft mounted sniffer system (personal information from Ward de Roy, 26 November 2021). In the recent report by Knudsen *et al.* (2022) an average of 185 kg fuel/kWhr was calculated for more than 2000 ships sailing in Danish waters. This value is somewhat lower (7.5%) than the constant value used in our calculations for the general statistics.

3 Results

3.1 General data description

In the period from 10-10-2019 to 1-11-2021[6], the emissions of more than 13 000 individual plumes were measured. In total 3479 different ships where observed. Statistics of all plumes are given in Table 2 (note by using a constant *SFOC* of 200 kg fuel/kWhr). The 10-percentile is a measure for the minimum NOx emission, without being determined by a single value but by the lowest 10% of the measurements. This means that 10% of the measured emission rates are lower than the percentile. The same holds for the 90-percentile, but then taking into account the 10% highest values. Whether the vessel was sailing into or out of the port of Rotterdam was determined by the heading of the ship (from the AIS signal). There is no clear difference in NO_x emission between ships leaving or arriving the port. We do observe a clear increase in NO_x emission when the speed over ground (SOG) is over 15 knots. This is mainly seen as an increase of the 10-percentile, meaning that the NO_x emission factors at higher speeds are indeed higher than for those for a SOG below 15 knots.

Table 2 Statistics of NOx emissions (average, standard deviation, 10-percentile and 90-percentile) given different group characteristics (SOG is speed over ground).

Group	Amount [#]	Average [g/kWhr]	STD [g/kWhr]	10-percentile [g/kWhr]	90-percentile [g/kWhr]
All	13 339	10.8	4.8	5.0	16.7
Port incoming	6 477	10.8	4.6	5.1	16.6
Port outgoing	6 427	10.8	5.0	4.8	16.9
SOG<5 knots	244	9.7	4.6	3.9	15.6
5 knots ≤SOG<10 knots	4 880	10.4	4.8	4.8	16.7
10 knots ≤SOG<15 knots	6 902	10.8	4.9	4.8	16.8
15 knots ≤SOG<20 knots	1 297	12.3	3.7	7.8	16.6

3.2 Data Selection and analysis

As suggested by ILT we have focused our investigations on the ships that we have monitored more than once. From this data set we have worked with a list of 50 vessels that were observed mostly. Vessels with specific tasks such as dredgers and tuggers were excluded from the list. These are not interesting because they are often not really sailing and probably their emissions are dominated by the emissions of auxiliary engines. This resulted in a shortlist which included a total of 23 vessels.On average the vessels on the list passed the monitoring station 40 times with 92 times as maximum.
Using this shortlist, we were able to track most vessels with respect to details on the engine and the keel laying date. Using this information, we can compare observed emission factors with IMO standards. NB, we have not corrected for loads.

[6] Data from 16-6-2020 up to 22-2-2021 were excluded since issues occurred with the NO_x monitor. Thus, no NO_x emissions were derived for this time period.

3.3 Findings

In order to get an overview of a large dataset a so called boxplot can be made. A boxplot depicts the main statistics of a dataset. Figure 5 depicts which statistics are visible in a boxplot.

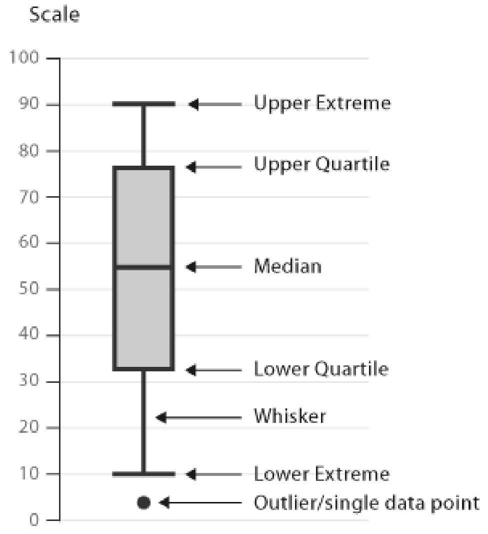

Figure 5 Explanation of a boxplot.

Figure 6 shows the results of the 23 vessels observed most. The observed emission rates vary across a large range: from 3 to 20 g/kWhr. Usually, 69% of the measured values lie within plus or minus 25% of the observed average value. This result illustrates how large deviations observed for a single vessel may be. This range is probably caused by measurement variance, possibly by uncertainty in the load and the uncertainty in the correction for not measuring NO_2. It is relevant to note that the load is not corrected for the river flow (depending on the tides).

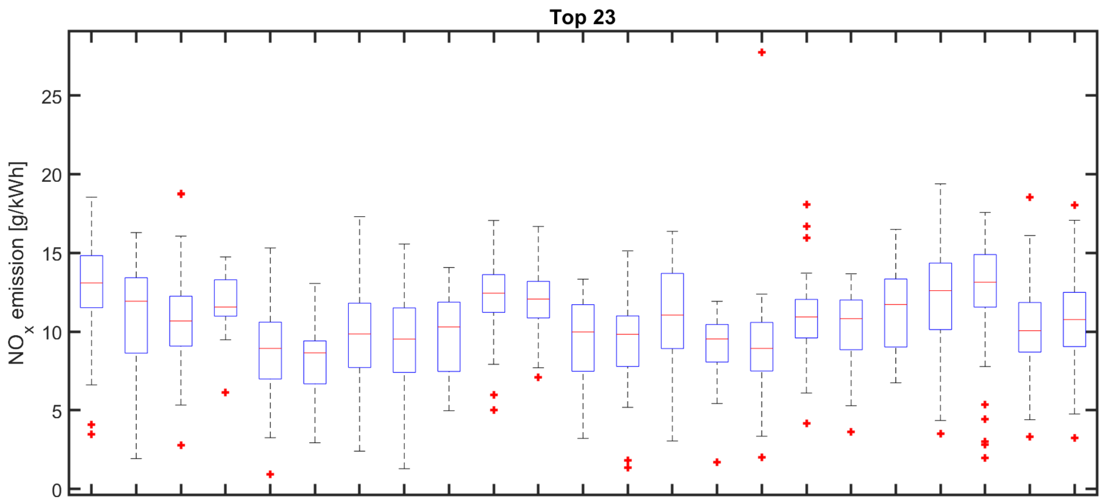

Figure 6 Boxplot of observations of individual vessels that were monitored several times. The top 23 vessels observed most are presented given the time period 10-10-2019 till 1-11-2021. The graph Figure 5 shows the meaning of the boxplot. The red stars indicate observed emission rates higher than the 95% or lower than the 5% values.

Figure 7 shows the average NOx emission of the 23 ships given their *rated engine speed.* The variability in the observed emissions can be used to estimate the uncertainty in the derived average. Note that it is difficult to compare these results with IMO standards, since the engine load is not known but estimated. The variability in the observed emissions of individual ships observed on different occasions is not large and nearly 20%. The uncertainty[7] calculated from that is also presented in Figure 7. This uncertainty is quite low and on average only 4.2%. From Figure 7 it is apparent that observed emission factor of both the Tier I and Tier II vessels are in general within IMO norm (when taken into account the error). Only one Tier I vessel with an RPM of 720 seems above the IMO. The average NO_x factor for this ship is 12.85 g/kWhr, when taken into account the standard error the NO_x factor is 12.41 g/kWhr when 12.06 g/kWhr is allowed given the IMO norm.

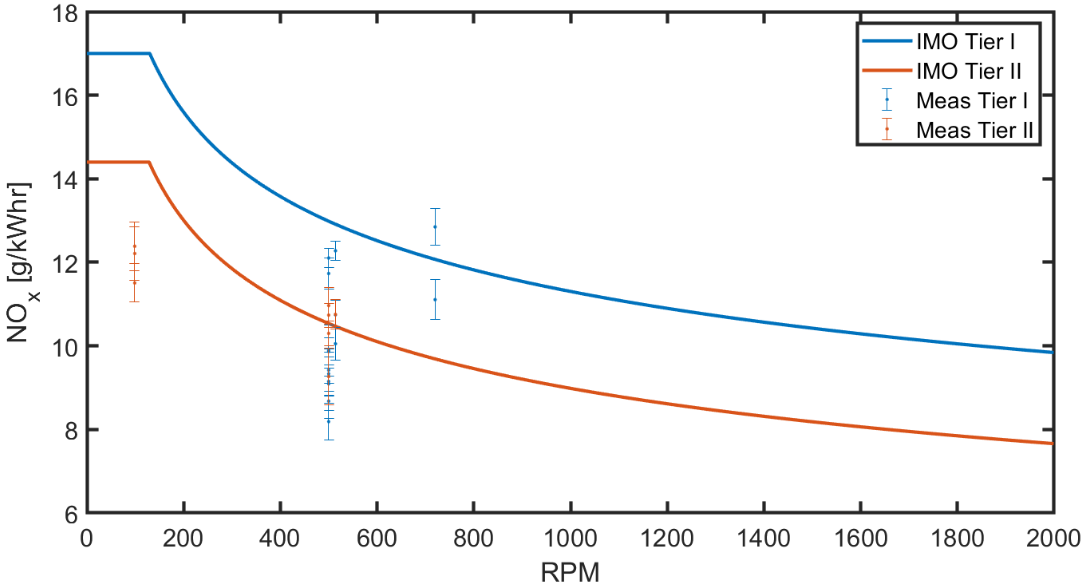

Figure 7: Average NOx emission per vessel given their Rated Engine Speed (in RPM). The error bar indicates the standard error in the average of the measured NOx emission.

Figure 8 and Figure 9 show the average emission rates for the different classes in Tier 1 and Tier 2. From these figures, it is apparent that at higher RPMs the estimated NO_x emissions are closer to the IMO norm. This is partially due to the fact that the IMO norm decreases at higher RPM, but partially also due to higher NO_x emissions. Although the number of observed vessels is low, it is interesting to note that emission rates of Tier 2 vessels are on average even somewhat higher than Tier 1 vessels (11 g/kWhr compared to 10 g/kWhr on average).

[7]The uncertainty is calculated as the observed standard deviation divided by the square root of the number of observations. Very much like the standard error.

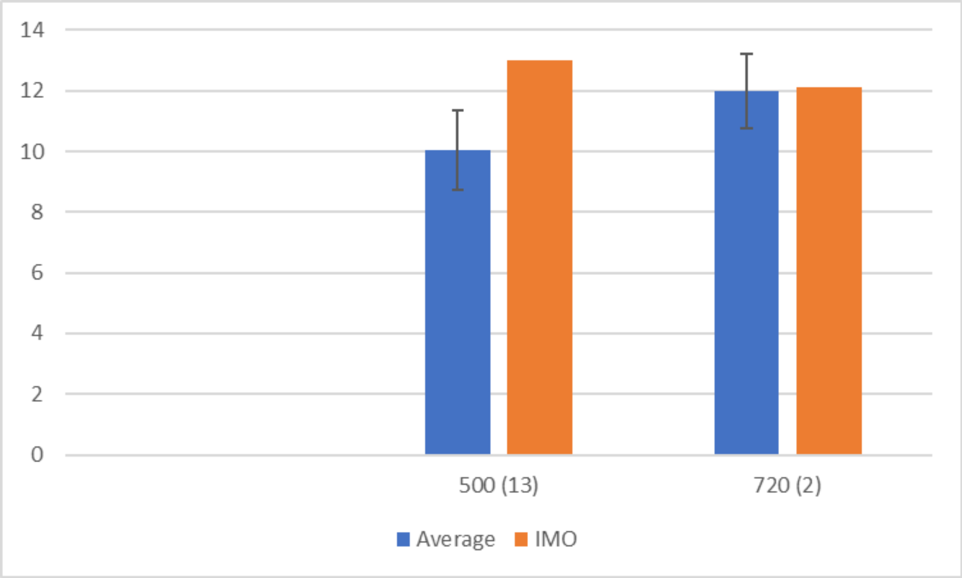

Figure 8 Averages of observed NO_x emission factors for Tier I vessels and the IMO norms for these vessels per RPM (noted on the x-axis). The number of observed vessels is shown between brackets.

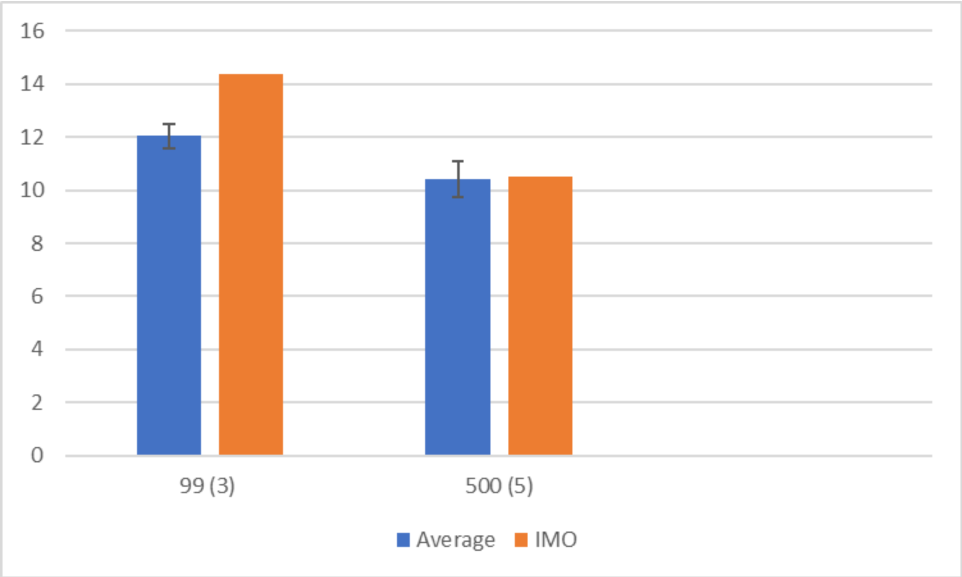

Figure 9 Averages of observed NO_x emission factors for Tier I vessels and the IMO norms for these vessels per RPM (noted on the x-axis). The number of observed vessels is shown between brackets.

4 Conclusions

ILT has asked TNO to start a project to investigate the options to monitor NO_x emissions using the existing instrumentation located at the entrance of the port of Rotterdam, at the end of the year 2021.
The goals of the project were therefore:

- To derive emission factors of NO_x of individual vessels by remote sensing using the sniffer equipment mounted at the port entrance in Rotterdam.
- To investigate the options and limitations to use these emission factors in the process of enforcement of emission standards for NO_x.

Emission factors for nitrogen oxides were calculated for each vessel passing the measurement site from 10-10-2019 till 1-1-2021. As suggested by ILT, our investigations were focussed on the ships that we have monitored more than once. From this data set we have worked on the 23 vessels that were most observed. From the analysis we conclude:

- The emission rate calculated from single plume measurements can vary by up to a factor of 4.
- The averages of the emission factors observed for a single vessel, with multiple passes, have reasonably low standard deviations, with an uncertainty of only 4.2% on average.
- To compare these emission rates with IMO norms the specific fuel efficiency needs to be known. This value, is depended on engine load. In this analysis, the base fuel efficiency, service speed and speed over ground of the vessel are taken into account to determine the load. Taking into account the influence of the tides on load may improve the estimate of the specific fuel efficiency.
- The uncorrected emission factors were compared to IMO norms. Exceedances of these norms, of the 23 ships taken into account, was only observed for one Tier I vessel (taken into account the averaged emission factors per ship and standard error). However, non-compliancy cannot be concluded from these measurements, since a range of engine loads need to be considered in the IMO norm. Over 70% of the NO_x IMO norm is in engine load between 70 and 100%, which are in general not the engine loads that occur close to ports.

From our observations and analyses, we conclude that:

- At this stage a single measurement of the NO emission rate is not accurate enough to be used in enforcement or even targeting.
- The average emission rate derived from more observations (ranging from 22-78 observations in our cases) appeared to be accurate with an average uncertainty of 4.2%. This would allow us to indicate potential large emitters with good accuracy and could be useful in the process of targeting.
- Tier II ships taken into account in this research do not clearly show lower NO_x emissions compared to Tier I ships. This could be caused by the fact that the Tier II engine are tuned to mainly give low NO_x emissions at higher power and give higher NO_x emissions at lower power. Close to the port the power on the engine is in general fairly low.

5 Recommendations

In view of the results of this research a few recommendations may be given. First of all a comprehensive database where the rated engine speed in RPM and also the service speed of a multitude of vessels are given would allow for a more comprehensive analysis taken into account more ships. Now due to these limitations we only focused on the top 23 vessels (excluding draggers and tugger vessels).

The load on the engine of the vessel is in this study estimated from the service speed and *SOG*. A more comprehensive approach, which also takes into account the influence of the tidal flow is also possible. This would give an even better estimate of the load and thereby *SFOC*. However, it is still on estimation of the engine load. Ideally, the engine loads should be known, for example by adding it to the AIS signal.

The current experimental set-up is focused on determining the fuel Sulphur content of the ships passing by. To this end measurements of only NO suffice. However, if NO_x emission factors are to be reported in the future both NO and NO_2 need to be measured simultaneously. This would mean adding a NO_2 monitor to the experimental set-up or employing a monitor with two measurement cells. If both NO and NO2 are measured an estimation of NO_x emission factors could be added to the near-real-time webpage already displaying the fuel sulphur content (note in that case a constant *SFOC* would need to be assumed, since not all data is present per ship to calculate the load dependent *SFOC*).

Given the variability among plumes of similar ships it is not possible to verify possible non compliancy from single plumes. However, by taking into account a multitude of plumes (>15) we can get a reliable estimate of the NO_x emission factor. A more in depth analysis of the NO_x emission factors could be carried out on the dataset. For example, also the size of the vessel could be considered when looking at the NO_x emission factors of different vessels. Also whether or not a vessel has a two- or four-stroke engine could be considered. A histogram of the occurrence NO_x emissions factors could help to identify how often certain NO_x emission factors occur.

In this study the in depth analysis were carried out on Tier I and Tier II vessels, no Tier III vessel passed by our station a sufficient amount of times to be taken into account. However, the NO_x emission factors allowed for Tier III is substantially lower than Tier I and II (by around a factor 4 and 5 respectively, see Figure 4). Furthermore, Tier III ships can in general switch on and off system which lower the NO_x emissions. Both this and the low IMO norm make it more vulnerable for violations, but also easier detectable if this is the case by our sniffer system.

The focus in this study was to determine NO_x emission factors and investigate how these can be compared to IMO norms. When looking at nature areas around the port of Rotterdam, some sensitive areas like Grey dunes (EU code H2130A) Natura 2000 areas exist. Hensen et al. (2017) already showed that near Hoek van Holland the critical load for nitrogen deposition of these types of dunes are in some locations exceeded. This means that nitrogen is damaging the biodiversity in these particulate nature areas. From a nature point of view the less NO_x emission from shipping the better. Given this perspective and fact that the Tier III IMO norms are much stricter than Tier I and II monitoring NO_x emissions to register if the expected decrease of NO_x emissions is met is worthwhile.

6 References

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7 Signature

Petten, 1 August 2022

TNO

ValidSigned by Thérèse Maarschalkerweerd
on 2022-08-01 12:04:13

T.V.P. Maarschalkerweerd
Project Leader

ValidSigned by Daniëlle van Dinther
on 2022-08-01 10:14:23

D. van Dinther
Author

A The sniffer system

The sniffer system is mounted in the tower indicated on the map (see Figure 3). The sniffer system draws air from circa ten meters above the ground of the island to a manifold in the tower. At the same time wind speed and direction are measured at a 10 m level above ground. The sniffer system measures concentrations in the plume of the ship. The SO_2, NO and CO_2 monitors draw air from the manifold and the concentrations are measured continuously. The presence of a plume is detected from the sudden rise of the NO concentration. At the same time the AIS receives information (such as its positions) on ships that are sailing in the direct vicinity of the tower. When a plume is detected, this software uses the wind direction and windspeed and AIS information to find which ship is responsible for the plume. Usually this works fine. Only in a few cases (for example when there is more than one vessel upwind of ship) it is difficult to find the ship.

The NO-NOx measurements were performed using a Thermo Scientific 42C instrument that measures NO by chemiluminescence light, being emitted from the reaction of NO with ozone. The instrument works in a dual channel principle where NOx (i.e. the sum of NO and NO_2) is measured when the air passes for some seconds through a heated Mo-converter (converting NO_2 to NO), being NOx the sum of NO and NO_2, and measuring only NO whenever the Mo-converter is bypassed. Other oxidized nitrogen compounds, in particular PAN and HNO_3, are also (at least partially) converted to NO by the Mo-converter and can thus interfere with the measurement of NOx. In order to increase the response time to a t90[8] of about 15 s the time constant of the instrument has been set to 1 s. It is not advisable to use the dual channel principal when the NO and NO_2 concentrations change rapidly in time, as is the case with ship plume measurements. Thus, the monitor at the port of Rotterdam is set to only measure NO. For calibration a reference gas mixture cylinder of around 200 ppbv NO in nitrogen and NOx free synthetic air for the zero calibration is used.
The CO_2 measurement is performed by a LI-COR LI-7000 optical instrument that measures infrared absorption in two wavelength bands around 5 µm using a broadband light source and bandpass filters. In these wavelength bands the species H_2O and CO_2 absorb strongly. The instrument has two measurement cells, one sample cell and one reference cell containing known concentrations of CO_2 and H_2O. The concentration in the sample cell is obtained by calculating the light absorption due to CO_2 and H_2O by comparing the intensities in the two cells. The flow through the LI-COR instrument is around 6 L/min, while the flow for the reference gas is 150 mL/min. This instrument responds faster than the SO_2 and the NO/NOx analyzer; the response time (t90) is < 5 seconds, depending on the pump speed. The calibration curve has been checked by a span gas calibration with at least two known CO_2 gas concentrations in the measurement range (e.g. 370, 395, 420 ppmv).

[8] The time required for the monitor to reach 90% of the final value.