EVALUATION OF EMISSION FACTORS ON THE ESTIMATION OF NOX FORMATION FROM A MANOEUVRING SHIP

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ABSTRACT

Oxides of Nitrogen (NO_X) are particularly harmful to human health, as such their emissions are closely monitored and controls are becoming increasingly stringent, especially in Emission Control Areas.

Currently NO_X control is achieved through the survey and certification requirements, as well as demonstration of in-service compliance. A mechanism to estimate in-service compliance allows designers to play out scenarios and study the impact of ship operations on the environment, including at the design stage. One potential route to achieve this is the use of Emission Factors; however several types exist and can generate quite different results. The reason for this discrepancy is due to NO_X formation being dependent upon engine operating conditions, and different Emission Factors treat this aspect in different ways.

As NO_X is dependent upon engine running conditions, and therefore ship operation, it is worthwhile evaluating the different Emission Factors on NO_X formation, especially as ships tend to spend more time in manoeuvring conditions around population dense areas such as inland waterways, ports and harbours.

The emission factors examined range from constant across the whole range of engine loads, constant across different modes of operation, to variable as a function of power and speed. It is suggested that Emission Factors which account for engine running conditions better represent reality compared to constant factors.

This paper describes the use of a ship manoeuvring simulator in conjunction with different Emission Factors to investigate the magnitude in deviation of NO_X emissions from standard ship manoeuvres.

Keywords: Emissions, Simulation, Off Design Condition,

1. INTRODUCTION

Mandatory regulations from bodies such as the International Maritime Organisation (IMO) restrict the amount of exhaust gas emissions from ships (MARPOL, 2005). Certain exhaust gas species are known to be harmful to human health and contribute to environmental problems such as global warming and acid rain. For these reasons mechanisms are required to estimate the amount of exhaust gas emissions produced from operating ships.

Ships frequently operate in transient, unsteady conditions, due to their response of unsteady environmental loading, or from manoeuvring in and around inland waterways, ports and harbours. The later has strong implications for estimation of NO_X emissions, a strong carcinogen. This transient operation can produce fuel consumption and exhaust gas emission estimates that are quite different to averaged steady-state calculations.

In order to examine the effect of ship operation on exhaust gas emissions, three species were chosen for analysis, Carbon Dioxide (CO_2), Oxides of Sulphur (SO_X) and Oxides of Nitrogen (NO_X). The former two species are not strongly dependent on engine operating conditions, whereas the latter, NO_X, is highly dependent on engine operating conditions. The same principle used in this study can also be used for other exhaust gas species.

Exhaust gas emission estimation is achieved through the use of emission factors (EF). Two types of emission factors are used; commonly used operation-independent factors for CO_2, SO_X and NO_X, and for comparison, a separate operation-dependent factor for NO_X is also used.

This paper discusses the use of a manoeuvring simulator coupled with exhaust gas emission factors to investigate the effect of transient and steady-state operation on exhaust gas emissions. The purpose is to raise awareness of the differences in magnitude resulting from using different emission factors for different operating conditions.

Case studies are developed which enable comparisons between different operating conditions, and different emission factors.

The exhaust-gas emissions models can be readily incorporated into other existing bridge and/or engine simulators to raise awareness of the effect of operation on emissions, perhaps akin to a speed-over-ground gauge.

2. METHODOLOGY

In order to simulate the effects that transient manoeuvring motion has on exhaust gas emissions, emission factors are incorporated into a manoeuvring simulator.

The simulation is stopped after the ship has travelled 10 nautical miles for each manoeuvre, representing a hypothetical voyage. The basis ship used in this study is the Esso Osaka, a ship which has undergone numerous manoeuvring experiments (ITTC, 2002), and for which the simulator used in this study has been validated (Trodden, 2014). The propeller is of the fixed pitch type.

Six test cases have been developed, segregated into two sets. These cases represent different magnitudes of manoeuvring and operating scenarios. Test cases 1 to 3, the first set, are run at a constant brake power of 9132 kW, equating to 91.4% of the MCR. Test cases 4 to 6, the second set, are run at a constant engine speed of 83.35 rpm, equating to 90.46% of the engine speed at SMCR.

For both sets of cases three different manoeuvres are examined; the 10/10 ZigZag, 20/20 ZigZag and a Dead-Ahead case. These manoeuvres are chosen so as to make a comparison between different levels of transient operation, and steady-state operation on the formation of NO_X from operation dependent, and independent emission factors.

The two sets of cases are chosen to represent two different running scenarios; constant power and constant speed. This allows an examination of how engine operation affects the estimation of NO_X production throughout the different manoeuvring operations.

The case studies, and their results, are summarised in Table 2 and Table 3 of the Results Section.

2.1 MANOEUVRING SIMULATION

A three degree-of-freedom simulator has been developed in the manoeuvring motions of surge, sway and yaw. The manoeuvring model is based upon the MMG model of Inoue et al. (1981), whilst the propeller's characteristics are modelled using the polynomials developed by Oosterveld and van Oossanen (1975).

2.2 ESTIMATION OF FUEL OIL CONSUMPTION

A MAN B&W S65ME-C8.5-TII slow speed Diesel engine is chosen as an example that is capable of providing the necessary power for the basis simulations. Specific Fuel Oil Consumption (SFOC) depends upon whereabouts on the engine-layout diagram the Maximum Continuous Rated (MCR) Power is situated. Once this point has been established, the SFOC can be estimated for different operating conditions based upon the diagram of Figure 1, obtained from the engine manufacturer's Project Guide (MAN, 2014).

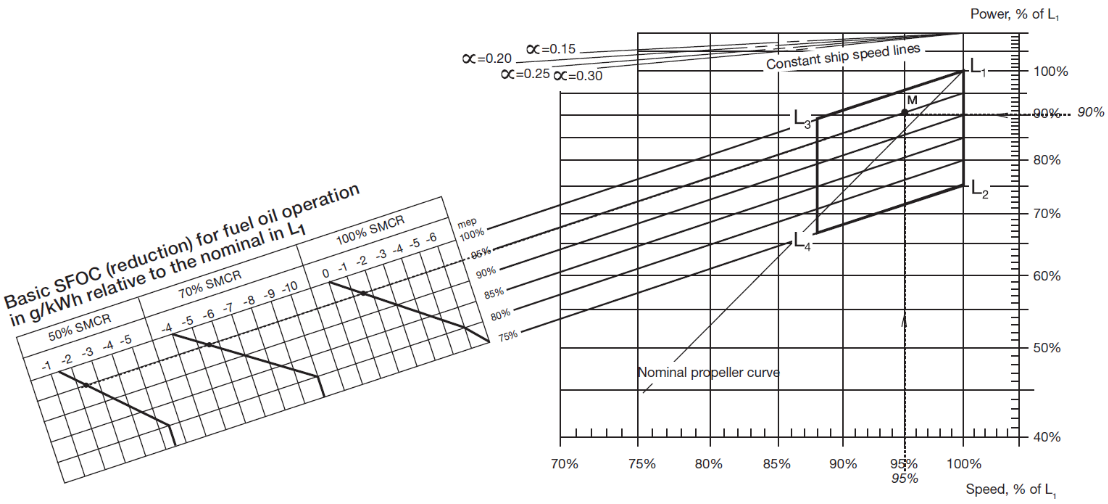

Figure 1: calculation of SFOC from MCR position [4]

The values for SFOC are used in the process to estimate the total exhaust gas emissions, as described in the following subsection.

2.3 EMISSION FACTORS

The three exhaust gas species analysed in this report are CO_2, SO_X and NO_X:

- CO_2 is an inevitable consequence of burning fossil fuel, the amount of emission depends on the carbon content of fuel and fuel consumption. CO_2 is recognised as one of the most potent gasses contributing to global warming.

- SO_X are produced by the oxidation of sulphur in fuel, and cannot be controlled by the combustion process. SO_X are a major source of acid rain and once emitted can be carried many miles in the atmosphere.

- NO_X formation is comparatively complex and is highly dependent on the oxygen concentration, temperature, and residence time within the combustion chamber. It is a gas that is especially harmful to human health.

Emission factors based upon stoichiometric combustion provide an adequate representation of emissions in the case of CO_2 and SO_X. For example, to calculate the CO_2 emissions from a fuel, the Carbon content of the fuel must be multiplied by the ratio of molecular weight of CO_2 to the molecular weight of C, that is 44:12.

The Carbon content of Heavy Fuel Oil (HFO) ISO 8217 Grades RME through RMK (ISO, 2012) is 84.93%, therefore, 1 gramme of HFO produces 0.8493 x 44/12 = 3.1141grammes of CO_2 when fully combusted.

In the case of NO_X formation, these operation-independent factors may not be as satisfactory. In order to examine this, three types of NO_X emission factors are used for analysis: A constant steady-state factor (IMO, 2014), a one which depends on mode of operation, and a factor which depends upon engine loading characteristics. These are examined to determine the degree of variability in values for emission estimation. The emission factor based upon mode of operation is obtained from Cooper (2002), values of which depend upon whether the ship is in cruising mode, or manoeuvring mode. The load-dependent NO_X emission factor depends upon engine power and speed was developed in-house and described in Equation 1.

$$\begin{aligned} Specific\ NO_X EF = {} & 69.0 - \left(0.000004586 \times (\%MCR^3)\right) - \left(0.000208 \times (\%MCR^2)\right) + (0.09645 \times \%MCR) \\ & - \left(0.000081357 \times (\%Speed^3)\right) + \left(0.021415 \times (\%Speed^2)\right) \\ & - (1.91517 \times \%Speed) \qquad \left[\frac{g}{kWh}\right] \end{aligned}$$

Equation 1

Operation-independent and mode-dependent exhaust gas emission factors are reproduced for a slow-speed main-engine burning Heavy Fuel Oil (HFO) in Table 1. The values for the mode dependent factors have been adjusted to account for new engines that were introduced up until 2005 (Trozzi, 2010), when MARPOL Annex VI entered into force.

Table 1: Emission Factors for main Slow Speed engines burning Heavy Fuel Oil

CO_2 Emission Factor [kg CO_2/tonne of fuel]	Load independent NO_X Emission Factor [kg NO_X/tonne of fuel]	Mode dependent NO_X Emission Factor (Cruising) [kg NO_X /tonne of fuel]	Mode dependent NO_X Emission Factor (Manoeuvring) [kg NO_X /tonne of fuel]
3114.1	78.46	89.7	65.1

3. RESULTS OF MANOEUVRING SCENARIOS

The results from running the Test Cases (described in the Methodology Section) on the developed simulator are listed in Table 2 and Table 3. For the purpose of the Mode-Dependent emission factors, cases 1,2, 4 and 5 are taken to be manoeuvring modes, whereas 3 and 6 are taken to be cruising mode.

Table 2: Emissions resulting from standard manoeuvres at constant engine power of 9132 kW over 10 nautical miles

Case	Manoeuvre	SFOC [g/kWh]	Mean Engine Speed [rpm]	Mean Resultant Ship Speed [knots]	CO_2 [t]	NO_X (Operation in-dependent) [t]	NO_X (Mode dependent) [t]	NO_X (Operation dependent) [t]	Mean NO_X Emission Factor (Operation Dependent) [kg NO_X/tonne of fuel]
1	10/10 ZigZag	161.33	90.49	9.54	7.61	0.192	0.15901	0.212	86.60
2	20/20 ZigZag	161.35	87.08	6.78	10.70	0.270	0.22375	0.301	87.78
3	Dead-Ahead	161.32	92.83	11.18	6.49	0.163	0.15057	0.178	85.51

Table 3: Emissions resulting from standard manoeuvres at constant engine speed of 83.35 rpm over 10 nautical miles

Case	Manoeuvre	SFOC [g/kWh]	Mean Engine Power [kW]	Mean Resultant Ship Speed [knots]	CO_2 [t]	NO_X (Operation in-dependent) [t]	NO_X (Mode dependent) [t]	NO_X (Operation dependent) [t]	Mean NO_X Emission Factor (Operation Dependent) [kg NO_X/tonne of fuel]
4	10/10 ZigZag	159.23	7128	8.80	6.35	0.160	0.13268	0.191	93.73
5	20/20 ZigZag	159.51	8007	6.50	9.68	0.244	0.2023	0.288	92.74
6	Dead-Ahead	159.73	6634	9.99	5.22	0.132	0.15039	0.157	93.37

Taking the operation-dependent NO_X emission factor as a base-line figure, the difference between the operation dependent NO_X emission factor and the base-line emission factor leads to changes in the absolute values of NO_X estimation from the base-line of +10.42%, +11.48%, +9.20%, +19.38%, +18.03% and +18.94% for cases 1 to 6 respectively. In the case of the mode-dependent NO_X emission factor, the changes in the absolute values of NO_X estimation from the base-line are -17.18%, -17.13%, -7.63%, -17.08%, -17.09% and +13.93% for cases 1 to 6 respectively.

From the above results, it can be observed that generally, the absolute values for NO_X emissions increase with an increased degree of manoeuvring, independent of the type of emission factor used. The exception to this is in the constant engine speed cases obtained from the mode-dependent emission factors, with the lowest NO_X emission arising from the 10/10 ZigZag, and highest value from the 20/20 ZigZag.

4. DISCUSSION OF SHIP OPERATION ON ESTIMATION OF EXHAUST GAS EMISSIONS

Figure 2 illustrates how the speed of the main engine changes with time over a 20/20 ZigZag manoeuvre. This provides an indication of the difference in engine operation compared to an averaged-speed, steady state run, and shows, as NO_X is a function of engine speed (or residence time), that using an operation-independent emission factor should be used with caution when considering emissions from a ship operating in transient conditions.

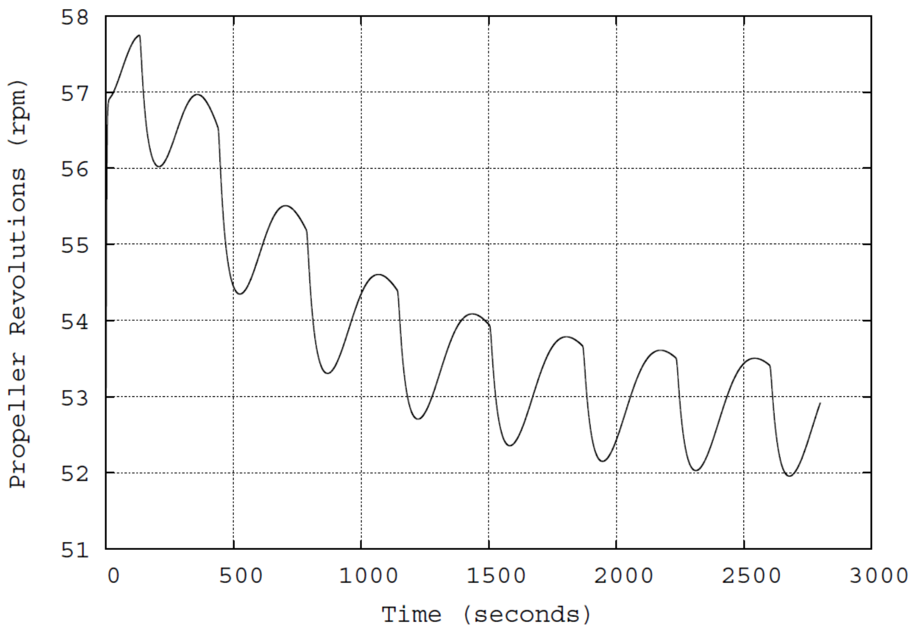

Figure 2: Variation of propeller speed with time during a 20/20 zigzag manoeuvre

Plotting the NO_X emission factors against the engine operating conditions, results in the graph of Figure 3. The range of operation for the manoeuvres examined in this paper do not reflect the full spectrum of engine operating conditions, but represents practical manoeuvring scenarios which can readily be reproduced.

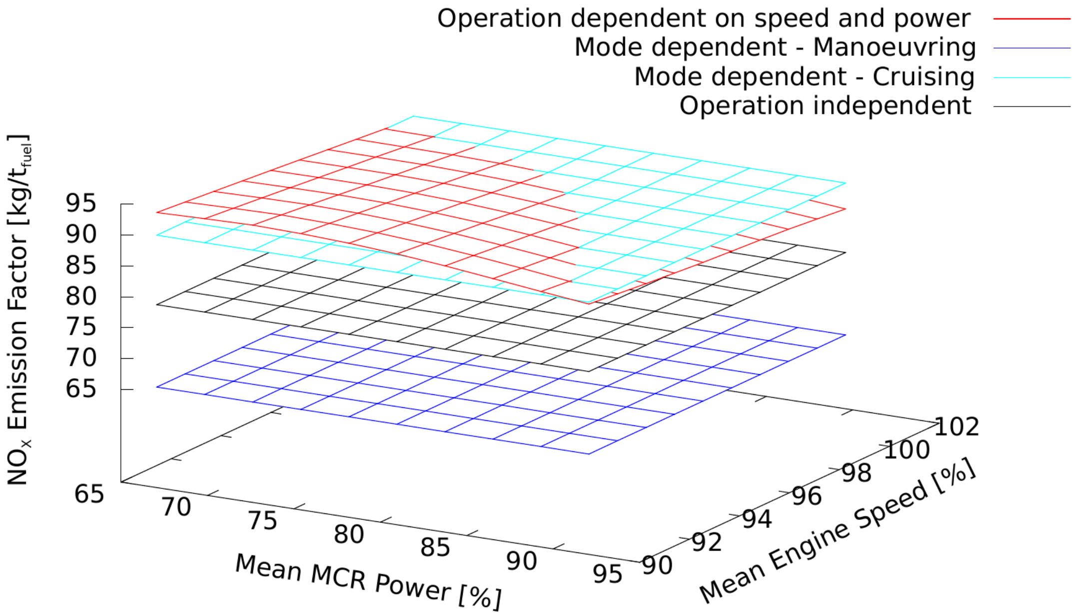

Figure 3: Variation in NO_X emission factor with engine running conditions.

As can be seen from figure 3, the cruising-mode dependent emission factors correlate well with the operation dependent emission factors, indicating that over the range of engine running conditions encountered throughout the six cases investigated, it seems more appropriate to use the cruising mode emission factor, rather than the manoeuvring one, even for the ZigZag manoeuvres. This suggests that the criteria which determine the operation of manoeuvring mode are different to the operating range conducted in the ZigZag manoeuvres, and are therefore beyond the range of applicability.

The operation-independent emission factor is seen to be an average value between the manoeuvring and cruising mode dependent factors.

In the following discussions, it must be borne in mind that a case running at a relatively higher resultant ship speed will have a relatively shorter run time as it will complete the 10 nautical mile voyage earlier.

Comparing the steady-state Dead-Ahead cases 3 and 6, where case 3 is running with 37.7% more power and 11.37% increased speed compared to case 6, resulting in an 8.42% decrease in operation dependent NO_X emission factors. This is intuitively correct as a higher engine speed results in a lower residence time for NO_X formation. However, even though case 3 has a lower operation dependent NO_X emission factor than case 6, and runs for a shorter period, case 3 still produces more absolute NO_X emissions than case 6; a 13.38% increase for load dependent estimation, and a 23.48% increase for load independent estimation. This is because case 3 has a higher fuel oil consumption, which depends upon whereabouts on the engine layout diagram the engine is operating. For the case of the mode-dependent emission factors, cases 3 and 6 are applicable to the limits of operation, as these cases have been classified as cruising mode. In the absolute mode-dependent NO_X emission values, case 6 results in a 0.12% decrease compared with case 3, which goes against the trend of the other emission factor values.

The difference between absolute values of NO_X as obtained from operation dependent, and independent emission factors are substantial, and highlights the significant role that the combination of engine speed and load plays in NO_X production. This demonstrates that one needs to exercise caution when using operation independent emission factors.

Discounting the mode-dependent NO_X estimation values, it will be seen that both the Dead-Ahead cases produce the least amount of absolute NO_X from the two sets, however, in actual fact the 20/20 ZigZag of case 5 has a lower emission factor than the Dead-Ahead case 6. As noted in the previous section, for the first set of cases (constant power), the NO_X emission factors steadily increase with an increasing amount of manoeuvring.

However, for the constant engine speed cases, the situation is different. A peak in the NO_X emission factor is reached at the 10/10 ZigZag and actually starts to decrease with increasing manoeuvring. This situation again arises from NO_X formation being related to both engine speed and power.

The above aspects demonstrate that it is not always intuitive as to how NO_X production is related to ship operation, it being dependent upon how the ship is achieving that operation.

These interrelated properties indicate that a time-domain manoeuvring simulator lends itself especially well to prediction of NO_X emissions. When used in conjunction with operation-dependent emission factors can provide increased realism, and therefore a higher degree of accuracy, prediction of exhaust gas emissions, compared to commonly used averaged-speed, dead-ahead, operation-independent approaches.

The emission factors used so far in this research have themselves not been dependent on time, and therefore do not truly capture transient engine operation, only the variation in loading that arises over time. To improve upon this further, a time-domain engine simulator can be coupled to the manoeuvring simulator, enabling the modelling of transient loading conditions, and the thermodynamics of the engine, which is so important when considering the formation of NO_X.

5. CONCLUSIONS

It has been shown that there is a significant difference in the amount of NO_X produced as estimated from commonly used steady-state NO_X emission factors, mode-dependent emission factors and operation-dependent NO_X emission factors.

It is further demonstrated that, due to the attitude of a ship travelling through the water, differences in predicted required power arise compared to that of the steady-state, dead-ahead calm water estimate. Again, it is the latter case that is often used when predicting exhaust gas emission estimates.

Additionally, it is not always intuitive as to how the extent of NO_X formation results from the type of ship manoeuvre, illustrating that the use of a simulator can be used to improve the accuracy of these estimates by accounting for the changes in loading from manoeuvring, the environment, and the dynamic response of the propulsion system. This also potentially allows scenarios to be played out to determine compliance with regulations and aid in logistic management.

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