UCL ENERGY INSTITUTE

A Case Study of Fuel Monitoring and Efficiency Indicators for INTERTANKO

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Executive Summary

The study investigates the CO_2 emissions and other relevant data collected over a five-year period from 11 "identical ships", namely ships:

- built according to the same design
- built by the same shipyard
- operated by the ship management company
- having similar systems for measuring and obtaining data.

These ships have same Estimated Index Values but they have variable operational performance as expressed through their annual EEOIs. Since these ships are identical and operated by the same ship operator, they do represent a unique opportunity to better understand their CO_2 emissions and to identify the impact that some important environmental, commercial and contractual factors have on their operational performance. To that extent, the study provides direct measurable challenges and obstacles to determine a simple methodology to assess the operational efficiency of a ship.

The data collected reveals a poor relationship between individual ship's total annual CO_2 emissions and their EEOI values. In one case, the ship with the highest amount of CO_2 emissions over one year was also the ship with the lowest (best) EEOI.

Up to 60% of the variation in EEOI values is due to contractual factors such as speed, total amount of cargo carried and the share between laden and ballast voyages. The remaining 40% of the variability on the EEOI values could be attributed to: the environmental conditions (sea state and the climate in which the ship operates), the commercial conditions (e.g. nature of cargo, the calorific value of fuel used) and the maintenance and technical specifics of the different ships (hull coating, cleaning, hull and propeller fouling, engine wear). Except the latter, all other factors are in principle not under the control of the ship operator.

The study also analyses the relation between EEOI and two alternative energy efficiency indicators which were proposed earlier at IMO and which include proxies for transport work. All three metrics produce differing values and different relative hierarchies of efficiency. No two metrics/indicators were found to be well correlated or produce similar rankings, suggesting that all these different metrics are significantly different in what they actually represent. The two proxies addressed are not good approximations for the actual transport work and further distort the estimation of a ship's actual performance on the overall transportation efficiency.

It can be concluded that although a ship can be managed in a consistent manner, there may still be significant inter-year variations of their CO_2 emissions reported on the service provided.

These variations are due to factors which are not under the control and decision of the ship operators. Therefore, there is a significant difference between the ship's technical efficiency capability and the ship's performance in operations. Data collected from ships will always reflect the latter which is the actual "energy efficiency of transportation at sea", including such aleatory factors.

Introduction

Ongoing work at IMO is developing a fuel data collection system (REF) and is likely to also include the collection of a number of related parameters (e.g. a proxy for transport work). One potential use of data collected in this way is to understand trends and variations in fuel consumption and energy efficiency – both variations over time and variations between different ships.

This study explores a number of issues related to the monitoring and collection of data from ships, using a case study on a fleet of technically similar ships and data collected for these ships during the period 2010-2014.

Case study fleet

The dataset used for this investigation is a fleet of 11 sister ships, all product/chemical carriers. The ships were built to the same design in the same yard and have been owned, operated and managed by the same company over a period up to 11 years, inclusive of the period for which this case study is conducted. The ships are chartered in different ways, both time and spot charter to different clients, and are operated in different areas.
Very minor differences occur between the ship's technical specifications, see Table 1, and consequently result in similar Estimated Index Values, see Table 2 (the ships pre-date EEDI and so EIV is used here to provide an indication of their relative technical efficiency). No significant efficiency related retrofits were performed on any of the ships studied during the period of this study, and only routine maintenance and management was performed.

GT	DWT	LOA	Beam	Des. Draft	Des. Speed	Built	ME Power (kW)	AE Power (nominal) (kW)
25804	40471	179.78	32.2	10.5	14	Dec 2005	9480	975x3
25804	40416	179.89	32.2	10.5	14	Apr 2006	9480	975x3
25804	40416	179.92	32.2	10.5	14	Oct 2006	9480	975x3
25804	40616	179.93	32.2	10.5	14	Jan 2007	9480	975x3
25804	40382	179.83	32.2	10.5	14	April 2007	9480	975x3
25804	40447	179.98	32.2	10.5	14	Aug 2007	9480	975x3
25864	40416	179.94	32.2	10.5	14	Jul 2008	9480	975x3
25814	40400	179.9	32.2	10.5	14	Dec 2008	9480	975x3
25864	40404	179.88	32.2	10.5	14	Jan 2010	9480	975x3
25864	40334	179.95	32.2	10.5	14	Apr 2012	9480	975x3
25949	40030	179.96	32.2	10.5	14	May 2013	9480	975x3

Table 1: Vessel characteristics

EIV (gCO2/tnm)
12.4
12.4
12.4
12.4
12.4
12.4
12.4
12.4
12.4
12.5
12.6

Table 2: Estimated Index Values for each ship using an SFC of 170 g/KWh and 215g/KWh for main and auxiliary respectively. and a carbon factor of 3.114 teCO2/teFuel and 3.206 teCO2/teFuel for main and auxiliary respectively.

The ships each have a number of different systems for measuring and obtaining data. These vary in their frequency and parameters measured, see Table 3. A QA and further data description is provided in Appendix 1 at the back of this report. Throughout this report, the names of the ships have been removed in order to anonymise the results. Consistent colours on charts are used to indicate the different ships.

Dataset name	Frequency	Average number of observations per vessel	Fields reported (most relevant)
VAF	15min	50000	Torque, speed over ground, rpm, power, fuel con
Polestar	6hour	5000	Speed, wind force, wind dir, pressure, swell/wind wave height, swell/wind wave dir, swell/wind wave period
Noon	24hour	2000	Mean speed over ground, mean rpm, fuel con, wind force, wind dir, sea state, swell dir, slip
Port Departure Reports	At each departure	300	Cargo volume, draft fwd/aft

Table 3: data acquisition systems used

Variability in emissions and EEOI

The total annual CO2 emissions, for both main and auxiliary consumers, is calculated using total fuel consumption and fuel related CO2 emissions factors. Figure 1 displays the variation in total emissions over the period 2010-2014, for each of the 11 ships. The annual aggregate average EEOI is also calculated for the same period and fleet, and displayed in Figure 2. Total emissions and average EEOI vary consistently between 13-18,000 tonnes and 14-22 gCO2/tnm respectively, with some outliers either side of these ranges. The variation in EEOI magnitudes between ships (e.g. ship A compared to ship B) is greater than the variation for any one ship's annual aggregate EEOI over the period of the study.

The EEOI and total emissions are not necessarily related, for example in 2013, the ship with the highest emissions is also the ship with the lowest (best) EEOI. Further evidence for this can be seen in the plot of all years and all ship's EEOI vs. emissions (Figure 3), which shows a very weak correlation ($R^2 = 0.03$).

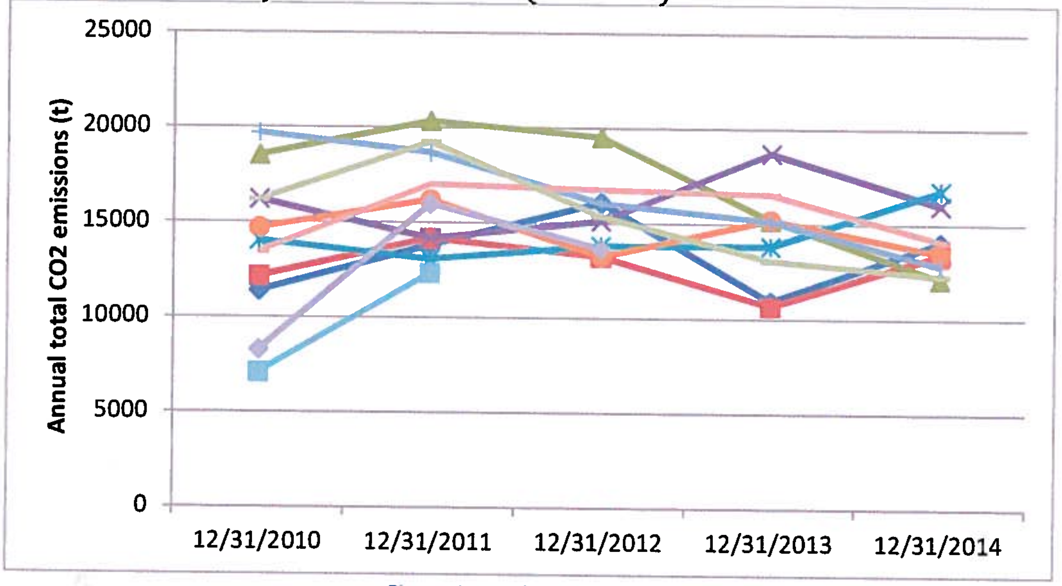

Figure 1: Total emissions (main and auxiliary)

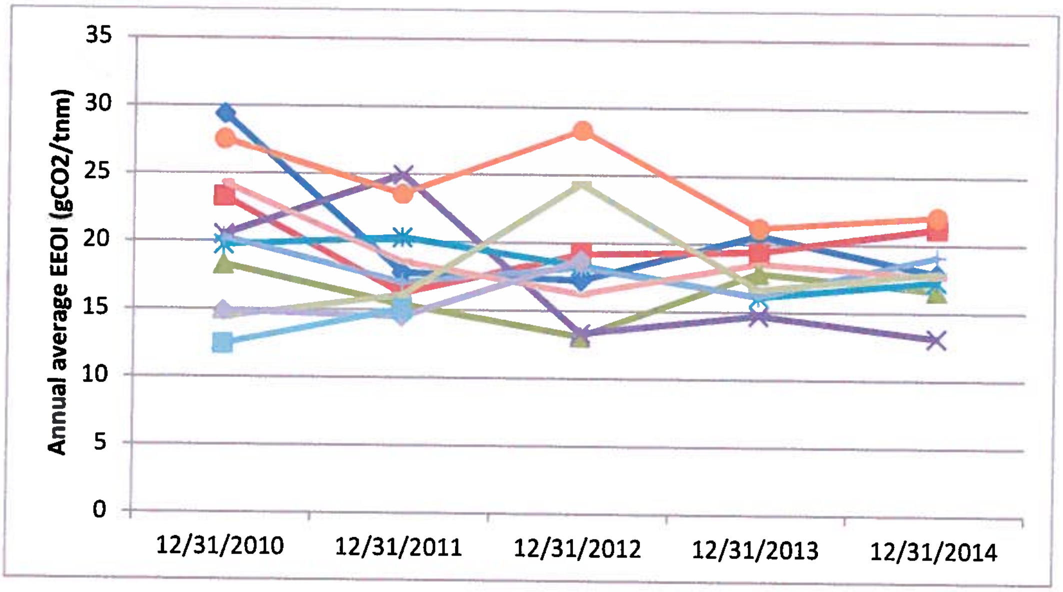

Figure 2: Annualised EEOI

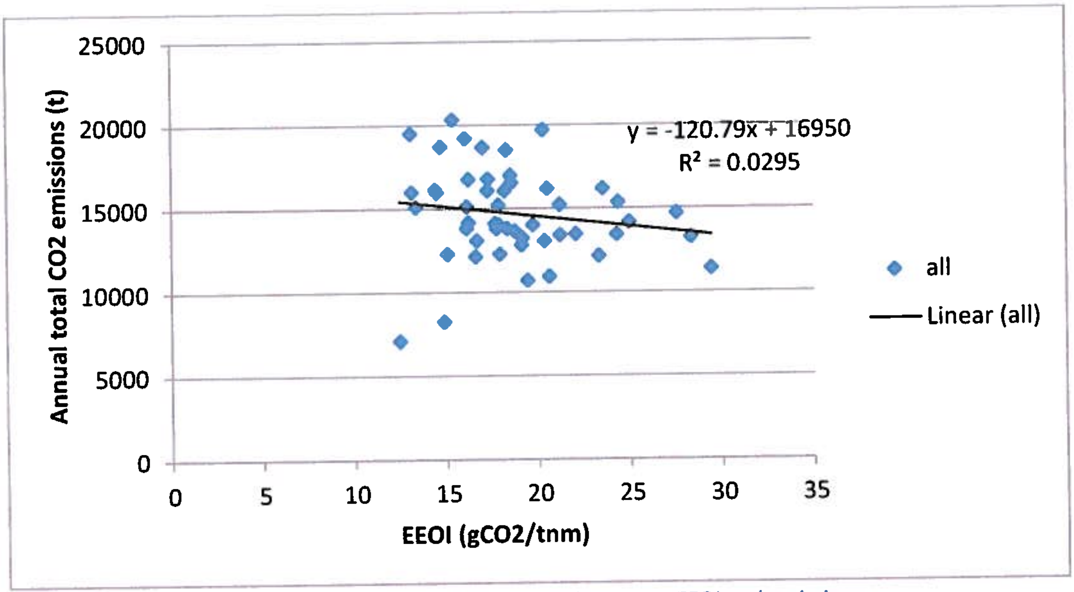

Figure 3: Relationship beetween EEOI and emissions

Understanding the variation in EEOI

Variation in EEOI can be related to a number of different influences, which can be looked at both in isolation and in combination. Terms used in the following text and figures include:

- **transport work** (the total tonnes nautical miles of loaded cargo work done by the ships)
- **payload utilisation** (the average cargo carried when loaded), if all else is equal, greater payload utilisation results in lower EEOI
- **allocative utilisation** (the average time in loaded condition vs. ballast condition), if all else is equal, greater allocative utilisation results in lower EEOI
- **speed factor** (the relationship between design and operating speed shown below, note higher operating speeds lead to lower values of speed factor), if all else is equal, greater speed factor results in lower EEOI. The speed factor is formulated to be indicative of the amount of variation in EEOI created by speed changes, but assumes a cubic relationship between fuel consumption and speed which may not strictly be the case. The quadratic relationship appears below because transport work is linearly related to speed (higher speed increases fuel consumption by a cubic as well as linearly increasing transport work) and therefore one exponent of speed in a factor to normalise EEOI is cancelled out.

$$\left(\frac{v_{des}}{v_{ht}^{op}}\right)^2 = \text{the speed factor (SF)}$$

Figures 4 to 7 show the variation in these parameters for each of the ships over the time period 2010 to 2014. The speed factor shows a gradual increase which indicates a trend of decreasing operating speed over the period, something which is consistent with other studies on similar data for the same period (REF RBSA study). The ships within the case study fleet travelling close to design/reference speed, or slower, in 2010 and by 2014, all were slow steaming by varying amounts (by between approximately 10-20% less than design/reference speed in 2014).

During the same period, the total transport work (Figure 5) shows significant variation. The same ships can be seen performing markedly different (100% variation) amounts of transport work year-on-year. Decomposing the transport work into some of its constituents: allocative and payload utilisation, displays some explanation for that variation. Notably, one of the ships is operated at 70-80% allocative utilisation (ratio of loaded:ballast time) during 2013 and 2014, which coincides with the achievement of high transport work.

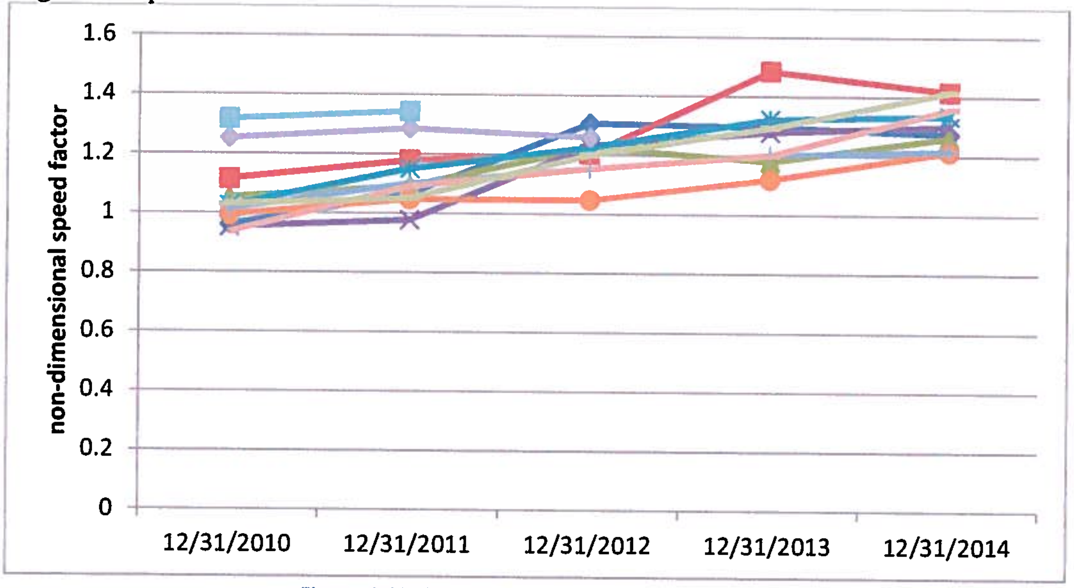

Figure 4: Variation in speed factor between ships and over time

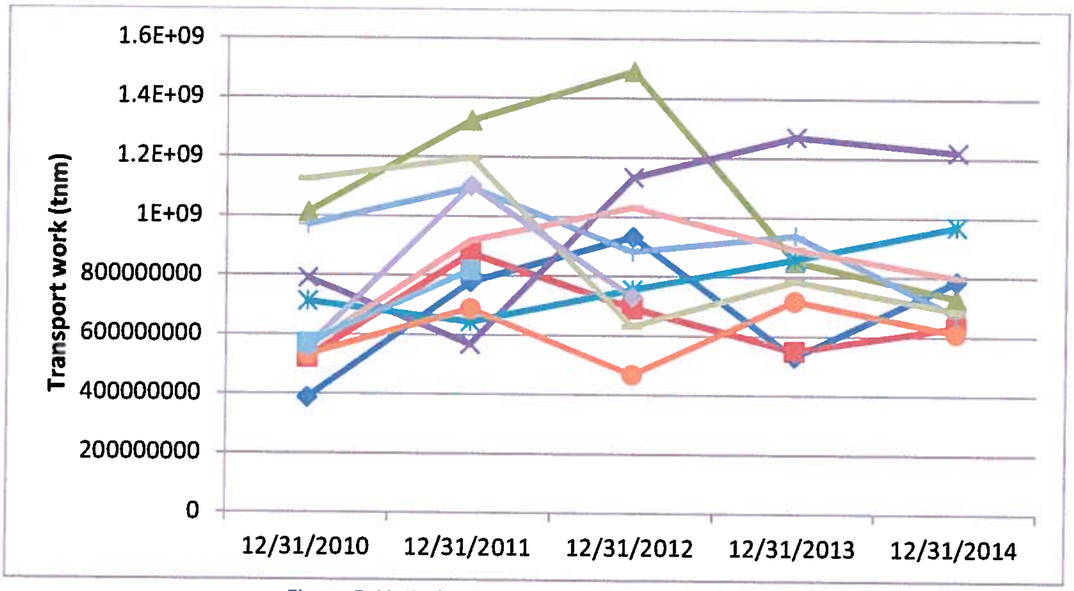

Figure 5: Variation in transport work between ships and over time

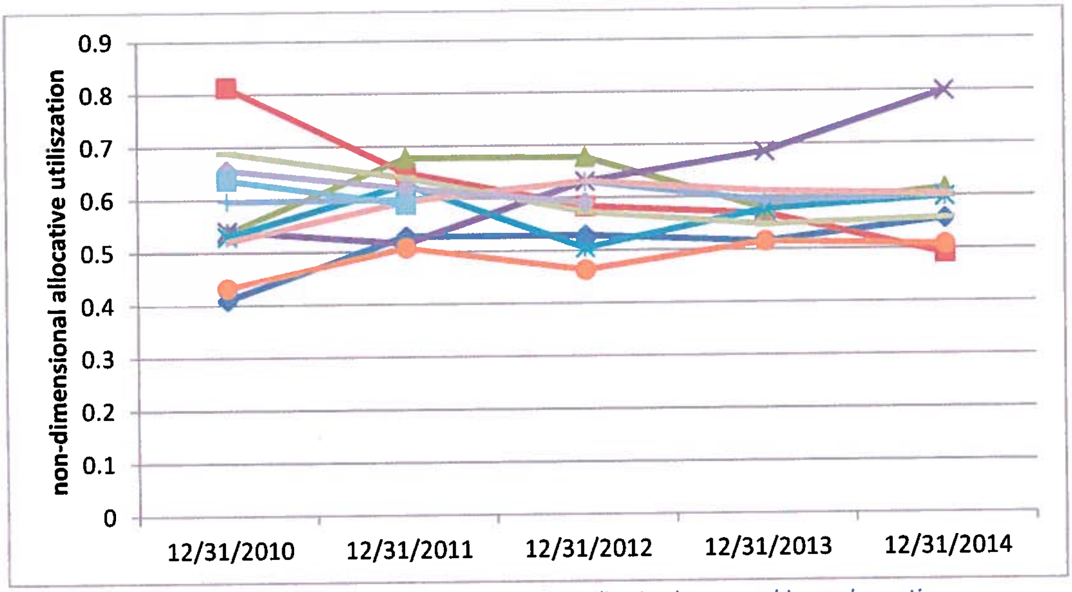

Figure 6: Variation in allocative utilisation between ships and over time

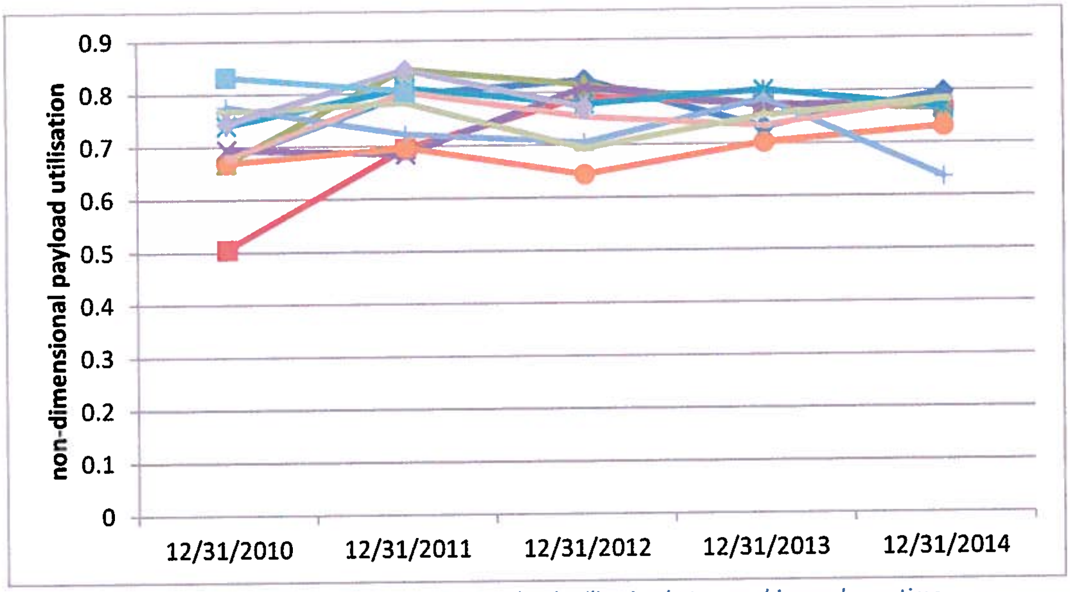

Figure 7: Variation in payload utilisation between ships and over time

Figure 8 shows a test of the relationship between a combination of several of these parameters which influence EEOI: speed factor, allocative and payload utilisation. Whilst a good correlation can be observed, confirming that these parameters in combination can explain some of the variability in EEOI observed in Figure 2, the calculated R^2 is 0.61, which means that only approximately 60% of the variability has been captured in these parameters.

Table 4 provides some further values for the correlation coefficient of different parameters, taken both in isolation and in combination. Similar values are obtained for allocative and payload utilisation, with transport work (which includes the influence of both allocative and payload utilisation variations) capturing approximately 50% of the variability. Including the speed factor then increases the variability captured further (as noted above). Speed factor in itself is a comparatively poor indicator of the total variability in EEOI, however it is shown to be significant even though the variation in

average operating speeds (between reference speed and 20% less than operating speed) is low.
In total, the majority of the variability (60%) in annualised EEOI is captured by parameters that are typically outside of the direction of the shipowner/manager/operator – the speed, cargo carried and sequence of voyages. There must also be sources of variability attributed to sources other than just these factors. These could include:

- the maintenance and technical specifics of the different ships (hull coating, cleaning, hull and propeller fouling, engine wear)
- the specifics of the fuel used (calorific value)
- the specifics of cargo heating and auxiliary fuel use for different cargos (which may also be outside of the control of the shipowner)
- the environmental conditions (wind, wave and current environment) that the ship operates in, as well as the air and sea temperatures (which in turn can affect engine performance, auxiliary and cargo heating loads, hull and propeller fouling etc.)
- other specifics of the operation of the ship by the crew (e.g. decisions made to speed up or slow down during the course of the day or voyage, onboard practice with maintenance and running of auxiliary machinery etc.)

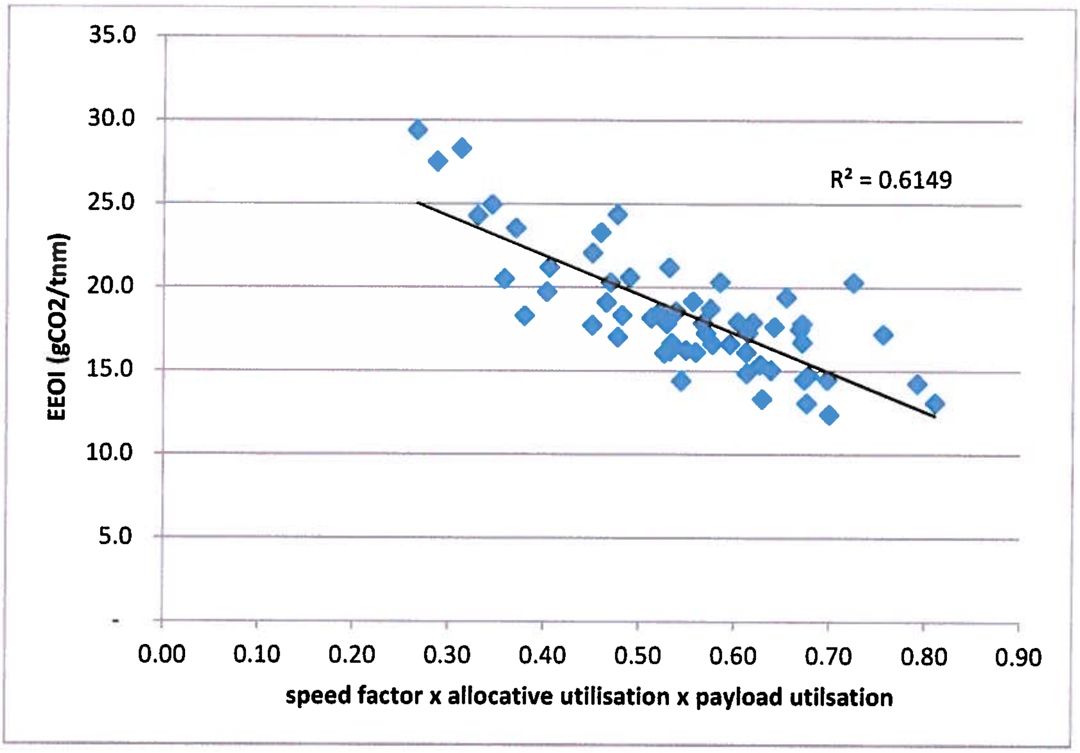

Figure 8: Relationship between EEOI and the combination of several parameters that influence EEOI

Parameter(s)	R^2
Allocative utilisation	0.42
Payload utilisation	0.44
Transport work	0.50
Loaded days	0.37
Speed factor	0.24
Allocative utilisation x payload utilisation x speed factor	0.61

Table 4: Correlation coefficients, relative to EEOI, for different calculated parameters

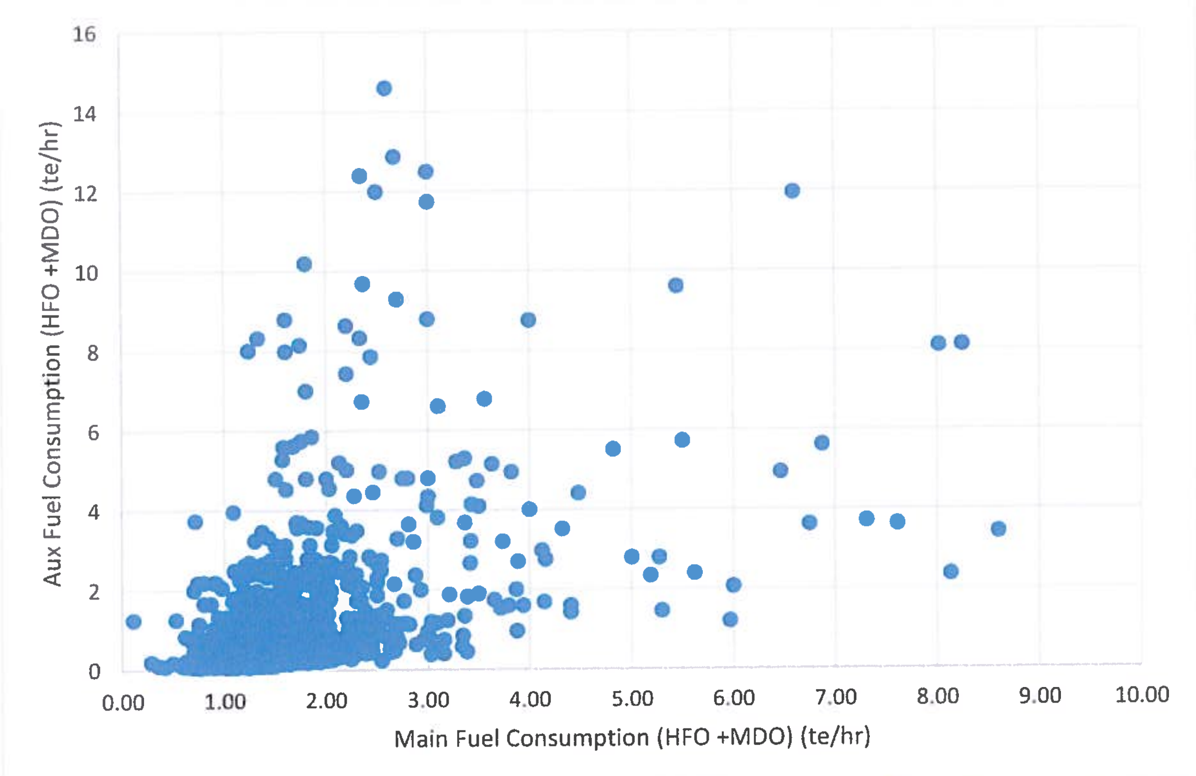

Figure 9: Relationship between auxiliary and main engine fuel consumption when the vessel is classified as loaded. For both main and auxiliary, HFO and MDO is summed. The view is restricted to Main Fuel consumption below 10te/hr (removes 6 datapoints) and auxilliary restricted to below 15te/hr (removes 10 datapoints). Each observation is the total fuel consumption within the noon report period divided by sailing time.

Transport supply as a proxy for transport work

Transport work, the cargo mass x distance travelled (summed over all loaded voyages in a time period), has been shown to be a significant parameter in the variability in EEOI. However it is not always available. Using the data from this case study, its possible to investigate the quality of different proxies for transport work and therefore the consequence of substituting actual transport work with one of its proxies.
A commonly discussed proxy for transport work is the transport supply. This is the theoretical maximum transport work, which would be achieved if a ship is fully loaded on every passage/voyage. It is calculated as deadweight x total distance travelled (including all ballast and loaded voyages). It is equivalent to setting the allocative and

payload utilisation to 1 (compare with Figure 6 and 7 to see their actual values for this case study fleet).

Figure 10 displays the comparison between transport work and transport supply. The linear fit implies that 74% of the variation in transport work can be described by the variation in transport supply. Figure 11, however, which examines the correlation between transport supply and EEOI shows that only a small amount (less than 4%) of the variability in EEOI can be attributed to transport supply. This implies that relative to transport work (R^2 of 50%, in Table 4), transport supply is a poor explanatory variable for variations and trends in EEOI.

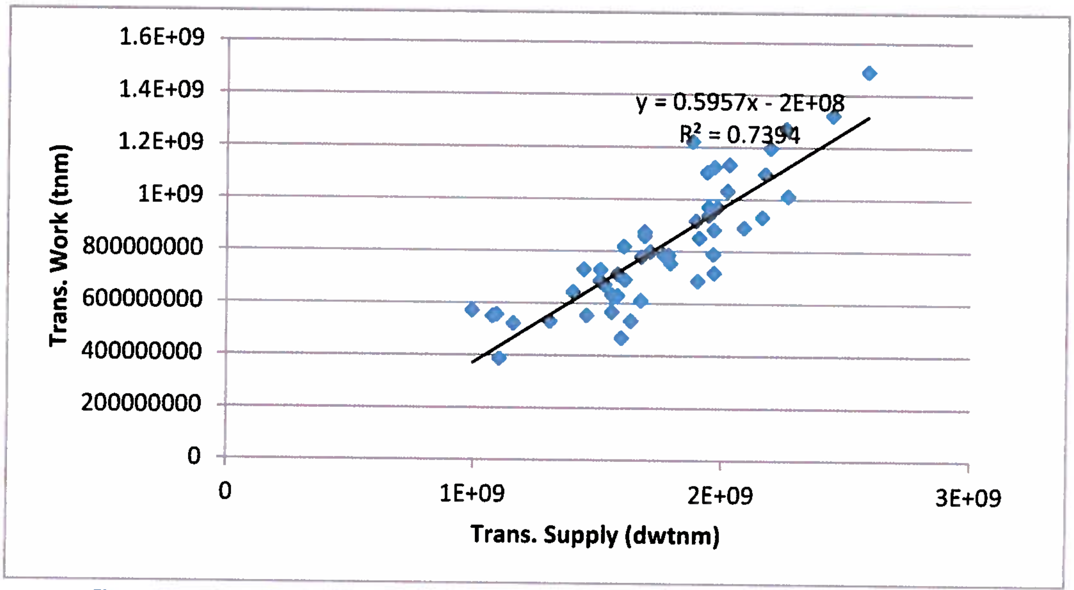

Figure 10: Comparison of transport work with the proxy for transport work, transport supply

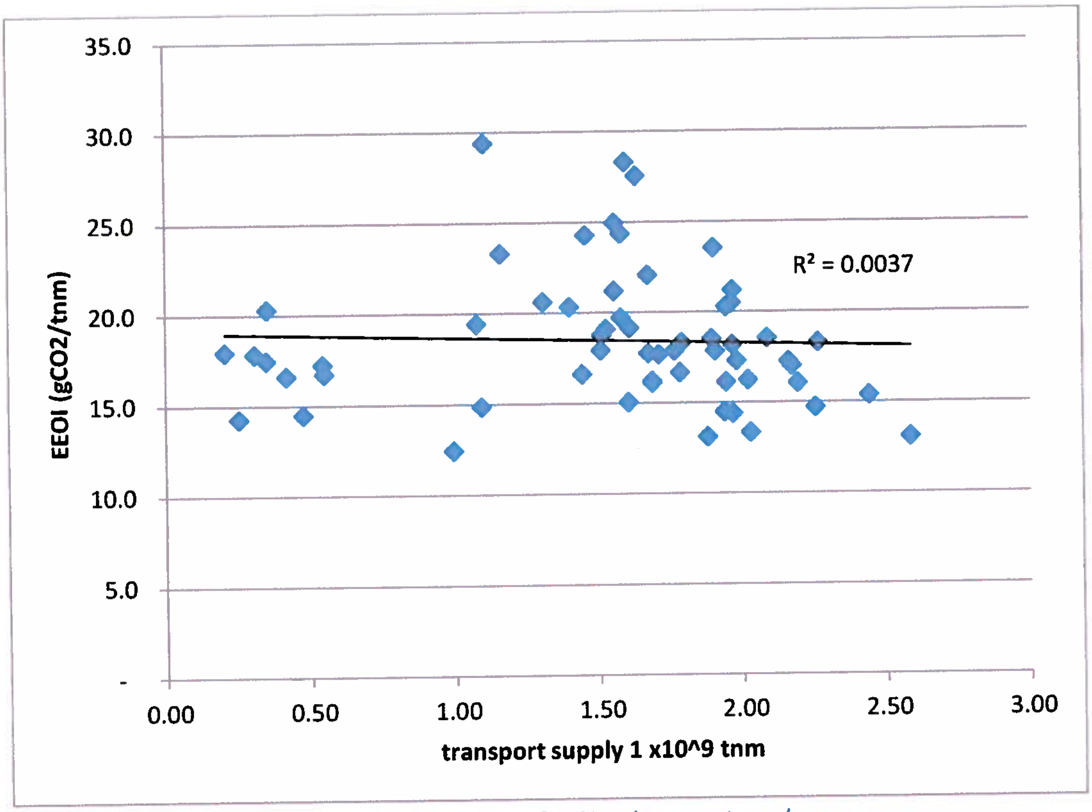

Figure 11: Correlation of EEOI and transport supply

Potential alternative calculations of efficiency

A number of alternative metrics/indicators for EEOI have been proposed (MEPC 67/5/4 – referred to here as EEJI and MEPC 65/4/19 referred to here as EEUSI). All of these indicators are intended to represent 'in-service' efficiency based on the actual activity and operation of a ship.

Calculations were performed on the case study fleet for each of these alternative metrics/indicators. Added to this was also the calculation of EETI and EIV for each of the ships – both estimates of the ship's technical efficiency in a reference condition as opposed to its operational efficiency. EETI is estimated by deducting the effects of speed and transport work (allocative and payload utilisation) from the EEOI, a full derivation can be found in (MEPC 69/INF.26 and "Understanding the Energy Efficiency Operational Index: data analysis on ships tanker ships for INTERTANKO", UCL Energy Institute).

Metric/indicator	units	Description
EEOI	gCO2/tnm	Operational efficiency
EEUSI	J/hour	Operational efficiency using transport work proxies
EEJI	gCO2/tnm	
EETI	gCO2/tnm	Technical efficiency in a reference condition
EIV	gCO2/tnm	

Table 5: List of metrics/indicators used in this study

The pairwise comparison of each of these indicators with each other is shown in Figure 12, along with the distributions of each parameter. All values (except EIV) are calculated for an annual time period for each ship and for each of the years of operation (2010-2014). Whilst the values of R^2 are not calculated, it is clear that there is no significant relationship between EEOI, EEUSI and EEJI – all three metrics produce differing values and different relative hierarchies of efficiency. Given that both EEUSI and EEJI use proxies for transport work, this indicates, further to the evidence shown in Figure 10 and 11, that these proxies are not good approximations for the actual transport work and therefore distort the estimation of a ship's actual operational efficiency.

Taking EETI as the most meaningful indicator of the relative technical efficiency of the ships (because it has corrected for variations in speed and utilisation representing approximately 60% of the variability in EEOI), there is shown to be only a weak relationship between EETI and EEOI, EEJI and EEUSI. This indicates that none of these three operational efficiency indicators, is a good representation of the relative technical efficiency of different ships.

These findings can further be demonstrated by comparing the different rankings achieved by the different metrics/indicators for each ship in each year. Table 6 shows the highest ranked ship (lowest/best score on each metric/indicator), according to each of the different metrics/indicators. Whilst in 2 years, EETI, EEUSI and EEJI are consistent (2012 and 2013), generally the metrics/indicators all show significant variations.

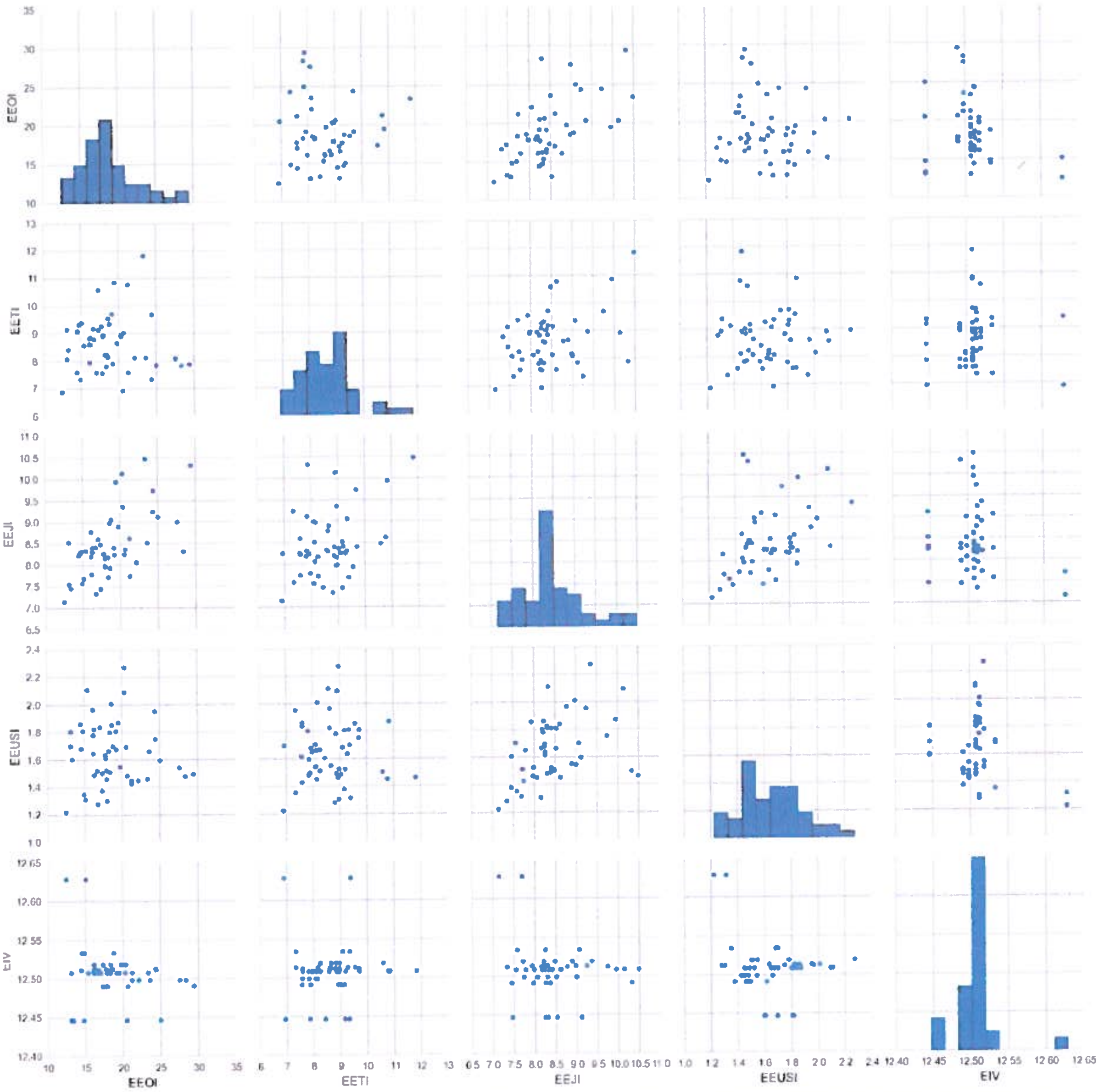

Figure 12: Pairplots for the indices to indicate correlations between indices. The table shows the top ranked vessel in each category for each year.

Year	EEOI	EETI	EEUSI	EEJI
2010	A	F	I	J
2011	B	G	D	I
2012	C	B	B	B
2013	D	A	A	A
2014	D	H	J	D
2015	E	D	H	E

Table 6: highest ranked ship according to each index in each year (the ships have been randomly anonymised with their full name replaced with a letter)

Discussion of EETI and EEOI

The case study fleet provides a good opportunity to further investigate the viability and robustness of the indicator EETI for estimating the relative technical efficiency of ships using annual operational data – particularly in relation to the use of EEOI as a comparator between ships. A first step is to look at the variability in both indicators. The frequency distribution shown in Figure 13 shows that there is a larger variability in the EEOI when compared with the variability in EETI – which is to be expected for a fleet of technically very similar ships where the main source of variability is likely to be differences in the way the ships have been operated.

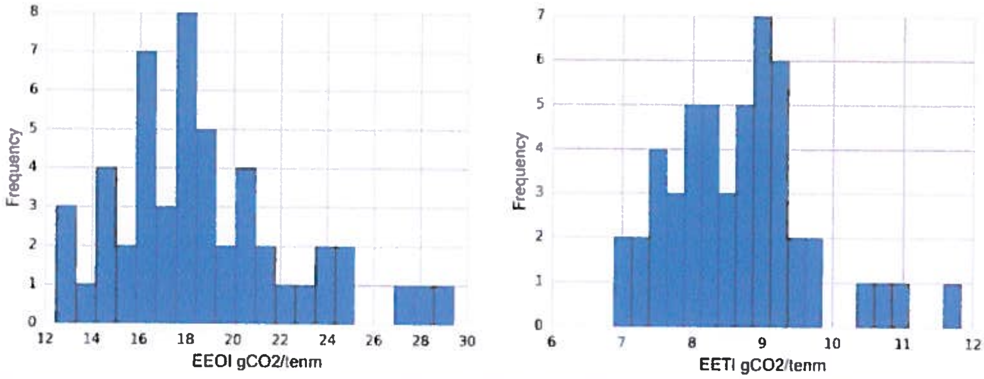

Figure 13: Histograms of Annual EEOI and Annual EETI for whole fleet across all years. 2015 is excluded as only complete data is available for the previous years. Mean and std of EETI: 8.66, 1.0 (12%). Mean and std of EEOI: 18.71, 3.89 (20%).

The EETI calculated for each of the ships in turn and for each year, is plotted in Figure 14. This shows that whilst there appear to be some outlier values, there is a tight grouping for these technically similar ships and the trend is for a gradual increase in EETI over time. Whilst on any individual ship, maintenance, dry docking and retrofits could cause relative reductions in EETI year-on-year, this gradual increase is consistent with an aging fleet where component efficiencies (e.g. hull, propeller and engine performance) deteriorate over time.

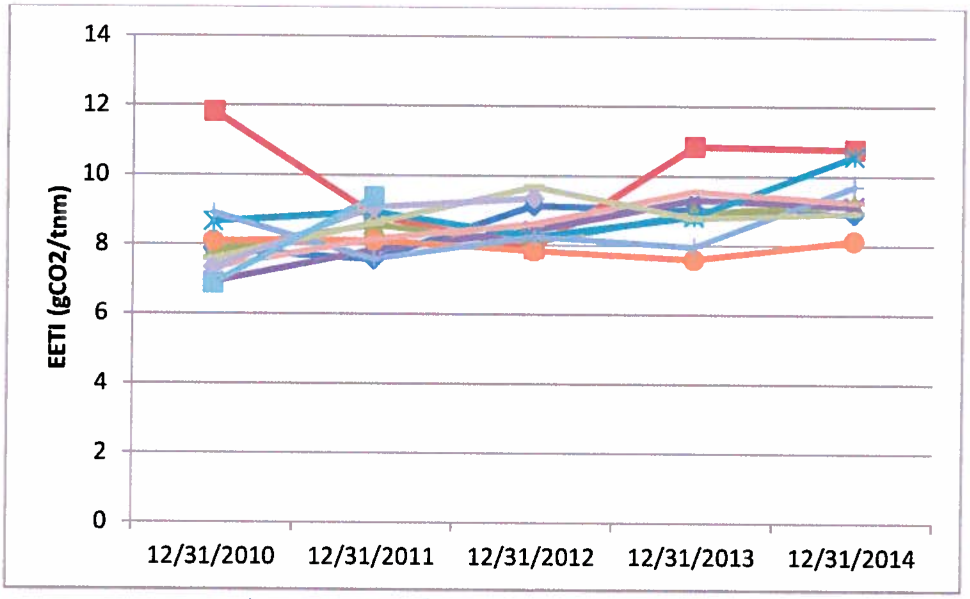

Figure 14: Time series of annual EETI for each vessel

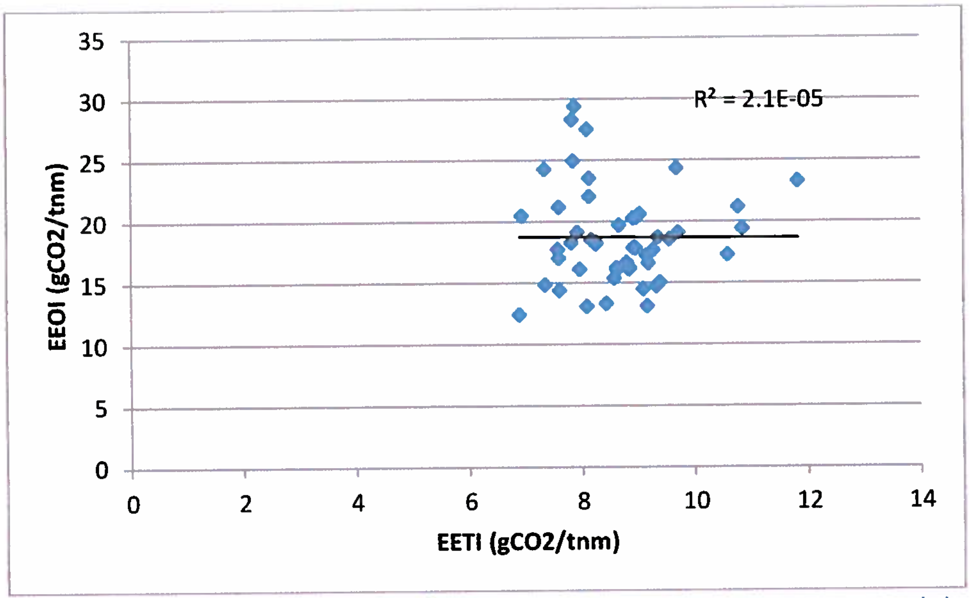

Figure 15: EETI vs EEOI with all data plotted and trendline fitted. Zero values of EETI and EEOI are removed along with data for 2015

As EETI is related to EEOI through corrections applied to speed, allocative utilization and payload utilization, reductions in EETI will affect overall EEOI. Operational improvements that result in more efficient utilisation of a ship (e.g. virtual arrival) will have negligible impact. The corollary is that market conditions which can strongly impact the operational factors (average speeds, utilisation) should also not create significant variations in EETI. Conversely, investment in retrofits of energy saving technology should have a direct (benefiting) impact on EETI and should be more apparent in this indicator than in the EEOI.

One issue which complicates EETI is its calculation, as the EETI must be determined for a reference condition, and requires a conversion relating speed and fuel consumption that if incorrect can misrepresent performance/efficiency at high or low speeds. As has been highlighted in many other publications, depending on the ship type and its machinery, the relationship between fuel consumption and speed is not always well captured by a simple cubic relationship. In such instances the speed factor may be calculated using a more sophisticated mapping of the relationship between speed and fuel consumption – if the data is available.

Furthermore, as EETI is very sensitive to the reference speed, the selection of this value is important. Most likely, this reference speed can be the 'design speed' if this is known but this is reliant on the reporting and quality of data used in its calculation.

Time period and EEOI

Another benefit of EETI is that it can correct for variations that occur as a function of the duration of passages and voyages. Figure 16 shows the relationship between voyage length and EEOI for all ships and all voyages over the period 2010-2014. Whilst there are a number of outliers, the general trend is that shorter voyage lengths result in higher EEOI.

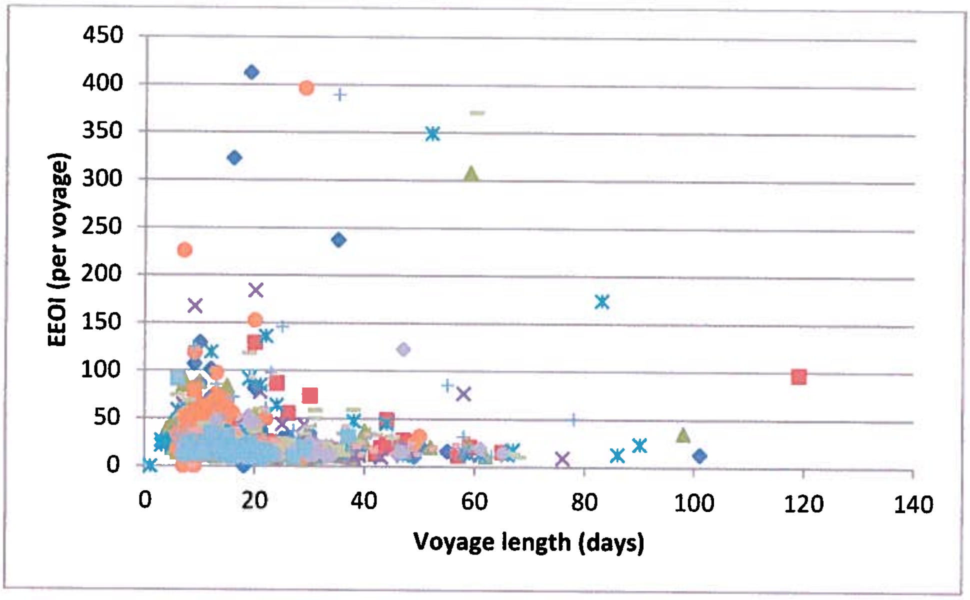

Figure 16: EEOI versus voyage length.

A further result of this variability in voyage length and its relationship to EEOI is that a small number of voyages can have a significant effect on the annualised calculation of an indicator. This can be illustrated using the example of one of the ships considered (referred to here as ship X), as shown in Figure 17 where a small number of outlier voyages can have the effect of significantly increasing the annual EEOI (shown in Figure 18 for the period 2010-2014).

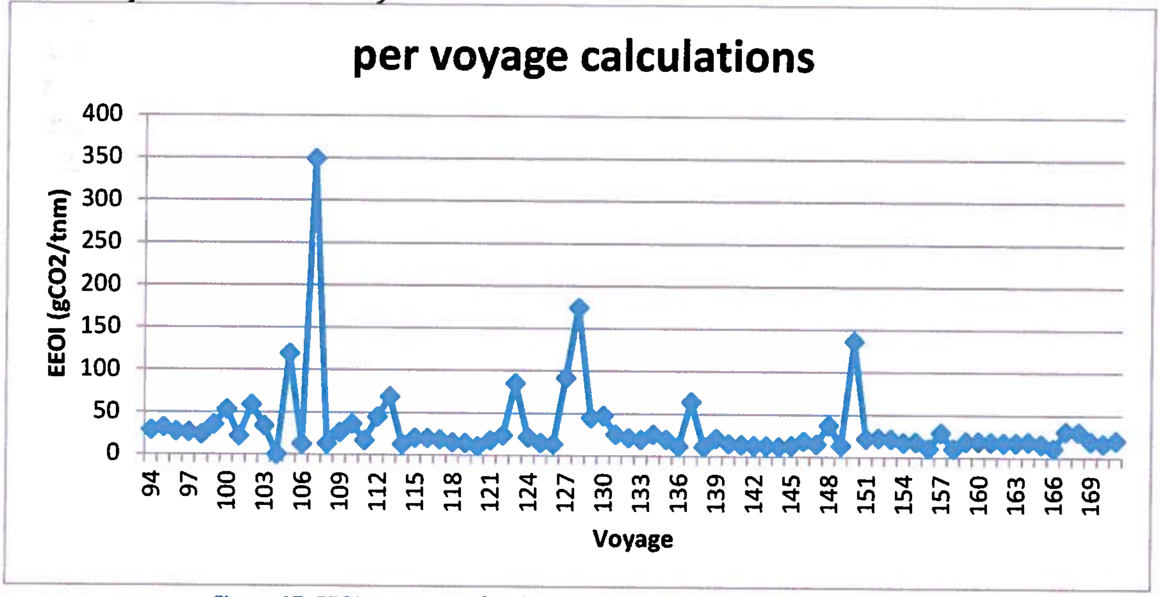

Figure 17: EEOI per voyage for ship X. 2010 includes voyages from 94 to 119.

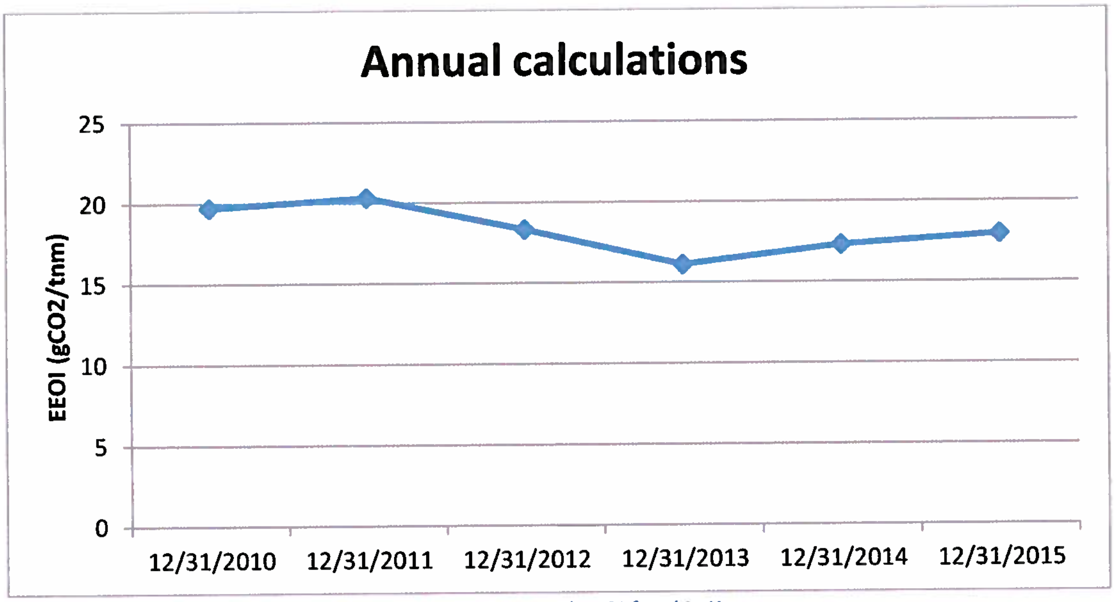

Figure 18: Annual EEOI for ship X

A further issue is that any static periods may have the effect of annual EEOI becoming more sensitive to individual voyages. On a macro level, any market corrections (or unstable market conditions) could possibly have the effect of creating volatile values of annualised EEOI if vessels are repositioned to certain areas, put into cold or hot layup, or drydocked/retrofitted.

Concluding remarks

- The fleet, which contains 11 technically identical sister ships, wall built, owned and managed consistently and by the same entity, provides an excellent case study for investigation of the collection of data and its use to calculate different indicators and metrics
- For these 11 ships, over the period 2010-2014, large variations in annual emissions (13-18,000 tonnes) and annual EEOI (14-22 gCO2/tnm) occurred, with variability both year-on-year and between ships. Within that variability, a given ships EEOI or total emissions in 1 year provide little indication of its EEOI or total emissions in the following year.
- The variability in EEOI can be partially explained through the variability in transport work (caused by variability in loaded days, allocative utilisation and payload utilisation), and variations in operating speeds, between ships and years of operation.
- When combined, speed, allocative and payload utilisation explained approximately 60% of the variability in EEOI. This majority cause for variability in EEOI was attributable to parameters that are predominantly outside of the shipowner/manager's control and are more commonly determined by the environmental conditions as well as commercial conditions (e.g. type and transportation requirements for the cargo) and contractual conditions (speed, payload, etc.) .
- The performance of transport supply (dw tnm) as a proxy for transport work was considered and whilst transport supply and work, for this fleet, are approximately

correlated, only a weak relationship could be found between transport supply and EEOI. This suggests that transport supply is not a good explanatory variable for EEOI.

- A number of different operational and technical estimates of energy efficiency were calculated for the case study fleet using various proxies and corrections. No two metrics/indicators were found to be well correlated or produce similar rankings, suggesting that all these different metrics are significantly different in what they actually represent.
- EETI, a metric that corrects for the dominant sources of efficiency variability that are outside of the owner/manager's influence (speed and utilisation), was shown to produce a more narrow-banded distribution than EEOI (consistent for a fleet of technically similar ships), and trends consistent over time with low average rates of performance deterioration (consistent for a fleet of aging ships).
- The EEOI can be considered to be distribution with "fat tails". As shown throughout this case study's analysis, although a vessel can be managed in a consistent manner, it may still have significant inter-year variations.

Appendix 1: Data and data QA

These calculations were produced using data in the following fields:
'name', 'Date', 'Sailing time', 'Mean Speed', 'Mean Main Eng', 'HFO Main', 'MDO Main', 'Draft Aft', 'Draft Fwd', 'Cargo volume', 'Voyage No', 'Fuel Type', 'Distance sailed', 'DWT', 'Days Elapsed', 'Mean Draft', 'HFO Aux', 'MDO Aux', 'Design_Aux_Power_kW', 'Design_Prop_Power_kW', 'Design_Speed'
This data is typically available in noon reports supplemented by the technical specification of the vessel. Where the data is not readily available it can often be readily derived from other reported variables.
In addition, there are several parameters that can be set such as reference speed and reference draught but these can be set to their design values. Other variables within the parameters worksheet can be used.

Model Data filtering and QA

Below are specific assumptions and filtering that were done on the data.

- Some cargo volumes are set as 1 or 2 – these are filtered
- Voyage numbers are assumed to increase sequentially – unless they are a combined voyage number in which case they are not altered.
- Voyages are all taken from the the ship operator's (or company's) calculations dataset. However, draft is still taken from Port Departure Reports dataset.
- Reported fuel consumptions appear to be acceptable.
- Consistency check of mean speed, distance sailed and sailing time. Of 20000 observations this removes about 500. However, a sample check of these observations shows that the distance sailed (there is no reported speed or sailing time for these observations) is very low (<50nm).
- Additional filtering takes place within the excel model which removes invalid observations resulting in 30 observations being removed. The additional filtering is shown below:
    - Speed is filtered to be between 0 and 30nm/hr.
    - Cargoes between 0te and 1000te are filtered out.
    - Cargoes greater than 1.1xDWT of the vessel are removed.
- For some observations, voyages number reverted to aprevious voyage number. The voyage numbers were all checked that the voyage number was always increasing (this was not possible for a combined voyage number) – this changed 160 observations in total.
- When observations are filtered out, no substitution takes place with alternative values. For example, if a voyage was 5 days and one of the noon report observations was removed, then the voyage would become four days.
- All vessels are set to 9480kW Main engine power, all vessels had three sets of 960kW auxiliary.
- All vessels have a design speed of 15kts

EEOI Comparison

Here we show a brief comparison of the Company's Calculations dataset and that generated in the phase 1 model.

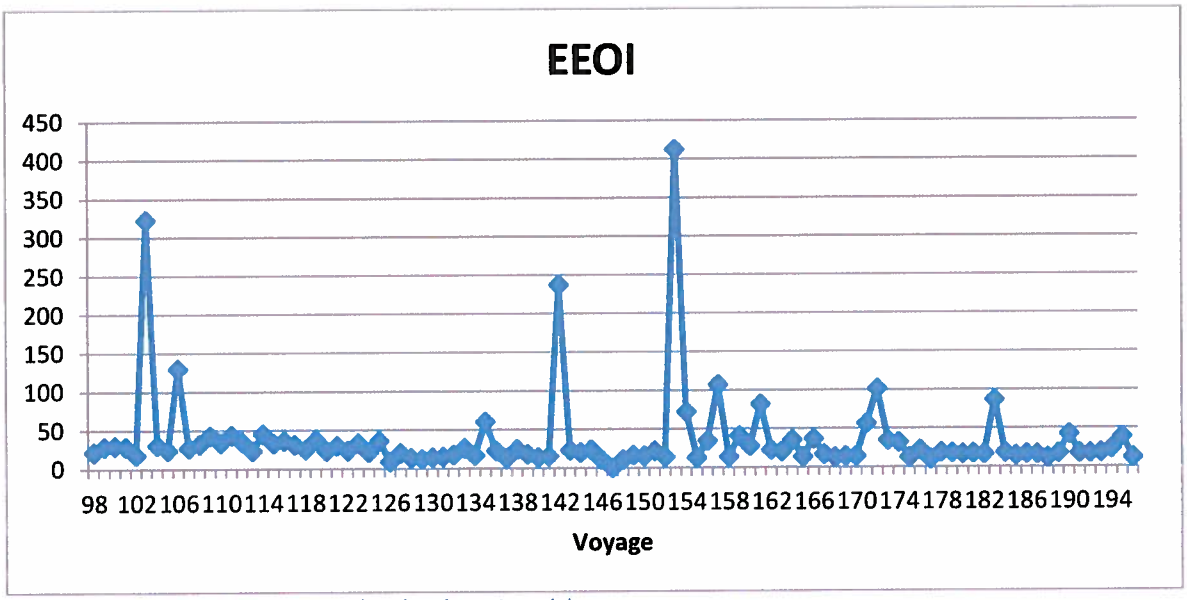

Figure 19: Voyage EEOI as generated in the phase 1 model.

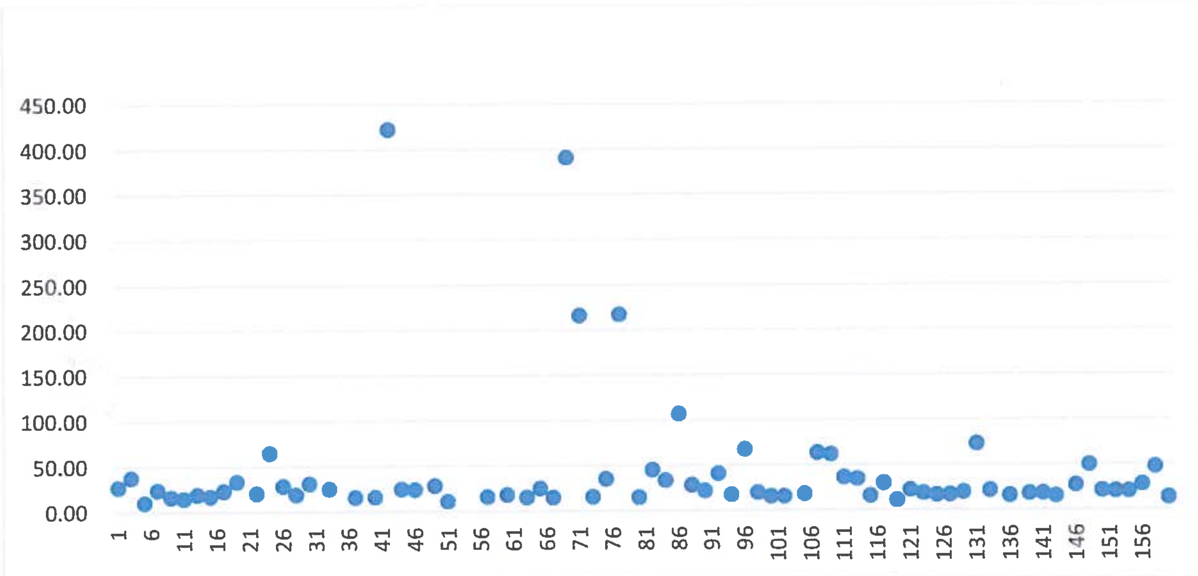

Figure 20: Company's Calculated EEOI for voyages for Ship. This is taken from the legs spreadsheet rather than voyages spreadsheet as voyages spreadsheet uses incorrect transport work values – see voyage 103 for example.

Comparing estimates from the noon report with those calculated by the Company, we see strong correlations for the EEOI but the magnitude is different. The main reason for the discrepancy is the difference in fuel consumed reported in the noon reports and that reported in Company's EEOI worksheets. The strong correlation in the fuel and EEOI estimates suggests that if the noon report data is at the very least strongly correlated with the Company's calculations and therefore of a suitable quality for further analysis.

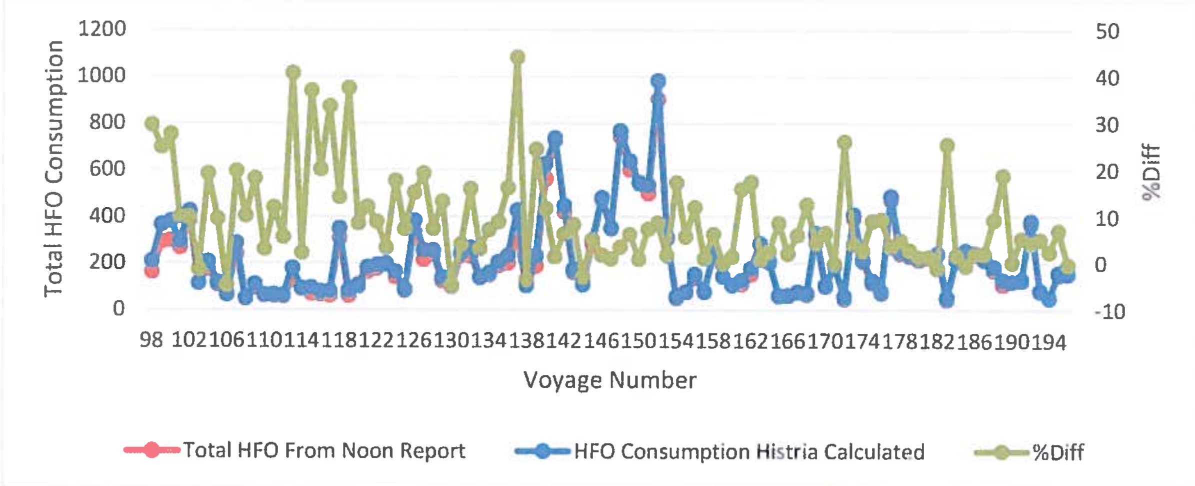

Figure 21: Compared reported voyage HFO(main and aux) for Ship (left axis) and the % difference in these estimates (green line and right axis). Positive % difference indicate the Company's HFO calculated is greater than noon reported estimated.R2 of Company's Calculated HFO regressed against noon HFO is 0.991 with a coefficient of 1.04 and intercept of 4.99.

For comparison VAF estimated fuel consumption is shown for two voyages for the Ship. The VAF estimate is assumed to be both Main and Auxiliary consumption. Therefore the reported amounts of HFO and MDO combined should be an upper bound to this. Noon HFO Main plus Noon MDO main should be equal to VAF estimated. The noon report values seem to significantly underestimate the fuel consumption for propulsion The VAF estimated is calculated by:

$$F_v = 1000 \sum_i \delta T_i v_i r_i$$

Where

- Fv = Fuel consumption for voyage v
- Delta_t_i = Elapsed time in hours since last observation
- V_i = speed at time i
- R_i = rate of fuel consumption (kg/nm)

This formula assumes the vessel has been operating in that state for the full period between observations.

Voyage Number	Noon HFO Main	Noon MDO Main	Noon HFO Aux	Noon MDO Aux	HFO	MDO	VAF Estimated
195	104.555	0	45.48	10.25	160.5823	18.5006	139
196	135.28	55.68	20.72	34.19	155.4668	121.911	247

Table 7: Comparison of reported fuel consumption and that estimated from VAF.

Appendix 2: Calculations

The following formulae were used in the accompanying excel tool. All columns of data are effectively either these indices or their decomposed values.

EEOI Formula

$$EEOI = 1x10^6 \frac{\sum\sum F_{ij} C_j^F}{\sum m_i^L D_i^L}$$

Where

- EEOI (gCO2/tenm)
- I = voyage
- J = fuel type
- Fij = amount of fuel consumed (te) for voyage I and fuel type j (in both auxiliary and main engines)
- CjF = Carbon factor (gCO2/gFuel) for fuel type j
- miL= cargo mass (te) on voyage i. For voyages containing multiple drop-offs, this value is distance weighted.
- DiL= distance travelled (nm) in loaded leg of voyage i

EETI Formula

$$EETI = \frac{1x10^6 C^F F_d^{ref}}{v_{ref} DWT 24}$$

where

- EETI (gCO2/tenm)
- Fdref = fuel consumed (te/day) per day in reference condition
- CF = Carbon factor (gCO2/gFuel)
- Vref=reference speed (nm/hr)
- DWT = deadweight (te) of vessel

For each noon report observation we calculate the EETI using the admiralty formula.

$$F_d^{ref} = (\frac{v_{ref}^3}{v_{obs}^3})(\frac{T_{ref}^{\frac{2}{3}}}{T_{obs}^{\frac{2}{3}}}) F_j^{obs} (\frac{SAILING\_TIME}{24})$$

Where

- T = Mean draft
- SAILING_TIME in hours

We then scale this over the whole voyage period for each reported fuel consumption Payload Utilisation, Allocative utilization and speed factor can be used to relate EETI to EEOI as discussed in Parker and Smith (2014) in the following formula

$$EETI \sim EEOIxSFxPUxAU$$

$(\frac{v_{des}}{v_{ht}^{op}})^2$ = the speed factor (SF)

$\frac{m_i^L}{DWT}$ = the average payload utilization (PU)

$\frac{d_i^L}{(d_i^L + d_i^B)}$ = the average allocative utilization or ratio of laden days to total sailing days (AU)

EIV Formula

The EIV is taken from Faber et al (2015).

$$EIV = \frac{C_{ME}^F SFC_{ME} P_{ME} + C_{AE}^F SFC_{AE} P_{AE}}{v_d DWT}$$

where

- EIV (gCO2/tenm)
- P_{ME},P_{AE} – The power (kW) of the main and auxiliary engines respectively
- CF = Carbon factor (gCO2/gFuel) for each of main engine and auxiliary engine
- Vdes=design speed (nm/hr)
- DWT = deadweight (te) of vessel

EEJI Formula

The EEJI formula is taken from MEPC 67/5/4 (2014):

$$EEJI = 1x10^6 \frac{\sum\sum F_{ij} C_j^F}{DWT \sum(D_i^L + D_i^B)}$$

where

- EEJI (gCO2/dwtnm)
- DiL= distance travelled (nm) in loaded leg of voyage i
- DiB= distance travelled (nm) in ballast leg of voyage i

EEUSI Formula

The EEUSI formula is taken from *MEPC 65/4/19 (2013).*

$$EEUSI = \frac{\sum\sum(\frac{F_{ME,ij}}{sfc_{ME}} + \frac{F_{AE,ij}}{sfc_{AE}})}{3.6\sum T_i^L + T_i^B}$$

where

- EEUSI (kJ/hr)
- T^L, T^B: Time spent load/ballast

References

Jasper Faber, Maarten 't Hoen, Marnix Koopman, Dagmar Nelissen, Saliha Ahdour. Estimated Index Values of New Ships Analysis of EIVs of Ships That Have Entered The Fleet Since 2009 Delft, CE Delft, March 2015

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