Modelling Ship Emission Factors and Emission Indices

Murphy A.J. [a*], Landamore M.J. [a], Pazouki K. [a], Gibson M. [a]

[a]*School of Marine Science and Technology, Newcastle University, Queen Victoria Road, Newcastle upon Tyne, NE17RU, UK*

Abstract

Despite being one of the most efficient forms of transport, the contributions of shipping to GHG and poisonous gas emissions are a cause for significant concern. In the case of GHG (principally CO_2) the concern is shipping's contribution to global warming, whereas the other poisonous exhaust gas emissions reduce air quality; particularly in ports and near coastlines, affecting the health of neighbouring populations.

Indices can be used to rank or benchmark different ocean-going ships and as a tool for incentivising shipping to operate in an environmentally-friendly manner. That is, indices can be used to apportion cost to harmful emissions which is then passed on to operators by offering incentives or attributing penalties to ships relative to a benchmark.

Many ports have adopted such an approach; however the rationale and effectiveness of these schemes is not completely transparent. Furthermore, the emissions factors which underpin the assumptions for predicting the actual quantity of emissions produced are highly aggregated, generally dated and concentrate mainly on the emissions produced under design operational conditions, which is not a true representation of emissions produced in off-design operating conditions when manoeuvring in and operating near port.

This paper considers both emissions factor prediction methods and the effectiveness of current and possible forms of future indexing schemes. Prediction models have been developed using data-driven methods and these are explained and their accuracy and applicability are highlighted. Furthermore, sensitivity studies exploring the effectiveness and weaknesses of different existing index schemes and the potential form of indices suitable for the future are presented. Reference is also made to how emissions factor prediction models can complement the indices, thus eliminating the tendency towards rewarding environmental incentive based on emissions assumed to be produced during design operation rather than actual off-design operation of ships near or in port.

Keywords: Ship exhaust-gas emissions; Ship emission indices; Environment incentive schemes; Emission factors

1. Environmental Index Schemes for Ships

The maritime industry recognises the need for improved air quality in ports and coastlines in order to maintain good health for populations living in surrounding areas, requiring a reduction in harmful exhaust-gas emissions from ships. An ever increasingly popular method adopted to influence a move towards environmentally-friendly practice is the use of indices to rank the environmental impact of buildings, products and transport modes. And, in the context of air-pollution from shipping, one approach that has been recently adopted by a number of ports is to attempt to apportion costs to harmful emissions by offering incentives to cleaner ships based on some relevant index. However the rationale and effectiveness of these schemes is not completely transparent and there is also considerable uncertainty associated with the emission factors used for estimating the amount of actual emissions produced.

A study conducted as part of the Clean Baltic Sea Shipping (CBSS, 2012) consortium identified 49 different initiatives used to assess the environmental performance of ships. Many of these have been developed to address a single pollutant; however two of the more widely used - the Environmental Ship Index (ESI) and Clean Shipping Index (CSI) - have been developed to incorporate several pollutants and are used for the focus of this study, to investigate how different regimes of incentive or penalty are used to assess the impact of a ship or fleet on the environment, and in turn, how this can be quantified economically. Furthermore, the emissions factors which can be used to more accurately predict the actual production of emissions are considered.

[*] Corresponding author. Tel: +44-191-222-8207
Email address: a.j.murphy@ncl.ac.uk

1.1 The Environmental Ship Index (ESI) and Clean Shipping Index (CSI)

ESI, run by the *World Ports Climate Initiative (WPCI)* assesses the impact of SO_X and NO_X emissions by providing scores based on a ship's emissions compared to current legislative guidelines. The index also incorporates recognition for reduced CO_2 through awarding an improved index to ships reporting the EEOI and rewards the potential for zero ship emissions whilst alongside by recognising the presence of an OPS (Onshore Power Supply) connection on board. ESI classes itself as a '*good indicator of environmental performance of ocean going vessels*' (WPCI, 2013). Similarly, the CSI adopts a scoring system which assesses exhaust gases (SO_X and PM; NO_X; and CO_2), along with other environmental problems such as cleaning chemicals, refrigerants, treatment of ballast water and other issues associated with shipping (Clean Shipping Project, 2012).

The ESI is used by a number of ports for offering incentives to cleaner ships through discounted port dues. The CSI is essentially used by carriers to gain competitive advantage through being able to demonstrate their green credentials to environmentally conscientious clients.

In order to assess the effectiveness of each of the indices, sensitivity analyses have been carried out to determine which factors have the biggest impact on a score, and how combinations of factors may result in higher or lower scores being awarded. Although each index uses different methods to calculate each score function, a reasonable comparison has been made between the exhaust gas emissions terms in each index and their economic implications are also considered.

2. Analysis of the Environmental Ship Index

The equation that generates the ESI is,

$$ESI = \frac{2(ESI\ NO_X) + ESI\ SO_X + ESI\ CO_2 + OPS}{3.1} \quad (1)$$

For reasons that are not clear, whilst this formula will generate a value between 0 and ~111.3, the ESI score awarded is capped at 100. Furthermore,

$0 < \frac{2(ESI\ NO_X)}{3.1} < \sim 64.5$,

$0 < \frac{ESI\ SO_X}{3.1} < \sim 32.3$,

$0 < \frac{ESI\ CO_2}{3.1} < \sim 3.2$ and

$0 < \frac{OPS}{3.1} < \sim 11.3$.

These terms are illustrated in Figure 1 which highlights the relative importance within the ESI attributed to mitigating the respective pollutants and having the potential to emit zero pollutants whilst alongside, through having an OPS connection. These weighting factors combined with the 100 point cap implies that a maximum ESI can be achieved without maximum scoring in each category, allowing ships flexibility to prioritise their performance per category.

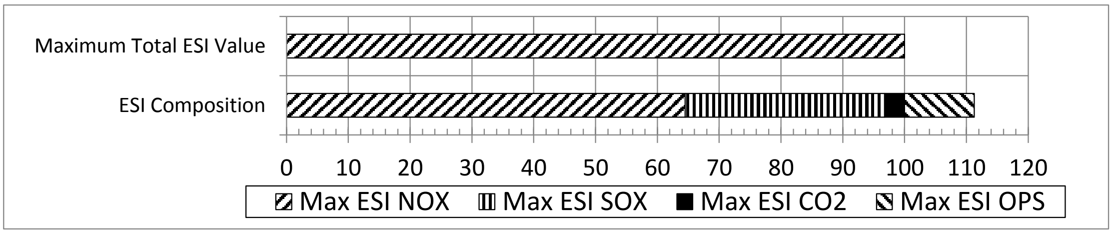


Figure 1. Relative weightings of the terms making up the ESI

Calculation of each of the terms in Equation (1) are considered next.

2.1 ESI NO_X

This term accounting for NO_X pollution generates a raw value between 0 and 100 according to,

$$ESI\ NO_X = \frac{100}{\sum Installed\ Power}\left[\sum_{i=1}^{N_{Engines}}\left(\frac{NO_{X_{Limit}} - NO_{X_{Rating}}}{NO_{X_{Limit}}}\right)_i .(Rated\ Power)_i\right] \qquad (2)$$

where the $NO_{X_{Limit}}$ is that prescribed by IMO Tier 1 compliance.

Notably, because this formulation is divided through by total installed power and due to the fact that the contribution to a positive score is in relation to exceeding the Tier 1 regulations, which is a decreasing function of nominal engine speed, it does not necessarily reward a low NO_X output in absolute terms. That is, for example, a vessel making modest reductions in NO_X output from large slow speed Diesel engines, which could be producing more NO_X, in absolute terms, than vessels with the same installed power using medium speed engines, could still generate a lower ESI NO_X score contribution. This could therefore be seen as a weakness in this environmental index.

2.2 ESI SO_X

This term accounting for SO_X pollution generates a raw value between 0 and 100 according to,

$$ESI\ SO_X = 30x + 35y + 35z \qquad (3)$$

where x, y and z represent the relative reduction in the % sulphur content of three fuel types bunkered in the preceding two quarters against benchmark values as follows:

For HFO: $x = \frac{3.5 - \%S}{3.5 - 1.0}$ (4)

For Low Sulphur HFO or MDO/GO: $y = \frac{1.0 - \%S}{1.0 - 0.5}$ (5)

For Low Sulphur MDO/GO (or LNG): $z = \frac{0.5 - \%S}{0.5 - 0.0}$ (6)

If a fuel type is bunkered multiple times over a given 6-month period, the mass averaged % sulphur content is used. However, there is no mass averaging of the sulphur content between fuel categories and this also suggests a weakness in the ESI scoring system. That is, there is no apparent minimum to the bunkered amount of each fuel type for generating a score which, as illustrated in Table 1, suggests that a vessel which bunkers a modest amount of the lower sulphur fuels could still benefit from the full weighting in terms y and z, yet can emit more sulphur dioxide than a vessel bunkering the same amount of HFO fuel only with the maximum relative reduction in sulphur.

Table 1. Comparison of two bunkering scenarios

Bunkering Scenario	x, y and z values	ESI SO_X	Tonnes of SO_2 emitted
200 tonnes HFO, 1 %S **0 tonnes MDO** **0 tonnes MDO LS**	$x = 1.0$ $y = 0.0$ $z = 0.0$	30	4.0
150 tonnes HFO, 3.5 %S **25 tonnes MDO, 0.5 %S** **25 tonnes MDO LS, 0.0 %S**	$x = 0.0$ $y = 1.0$ $z = 1.0$	70	10.75

2.3 ESI CO_2

This term, accounting for CO_2 pollution, is simply assigned a raw value of 10 for voluntary reporting the EEOI, otherwise it is zero. This indicates an almost negligible recognition for low carbon shipping.

2.4 OPS

This term, accounting for the ability to emit zero emissions alongside, is awarded a value of 35 if the ship is fitted with an Onshore Power Supply (OPS) connection, otherwise, zero is awarded – interestingly there is no compulsion to use OPS. Furthermore, since this index has some of its aim in reducing emission in port, this low contribution to the ESI score is perhaps surprising, although may recognise the limited opportunities to actually use OPS in port due to lack of comprehensive land-side OPS infrastructure.

3. Analysis using the Environmental Ship Index

3.1 Evaluation of ESI scores

According to the *World Ports Climate Initiative* (WPCI, 2013) there are a total of 2166 participating vessels in the ESI Scheme. Data was acquired for the top 50 scoring vessels and that data was analysed and is presented in ESI rank order showing the breakdown of the constituent elements in Figure 2. The average ESI score of the top 50 vessels is ~48, a little under half the maximum score, with the top score being ~80, jointly held by two vessels, and the lowest score in the top 50 being ~47. Figure 2 illustrates how some ships ESI scores are heavily influenced by the specific score functions e.g. ship 4, whose total ESI score is heavily influenced by a strong score in NO_X, has a higher overall score than most of the other ships despite not scoring at all for CO_2 and OPS, and low scoring for SO_X. Indeed, the two highest scoring ships have received 0 points in both the CO_2 and OPS categories. Conversely, ship 48 is at the lower end of the scoring table despite receiving scores for each category. This demonstrates that high scores can be achieved with ESI without necessarily having an overall benefit to the environment as a whole.

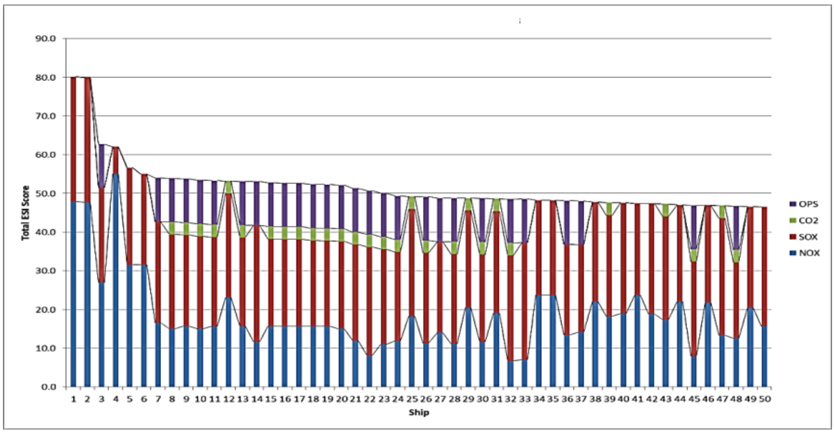


Figure 2. Constitution of Total ESI Score for the top 50 scoring ships

Figure 3 compares the mean ESI score by respective ship categories of the top 50 ESI scoring ships. Aside from LNG ships, there is no significant difference between the mean scores of each of the other categories, suggesting, perhaps surprisingly, that environmental impact does not vary greatly between ship types. There are in fact only two LNG carriers and these are the two highest scoring ships in Figure 2, illustrating once again the high importance put to fuel type, with zero sulphur content in LNG, and low NO_X emission rating in g/kWh.

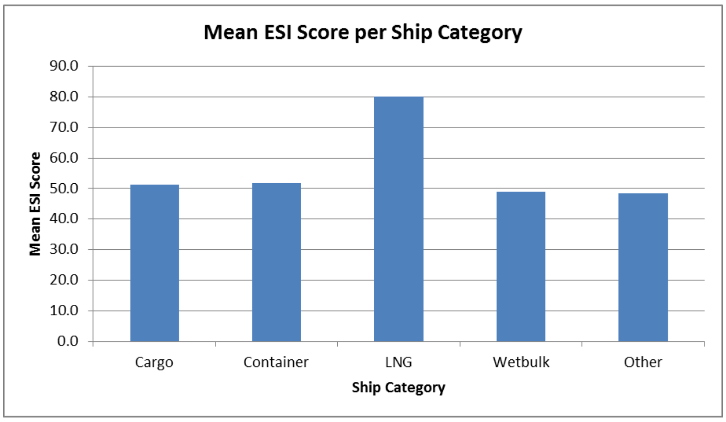


Figure 3. ESI score per ship category for top 50 ESI scoring ship sample

3.2 Impact of ESI scores on port charges

Many ports offer economic incentives to ship owners to become more environmentally friendly by offering discounted port fees to ships with good ESI scores. For this study participating ports in the North Sea region have been used.

The level of discount offered for ESI participation is left entirely to the discretion of the individual port - there is no legislation or guidance in place to control this. As illustrated in Table 2 this has led to highly variable and complex pricing structures between ports meaning the incentive for a ship to harbour in one port is different to the incentive for the same ship harbouring in a different port. Discounts are offered by all of the ports listed providing a minimum ESI score of 20 points is achieved by a given ship. It is notable that in all cases the incentives are offered at a fixed rate for simply exceeding a threshold ESI score, ranging from 20 to 50, which are generally low in comparison to the average ESI of the top 50 scoring ships and also suggests a lack of incentive for ships to strive to improve their ESI scores above the thresholds set at the ports they frequent.

The average incentives (discount) per ship type at each port, using the top 50 sample of ships, have been calculated and presented in Figure 4. Ship discount per ship type varies from port to port as shown above. E.g. at Kiel and Groningen, the biggest discounts are given to LNG ships, while at many of the other ports (Rotterdam, Amsterdam, Oslo, Bremen, Wilhelmshaven, Setubal), the biggest discounts are given to containerships. This suggests that ports do not have a universal policy in terms of port dues for specific ship classifications, as the comparable discount rates are different from port to port.

Interestingly, while Figure 3 demonstrated very little difference in ESI score between ship types (excepting LNG), the value to each ship type within individual ports is, on the contrary, quite variable.

Table 2. ESI discount incentives at selected North Sea ports

Port	ESI points requirement	Discount	
Rotterdam	≥ 31 points	10%	***Amsterdam GT - Class reward:*** ESI ≥ 20 points (bonus given to ships with ESI ≥ 31 points). Incentive dependent on Gross Tonnage (GT) - For ships with ESI ≥ 20 = ESI score/100* "GT-class reward"; for ships with ESI ≥ 31 add 1/4 GT-class reward. Discount system: ships categrised with GT-class reward between 1-3000, discount = €200; 3001-10,000, discount = €500; 10,001-30,000, discount = €900; 30,001-50,000, discount = €1,200; > 50,000, discount = €1,400.
	≥ 20 points	10% (if number of ships with 31 points does not meet quota of 25)	
Oslo	25-49 points	20%	
	≥50	40%	
Bremen & Bremerhaven	≥ 20 points	5%	
Kiel	≥ 31 points	10%	
Setubal	≥ 31 points	3%	
Hamburg	> 50 points	10% (capped at €2,000)	
Antwerp	≥ 31 points	10%	
Wilhelmshaven	≥ 31 points	5%	
Zeebrugge	≥ 20 points	10%	
Groningen sea ports	≥ 20 points	5%	
Amsterdam*	≥ 20 points	For ships with ESI ≥ 20 = ESI score/100* "GT-class reward"	
	≥ 31 points	For ships with ESI ≥ 31 add 1/4 GT-class reward	

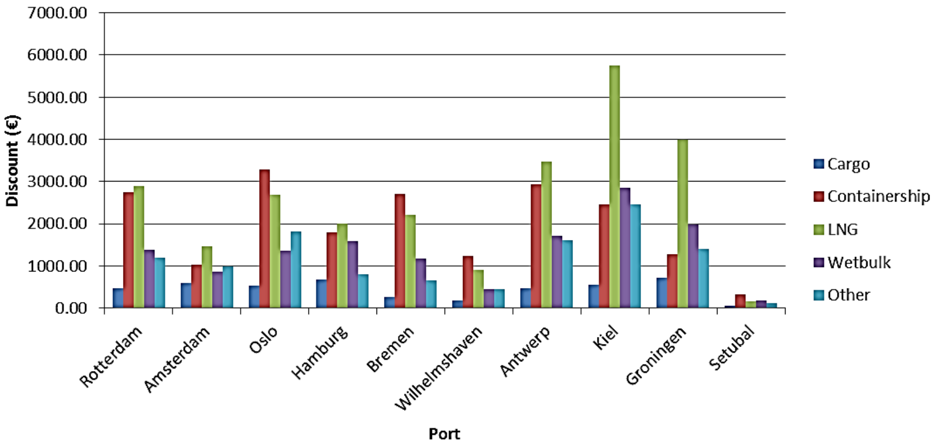


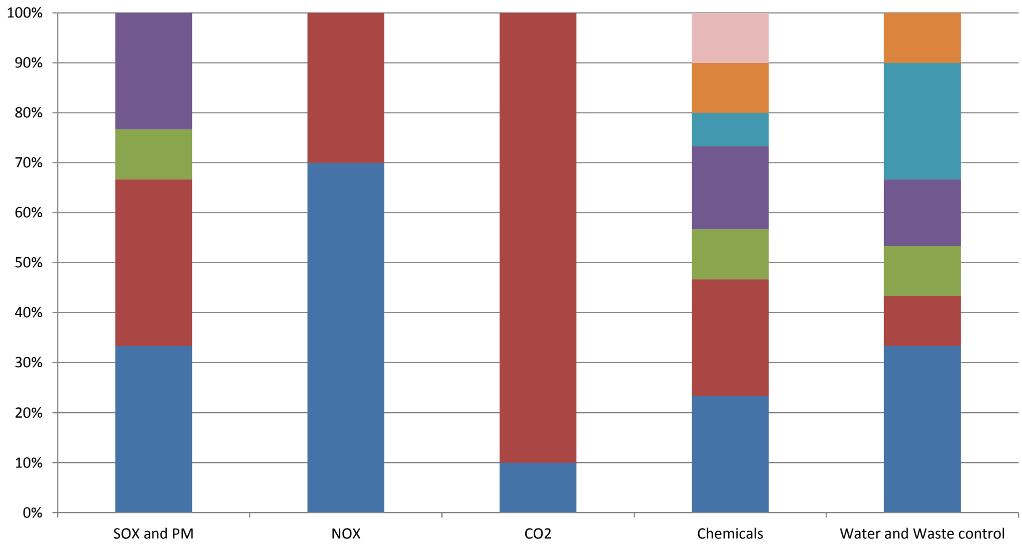
Figure 4. Average discount per ship type at each port based on the top 50 ESI scoring ships

4. The Clean Shipping Index

4.1 Calculation of a CSI score

The Clean Shipping Index is somewhat more complex than the ESI and is made up from five different categories: SO_X (also noted as a proxy for PM); NO_X; CO_2; Chemicals; and Water and Waste. Each category contributes a score out of 30 towards a possible total of 150. Therefore, unlike the ESI, each category carries equal weighting. A full explanation of each category is provided at the Clean Shipping Index website and Figure 5 provides a graphical overview.

In the context of this research, we were only concerned with the elements of the index relating to exhaust gas emissions. In this respect, there is a similar rationale in the CSI as in the ESI for awarding points for the raw NO_X score. Points awarded for SO_X emissions in the CSI is perhaps more rational than in the ESI, since a total mass averaged sulphur content from all fuels is used. Furthermore, also unlike the ESI, the CSI, as well as giving greater relative weight to CO_2 performance, also gives greater attention to it by actually awarding points for CO_2 performance based on a ship's EEOI compared to a reference value on a sliding scale, rather than in the case of the ESI, simply reporting data on the EEOI.



KEY		**Chemicals**	**max. score**
SO_x and PM	**max. score**	Antifouling	7
operation in non ECA's and ECA's (total yearly average)	10	Stern tube oil	7
		External hydraulic fluids	3
Operation in ECA's (yearly average)	10	Gear oil for thrusters and CP propellers	5
Harbour bonus	3	Boiler/cooling water treatment	2
SO_x/PM aux. engines	7	Cleaning agents	3
		Refrigerants	3
NO_x			
NO_x main engines	21	**Water and Waste control**	
NO_x aux. engines	9	Ballast water treatment	10
		Sewage/black water	3
CO_2		Garbage handling	3
Reporting of CO_2 emission information	3	Sludge handling	4
		Bilge water treatment	7
CO_2 emission performance	27	crew awareness	3

Figure 5. Constitution of CSI score functions

4.2 Using a CSI score

In comparison to the ESI, there are no direct financial incentives for using CSI; rather it is promoted as an index to be used as a bargaining tool in procurement situations while attempting to attract business from environmentally conscientious clients. As such, the Index claims to have been designed to provoke more detailed discussion rather than as an absolute indicator of environmental performance. Therefore, rather than directly use the absolute value of the CSI, a ship (or carriers') is classified as green, yellow or red if it meets the respective criteria presented in Table 3. Notably, to be classed as "green" vesels must gain a minimum score in each category as well as a minimum overall score.

Table 3. CSI score categories

Category	For Carriers (Fleets)	For Individual Vessels
GREEN	≥90% vessels reported and the carrier verified, ≥40% weighted total score	The vessel verified, total score ≥50%, ≥35% in all fields
YELLOW	≥20% vessels reported ≥10% weighted total score	Total score ≥20%
RED	<20% vessels reported or, <10% weighted total score	Total score <20%

5. Comparisons between the ESI and CSI

5.1 Comparison of CO_2/OPS components of the ESI and CSI

In the CSI there is not an individual component for OPS, although, it does account for 1 point in the CO_2 term of the CSI and therefore it may be fair to consider OPS and CO_2 together for both Indexes. As noted earlier, in the ESI, there are a total of 3.2 + 11.3 = 14.5 points available in this category – and despite the cap in the ESI, these could be considered as potential % contributions out of 100 total available points. For the CSI, noting that the scale for CO_2 point scoring is perhaps more rational, with essentially a sliding scale according to EEOI performance a total of 30/150 marks is available for the complete CSI – representing a 20% weighting. On the other hand, since we are only concerned here with exhaust-gas emissions, the CO_2 elements of the CSI in these terms represents a potential for 33.3%. In either case, the CSI gives a higher importance to low-carbon shipping.

5.2 Comparison of NO_X components of the ESI and CSI

Due to the fact that the two methodologies for calculating the NO_X scores in each index are somewhat different it is necessary to make some assumptions to compare these. Despite this, the following rationale provides some insight into the relative credit as compares to environmental improvement that each index offers. The CSI scoring system is essentially a stepped scale with a set amount of points available for meeting specific criteria. Table 4 compares the CSI scores for meeting each criteria with the ESI scores for ships assumed to have both main and auxiliary engines all meeting the same criteria. Interestingly, the CSI is generally more generous in awarding points within the NO_X category (viewed as %) for meeting each criteria – however, when considered as a % of the total index or even just considering the emissions components in the case of the CSI, the ESI is generally more generous than the CSI – essentially meaning that a relatively high ESI score can be gained for producing more NO_X than is the case for CSI.

Table 4. A comparison of the NO_X scores generated by ESI and CSI

NOx Level Achieved	ESI Score % NOx component	CSI Score % NOx component	ESI Score % of Total ESI	CSI Score % of Total CSI	ESI Score % of Total ESI	CSI Score % of Emissions Components of CSI
Tier 1 *	0.0%	26.7%	0.0%	5.3%	0.0%	8.9%
Tier 2 **	19.2%	40.0%	12.4%	8.0%	12.4%	13.3%
30% below Tier 1	30.0%	53.3%	19.4%	10.7%	19.4%	17.8%
40% below Tier 1	40.0%	70.0%	25.8%	14.0%	25.8%	23.3%
Tier 3	80.0%	100.0%	51.6%	20.0%	51.6%	33.3%
Zero NOx	100.0%	100.0%	64.5%	20.0%	64.5%	33.3%

* For CSI Tier 1 engines since built after 2000 are awarded a score of 0, this example is given for engines pre-dating 2000.
** Because Tier 2 NO_X levels are not a fixed % below Tier 1 across the range of engine speeds and the fact that the ESI NO_X formula (Equation 1) is dependent on the relative power between main and auxiliary engines, engines complying to Tier 2 levels generate a range of scores for the ESI depending on the ratio of main engine to auxiliary engine installed power and what type of engines are assumed to be used. However the variation is within the range of only 5% of the NO_X component and therefore here an average value is used.

5.3 Comparison of SO_X components of the ESI and CSI

Similar to the case for NO_X, the methods for generating a SO_X score in the CSI is a stepped scale for meeting discrete fuel sulphur content criteria, whereas for the ESI the scale is partially based on sliding scales within three subsets of fuel types. Acknowledging the earlier observation that in reality it is possible to generate relatively high ESI SO_X scores through judicious bunkering strategies, nevertheless a similar rationale as that with the NO_X scores comparison has been used to provide an indication of the relative importance of reducing fuel sulphur content in each index and this comparison is presented in Figure 6. The CSI scores are based on a mass-averaged sulphur content of all fuels used in the past year, with a 3 point bonus available for using very low sulphur content fuel whilst in harbour. In this comparison, the graphs for ESI are plotted as if an ocean-going vessel exclusively bunkered a single fuel type of the respective sulphur content over the range. Despite the stepped nature of the CSI points system, there is a good deal of similarity between the ESI and CSI when considering relative progress through the SO_X component of the index (Figure 6(a)) and also in terms of relative contribution to the exhaust-gas emissions components of the CSI as compared to the total ESI (Figure 6(c)). Of course, taken across the compete CSI, there is diminished importance put to SO_X owing to the inclusion of the non- exhaust-gas-emissions components (Figure 6(b)).

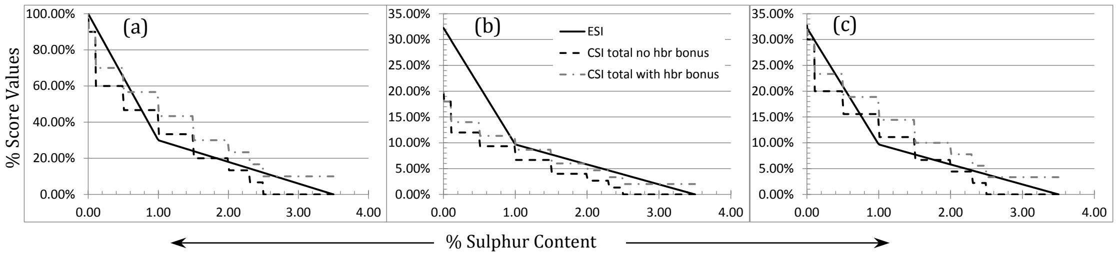


Figure 6. A comparison of SO_X scores generated by ESI and CSI. (a) Compares % contributions to SO_X component of each index. (b) Compares % contributions to the total of the respective indexes. (c) Compares % contributions to the emissions components for the case of the CSI.

6. Ship exhaust-gas emission factors

What is notable about the indices studied in this work is that the input to the scoring gives little consideration for the actual amount of any emission actually produced in some cases. For CO_2 there is some validity in using adherence to an EEOI reference which is the case for the CSI, although not for the ESI. Similarly, using fuel sulphur content may be a good proxy for SO_2 production, although neither index correlates this against transport effort and only the CSI uses a mass averaged value for fuel sulphur content. Furthermore, neither index pays any attention to the actual amount of NO_X that is produced, but rather relies on the engines test-bed rating of NO_X production – which will be markedly different to actual levels of NO_X produced, which has as more to do with the specific operational conditions at any given time than specifically fuel type or performance under test conditions. Noting this, we have also considered in some detail the emissions factors for ships engines and, in particular, NO_X emissions factors.

Exhaust gas from the marine Diesel engines largely consists of nitrogen, oxygen, carbon dioxide and water vapour, with some small quantities of carbon monoxide (CO), oxides of sulphur and nitrogen (SO_X and NO_x), non-combusted hydrocarbons (HC) and particulate materials (PM). Of these exhaust gas species; SO_X, NO_X, CO, HC and PM are considered noxious emissions. Depending on the sulphur content and lower heat value of fuel, types of fuel, speed and efficiency of the engine, noxious emissions amount between 0.25 and 0.4 per cent by volume of the exhaust gas. MAN Diesel has provided the percentage of actual pollutants generated by an 18-cylinder NO_X-optimized medium speed engine running at full load on a typical heavy fuel oil with 4% sulphur content. MAN Diesel declared emissions of 460kg of noxious compounds out of approximately 136 tonnes of exhaust gas per hour, which accounts approximately for 0.35% of total exhaust gas emission. Of the 0.35%, NO_X contributes 0.17%, sulphur dioxide 0.15%, HC 0.02%, carbon monoxide 0.007% and soot/ash 0.003% (Woodyard, 2009).

Carbon dioxide, although non-toxic, has attracted global attention as it contributes to anthropogenic climate change. Unlike noxious emissions, carbon dioxide represents a higher percentage of total exhaust gas emission. The results from the MAN Diesel experiment shows some 6% of the exhaust gas emissions from the test engine is carbon dioxide. The amount of carbon dioxide emission depends on burnable carbon content of fuel and fuel consumption – related to engine efficiency for a given unit of useful work.

Current strategies of port authorities and regulatory bodies such as IMO focus on stricter regulations for the emissions of air pollutants from shipping within special and near coast areas. Hence they require ships to operate under controlled conditions in order to minimize the impact of noxious emissions to the local environment. However, the level of pollution in the coastal area may be augmented by the released air pollutants from ships operating at open sea. The chances exist that emitted pollutants may be transferred to local areas due to the weather conditions.

Despite the regulations that target some noxious emissions from ships, actual ship emissions from operations under varying conditions, taking into account engine, propeller and hull as a system, has generally been neglected. Therefore the accurate prediction of noxious emissions from ships under varying operational conditions and understanding of environmental model of the area that the ship operates are essential elements, not only from tactical point of view, but also to facilitate strategic decisions on fleet operation management.

In order to develop an emission prediction model, it is worthwhile to review how each species of exhaust is formed in a marine Diesel engine.

7. Formation of exhaust species

Nitrogen Oxide (NO_x): NO_X comprises of both nitric oxide (NO) and nitrogen dioxide (NO_2). Nitric oxide is generated thermally from nitrogen and sufficient oxygen at high combustion temperature inside the cylinder. Diesel fuel contains only a very small amount of nitrogen and hence formation of NO can almost happen through the oxidation of atmospheric nitrogen. A major hurdle in understanding the mechanism of formation and thus modelling its emission is due to highly heterogeneous and transient nature of combustion in Diesel engines. Although NO_X is the combination of both NO and NO_2, there are some distinctive differences between these two. Apart from their physical characteristics, NO_2 is five times more toxic than NO. There are four different mechanisms that lead to the formation of nitric oxide in the combustion chamber.

- The formation of thermal NO at high temperature in the combustion chamber under slightly lean condition with burned products.
- The prompt NO which is due to the reaction of N_2 from combustion air with hydrocarbon radicals in the fuel.
- The fuel NO that is formed from fuel bound nitrogen.
- N_2O that is activated at lower temperature than the thermal NO in a fuel-lean and high pressure environment.

Sulphur Oxide (SO_x): SO_X emissions from Diesel engine, which mostly consists of sulphur dioxide with small amount of sulphur trioxide, are produced by the oxidation of sulphur in the fuel and cannot be controlled by the combustion process. Sulphur oxides are a major source of acid rain and once emitted, are a trans-boundary pollution problem. SO_X can be carried miles in the atmosphere before being deposited in waters such as lake and streams.

Non-combusted Hydrocarbons (HC): produced by the incomplete combustion of fuel and lubricating oil and are partially carcinogenic. HC emissions are typically low for modern Diesel engines.

Particulate matter (PM): is a complex mixture of organic and inorganic compounds from the exhaust gas of a Diesel engine, and caused by incomplete combustion. Particulate matter constitutes not more than approximately 0.003% of the exhaust gases of Diesel engines.

Carbon monoxide (CO): resulting from the incomplete combustion due to lack of local air/oxygen. It is highly toxic but only in high concentrations.

Carbon dioxide (CO_2): is an inevitable consequence of combustion of all fossil fuels. Lower specific fuel consumption translates to the reduced carbon dioxide emission under similar given condition. Environmental concern on the emission of carbon dioxide has stimulated plans to limit the growth of such emissions. The action from International Maritime Organisation (IMO) on the emission of Green House Gases (GHG) has resulted in development of Energy Efficiency Design Index (EEDI), which set minimum standard for new ships. EEDI will become mandatory from 2015 and its standard will be stricter over time, targeting 10% improvement in emission of GHG for the ships built in 2015-19, 15-20% for 2020-24 and 30% for ships built after 2024. The plan would incentivize ship owners and operators to reduce GHG emissions and improve the efficiency of their fleet management.

8. Prediction of exhaust gas from ships

In order to make a judgement on the operational performance of ships and effectiveness of strategic decisions actual measurements or accurate predictions of the different emission species in real time are important. Measurements of ships emissions can be used to monitor and ultimately optimise the shipping activities. On-line monitoring of ships emissions enables and facilitates efficient management of voyage toward cleaner environment. However, this requires regular and reliable measurement at the appropriate frequency. One straightforward way is direct measurements of exhaust species, but difficulties in the direct measurement lead to poor fleet management. Direct measurement difficulties can be due to:

- Lack of appropriate on-line instrumentation
- Reliability of on-line instruments

In either case, optimization of voyage profile cannot be implemented and in extreme cases, may result in inefficient management and pollution control.

One alternative method to this is to predict the amount of emissions from marine engines by knowing the operating conditions. The quality and quantity of exhaust gas species emitting from marine engines are dependent on the operating conditions, the adjustment made to the engine's and quality of fuel used. Hence it is possible to monitor the engines emissions inferentially by the measurement of operational parameters. In such measurement system the objective is to model the relationship between engine operating parameters and emissions.

Much research has been carried out by the research institutions and classification societies to determine emission factors (g/kWh) for the species of concern in the Diesel engine exhaust gas. This, in fact, simplifies the calculation of emissions released for the whole or part of the mission profile of a ship. David Cooper (2002) reviewed the outcomes of conducted research since 1990 and proposed emission factors for Diesel engines exhaust gas for slow speed, medium speed and high speed Diesel engines operating "at sea" and "during manoeuvring". The emission factors for main engines and auxiliary engines are presented in the Tables 5-7.

It is, however, worthwhile to mention that emission factors presented in the Tables 5-7 are valid for Diesel engines manufactured prior to the year 2000. There are also some important issues and assumptions about the emission factors:

- It is assumed that all carbon and sulphur present in the fuel is combusted to form CO_2 and SO_2 respectively. Sulphur contents of fuels were assumed to be 0.25% for Marine Gas Oil (MGO), 1.0% for Marine Diesel oil (MDO) and 2.7% for Residual Oil (RO) with reference to IMO MEPC (2001). The carbon content of all fuels has been assumed to be 86.7%, which corresponds to a CO_2 emission of 3179 kg per tonne fuel burnt.
- NO_X emission factors have not been generated for different engine sizes and factors were only derived based on the engine speeds (slow, medium and high) and fuel types.
- Emission factors for main engines operating at sea were obtained by averaging all measurements taken for the engine loads between 70% and 100% of MCR. In a similar manner emission factors for auxiliary engines were obtained from averaging all measurements in a dataset for the engine loads between 40% and 80% MCR.
- Emission factors for the operation of main engines during manoeuvring and port areas (Table 6) were obtained by multiplying "at sea" emission factors by 0.8 for NO_X and 3.0 for HC. In addition, it was assumed that specific fuel consumption would be increased by 10% and thereby emission factors for SO_2 and $CO_2$for engines operating at low load (20% of MCR or Lower).

Table 5. Emission factors in g/kWh regarding engine / fuel type for MEs “at sea”. SSD = slow speed Diesel, MSD = medium speed Diesel, HSD = high speed Diesel, MGO = marine gas oil, MDO = marine Diesel oil, RO = residual oil.

Engine type/Fuel type	**NO_x**	**SO_2**	**CO_2**	**HC**
SSD/MGO	17.0	0.9	588	0.6
SSD/MDO	17.0	3.7	588	0.6
SSD/RO	18.1	10.5	620	0.6
MSD/MGO	13.2	1.0	645	0.5
MSD/MDO	13.2	4.1	645	0.5
MSD/RO	14.0	11.5	677	0.5
HSD/MGO	12.0	1.0	645	0.2
HSD/MDO	12.0	4.1	645	0.2
HSD/RO	12.7	11.5	677	0.2

Table 6. Emission factors in g/kWh regarding engine / fuel type for MEs “in port” and “manoeuvring”. SSD = slow speed Diesel, MSD = medium speed Diesel, HSD = high speed Diesel, MGO = marine gas oil, MDO = marine Diesel oil, RO = residual oil.

Engine type/Fuel type	**NO_x**	**SO_2**	**CO_2**	**HC**
SSD/MGO	13.6	1.0	647	1.8
SSD/MDO	13.6	4.1	647	1.8
SSD/RO	14.5	11.6	682	1.8
MSD/MGO	10.6	1.1	710	1.5
MSD/MDO	10.6	4.5	710	1.5
MSD/RO	11.2	12.7	745	1.5
HSD/MGO	9.6	1.1	710	0.6
HSD/MDO	9.6	4.5	710	0.6
HSD/RO	102	12.7	745	0.6

Table 7. Emission factors in g/kWh regarding engine / fuel type for AEs. MSD = medium speed Diesel, HSD = high speed Diesel, MGO = marine gas oil, MDO = marine Diesel oil, RO = residual oil.

Engine type/Fuel type	**NO_x**	**SO_2**	**CO_2**	**HC**
MSD/MGO	13.9	1.1	690	0.4
MSD/MDO	13.9	4.3	690	0.4
MSD/RO	14.7	12.3	722	0.4
HSD/MGO	10.9	1.1	690	0.4
HSD/MDO	10.9	4.3	690	0.4
HSD/RO	11.6	12.3	722	0.4

9. Discussion of exhaust-gas emission factors

The emission factors presented in the Tables 5-7, although valid for the engines built before 2000, may not be applicable for modern Diesel engines. Engine manufacturers, since adoption of Annex VI, have tried to modify their engines and reduce NO_X emissions to meet the requirement as enforced by IMO. On the other hand, the specific fuel consumptions considered in the report IVL Swedish Environmental Research Institute were higher than what is expected from the modern engines and hence suggested emission factors for CO_2 and SO_2 are higher than what should be in reality. In addition, emission factors for the reduced main engine power(less than 70% of MCR), due to the lack of data, have not been considered and therefore, any voyage optimization by adopting slow steaming may not represent the actual emissions. This suggests updated emission factors for the modern main engines.

Emission factor for SO_x: This emission mostly comprise sulphur dioxide and is a function of sulphur in the fuel. SO_X emission factor can be calculated using oxygen demand relationship to sulphur content for the complete combustion to generate SO_2 and specific fuel consumption of main engine. It is, however, assumed that all sulphur in the fuel has turned into sulphur dioxide. The following formula can be used to calculate the emission factor:

$$SOx\ emission\ factor\left(g/_{kWh}\right) = SFC\left(g/_{kWh}\right) \times \%\ m/_{m}\ of\ Sulphur\ in\ fuel \times 64/_{32} \qquad (7)$$

Sulphur content of fuel can be obtained from bunker receipt and engine manufacturers provide the specific fuel consumption of their engines for various loads (Figure 7). This information can be used to calculate the emission factor for any operational engine load.

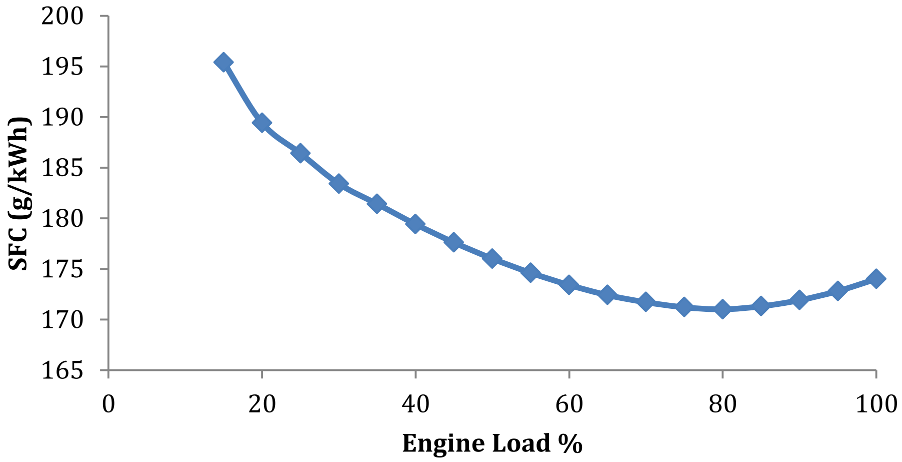


Figure 7. Specific Fuel Consumption of MAN engine (6S70MC-C)

Emission factor for CO_2: IMO has published guidelines for the use of Energy Efficiency Operational Indicator (EEOI) for ships. The objective of these guidelines is to provide assistance in minimizing the greenhouse gas emissions from ships (IMO, 2009). In this document, non-dimensional conversion factors for different fuels have been introduced, essentially using,

$$CO_2\ emission\ factor\left(g/_{kWh}\right) = SFC\left(g/_{kWh}\right) \times \%\ m/_{m}\ of\ Carbon\ in\ fuel \times 44/_{12} \qquad (8)$$

These non-dimensional conversion factors can also be turned into CO_2 emission factor (g/kWh) if multiplied by the SFC (g/kWh) of engine i.e.,

$$CO_2\ emission\ factor\left(g/_{kWh}\right) = SFC\left(g/_{kWh}\right) \times C_f \qquad (9)$$

Emission factor for NO_x: Influencing factors in the formation of NO_X are temperature and oxygen concentration. The greater amount of thermal NO_X will be produced due to higher combustion temperature and higher residence time at high temperature. This means slow-speed two-stroke engines generate more NO_X emission than medium and high speed four-stroke engines (Woodyard, 2009). This actually reflects the importance of speed for the calculation of NO_X emission factors.

Korean engine manufacturers performed the official tests to compare the NO_X emissions from the same engines under E2 (Constant speed main propulsion) and E3 (Propeller-law operated main and auxiliary engines) test cycles. The results for each test cycle for the same engines show that engines subjected to E3 test cycles produces higher NO_X emission on average than the same engine when subjected to E2 cycle (Figures 8 & 9). It was then concluded that since the engine speed is related to the residence time in the combustion chamber, NO_X emission is then directly linked to the engine speed (IMO, 2006).

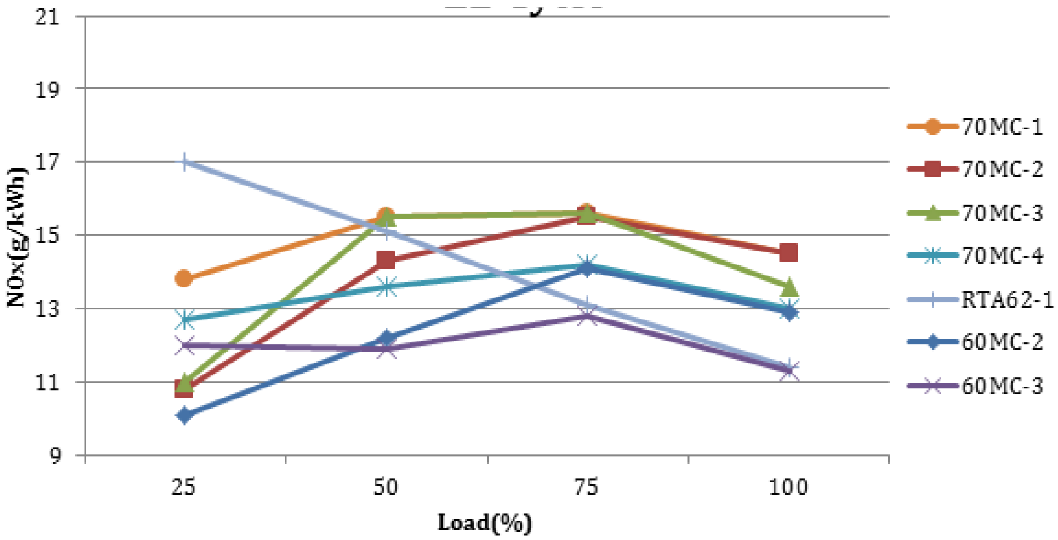


Figure 8. Exhausted NO_X at each load (E2 Cycle)

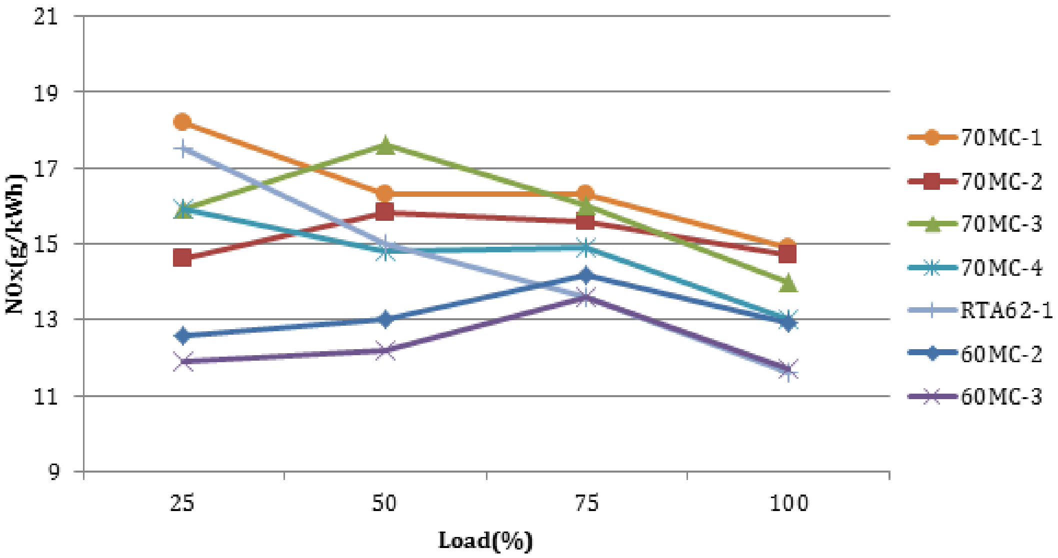


Figure 9. Exhausted NO_X at each load (E3 Cycle)

Using intelligent and data-driven methods (Murphy & Pazouki, 2012), we have used the results of the conducted tests to develop formulas for the NO_X emission factors suitable for modern slow speed two-stroke Diesel engines. Data presented in the Figure 7 were averaged out for each load condition with the SE of 1.36, 1.07, 0.64 and 0.77 for 25%, 50%, 75% and 100% MCR respectively. The propeller law was then applied to determine the percentage of engine speed in order to incorporate both power and speed for the prediction of NO_X emission factor. Multi Linear Regression (MLR) method was used to model the relationship of % of power and % of speed to the NO_X emission factor. Predicted results from the MLR model was statistically analysed to ascertain the accuracy of the model. The calculated Root Mean Squared Error (RMSE) and Linear Correlation Coefficient (LCC) of the model are 0.267 and 0.94 respectively. The formula for propeller law operated main engines includes both % of power and speed to factor in their effect on the formation of NO_X. The formula for the NO_X emission factor for the constant speed main propulsion engines didn't include speed as engine speed remained the same as maximum throughout. Therefore polynomial regression formula was obtained for the calculation of NO_X emission factor with RMSE and LCC values as 0.267 and 0.999 respectively. The resulting Equations are presented next.

Propeller-law operated main engines

$$NO_x emission\ factor\ \left({}^{g}/_{kWh}\right) = 8.73 - (9.15 \times \%MCR) + (13.9 \times \%Speed) \quad (10)$$

Constant-speed main propulsion engines

$$NO_x emission\ factor\ \left({}^{g}/_{kWh}\right) = -(7.25 \times \%MCR^3) + (2 \times \%MCR^2) + (7.71 \times \%MCR) + 10.56 \quad (11)$$

In order to compare the results of prediction of updated emission factors using Equation (10) and that proposed by Cooper (2002) a MAN Slow Speed Diesel engine was selected and emission factors were calculated. The results, presented in Table 8, show substantial difference at higher loads (e.g. 19.9% for 75% of MCR). Therefore, it is suggested that the while the work of Cooper (2002) may provide emission factors accurate for engines built prior to 2000, these new emission factors may be more appropriate for more recent engines and factors in changes in emission factors as engine load changes, allowing optimisation of voyage profile, in particular while adopting slow steaming.

Table 8. Comparisons of emission factors for NO_X for Slow Speed Diesel Engines burning Residual Oil

6L70MC-C			**NO_X emission factor (g/kWh)**	
Load	Power	Speed		
% SMCR	kW	r/min	**Authors updated formula**	**IVL Proposed emission factors (Cooper, 2002)**
100	19,620	108	13.48	18.1
95	18,639	106.2	13.71	18.1
90	17,658	104.3	13.92	18.1
85	16,677	102.3	14.12	18.1
80	15,696	100.3	14.32	18.1
75	14,715	98.1	14.49	18.1
70	13,734	95.9	14.67	18.1
65	12,753	93.6	14.83	18.1
60	11,772	91.1	14.96	18.1
55	10,791	88.5	15.09	18.1
50	9,810	85.7	15.18	18.1
45	8,829	82.8	15.27	18.1
40	7,848	79.6	15.31	18.1
35	6,867	76.1	15.32	18.1
30	5,886	72.3	15.29	18.1
25	4,905	68	15.19	18.1
20	3,924	63.2	15.03	14.5
15	2,943	57.4	14.75	14.5

10. Conclusions

The maritime industry recognises the need for improved air quality in ports and coastlines in order to maintain good health for populations living in surrounding areas, requiring a reduction in harmful exhaust-gas emissions from ships. In the context of air-pollution from shipping, attempting to apportion costs to harmful emissions by offering incentives to cleaner ships based on some relevant index as an approach which is gaining popularity, but efforts so far are generally disparate and piecemeal. Additionally, there is a lack of transparency and simplicity to the rationale and effectiveness of these schemes, and considerable uncertainty associated with the emission factors used.

As examples of 'best' current practice in air emission monitoring for port-based incentive, ESI and CSI have been studied and compared. A number of key differences as well as similarities become clear:

Factor	ESI	CSI	Notes
Application	Monetary value as reduction in port dues, but complex, port-specific & varies with ship type	No direct monetary value attributed, used as a 'green badge' for environmentally conscious customers	
Spread	International, but voluntary (WPCI)	Sweden	
Overall emission balance	Dominated by NO_X emissions, hence high scoring LNGCs. Actual operation of ship of less importance. Very similar scores for other ship types.	Equal weighting applied to 3 main categories, scores are broadly scaled with impact throughout.	ESI is more susceptible to 'rule-breaking' and 'box-ticking' endeavours as a number of elements can generate high scores without the actual emissions being reduced. CSI is more complex to administer but more reliable as a measure of environmental impact.
NO_X	64.5% of total, maximum available score (zero NO_X)	33.3% of total, maximum available score (zero NO_X or tier III)	A more polluting ship can gain a higher equivalent normalised ESI score; conversely, ESI provides greater incentive to reduce NO_X towards zero, e.g. a Tier III engine will score maximum points under CSI, but only equivalent to 51.6% ESI (of 64.5%).
SO_X/PM	Based on fuel Sulphur content of bunker types, but not relative mass, so a high score can be artificially gained	Based on mass-averaged fuel Sulphur content pus bonus for use of very low S fuel in port.	Both show similar contribution of SO_X component to air emissions total if 1 fuel type only is bunkered. Whilst ESI score can be massaged to appear artificially high, if presence of ECA near port is assumed, then reduced SO_X near port is enforced, so from port's perspective, goal is achieved?
CO_2/OPS	Score of up to 14.5 available (3.2 for EEOI reporting, 11.3 for OPS capability) out of 111.3 (but capped at 100). No scale applied, scores are either awarded or zero.	33.3% of air emissions score, scaled w.r.t. EEOI performance	More comprehensively considered by CSI, notable that highest scoring existing ships reporting ESI score zero here. ESI only requires existence of EEOI reporting/OPS capability, not its use/value.

The analysis of these two key indices has highlighted a number of strengths and weaknesses of each, both in their current intended application, and as a baseline for a more broad-based model, delivering overall monetisation of external environmental costs from emissions.

Within any model for monetisation of emissions, accurate apportionment of those emissions remains an issue. Simplified engine and fuel factors for NO_X and SO_X emissions tend to disregard a number of factors which can have a significant impact on the actual measured emissions, for example engine load. When considering emissions in or near areas of population, the transient loads on the engine can have a significant impact.

For this reason, it is necessary to consider how to more accurately model the real-time emissions characteristics of actual ships, so that actions are not taken which may have unintended consequences in the precise area we wish to control. The presented updated formulae for NO_X emission factor demonstrate a significant departure from those proposed by Cooper (2002), and have the potential to impact upon actual delivered versus predicted NO_X emissions significantly. In the current economic climate, characterised by a protracted period of global recession and stagnation, leading to low freight rates against maintained relatively high fuel prices, shippers are turning to initiatives such as slow steaming and voyage optimisation to cut their costs. These results demonstrate that the achieved NO_X

emissions under this scenario could differ significantly from those which might be predicted by a traditional emission factor model.

Emission factors for both SO_X and CO_2 for a given fuel are proportional to engine load, and therefore equally susceptible to inaccurate assessment of transient loads, as well as impacts of slow steaming.

An incentivised port due scheme capable of delivering real (and fair) environmental benefits from ships' exhaust gas emissions, both at sea and near population centres therefore needs a number of elements to come together:

- It should consider global GHG emissions (including transient load conditions), and incentivise efforts to reduce them (e.g. through EEOI, as CSI does);
- It should consider local air quality impacts (i.e. NO_X , SO_X, PM), in particular it should take account of the transient load conditions encountered near shore and in port (updated emission factors);
- It should deliver measurable financial benefit to the shipper (as ESI does);
- It should provide an opportunity for zero-emission operation in port (OPS) to be rewarded (as ESI does, CSI benefit is small) to encourage ports in turn to provide the infrastructure;
- It should be simple to administer and comply with, and provide potential net financial benefit.

Finally, any incentivisation of 'green' shipping must meet two key criteria if it is to have any validity: it should be adaptable or scalable, so that it may continue to reward early-adopters as international legislation becomes more stringent, and it should be quick, i.e. it should be in place and available as soon as possible, to 'bridge the gap' in terms of the time lag between discussion and adoption of legislation, and its implementation (often staged). This is particularly important in the case of GHG emissions, as climate models demonstrate very clearly that actions to mitigate emissions are required now if we are to avoid dramatic changes being required further down the line, or uncontrollable future global warming. Common sense dictates that the sooner any emission is controlled, the greater the cumulative harm reduction available.

It must also demonstrate real value to the shipper (and port if that is to be the means of collection): a voluntary scheme which is more financially onerous to administer than the maximum available benefit can offset, will fail. In the long term, incorporation of such an emissions indexing scheme into mandatory legislation may be considered, but does not form part of this study (it is widely expected that IMO will mandate a CO_2 fuel levy scheme, however, this is not the current direction of activity at IMO to address NO_X and SO_X).

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