BETTER SHIPS, BLUE OCEANS

Ship emission model validation with noon reports

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Ship emission model validation with noon reports

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1 INTRODUCTION

Within the European Sustainable Shipping Forum (ESSF), sub-group Air Emissions, as well as within the Dutch authorities' Energy Act, the need for an evaluation of emission models was identified.

Shipping models are based on measurable variables which are not directly related to emission, such as Gross tonnage or ground speed. The relation between power and speed over ground is used to calculate emissions based on grams emission per produced kilowatt by applying an emission factor. The actual emission factor can be considered sufficiently accurate. The relation between power and speed over ground however is questionable as this relation is affected by many parameters such as loading condition, trim, fouling, water depth, current and weather.

Moreover the operation as well as the technical configuration of vessels have been modified over time; vessels are trading at lower speeds and engines have been optimised to this pace. The industry has been under enormous commercial pressure resulting in efforts being made to reduce fuel consumption per shipped unit of cargo as much as reasonably possible. An evaluation of the used models is therefore required.

Noon and voyage reports from 91 vessels for a period of more than 1 year has been collected from various Dutch ship owners. The majority of the data used for the analysis consisted of general cargo ships, which represent about 53% of the ships operated by Dutch operators (Figure 1). Nevertheless, also some large container ships, ferries and bulk carriers were included in the database. After having signed a non-disclosure agreement TNO provided estimations of fuel consumption of 91 vessels only based on vessel speeds and IMO-numbers.

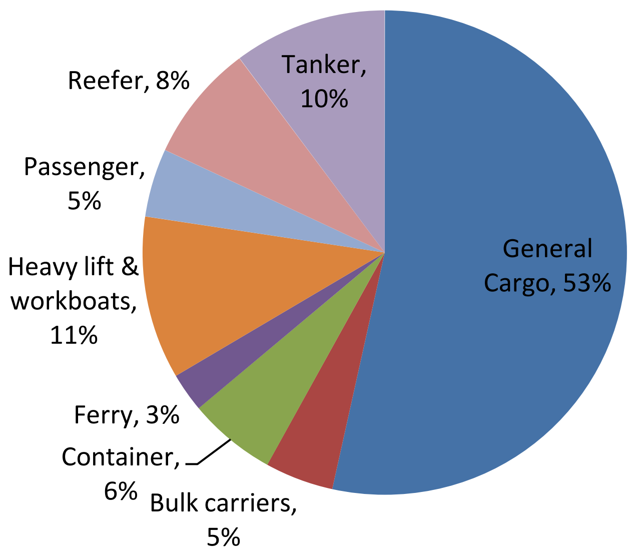

Figure 1: Vessel types >5000GT operated by Dutch ship operators

The objective of this investigation is to evaluate the existing TNO shipping emission model by comparing it with the actual consumed fuel reported by vessels in noon-reports. Emissions factors are for most types directly related to the amount of consumed fuel and therefore the fuel consumption can be used to demonstrate the correctness of the models.

In Chapter 2 the emission model as provided by TNO is introduced. The model was originally developed to give a broad overview of annual emissions of ships in Dutch waters, and lacks therefore accuracy on individual ship basis. The investigations in this report focuses on improvements in the model to obtain get more accurate results. Chapter 3 describes how the model is used to calculate the fuel consumption and what the differences in fuel consumption are compared to the quantities reported by the ships.

In Chapter 4 the sensitivities of the model to various operational conditions are discussed: the speed/power curve, the operating profile and variations in displacement. Improvement of the model can be made for these parameters without requiring additional information other than empirically derived parameters and factors.

Finally, in conclusions and recommendations to improve the TNO emission model are given in Chapter 5.

2 EMISSION MODEL DESCRIPTION

The TNO emission model (see Appendix 1 for a detailed description) has been developed to calculate the fuel consumption of ships and corresponding air emissions based on minimum input of data. The model requires the following input parameters;

- Ship IMO number
- Total sailing distance
- Total sailing hours
- Average ship speed during the sailed hours

The IMO number is used to retrieve the design speed, engine power and engine type of the ship from an external database of the Port of Rotterdam.
The following formula is used to calculate the emission factor per nautical mile.

Emissions = *Emission factor* * FC_{ME} + FC_{AUX} * *Hours sailing*

The emission factor depends on fuel, engine type and engine loading. This information is obtained from lookup tables and the reported information of the main engines. The fuel consumption per day is determined from the following equation:

FC_{ME} = CRS_{cor} * *Active_Engines* * *MCRss* * *Power* * *SFOC* * *24/1000*

Where:

FC	: Daily fuel oil consumption (ton/day)
CRS_{cor}	: Correction Reduced Speed factor/ ship resistance factor: $CRS_{cor} = \frac{\left\{\left(\frac{V_{actual}}{V_{design}}\right)^3 + 0.2\right\}}{1.2}$
Active_Engines	: number of active engines involved in normal propulsion (-)
MCRss	: fraction of power to reach service speed (0.85 for single engine ships, for more engines see table A-2)
Power	: Installed power of a single engine (MW)
SFOC	: specific fuel oil consumption (175g/kWh for engines >3MW)
24/1000	: 24 hours/day;1000 kg/ton

FC_{AUX} = Installed Auxiliary engine power * loadfactor * SFOC.
For those ships were no information is available, 6.3% of the main engine installed power is used, and multiplied with a SFOC value.

The model was developed and validated based on a large database of design speed/power and fuel consumption data. With sufficient ships in the database, the model is considered accurate. The accuracy of the model for individual ships might however be low due to the limited input data for the model. The following important assumptions are taken in the model which could affect the accuracy of the emission calculation for individual ships:

1. The speed/power curve is assumed to be of a 3rd order plus a constant. In reality this differs per ship and has consequences to the correction reduced speed factor.
2. The operating profile vessel (in terms of speed or power) is not included.
3. It is assumed that the vessel sails in design loading conditions, while in practice ships often sail at part load.
4. The SFOC could be incorrect, since the engine loading curve for individual ships is not included. In the model 2 generic engine loading curves are used for a 2 stroke and 4 stroke engine type. In practice this generic estimation could affect the accuracy of the emission calculation for individual ships.

A more detailed description of the model is included in Appendix 1 of this report.

3 EMISSION MODEL VALIDATION

Noon report data from 91 vessels was collected from various Dutch operators operating general cargo ships. The noon reports include the average speed over ground, total fuel consumption and total sailing time over a period of approximately 1 year for each ship. The data was filtered for outliers and checked for consistency prior to further analysis. The IMO number together with speed and hours sailing was used by TNO to predict the fuel consumption, and subsequently emissions using their emission model. A comparison is made with the actual reported annual consumption and the one calculation by the model from TNO.

Figure 2 shows the predicted fuel consumption by the emission model compared to the reported fuel consumption. It shows that the average emissions for the 91 analyzed vessels is, considering the limited of number of ship specific data that is provided to the model, good; within a few percent of the reported fuel. The error for individual ships for the analyzed ships is in the order of 10-50% (or 20% standard deviation) due to differences in performance, hull form, operating mode, loading, fouling, environment, route etc. between vessels that are not considered in the model.

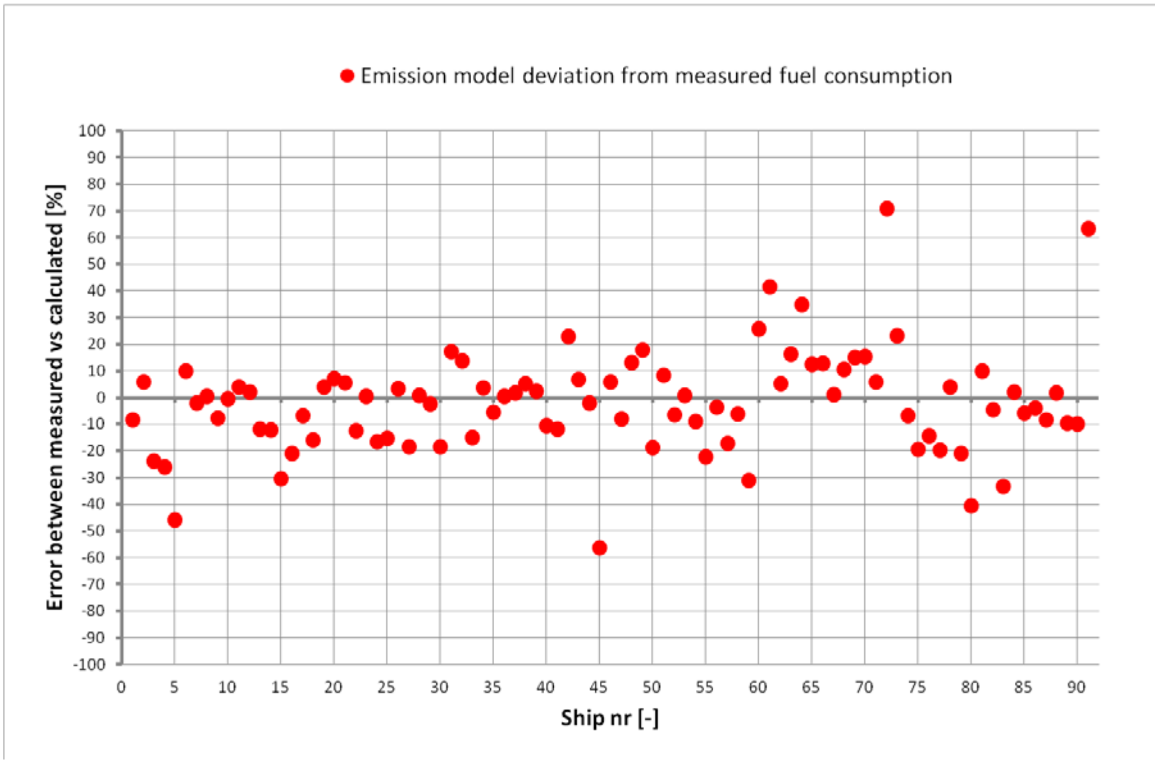

Figure 2 Percentage difference in reported fuel vs. predicted fuel for 91 ship's.

The data in the used database contains a number of sister ships. In Figure 3 sister ships are grouped in colours (other than red). This shows that the same level on inconsistencies exist even within a series of sister ships. This implies that the lack of details in the operating conditions (speed, displacement) and ability to accurately correct for ship speed (speed/power curve) are important contributors to the inaccuracy of the model.

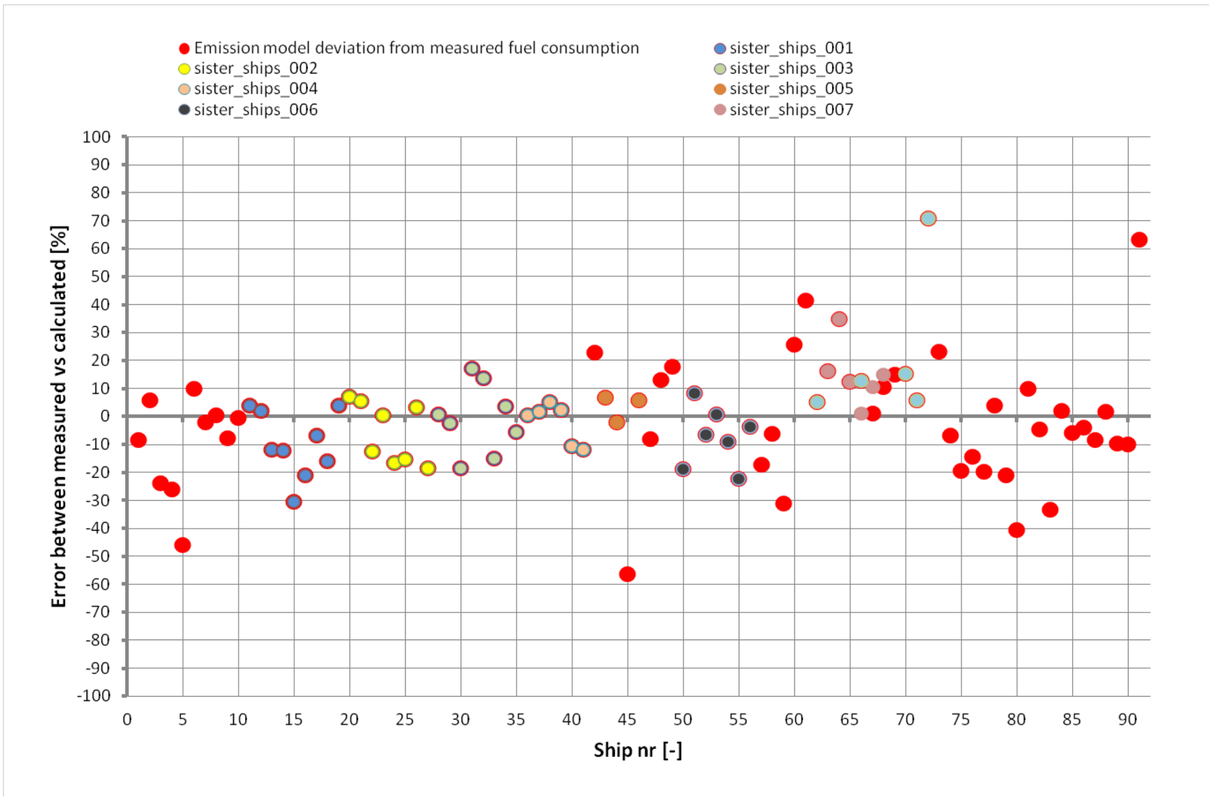

Figure 3 Percentage difference in reported vs. predicted fuel for 91 ship's, with indicated sister ships.

The current investigation focuses on reducing the scatter, i.e. improving the prediction of fuel consumption (and hence emissions) of individual ships.

4 EMISSION MODEL SENSITIVITY

The emission model is developed based on a minimum of input data (average speed, IMO number and running hours). This has consequences to the accuracy of the model output. The implications of the following assumptions is evaluated:

1. Use of a speed-power curve in the form of $P = \frac{Vs^3+0.2}{1.2}$ versus the actual speed/power graph
2. Use of a single average ship speed versus consideration of a speed operating profile
3. Use of design draft versus use of a loading profile

Other sensitivities, e.g. the effect of hull fouling, wind and wave resistance, variations in loads of auxiliary engine loading, variations in fuel quality, environmental effect on main engine operation are not included in this analysis due to the unavailability of relevant details in the noon report data. Also these parameters contribute to the errors found in the Figure 2.

4.1 Speed power graph vs. TNO CRS polynomial

The CRS (Correction Reduced Speed) factor used in the model is based on a 3rd power curve in the form of $P = \frac{Vs^3+0.2}{1.2}$. The term 0.2 is included to account for very low speeds, e.g while sailing in harbor areas, where a third power would underestimate the required power. When a third order power curve would be used the power would go through zero power at zero speed. In reality engines are not capable of running below approx. 10% load. Although the basis of a third order polynomial is based on hydrodynamic principles, the additional terms of 0.2 and the division by 1.2 make the curve far less steep compared to a 3rd order curve.

The validity of the CRS power curve is evaluated for 21 ships of various type, size and speed, for which model tests have been done. Figure 4 shows an example of one of these vessels. It shows that the model test speed-power graph can be represented fairly well using a regression curve in the form of $P=V^{3.2}$. The CRS factor used in the TNO model over-estimates the power required to reach a certain speed. The relative error between the Model test curve and the CRS curve has been calculated for all 21 ships and plotted in Figure 5. It shows that for all evaluated vessels the CRS curve over-predicts the power requirement compared to model test results at speeds lower than design speed.

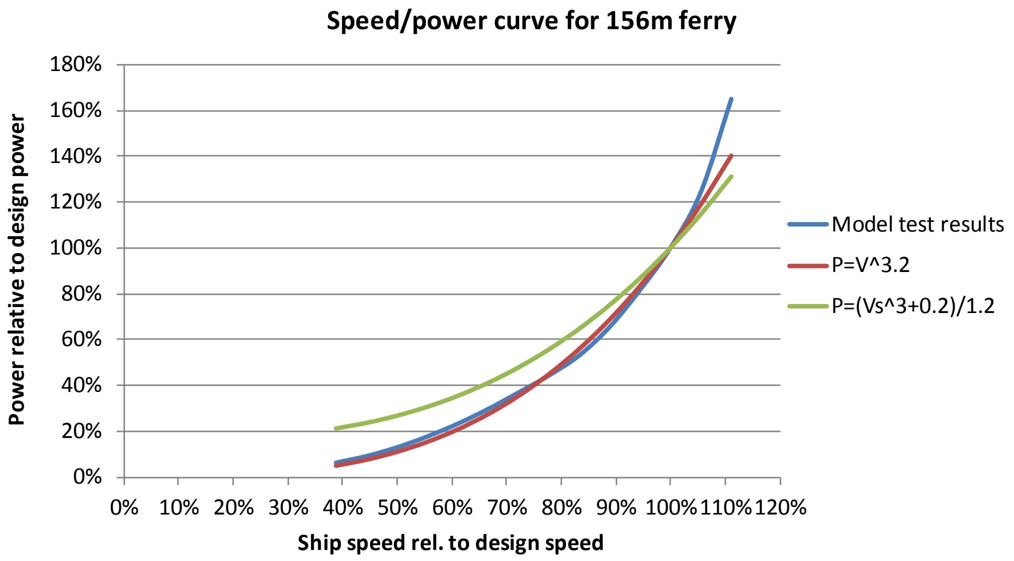

Figure 4: Comparison of speed-power curves from Model test and 2 regression curves for a ferry

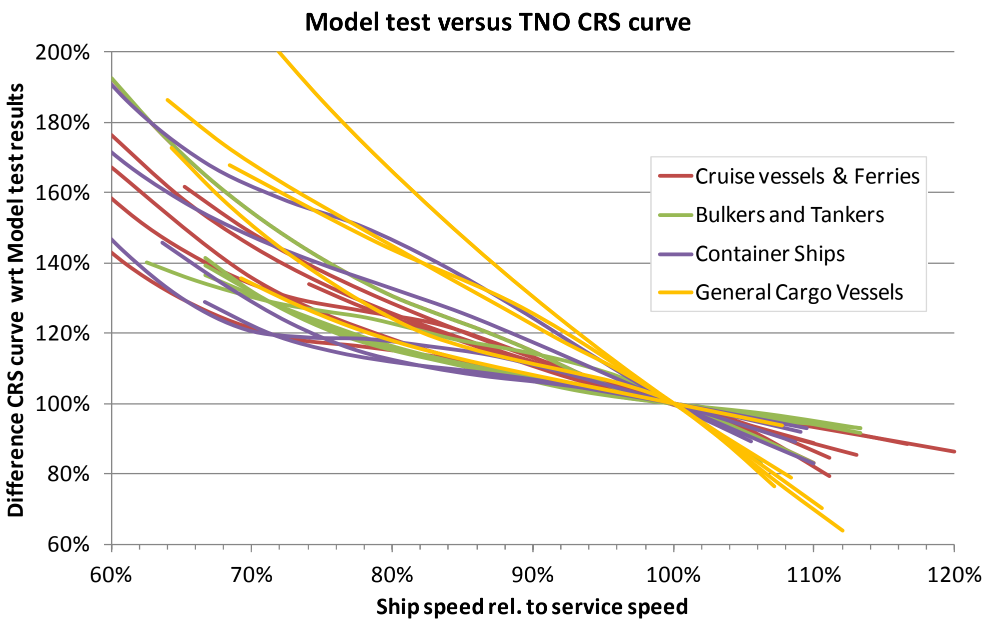

Figure 5: Relative difference between model test and CRS curve for 21 vessels

A better representation of the speed/power curves would be to use a power curve in the form of $P = V^{3.2}$ as shown in Figure 6. By using this curve, the power requirement for off-design speed conditions would be predicted with less error. At speeds less than 60% of the design speed less validation material is available from model tests. At these speeds the use of the suggested speed-power relationship may be inaccurate. However, as will be seen in the following chapter, many ships sail at speeds higher than 60% relative to their design speeds. Therefore the impact of the uncertainty increase at low speeds is small.

Attempts were made to further refine the regression curve, e.g. by including a term for block coefficient, Froude number, length-displacement ratio or Length over Beam ratio. Based on the 21 vessels in the dataset it seems that shorter vessels are have a higher order speed-power curve than larger vessels (Figure 7). However, the correlation is too poor to derive reliable correlation coefficients. It shows that especially general cargo ships are responsible for the large scatter in the speed-power curves in Figure 6, as they come in many types and sizes, from full ships to slender coasters.

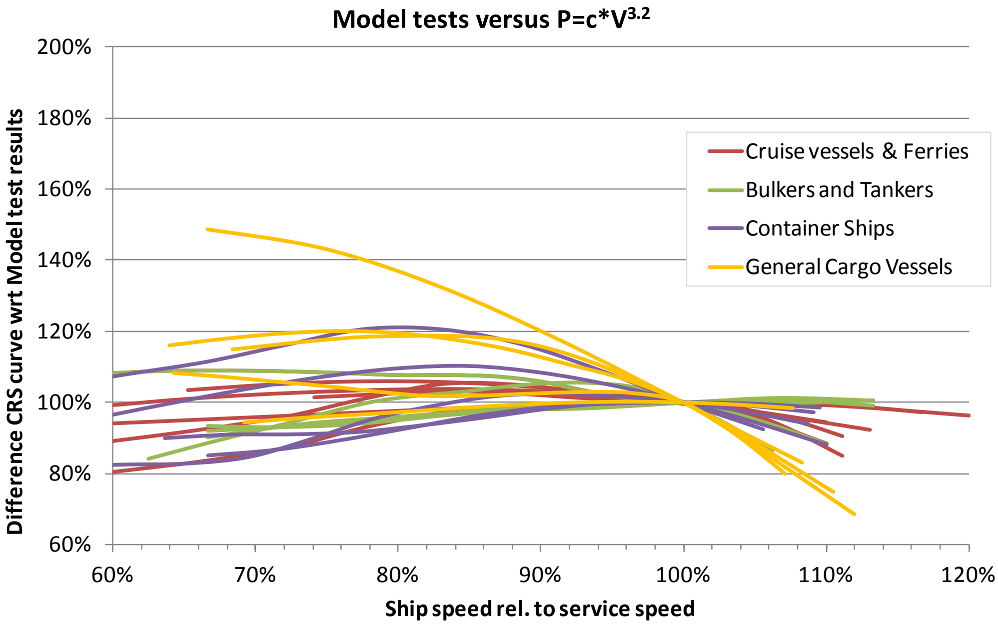

Figure 6: Relative difference between model test and P=Vs^3.2 power curve for 21 vessels

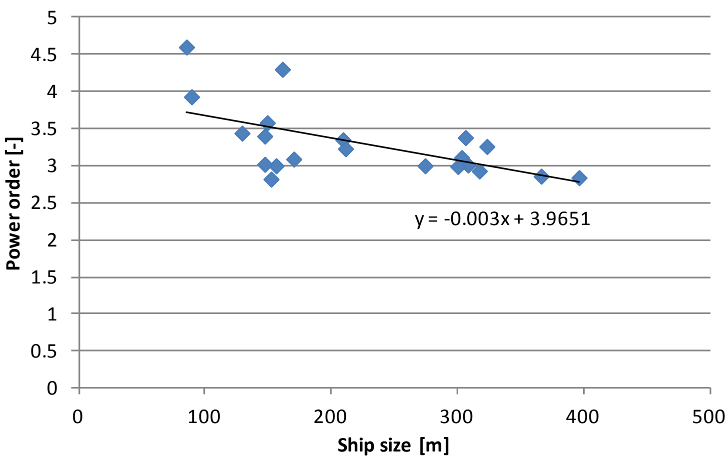

Figure 7: Relationship power order P=V^n and ship length for 21 vessels

Figure 8: Relative difference between model test power curve Refined regression model for 21 vessels

It can be concluded that the CRS power curve used in the TNO emission model results in strong over-estimations of the required power at part-load. The use of a power curve in the form of $P=V^{3.2}$ will improve the performance prediction. Further refinement of the curve can be obtained when a larger database with speed/power curves is evaluated. However, this is outside the scope of this project. It can be expected that the power requirement for part load operation for general cargo ships will be less accurate than bulk carriers, tankers, container ships or ferries.

When the model is used to predict performance when ships sail at very low speeds in shallow rivers and harbour areas, the use of a power curve in the form of $P=V^{3.2}$ will give an under prediction of the required power. However, due to budget constraints no investigations are made to derive a general applicable speed-power relation for various water depths, speeds and vessels under the 50% design speed.

4.2 Sensitivity of speed operating profile

The TNO emission model is initially made to be used with AIS data with an update frequency of 2 minutes. By using 2-minute speed information, the speed operating profile is taken into account. If the model is however to be used with annual averaged speed information, errors are made in the calculation of emissions.
The non linear relation between speed and power makes calculating average power from a single average speed prone to large errors. Similar as with driving a car, driving fast towards a traffic light and standing still consumes more fuel than driving at a constant (slower) pace to the traffic light and having to wait less long for green light. Both cars will travel the same distance and will take the same time to go through green light, but will consume different fuel quantities. The same analogy applies to the Emission model. The Emission model predicts fuel consumption based on the assumption that ships sail at a constant speed throughout the year. In reality ships are likely to sail at different speeds. The error that is made in the prediction of fuel consumption contributes to the scatter found between individual ships in Figure 2.

The speed operating profile of individual ships is not part of the input of the Emission model, as this information is often not available. To understand the impact of using a single, annual average ship speed compared to having a detailed speed-power profile, the operating profile of 71 vessels, mainly general cargo ships and ferries, has been extracted from a database of noon report data. The speed operating profile for 30 ships is shown in Figure 9. It shows the speed distribution over time in the form of a histogram.

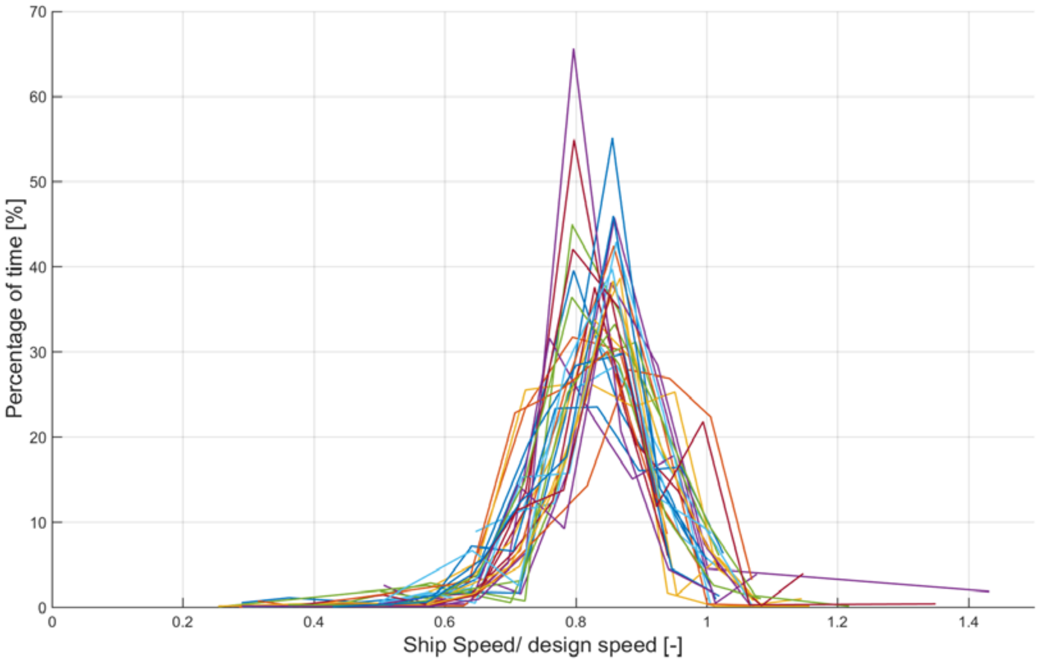

Figure 9 Speed operational profile as percentage of the design speed.

It shows that most ships indeed do not sail at a single constant speed, but that the sailed speed varies about +/-15% around a mean speed. The impact on fuel consumption of the fact that ships sail at different speeds and not on a constant pace is shown in Figure 10. It shows the difference in total fuel consumption when fuel consumption is calculated using a constant speed, versus using a distribution of speeds. The used data is based on the speeds reported in noon reports.

The calculation for both is as following:

1. Fuel consumption using a single speed:

$$FC_1 = V^{3.2} * Time * SFOC$$

2. Fuel consumption using a speed distribution follows as a weighted average:

$$FC_2 = \sum_{i=1}^{n} (V_i^{3.2} * Time_i) * SFOC$$

Where n is the number of bins in the speed histogram.

Figure 10 shows the results for 63 ships. The differences indicate the improvements that could be made in the emission model when speed operating profiles would be available. It also shows the importance of having this data. The fuel consumption calculated using the speed-operating profiles would, for the tested vessels, be around 8% higher than if a constant speed would be used.

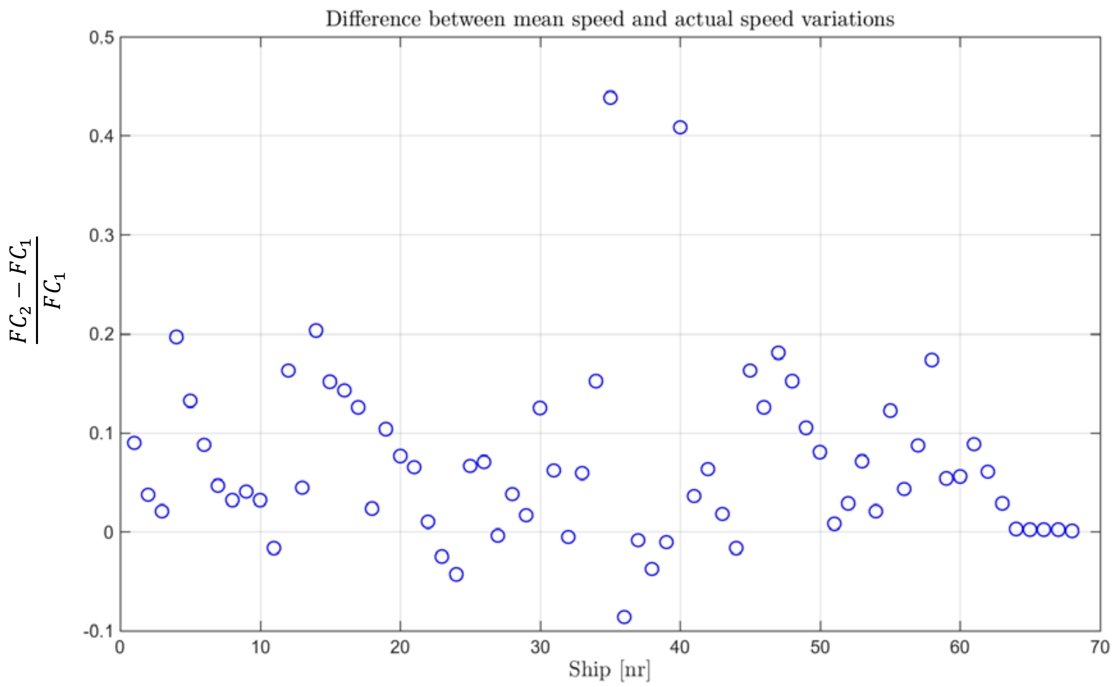

Figure 10 Effect of speed operating profile on required power

Unfortunately, detailed information of the speed-operating profile for each vessel is not likely to be available for general emission predictions. To still make an improvement of the model possible, an investigation was made whether the speed-operating profile could be generalised by a normal distribution with a "general applicable" shape (i.e. standard deviation). When the speed-operating profiles in Figure 9 are assumed to be normal distributed, the standard deviation may be calculated from the speeds reported in the noon reports. The standard deviation of 71 ships is plotted in Figure 11, expressed the relative speed variation compared to the design (service) speed.

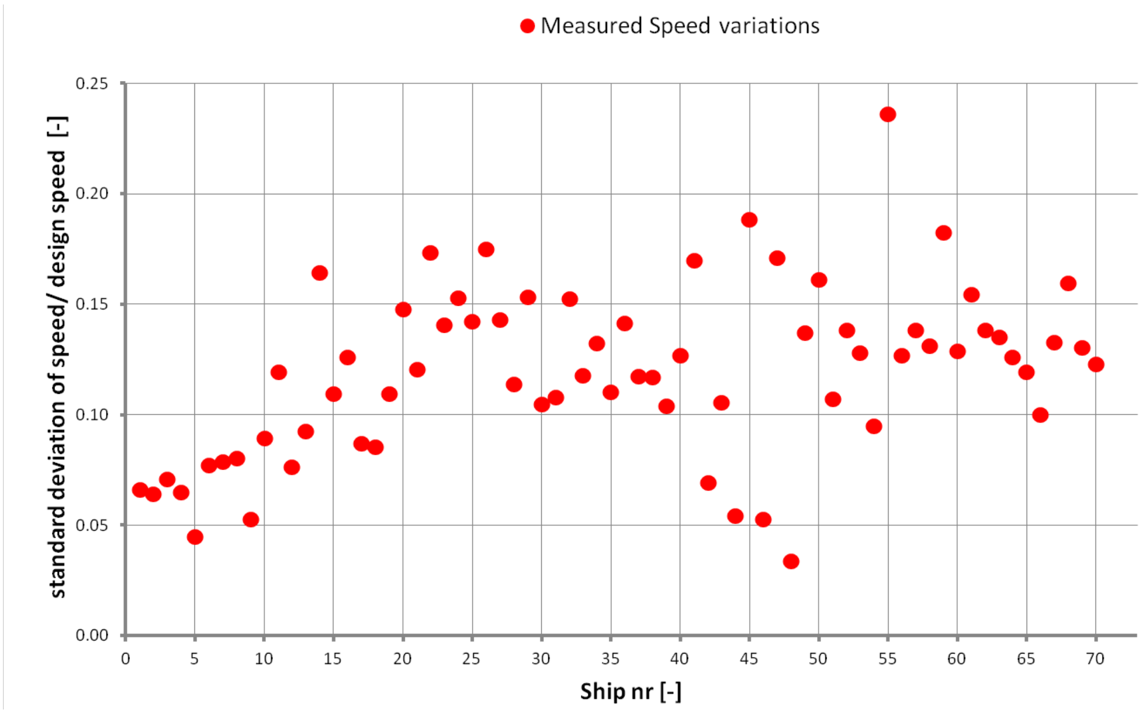

Figure 11: Standard deviation of reported ship speeds

As expected, the standard deviation varies greatly between ships. Ferries (the first 5 ships on the left of Figure 11) sail with relatively constant speed, and ships on a liner service will also sail with other speeds than ships on the spot market, changing route and type of cargo frequently. Regardless the scatter, it shows that more accurate fuel consumption predictions can be made when a spread in speed is used in the calculations for fuel consumption than when a single average speed is used (with a standard deviation of $\sigma = 0$). Based on Figure 11 one can assume an average standard deviation for general cargo ships of 0.14 (14% of the design speed). Now, the equation for normal probability distribution function can be used to generate a speed-operating profile:

$$y = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

Where $\sigma = 0.14$ and μ= the mean (annual) speed. X and y give the speed operating distribution. This is used to predict the total fuel consumption, and compared to the fuel consumption when a single annual average ship speed would be used. The results are shown in Figure 12.

$$FC_3 = \sum_{i=1}^{n} (V_i^{3.2} * y) * SFOC$$

With n the discretisation step.

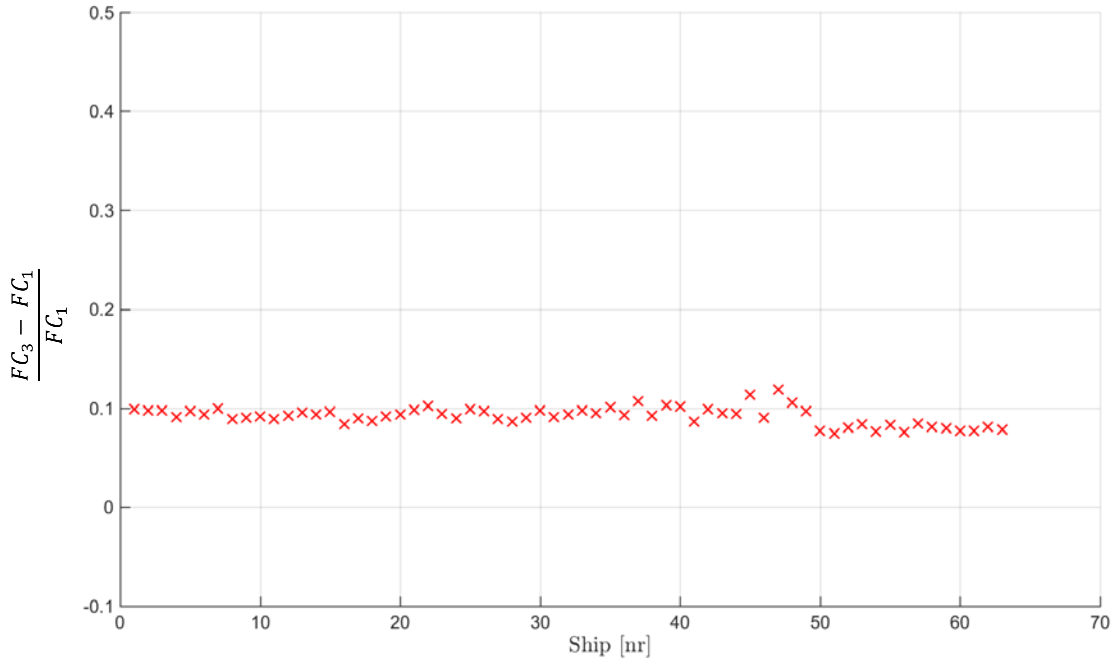

Figure 12 Effect of using a normal distribution as speed-operating profile on fuel consumption

The results are different then when the actual speed-operating profiles are used, as plotted in Figure 10. The mean difference, around 10% higher fuel consumption, is the same. The large differences between individual vessels can be caused by two factors:

a. The standard deviation cannot be considered the same for each ship (see Figure 11)

b. The speed-operating profile cannot be represented accurately by a normal probability density function.

The fact that large errors are made when a standard deviation of 14% is used for all ships in the database is clear from Figure 11. The question whether a normal distribution can be used to represent the speed-operating profiles is shown in Figure 13. In this graph the fuel consumption calculated using the actual speed-operating profiles is shown (based on speeds reported in noon reports), as well as the fuel consumption when the actual speed-operating profile is fitted using a normal probability density function. The used standard deviation for each ship is hereby different and calculated using the noon report data.

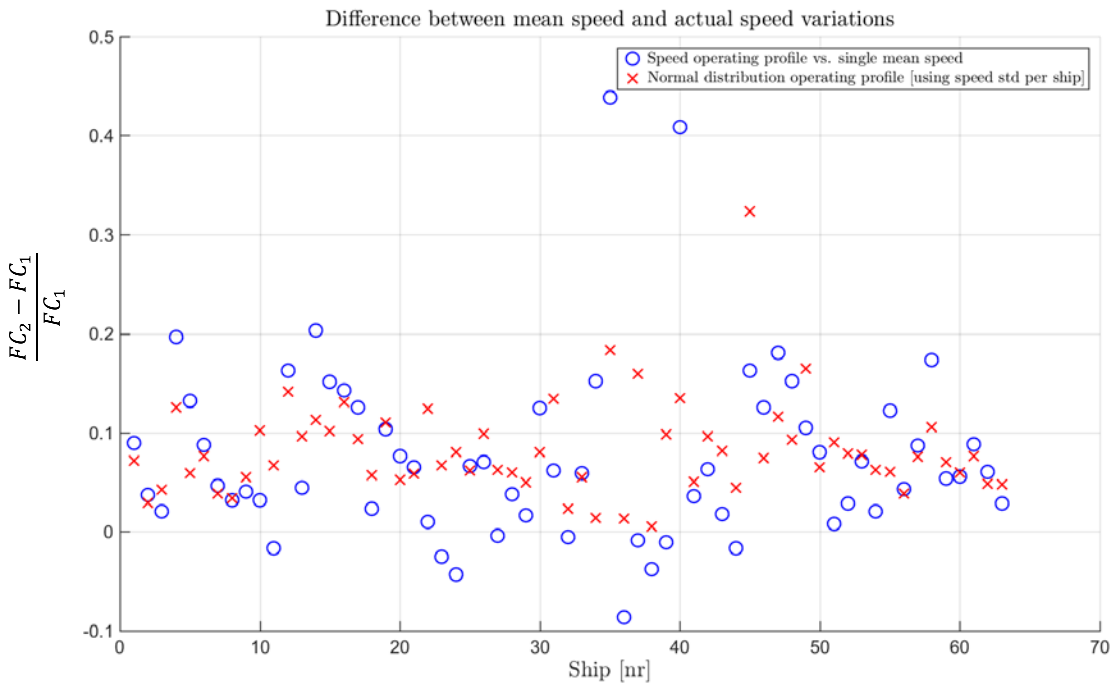

Figure 13 Actual Fuel consumption and fuel consumption using a fitted normal distribution speed operating profile

Figure 13 shows that a normal probability density function doesn't fully match the shape of many speed operating profiles. For ships sailing e.g. at two distinct loading conditions, the speed is also often at two distinct magnitudes. In these cases a normal probability density function is not suitable. However, having only the standard deviation of the speed for each ship, in combination with the assumption of a normal probability density function, would improve the emission predictions greatly.

Over all it can be concluded that the unavailability of information on speed variations are important causes of errors in the emission prediction model. There is a systematic offset in the fuel consumption predictions of about 10% due to the fact that it is assumed that ships sail at a constant speed throughout the year. Inclusion of a normal probability density function with a standard deviation of 14% of the design speed will remove this offset. It will however not improve the accuracy of the fuel consumption predictions for individual ships.

Hence the use of high frequent ship speed data (from AIS) is necessary to avoid up to 20% errors in emission predictions that cannot be removed by general applicable correction factors.

4.3 Sensitivity of displacement

The TNO emission model assumes that the ship sails in design draft (often referred to as full laden conditions), as no information of the displacement is used as input to the model. In reality ships rarely sail in full laden conditions. To get a general idea of the in-service loading condition, draft data of ships entering and leaving the port of Rotterdam (at the 'Maasmond') were evaluated over the period 1-1-2016 until 1-6-2017. Around 41.000 vessel movements in and out of the harbour were recorded. Data was collected based on AIS, which is expected to be sufficiently reliable for the purpose of making general load profiles[1]. The results are included in Table 1. It shows the mean loading as percentage of the design loading of the ship. The number of crossings are included to give an indication of the relevance of the data.

Table 1: Average loading for vessels entering and leaving Rotterdam harbour over 1-2016 till 6-2017

Ship type	# Crossings inwards	Loading (T_{mean}/T_{design})	# crossings outwards	Loading (T_{mean}/T_{design})
Bulk carrier	1540	89%	1528	65%
Container Ship	9476	85%	9454	84%
General Dry Cargo	8407	82%	8338	78%
LNG ship	49	86%	48	83%
LPG ship	622	87%	631	76%
Miscellaneous	9946	65%	9952	64%
Oil tanker	3399	75%	3410	60%
Passenger / Ferry	2989	71%	2984	70%
RoRo ship	4318	86%	4326	85%
Supply vessel	227	86%	239	85%
Total	40973	82%	40910	74%

As can be seen many ships in Dutch waters sail with a relatively constant loading, about 15-20% lower than their design load condition. The following simplified load operating profile can be made (Table 2):

Table 2: Mean operating profile based on AIS crossings in Rotterdam Harbour

Ship type	% of time	Loading
Bulk carrier	50%	88%
	50%	65%
oil tanker	50%	76%
	50%	60%
general dry cargo	100%	80%
passenger/ferry	100%	70%
RoRo, Container, Supply	100%	85%

[1] Looije 2015, Comparison of draft information AIS and HAMIS data, MARIN report 70045-604-MSCN

The relationship between relative draft and power is not linear. The admiralty coefficient, defined as

$$\frac{\nabla_1^{2/3} V_1^3}{P_1} = \frac{\nabla_2^{2/3} V_2^3}{P_2}$$

is sometimes used to predict the relationship between displacement (∇), ship speed (V) and shaft power (P) in two conditions. According to this relationship a ship sailing at 85% of its design displacement will require approx. 89% of the power that is required in design load conditions. In practice this varies greatly. Many ships are equipped with a bulbous bow, and are designed for a narrow draft range to get the highest efficiency gain from this. Part-load operation may result in a increase in hull resistance if the bow is not submerged correctly. For 17 ships of various type and size the relationship between sailing in ballast and sailing in design conditions was evaluated based om model tests. The results are shown in Figure 14.

The model test results show that there is a large variation in power in part load conditions. For some ships the power decreases in accordance with the Admiralty coefficient as the displacement reduces, for others the power may even increase. This is due to the large variability in hull forms and design conditions. Without specific hull information it is practically impossible to predict the part-load performance of ships. It is therefore questionable whether a correction for displacement variations would increase the precision of the emission prediction model. Yet, the assumption that the in-service speed-power curve is comparable to design draft is incorrect; in most cases the power requirement between 60-80% of the displacement is lower than at design draft as shown in Figure 14.

A correction factor can be assumed to account for this lower power requirement, e.g. 10% based on Figure 14. However, this will not improve the accuracy of the model for individual ships; it will only result in a bias offset of the predictions. As shown in Figure 2 the average prediction accuracy is within a few percent for the tested ships. Including an e.g. 10% correction to power will result in too low predicted emissions.
Most ships sail with a slightly fouled hull, which increases the hull resistance. Also windage and wave resistance is not considered in the model, and results in a higher resistance compared to calm weather. Since the average predicted ship emissions are in line with the reported ship emissions, it seems that the latter factors cancel each other out. Even with the availability of high frequent draft information (e.g. from AIS data), a simple general applicable correction for displacement to improve emission predictions does not seem feasible. Detailed hull form data is necessary for this.

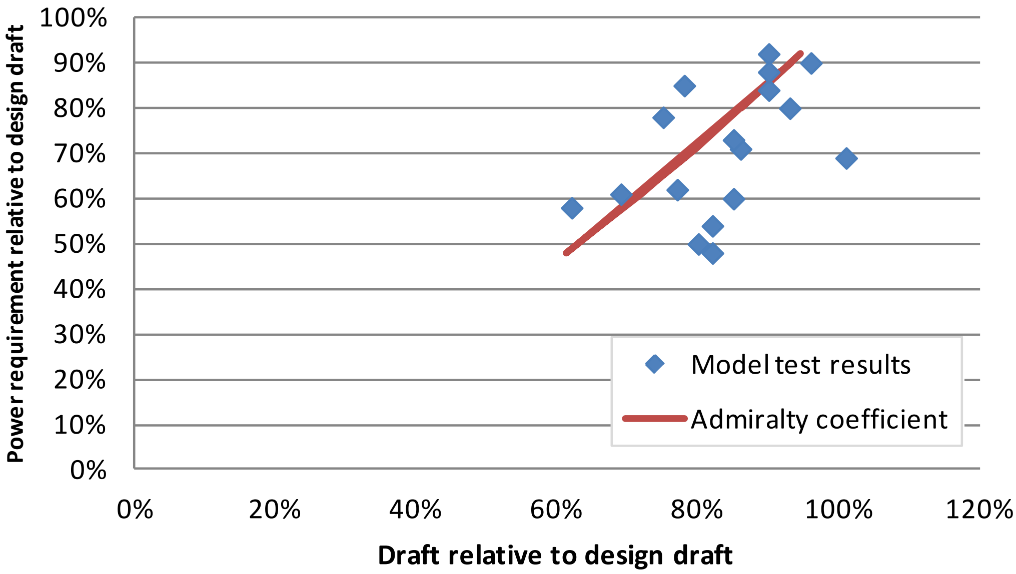

Figure 14: Relationship between loading and power requirement for 17 ships

5 CONCLUSIONS AND RECOMMENDATIONS

The Emission prediction model of TNO was evaluated using noon report data of 91 vessels, with the objective to make an inventory of areas where energy consumption may be relevant for emission models and to evaluate the existing shipping emissions. The following conclusions summarise the findings of the present project:

- The TNO emission model provides a practical way to quickly estimate ship emission figures for a large number of ships. Based on 91 analysed vessels, the average bias error in fuel consumption compared to reported fuel consumption figures is within a few percent
- The correction factor for prediction of power in off-design speed conditions can be improved by assuming a speed-power curve in the form of $P=V^{3.2}$ for speeds in the region 60-100% of the design speed
- When the emission model is used to calculate emissions based on annual average speed, the influence of speed variations are not taken into account. Using noon report data from 91 ships it was shown that no general applicable speed operating profiles can be determined that improve the accuracy of emission predictions. For best results, the emission model should be used with high frequent speed data (e.g. from AIS) so that speed variations can be included.
- Most ships sailing in Dutch waters sail at between 70-85% design draft. The hull resistance at this displacement is lower than in design draft, that is used by the model. This gives an offset in resistance prediction. However, hull fouling, windage and wave resistance result in an increase in resistance, which counterbalances the reduction in resistance due to lower displacement. Due to the large variability in hull form no general applicable correction factor can be made to account for displacement variations.

Wageningen, August 2018
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APPENDICES

APPENDIX I TNO Emission model description

Extracted from MARIN report 30508-1-mscn
Written by Jan Hulskotte, TNO

A1.1 Main Engines

During sailing and manoeuvring, the main engine(s) are used to propel/manoeuvre the ship. Their emission factors per ship, in g per kWh, were determined by TNO according to the EMS protocols [1, 2]. An English language report [5] is available, which covers the emission calculations in accordance with the EMS protocols. In the emission factor calculation, the nominal engine power and speed are used. For this study these parameters were taken from the LLI database of September 2016 as far as new valid data were available. In the case that only one single main engine is present, it is assumed that a vessel requires 85% of its maximum continuous rating power (MCR) to attain the design speed (its service speed). When multiple main engines are present some more assumptions have to be made in order to calculate the required power of the main engines. This is described in the next paragraph 0.

The following formula is used to calculate the emission factor per nautical mile.

Formula 1:

$$EF' = EF * CEF * \frac{P * fMCR}{V}$$

where:

EF'	Actual emission factor expressed as kg per nautical mile
EF	Basic engine emission factor expressed as kg per KWh (Table A-3/Table A-10)
CEF	Correction factors of basic engine emission factors (Table A-12/Table A-14))
P	Engine power [KiloWatts]
fMCR	Actual fraction of the MCR
V	Actual vessel speed [knots]

The correction factors of basic engine emission factors (CEF) reflect the phenomena that cause the emission factors to change when engines are active in sub-optimal power ranges.

Besides this change in emission factors, ships do not always sail at their designed speed. As such, the actual power use has to be corrected for the actual speed. The power requirements are approximately proportional to the ship's speed to the power of three. For very low speeds this approximation would underestimate the required power, since manoeuvring in restricted waters increases the required power. Furthermore, engines are not capable of running below a certain load (minimal fuel consumption of 10% compared to full load). To account for this, the cubed relationship between speed and power is adjusted slightly to:

Formula 2:

$$fMCR = CRS_{cor} * 0.85 = \frac{\left[\left(V_{actual} / V_{design}\right)^{3} + 0.2\right]}{1.2} * 0.85$$

Note that the Correction Reduced Speed factor CRS_{cor} has to be capped at a maximum of 1.176, since this is the value for which 100% engine power is reached. In Figure A-1 the relationship is shown between the speed relative to the service speed and the power relative to the rated power of the ships single propulsion engine as implied in formula 2.

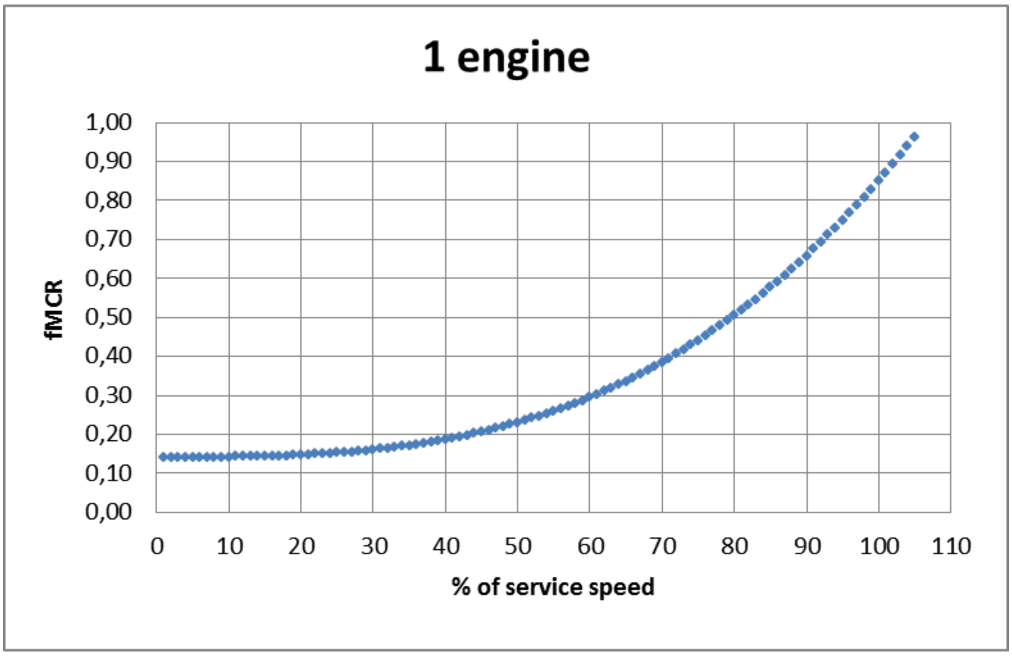

Figure A- 1 The relationship between service speed and fMCR at ships with one single propulsion engine used in emission calculations

A1.2 Multiple propulsion engines

When a ship has multiple main propulsion engines, probably not all of these engines will be used in all situations. For instance, many specialised ships have specialised installations that are only used when these ships are performing their specialised tasks (dredgers, supply ships, icebreakers, tugs etc.). Other ships may have redundant engine capacity for safety and other reasons (passenger ships, roro-ships). It is rather difficult to account for the usage of multiple engines within emission calculations, since many differences will exist between individual ship designs. All kinds of possible situations which are not known from the AIS-data may have different influence on emissions from different ships types. Nevertheless, ignoring the existence of multiple engines is not realistic. The presence of multiple engines on some ship types (i.e. passenger and roro-ships) could lead to serious underestimation of total emissions because only the power of the largest engine was taken into account until the emission calculation for 2010.

Before going into an analysis of the usage of main engines when multiple engines are present, it is interesting to analyse which number of engines occurs so often that it has a significant influence on total emissions. In table A-1 it is shown that at ships with multiple engines, only ships with 2 and 4 engines contribute significantly to the total installed power of the whole seagoing fleet. The same conclusion will probably hold with respect to the contribution to total emissions. Therefore, it can be justified to concentrate the analysis on ships with 2 and 4 propulsion engines.

Table A- 1 World seagoing fleet with number of installed main engines and their total installed power and average installed power per ship

Main Engine count	Ships count	Total power installed MW	Average power installed per ship MW	% of total power installed
1	109,489	534,901	4.9	80.9%
2	24,011	87,343	3.6	13.2%
3	926	4,459	4.8	0.7%
4	1,912	25,822	13.5	3.9%
5	89	1,551	17.4	0.23%
6	177	5,992	33.9	0.91%
7	4	139	34.8	0.02%
8	31	1,017	32.8	0.15%
9	6	261	43.5	0.04%
10	1	3.0	3.0	0.00%
12	2	15.6	7.8	0.00%
	136,648	661,504	4.8	100.0%

As a data source for daily fuel usage the ship characteristic database-item FUEL_CONSUMPTION of the LLI database was analysed. Daily fuel consumption is given for only about 10.000 ships. By far, most of these 10.000 ships are ships with a single main engine. In order to perform a check on the emission calculation, a check on the fuel consumption serves as a very good proxy. When fuel consumption is modelled properly, emission calculation probably will give results with comparable accuracy.

To estimate the daily fuel consumption of a ship (ton/day) we applied a very simple formula:
FC = Active_Engines * MCRss * Power * SFOC * 24/1000.

FC : Daily fuel oil consumption (ton/day)
Active_Engines : number of active engines involved in normal propulsion (-)
MCRss : fraction of power to reach service speed (0.85 for single engine ships, for more engines see table **A-2**)
Power : power of a single engine (MW)
SFOC : specific fuel oil consumption (kg/MWh)
24/1000 : 24 hours/day;1000 kg/ton

Note that the calculation of fuel consumptions is completely parallel to the calculation of emissions. Instead of EF, approximate values of the SFOC are used. Because (in the LLI database) the service speed is assumed, the values of CEF in the calculation can be ignored because the values will be very close to 1.

The SFOC (specific fuel oil consumption) applied is 0.175 (kg/kWh) for engines above 3 MW and 0.200 (kg/kWh) for engines equal to and below 3 MW. As a reference for these values, see for instance the tables A-3 to A-6.

As a reference for ships with multiple engines, the fuel consumption of ships with 1 main engine is shown. So far, a power setting of 85% MCR is assumed in modelling ship's emissions. It can be seen in Figure A2 that this assumption gives rather accurate results for the majority of ships (but not all ships) with one main engine. The 7918 ships of which data on fuel consumption was available had an average *calculated* fuel consumption of 24.8 ton/day by the main engine while the average *specified* fuel consumption was 26.1 ton/day. This implies that calculated fuel consumption (on average) on the service speed seems to be 5% lower than the specified fuel consumption. Given the number of possible uncertainties this does not seem to be a major difference.

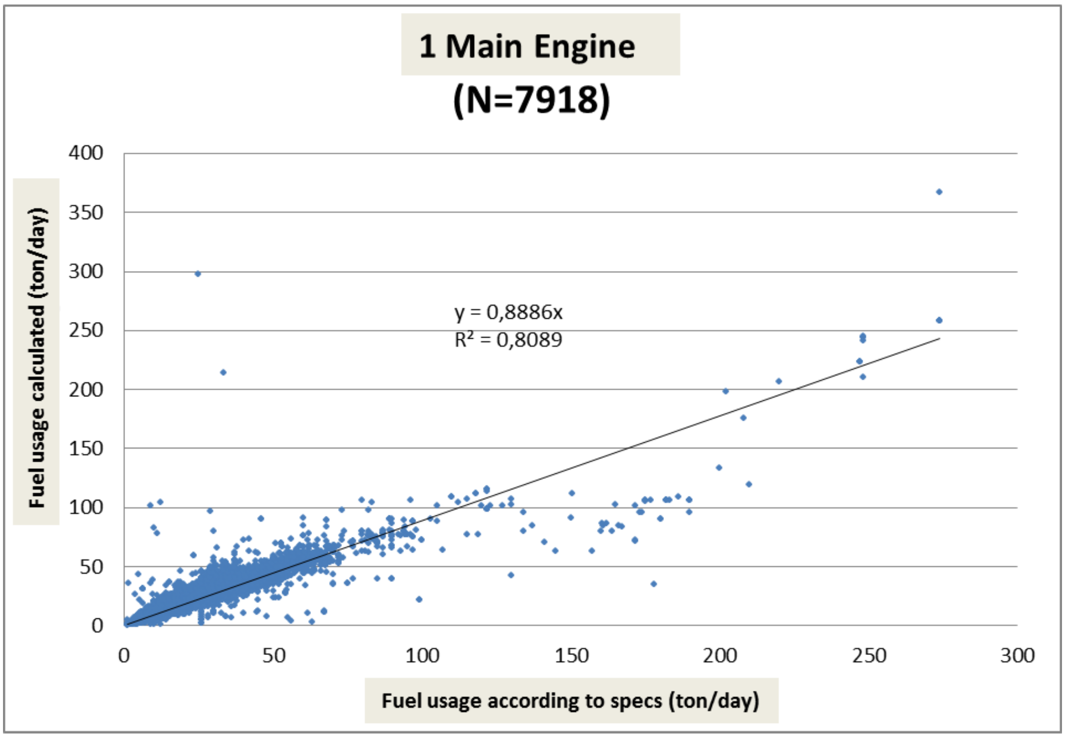

Figure A- 2 Calculated daily fuel usage of one engine ships compared with specifications

For ships with two main engines two active engines were assumed and 75% MCR (instead of the standard of 85% [13]) to reach the service speed. It can be seen in Figure A-3 that these assumptions give rather accurate results for the majority of ships with two main engines. The 546 ships of which data on fuel consumption are available show an average calculated fuel consumption of 35.7 ton/day while the average specified fuel consumption is 35.6 ton/day.

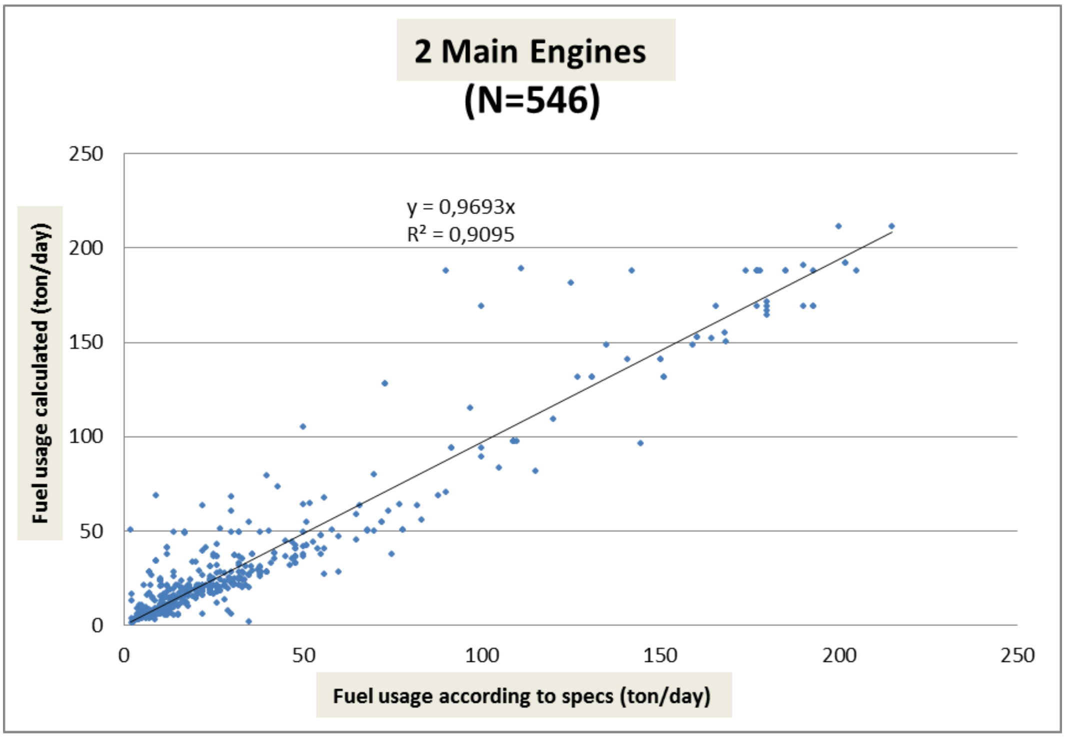

Figure A- 3 Calculated daily fuel usage of two engine ships compared with specifications

For ships with four main engines four active engines were assumed and also 75% MCR (instead of the standard of 85%) to reach the service speed. As can be seen in Figure A-4 much less data is available for four engine ships which causes more scatter in the data. The 29 ships of which data are available show an average *calculated* fuel consumption of 39.2 ton/day while the average *specified* fuel consumption is 32.8 ton/day.

It has to be mentioned that some data filtering was applied to four engine ships. Excluded in the analysis are special cases such as high speed ferries, supply and service vessels, tugs and fishing ships and one ship mainly propelled by LNG.

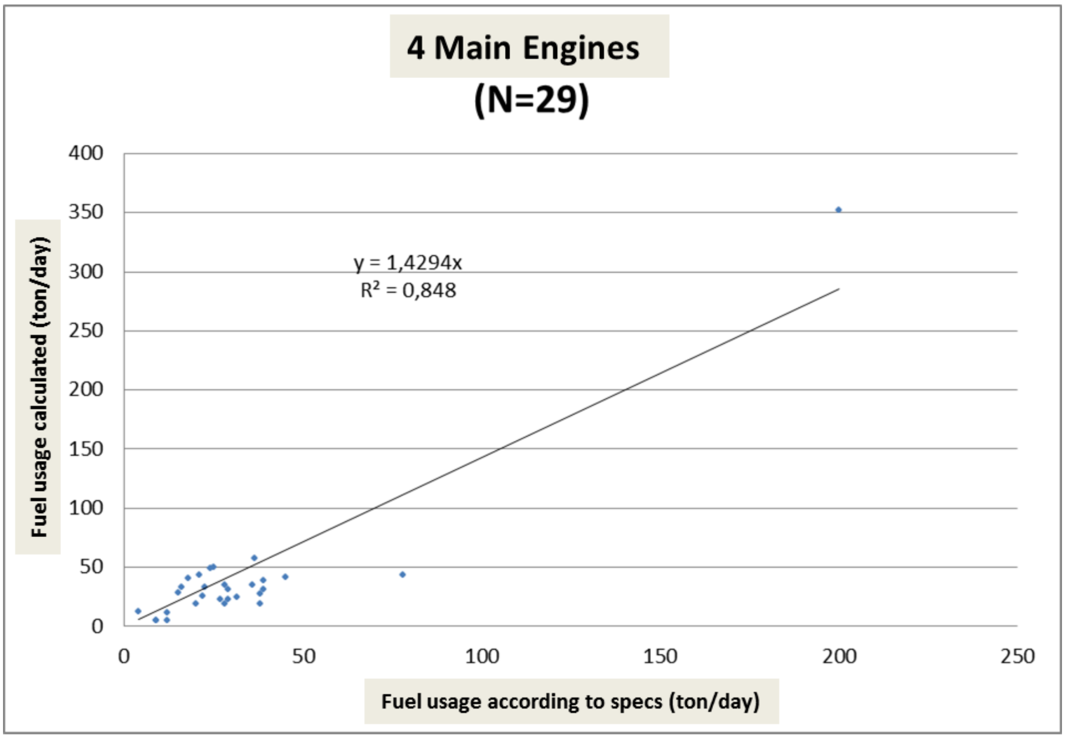

Figure A- 4 Calculated daily fuel usage of four engine ships compared with specifications

It can be argued that energy consumption of four engine ships seems to be overestimated by the assumptions that are applied, but with such a small dataset it is hard to determine whether the assumptions on ships with four main engines are correct or not. Even if there is an overestimation, this will probably not lead to big differences in total emissions, since the contribution of four engine ships in total installed power is below 4% (Table A- 1).

For ships with other numbers of main engines the available data did not allow any check of possible assumptions on the fuel consumption.

Apart from the check of fuel consumption of two and four engine ships as presented above, for ships with three or five to twelve engines additional assumptions had to made in order to enable calculation of emissions of these ships. These assumptions are shown in Table A-2 and are rather uncertain. However, the total installed power is only 2% and therefore, the influence on total emissions will be minimal.

Table A- 2 Maximum number of engines assumed to be operational for propulsion with multiple engines present and the fraction of MCR assumed (MCR_{ss}) to attain the service speed

Ship type	**Engines Present →** / **Engines Operational ↓**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**12**
Oil tanker	2	0.75	0.85								
	4			0.75							
Chemical/LNG/LPG tanker	2	0.75	0.85								
	4			0.75		0.75					
	6								0.75		
Bulk carrier	2	0.75	0.85								
	4			0.75	0.75	0.75					
Container ship	2	0.75	0.85								
	4			0.75	0.75	0.75	0.75	0.75			
	6								0.75	0.75	
General Dry Cargo	2	0.75	0.85								
	4			0.75	0.75	0.75		0.75			
RoRo Cargo / Vehicle	2	0.75	0.85								
	4			0.75	0.75	0.75		0.75			
Reefer	2	0.75	0.85								
	4			0.75	0.75						
Passenger	2	0.75	0.85	0.75		0.75			0.75		
Miscellaneous	2	0.75									
	4			0.75							
Tug/Supply	2	0.65	0.85	0.8	0.75	0.85	0.75	0.75	0.75		0.75
Fishing	2	0.75	0.85								
Non Merchant	2	0.5	0.85	0.75	0.75	0.75	0.75	0.75			0.75

The calculation of emissions with multiple engines becomes more complicated because the number of active engines has to be calculated separately. For this reason the calculation of EF' is slightly different from formula 1.

Formula 3:

$$EF' = EF * CEF * \frac{NoEA * P * fMCR}{V}$$

EF' Actual emission factor expressed as kg per nautical mile
EF Basic engine emission factor expressed as kg per KWh (Table A-3/Table A-10)
CEF Correction factors of basic engine emission factors (Table A12/Table A-14)
NoEA Number of active engines (engines that actually are working on a certain moment)
P Engine power of one single engine [Watts]
*f*MCR Actual fraction the MCR of active engines
V Actual vessel speed [knots]

Formula 4:

NoEA =
minimum (Engines Operational, round (CRS_{cor} * Engines Operational * MCR_{ss})+1)

(Note that the Number of active engines depends on the level of CRScor, which depends on the ships speed, and that the maximum number of active engines is equal to Engines Operational).

Formula 5:

*f*MCR= [Engines Operational]/NoEA * CRScor * MCRss

The *f*MCR for individual ship engines is linear inversely related to the Number of active engines (more engines active give lighter work for individual engines). In essence Formula 3 is the same as Formula 1 except the accounting of Engines Active in the available total Engine power and the application of modified *f*MCR in the selection of the CEF-values (Formula 5).

In Figure A-5 the relationship is shown between the speed relative to the service speed and the power relative to the rated power of the ships propulsion engines at ships with 4 propulsion engines as implied in formula 4 and 5.

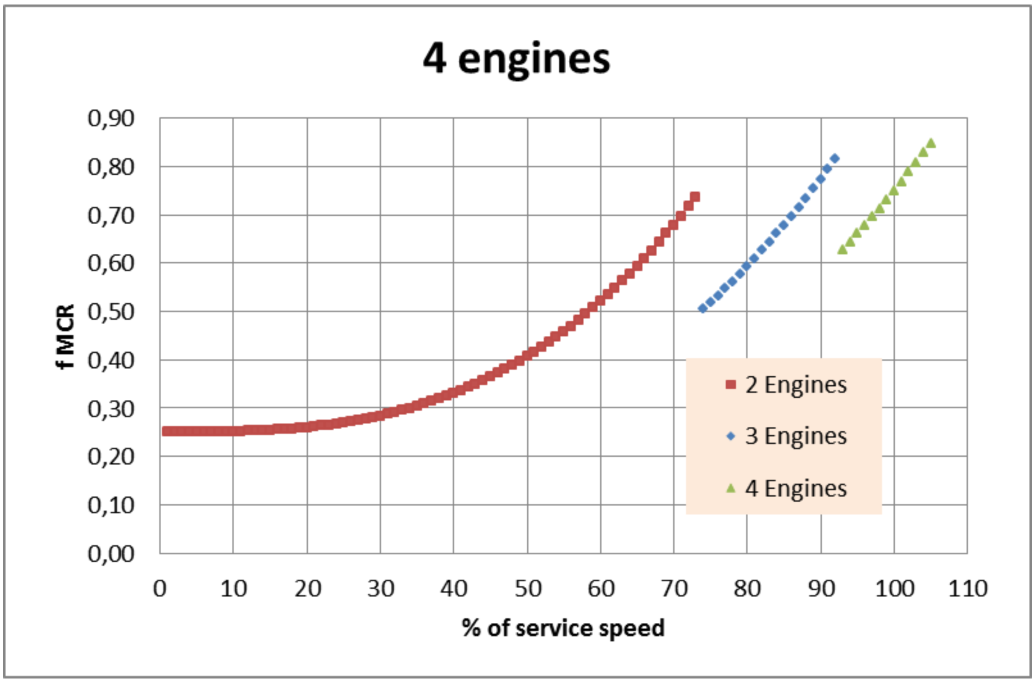

Figure A- 5 The relationship between service speed and fMCR at ships with four propulsion engines as used in emission calculations (formula 4 and 5)

A1.3 Auxiliary Engines and Equipment

Aside from the main engines, most vessels have auxiliary engines and equipment that provide (electrical) power to the ship's systems. There is very little information available on the use of auxiliary engines. Perhaps the best estimate to date has been made in the *Updated 2000 Study on Greenhouse Gas Emissions from Ships* report (Buhaug et al., 2008, [3]), to which many ship experts contributed. The percentage of the auxiliary power compared to the main engine power as presented in Table 14 of the Buhaug et al report [3] was used in this study. The percentage taken from Buhaug was multiplied with the main power of each individual ship of which no details of auxiliary power are included in the LLI-database. For those ships of which the auxiliary power was included in the LLI-database, the loadfactor of auxiliary engines given by Buhaug specified per ship type was applied on the biggest auxiliary engine of the individual ship as inferred from the LLI-database.

A1.4 Engine Emission Factors

Table A-3 to Table A-10 show the engine emission factors [1], [2] per engine type and fuel type expressed in grams per unit of mechanical energy delivered by ships engines (g/kWh). Partial implementation of the SECA according to the MARPOL Annex VI in 2016 has been assumed. The reason behind this decision is that very little response by national government(s) in Europe has been observed on the Trident Alliance initiative (a group of important stakeholders demanding proper enforcement). As a consequence, the sulphur percentage in heavy fuel oil is set on 0.5% and the sulphur percentage in marine diesel oil is assumed to be 0.25% in the NCP part of the SECA. In the harbour areas, however, full implementation is assumed (all fuels set on 0.1% m/m sulphur).
Linear relations exist between SFOC and SO2 and CO2 depending on fuel quality. SFOC values as such are not used in emission calculations.
PM-reduction is associated with sulphur reduction because a certain fraction of oxidised sulphur is emitted as sulphuric acid which easily condenses to sulphuric acid particles (PM) in exhaust gases. Based on the sulphur reductions, additional PM reductions were estimated applying a linear relationship between sulphur and PM as demonstrated in [12].

Table A- 3 Emission factors and specific fuel oil consumption (SFOC) applied on slow speed engines (SP) operated on heavy fuel oil (HFO), (g/kWh)

Year of build	NO_x	PM-HFO NCP[2]	PM-HFO Other[3]	SO_2 NCP	SO_2 Other	VOC	CO	CO_2	SFOC
1900 – 1973	16	0.47	0.43	0.84	0.42	0.6	0.75	666	210
1974 – 1979	18	0.46	0.43	0.80	0.40	0.6	0.75	635	200
1980 – 1984	19	0.46	0.43	0.76	0.38	0.6	0.75	603	190
1985 – 1989	20	0.46	0.43	0.72	0.36	0.6	0.63	571	180
1990 – 1994	18	0.46	0.43	0.70	0.35	0.5	0.5	555	175
1995 – 1999	15	0.35	0.33	0.68	0.34	0.4	0.5	539	170
2000 – 2010	~rpm[4]	0.35	0.33	0.67	0.34	0.3	0.5	533	168
2011 – 2016		0.25	0.23	0.66	0.33	0.3	0.5	524	165

[2] NCP: Dutch Continental Shelf
[3] Other areas: Include harbours areas
[4] Dependant on revolutions per minute (Table A-8)

Table A- 4 Emission factors and specific fuel oil consumption (SFOC) applied on slow speed engines (SP) operated on marine diesel oil (MDO), (g/kWh)

Year of	NO_x	PM-MDO NCP	PM-MDO Other	SO_2 NCP	SO_2 Other	VOC	CO	CO_2	SFOC
1900 - 1973	16	0.37	0.33	0.84	0.42	0.6	0.75	666	210
1974 - 1979	18	0.36	0.33	0.80	0.40	0.6	0.75	635	200
1980 - 1984	19	0.36	0.33	0.76	0.38	0.6	0.75	603	190
1985 – 1989	20	0.36	0.33	0.72	0.36	0.6	0.63	571	180
1990 – 1994	18	0.36	0.33	0.70	0.35	0.5	0.5	555	175
1995 – 1999	15	0.25	0.23	0.68	0.34	0.4	0.5	539	170
2000 – 2010	~rpm[1]	0.25	0.23	0.67	0.34	0.3	0.5	533	168
2011 – 2016		0.25	0.23	0.66	0.33	0.3	0.5	523	165

Table A- 5 Emission factors and specific fuel oil consumption (SFOC) applied on medium/high speed engines (MS) operated on Heavy fuel oil (HFO), (g/kWh)

Year of build	NO_x	PM-HFO NCP	PM-HFO Other	SO_2 NCP	SO_2 Other	VOC	CO	CO_2	SFOC
1900 – 1973	12	0.67	0.64	0.90	0.45	0.6	0.75	714	225
1974 – 1979	14	0.67	0.63	0.86	0.43	0.6	0.75	682	215
1980 – 1984	15	0.67	0.63	0.82	0.41	0.6	0.75	651	205
1985 – 1989	16	0.66	0.63	0.78	0.39	0.6	0.63	619	195
1990 – 1994	14	0.66	0.63	0.76	0.38	0.5	0.5	603	190
1995 – 1999	11	0.56	0.53	0.74	0.37	0.4	0.5	587	185
2000 – 2010	~rpm[1] 9[2]	0.56	0.53	0.73	0.37	0.3	0.5	581	183
2011 - 2016	~rpm 7[2]	0.56	0.53	0.90	0.36	0.3	0.5	571	180

Table A- 6 Emission factors and specific fuel oil consumption (SFOC) applied on medium/high speed engines (MS) operated on marine diesel oil (MDO), (g/kWh)

Year of build	NO_X	PM-MDO NCP	PM-MDO Other	SO_2 NCP	SO_2 Other	VOC	CO	CO_2	SFOC
1900 - 1973	12	0.37	0.33	0.90	0.45	0.6	0.75	714	225
1974 - 1979	14	0.37	0.33	0.86	0.43	0.6	0.75	682	215
1980 - 1984	15	0.37	0.33	0.82	0.41	0.6	0.75	650	205
1985 - 1989	16	0.36	0.33	0.78	0.39	0.6	0.63	619	195
1990 - 1994	14	0.31	0.33	0.76	0.38	0.5	0.5	603	190
1995 - 1999	11	0.26	0.23	0.74	0.37	0.4	0.5	587	185
2000 - 2010	~rpm[1] 9[2]	0.26	0.23	0.73	0.37	0.3	0.5	581	183
2011 - 2016	~rpm[1] 7[2]	0.26	0.23	0.72	0.36	0.3	0.5	571	180

[2] applied on auxiliary engines only

Emission factors of CO were reduced by a factor of 4 according to [16]. Emission factors of PM and SO2 at NCP were lowered based on observations of Chalmers University in commission of the Danish Ministry of Environment and Food concerning the enforcement of IMO SECA [17] .

Table A- 7 Emission factors of NO_X dependant on engines RPM

Year of build	RPM range	IMO-limits (g/kWh)	Emission factor NO_X (g/kWh)
2000 – 2010 (Tier I)	< 130 RPM	17.0	0.87 x 17.0
	Between 130 and 2000 RPM	$45 \times n^{-0.2}$	$0.87 \times 45 \times n^{-0.2}$
	> 2000 RPM	9.8	0.87 x 9.8
2011 – 2016 (Tier II)	< 130 RPM	14.4	0.93 x 17.0
	Between 130 and 2000 RPM	$44 \times n^{-0.23}$	$0.93 \times 44 \times n^{-0.23}$
	> 2000 RPM	7.7	0.93 x 7.7

The reduction factor for Tier II engines was adjusted from 0.85 to 0.93 and the reduction factor for Tier I engines was adjusted from 0.85 to 0.87. The information was based on IAPP-certificate engine data obtained in a project for the Port of London Authority (report still in preparation).

Table A- 8 Emission factors and specific fuel oil consumption (SFOC) of gas turbines (TB) operated on marine diesel oil (MDO), (g/kWh)

Fuel	NO_X	PM-MDO NCP	PM-MDO Other	SO_2 NCP	SO_2 Other	VOC	CO	CO_2	SFOC
MDO	5.7	0.140	0.065	1.55	0.62	0.1	0.32	984	310

Emission factors of steam turbines were partially adjusted according to Cooper [9].

Table A- 9 Emission factors and specific fuel oil consumption (SFOC) of steam turbines (ST) operated on LNG, HFO or MDO

Fuel	NO_X	PM NCP	PM Other	SO_2 NCP	SO_2 Other	CH4	VOC	CO	CO_2	SFOC
LNG	1.94	0.01	0.01	0.0	0.0	0.045		0.06	688	250
HFO	2.0	0.495	0.300	3.06	0.61		0.1	0.15	971	306
MDO	2.0	0.490	0.295	1.45	0.58		0.1	0.15	923	291

Emissions of more modern LNG tanker propelled mostly propelled by medium speed diesel engines fuelled by LNG were calculated by means of emission factors as shown in the table below.

Table A- 10 Emission factors and specific fuel oil consumption (SFOC) of medium speed engines (MS) operated on LNG, (g/kWh)

Fuel	NO_X	PM	SO_2	CH4	CO	CO_2	SFOC
LNG	2.0	0.02	0.0	2.43	0.2	450	162

The change-over from fuels at LNG-tankers in the model calculations is assumed dependent on the speed of the ships expressed as CRScor. Below a value of CRScor of 0.2 LNG-tankers switch from gaseous LNG to liquid fuel used by main engines according to the scheme presented in the table below. The fuels assumed to be used by auxiliary engines are also presented in the same table A-11.

Table A- 11 Fuel switch scheme of LNG-tankers in dependence of operational speed

Engine type	Main engines		Auxiliary engines	
	0.2 <= CRScor < 1.2	0 <= CRScor < 0.2	0.2 <= CRScor < 1.2	0 <= CRScor < 0.2
MS	LNG	MDO	MDO	MDO
MS	LNG	HFO	HFO	MDO
ST	LNG	MDO	MDO	MDO
ST	LNG	HFO	HFO	MDO

A1.5 Correction factors of engine Emission Factors

At speeds around the design speed, the emissions are directly proportional to the engine's energy consumption. However, in light load conditions, the engine runs less efficiently. This phenomenon leads to a relative increase in emissions compared to the normal operating conditions. Depending on the engine load, correction factors specified per substance can be adopted according to the EMS protocols. The correction factors were extended by distinction of different engine types in order to get more accurate calculations. Three engine groups were discerned: reciprocating engines, steam turbines and gas turbines.
The correction factors used are shown in Table A-12 to Table A-14 The list was extended by some values provided in the documentation of the EXTREMIS model [4].

Table A- 12 Correction factors for reciprocating diesel engines

Power % of MCR	CO_2, SO_2 SP	CO_2, SO_2 MS	NO_X	PM-HFO/ PM-MDO	VOC, CH4	CO
10	1.2	1.21	1.34	1.63	4.46	5.22
15	1.15	1.18	1.17	1.32	2.74	3.51
20	1.1	1.15	1.1	1.19	2.02	2.66
25	1.07	1.13	1.06	1.12	1.65	2.14
30	1.06	1.11	1.04	1.08	1.42	1.8
35	1.05	1.09	1.03	1.05	1.27	1.56
40	1.045	1.07	1.02	1.03	1.16	1.38
45	1.035	1.05	1.01	1.01	1.09	1.23
50	1.03	1.04	1.00	1.01	1.03	1.12
55	1.025	1.03	1.00	1.00	1.00	1.06
60	1.015	1.02	0.99	1.00	0.98	1.00
65	1.01	1.01	0.99	0.99	0.95	0.94
70	1.00	1.01	0.98	0.99	0.92	0.88
75	1.00	1.00	0.98	0.98	0.89	0.82
80	1.01	1.00	0.97	0.98	0.87	0.76
85	1.02	1.00	0.97	0.97	0.84	0.7
90	1.03	1.01	0.97	0.97	0.85	0.7
95	1.04	1.02	0.97	0.97	0.86	0.7
100	1.05	1.02	0.97	0.97	0.87	0.7

The correction factors for CO_2 en SO_2 are assumed to be equal. These newly added factors for CO_2 and SO_2 were derived from two recent publications [10] and [11] by taking interpolated values. A distinction was made for Slow-speed engines (referred as SP) and Medium and high-speed engines (referred as MS). Although correction factors for other substances may differ by engine type also, a numerical distinction was not possible so far.

Since steam turbines are predominantly used by LNG-carriers two types of fuels were assumed to be consumed: LNG and HFO. It was assumed that at lower engine loads (up to CRScor = 0.2) steam turbines are operated by HFO. On higher loads (from CRScor = 0.2) usage of LNG (boil-off gas) is assumed. The source of the correction factors of steam turbines was taken from the EXTREMIS model [4].

Table A- 13 Correction factors for steam turbines

Power % of MCR	CO_2	SO_2	NO_X	PM-HFO	VOC, CH4	CO
10	1.4	3.04	0.3	3	5.44	11.65
15	1.4	3.04	0.34	2.8	5.11	10.83
20	1.4	3.04	0.37	2.8	4.72	9.96
25	1.4	3.04	0.41	2.8	4.39	9.09
30	1.2	2.02	0.44	1.5	4.00	8.26
35	1.00	1.00	0.47	1.00	3.61	7.39
40	1.00	1.00	0.51	1.00	3.28	6.57
45	1.00	1.00	0.54	1.00	2.89	5.7
50	1.00	1.00	0.57	1.00	2.56	4.83
55	1.00	1.00	0.61	1.00	2.17	4
60	1.00	1.00	0.64	1.00	1.83	3.13
65	1.00	1.00	0.68	1.00	1.44	2.26
70	1.00	1.00	0.76	1.00	1.33	1.96
75	1.00	1.00	0.84	1.00	1.22	1.65
80	1.00	1.00	0.92	1.00	1.11	1.30
85	1.00	1.00	1.00	1.00	1.00	1.00
90	1.00	1.00	1.00	1.00	1.00	1.00
95	1.00	1.00	1.00	1.00	1.00	1.00
100	1.00	1.00	1.00	1.00	1.00	1.00

Correction factors for gas turbines were estimated with data from the ICAO Aircraft Engine Emissions Databank [7]. The emission behaviour of the GE CF6-6D (marine derivative: GE LM2500) and the Allison 501 (AN 501) was taken as representative for the two most occurring gas turbines in marine applications. CEF values in low power ranges have been changed since the 2011 calculation because an adapted interpolation scheme has been applied.

Table A- 14 Correction factors for gas turbines

Power % of MCR	CO_2, SO_2	NO_X	PM-MDO	VOC	CO
10	1.26	0.23	0.98	48.71	64.4
15	1.17	0.3	0.95	37.73	51.15
20	1.04	0.41	0.9	22.35	32.6
25	0.96	0.48	0.88	13.02	21.34
30	0.87	0.55	0.85	2.58	8.75
35	0.88	0.58	0.84	2.46	7.98
40	0.89	0.61	0.84	2.33	7.2
45	0.91	0.64	0.83	2.21	6.42
50	0.92	0.67	0.82	2.08	5.65
55	0.93	0.7	0.81	1.96	4.88
60	0.94	0.74	0.8	1.83	4.1
65	0.95	0.77	0.8	1.71	3.32
70	0.96	0.8	0.79	1.58	2.55
75	0.97	0.83	0.78	1.46	1.77
80	0.98	0.86	0.78	1.33	1
85	0.99	0.93	0.89	1.17	1
90	0.99	0.95	0.92	1.1	1
95	1	0.98	0.96	1.05	1
100	1	1	1	1	1

A1 EMISSIONS OF SHIPS AT BERTH

When a ship is berthed, in most cases the main engines are stopped. The auxiliary engines and equipment will be kept in service to provide (electrical) power to the ship's systems, on board cargo handling systems and accommodations.

The procedure for the calculation of emissions from ships at berth is derived from the EMS protocol with some minor modifications. The methodology was published in Atmospheric Environment [8]. In the EMS modelling system, a fixed value is assumed for the length of time at berth, for each ship type. In this study, the length of time at berth was derived for each individual event for each ship on the basis of AIS data. Ships with speeds below 1 knot were considered as ships at berth. Since the year of build of each ship was known, emission factors per amount of fuel dependant on the classification of year of build were applied. The amount of fuel used was calculated from the length of time at berth, ship type and volume in gross tonnage. The amount of fuel used at berth is more accurately determined in two reports on behalf of the CNSS project [14] , [15].

Table A- 15 Fuel rate of ships at berth, (kg/1000 GT.hour)

Ship type	Fuel rate
Bulk carrier	2.4
Container ship	6
General Cargo	6.1
Passenger <=30000 GT	8.9
Passenger > 30000 GT	32.4
RoRo Cargo	6.1
Oil Tanker	19.3
Other Tanker	14.5
Reefer	19.6
Other	9.2
Tug/Supply	15.6

Since January 1st 2010 the sulphur content of marine fuels used for ships at berth is regulated to a maximum of 0.1 percent. This implies that only marine gas oil with a sulphur content below 0.1 percent is allowed in harbours. The specification of fuel types at berth is adapted according to this new regulation (Table A- 16).

Table A- 16 Specification of fuel types of ships at berth per ship type (%)

Ship type	HFO	MDO	MGO/ULMF
Bulk carrier	0	0	100
Container ship	0	0	100
General Cargo	0	0	100
Passenger	0	0	100
RoRo Cargo	0	0	100
Oil Tanker	0	0	100
Other Tanker	0	0	100
Fishing	0	0	100
Reefer	0	0	100
Other	0	0	100
Tug/Supply	0	0	100

Table A-17 gives figures about allocation of fuel amount over engine types and apparatus during berth.

Table A- 17 Allocation of fuels usage in engine types and apparatus per ship type (%)

Ship type	Power (MS)	Boiler
Bulk carrier	90	10
Container ship	70	30
General Cargo	90	10
Passenger	70	30
RoRo Cargo	70	30
Oil Tanker	20	80
Other Tanker	50	50
Reefer	90	10
Other	100	0
Tug/Supply	100	0

In following Table A-18 to Table A- 21, the emission factors used for emissions at berth are presented.

Table A- 18 Emission factors of medium/high speed engines (MS) at berth, (g/kg fuel)

Year of build	NO_X	PM-MDO	VOC	CO
Fuel	all	MGO/ULMF	all	all
1900 – 1973	53	1.4	2.7	13
1974 – 1979	65	1.5	2.8	14
1980 – 1984	73	1.6	2.9	15
1985 – 1989	82	1.8	3.1	13
1990 – 1994	74	1.3	2.6	11
1995 – 1999	59	0.8	2.2	11
2000 – 2010	49	0.8	1.6	11
2011 – 2016	39	0.8	1.6	11

At berth usage of medium speed engines was assumed.

Table A- 19 Emission factors of boilers of boilers at berth, (g/kg fuel)

Fuel	NO_X	PM-MDO	VOC	CO
MGO/ULMF	3.5	0.7	0.8	1.6

Table A- 20 Emission factors of all engines and apparatus, (g/kg fuel)

Fuel	SO_2	CO_2
MGO/ULMF	4	3150

In tanker ships a reduction factor for boilers (50% for PM and 90% for SO_2) is applied to the emission factors, because gas scrubbers are often applied in order to protect ship internal spaces for corrosion by inert gases produced by boilers.

A2 FISHERIES

Fisheries source category covers emissions from fishing activities in the Netherlands, including inland fishing, coastal fishing and deep-sea fishing. Diesel engines are used to propel fishing vessels such as deep-sea trawlers and cutters, and to generate electrical power on-board fishing vessels. These diesel engines can be fuelled with either diesel oil (distillate) or residual fuel oil. The combustion process that takes place in these diesel engines causes emissions of greenhouse gases and air pollutants.

A3.1 Activity data

Two methodologies based on AIS-data are applied from 2016 onwards. For deep-sea trawlers the same AIS-based methodology as used for maritime navigation is applied (see Table A- 21) because essentially no fishing activities are performed on Dutch national territory, including the Dutch Continental Shelf. This means that these vessels essentially are only sailing towards and from remote fishing grounds. For the other fishing vessel categories (rather small vessels mostly cutters) another AIS-based methodology is described in detail by Hulskotte and ter Brake, 2017 [18]. This is essentially an energy based method whereby energy-rates of fishing vessels are split up by activity (sailing and fishing) with a distinction in available power of propulsion engine(s). For each fishery segment (combination of gear or catch method combined with power category) a fuel rate (kilogram/hour) for sailing or fishing was assessed by Turenhout et al., 2016 [19]. The distinction for each fishery segment between sailing and fishing is based on the actual speed of the fishing vessels as taken from AIS-data.

A3.2 Emission factors

The emission factors of small vessels (other than deep-sea trawlers) are assumed to be equal to emission factors of inland navigation because the engine types that are applied in these vessels are essentially the same.

Table A- 21 Emission factors and specific fuel consumption applied on fishing vessels, (g/kWh)

Engine year of build		VOC	NOx	CO	PM	SFOC
From	Till					
1959	1973	1.2	10.8	4.5	0.6	235
1975	1979	0.8	10.6	3.7	0.6	230
1980	1984	0.7	10.4	3.1	0.6	225
1985	1989	0.6	10.1	2.6	0.5	220
1990	1994	0.5	10.1	2.2	0.4	220
1995	2001	0.4	9.4	1.8	0.3	205
2002	2007	0.3	9.2	1.5	0.3	200
2008	2014	0.2	7	1.3	0.2	200
2015	2016	0.2	7	1.3	0.2	195

The year of build of the engines of (Dutch and former Dutch) fishing ships were initially purchased from Shipdata (http://www.shipdata.nl) in order to select the emission factors from table A-21. Part of this data concerned the engine type and model and the year of build. Data were enriched with engine changes when indicated on the website http://www.kotterfoto.nl and data of foreign fishing ships (including installing data of new engines) were added from the combined European fishing registers or the FIGIS-database managed by FAO.
As a fuel ultra low sulphur diesel fuel compliant with EN-590 specification was assumed to be used by the small fishery cutters.

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