E

MARINE ENVIRONMENT PROTECTION COMMITTEE
68th session
Agenda item 4

MEPC 68/INF.24/Rev.1
30 March 2015
ENGLISH ONLY

FURTHER TECHNICAL AND OPERATIONAL MEASURES FOR ENHANCING THE ENERGY EFFICIENCY OF INTERNATIONAL SHIPPING

The Existing Shipping Fleet's CO_2 Efficiency

Note by the Secretariat

SUMMARY

Executive summary:	This document provides, in the annex, a study of "The existing shipping fleet's CO_2 efficiency"
Strategic direction:	7.3
High-level action:	7.3.2
Planned output:	No related provisions
Action to be taken:	Paragraph 3
Related documents:	MEPC 59/INF.10; MEPC 67/6 and MEPC 67/20

Introduction

1 MEPC 67 approved the Third IMO GHG Study 2014 (MEPC 67/20, paragraph 6.5.6). Following the approval of the Study, the Secretariat received enquiries from several shipping industry stakeholders as to whether the IMO would be publishing updated data as set out in Table 9.1 "Estimates of CO_2 efficiency for cargo ships" in the Second IMO GHG Study 2009 (MEPC 59/INF.10). Having explained that the provision of this data had not been part of the terms of reference for the Third IMO GHG Study 2014, the industry stakeholders indicated that this data had been used to estimate the CO_2 emissions from their ships.

2 In response to those industry views, and to utilise the datasets prepared for the Third IMO GHG Study 2014, the Secretariat commissioned, using residue funds donated for the Third IMO GHG Study 2014 and other related research projects, an update of the data for ship CO_2 efficiency. The study, prepared by the UCL Energy Institute, is set out in the annex.

Action requested of the Committee

3 The Committee is invited to note the information provided.

***

The Existing Shipping Fleet's CO_2 Efficiency

UCL ENERGY INSTITUTE

Executive Summary, and Main Report
March 2015

Contents

Contents ... 2
Preface ... 3
Executive Summary ... 4
Results ... 4
Method ... 7
1. Introduction ... 9
1.1. Efficiency definitions ... 9
1.2. Aim and approach ... 11
2. Method ... 12
2.1. Definition of the metric used for energy efficiency and the existing data. ... 12
2.2. Approach for estimating cargo carried ... 12
2.3. Determining whether loaded or in ballast ... 13
2.4. Estimate of mass of ballast when loaded ... 15
2.5. Estimate of mass of fuel ... 15
2.6. Estimate of lightweight ... 16
2.7. Estimate of ship parameters ... 16
3. Shipping's energy efficiency ... 17
3.1. Bulk carriers ... 19
3.2. Chemical tankers ... 20
3.3. Container ships ... 21
3.4. General cargo ... 22
3.5. Liquefied gas tankers ... 23
3.6. Oil tankers ... 24
3.7. Refrigerated bulk ... 25
3.8. Tabular results, all years ... 26
3.9. Trends over time ... 29
3.10. Power law fits for EEOI against dwt ... 32
3.11. EEOI estimated with units gCO_2/TEU.nm ... 36
3.12. Fleet total transport work and fleet average EEOI ... 37
4. Quality assurance of estimation of work done and EEOI calculations ... 39
4.1. Filtering of results ... 39
4.2. Justification of representativeness of sample ... 40
4.3. Draught ... 43
4.4. Cargo mass ... 44
4.5. Distance ... 49
5. Comparison of shipping's efficiency relative to efficiency of other modes of transport ... 51
5.1. Sources of total efficiency of different transport modes from literature ... 53
5.2. Top-down estimates of aggregate average total efficiency ... 55
5.3. Bottom-up estimates of average total efficiency ... 56
5.4. Summary and discussion ... 58
References ... 60
Annex A: Bias analysis ... 63
Annex B: 2011 detailed results ... 66
Annex C: 2010 detailed results ... 73

Preface

This study of CO_2 efficiency of the existing shipping fleet was commissioned as an update of a section within the International Maritime Organization's (IMO) Second IMO GHG Study 2009 which estimated the total efficiency of the global fleet. The updated study has been prepared on behalf of the IMO Secretariat by University College London (UCL) Energy Institute using the results from the Third IMO GHG Study 2014. The work was undertaken by the individuals listed below.

Organization	Key individual(s)
UCL Energy Institute	Dr Tristan Smith
	Vishnu Prakash
	Lucy Aldous
	Philip Krammer

As this builds on the data from the Third IMO GHG Study 2014, the researchers behind this study acknowledge and thank the following organizations for their invaluable data contributions: exactEarth, IHS Maritime, Marine Traffic, Carbon Positive, Kystverket, Gerabulk, V.Ships and Shell.

The views and conclusions expressed in this report are those of the authors.

The recommended citation for this work is: The Existing Shipping Fleet's CO_2 Efficiency; International Maritime Organization (IMO) London, UK, March 2015; Smith, T. W. P.; Prakash, V.; Aldous, L.; Krammer, P.

Executive Summary

Results

1. Values of EEOI (Energy Efficiency Operational Indicator) are calculated for a sample of ships within each of the ship type and size categories used in the Third IMO GHG Study 2014. Data from the Third IMO GHG Study 2014 on an individual ship's CO_2 emission are combined with estimates of that ship's transport supply (measured in tonne nautical miles, t.nm or tonne kilometer, t.km) obtained from AIS observations of draught and estimates that relate draught to mass of cargo carried.
2. The calculations are performed on annual totals (using both estimated CO_2 emissions and estimates of total transport supply for individual ships) for the years 2010, 2011 and 2012. CO_2 emissions from both in port and at sea activity are included.
3. The results for the year 2012 are presented in Table 1 (in both sets of units commonly used), with the median providing a representative value for each ship type and size, and the values for the lower and upper quartiles demonstrating the range of the values (for the central 50% of the sample). EEOI can be seen to vary significantly both between different ship types and within each ship type's range of sizes. Furthermore, there can be large variations in EEOI within a given ship type and size category (indicated by the inter-quartile range).

Table 1: Calculations of EEOI for different ship types and sizes, 2012. Two sets of units are used: $gCO_2/t.nm$ (left) and $gCO_2/t.km$ (right)

		EEOI (gCO_2/t.nm)			EEOI (gCO_2/t.km)		
Type	Size	Median	Lower quartile	Upper quartile	Median	Lower quartile	Upper quartile
Bulk carrier	0-9999	44.5	32.8	70.4	24.0	17.7	38.0
Bulk carrier	10000-34999	15.4	12.5	21.2	8.3	6.7	11.4
Bulk carrier	35000-59999	11.7	9.27	15.1	6.3	5.0	8.2
Bulk carrier	60000-99999	10.7	8.99	13.3	5.8	4.9	7.2
Bulk carrier	100000-199999	5.83	5.04	7.04	3.1	2.7	3.8
Bulk carrier	200000-+	5.13	4.58	5.95	2.8	2.5	3.2
Chemical tanker	0-4999	51	38.2	70.2	27.5	20.6	37.9
Chemical tanker	5000-9999	33.7	28.6	43.1	18.2	15.4	23.3
Chemical tanker	10000-19999	23.7	19.9	28.8	12.8	10.7	15.6
Chemical tanker	20000-+	15.6	13.5	17.8	8.4	7.3	9.6
Container	0-999	34.6	29.4	42.5	18.7	15.9	22.9
Container	1000-1999	31.6	27.5	37.4	17.1	14.8	20.2
Container	2000-2999	24.7	22.1	29.8	13.3	11.9	16.1
Container	3000-4999	21.3	18.5	24.2	11.5	10.0	13.1
Container	5000-7999	20.5	18.1	23.2	11.1	9.8	12.5
Container	8000-11999	17.9	15.7	19.6	9.7	8.5	10.6
Container	12000-14500	13.2	12.4	13.9	7.1	6.7	7.5
Container	14500-+	-	-	-	-	-	-
General cargo	0-4999	38.2	23.7	61	20.6	12.8	32.9
General cargo	5000-9999	34.5	27.2	46.8	18.6	14.7	25.3
General cargo	10000-+	30.7	21	43.8	16.6	11.3	23.7
Liquefied gas tanker	0-49999	30.4	24.2	37.6	16.4	13.1	20.3
Liquefied gas tanker	50000-199999	16.3	13.6	21.9	8.8	7.3	11.8
Liquefied gas tanker	200000-+	18.6	14.6	24.5	10.0	7.9	13.2
Oil tanker	0-4999	70	51	105	37.8	27.5	56.7
Oil tanker	5000-9999	48.2	34.9	63.8	26.0	18.8	34.4
Oil tanker	10000-19999	36.4	28.4	51.7	19.7	15.3	27.9
Oil tanker	20000-59999	24	18.5	34.9	13.0	10.0	18.8
Oil tanker	60000-79999	16.5	13	21.2	8.9	7.0	11.4
Oil tanker	80000-119999	13.2	10.3	19	7.1	5.6	10.3
Oil tanker	120000-199999	10.8	8.88	12.4	5.8	4.8	6.7
Oil tanker	200000-+	6.57	5.21	8.43	3.5	2.8	4.6
Refrigerated bulk	0-1999	92.2	67.2	155	49.8	36.3	83.7

4. Some groupings of ship types and sizes contain ships with similar efficiency, whereas for other ship type and sizes there can be significant variability in efficiency. For example container ships in the 5000-8000 TEU size range have an inter-quartile range of EEOI that is 25% of the median (comparative similarity), whereas the 80-120,000 dwt oil tankers have an inter-quartile range of EEOI that is 66% of the median (indicating high variability between ships).
5. Lowest (best) median EEOIs are achieved by the largest bulk carriers and tankers. In nearly all ship types, the trend is for EEOI reducing with ship size. The exception to this rule is the liquefied gas tanker fleet where the largest ship size category has a marginally higher (worse) EEOI than the next smallest size category.
6. The drivers of EEOI are also calculated and presented in graphical and tabular format in the main body of the study. Utilization is quantified: both allocative utilization (the distance travelled loaded vs. the total distance travelled) and payload utilization (the average payload mass relative to the dwt of the ship). Overall utilization is the product of both payload and allocative utilization. Variations in utilization explain some of the differences in EEOI between ship type and size categories.
7. For some of the ship types (particularly bulk carriers and oil tankers), the largest ships have higher utilization than some of the smaller ships. However, in other instances, utilization reduces with ship size (e.g. container and general cargo ships).
8. In order to estimate trends over time, this study's estimates of EEOI for 2010, 2011 and 2012 are combined with estimates for 2007 obtained from the Second IMO GHG Study 2009 (in which it is referred to as total efficiency). By way of example, results for two ship types (bulk carriers and container ships) are presented in Figure 1 and Figure 2. For the case of the bulk carriers, many ship size categories (particularly the larger ship sizes) show some improvement in EEOI over the period 2010 to 2012. In the case of container ships, the results show a slight deterioration in EEOI over that period of time.

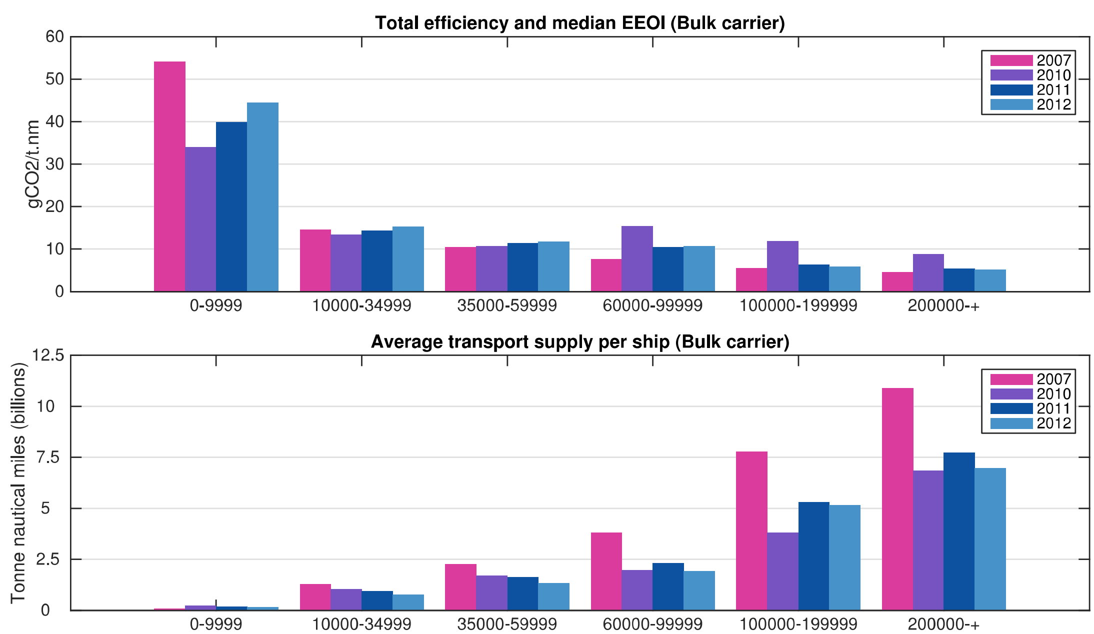


Figure 1: EEOI and transport supply 2007 to 2012, bulk carrier

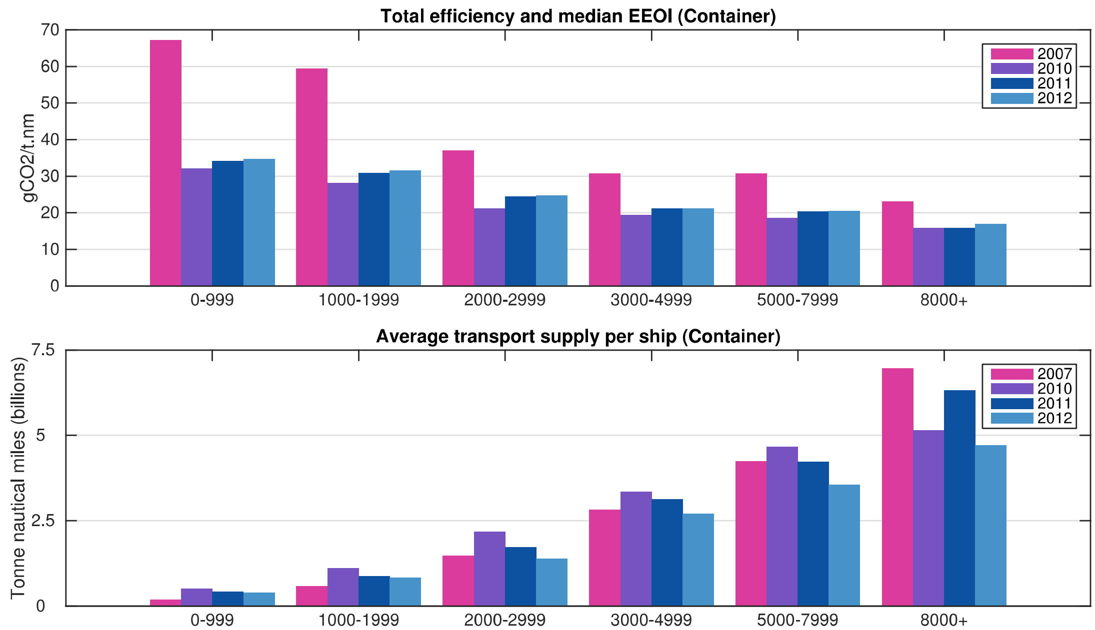


Figure 2: EEOI and transport supply 2007 to 2012, container ships

9. Some significant differences can be observed between the EEOI values estimated for 2007 and those values estimated in 2010, 2011 and 2012. Two potential explanations are, (a), a difference in EEOI calculation data and method between the Second and Third IMO GHG Studies and, (b), a substantial difference in operation between 2007 and 2012. The Third IMO GHG Study 2014 found the strong evidence of slow-steaming and associated emission reductions in the container ship fleet, which would support (b) as a plausible explanation for container ship's EEOI trends. However, the existence of differences in data and methods means that it is difficult to draw this conclusion definitively.
10. In addition to estimates of EEOI for the discrete ship type and size categories used in the Third IMO GHG Study 2014, power law best-fits are obtained for each ship type.
11. In all instances, EEOI is calculated with units of gCO_2/t.nm, however for the case of the container ships an additional estimation is also performed for the ship type's EEOI in gCO_2/TEU.nm. Because of an absence of data on a ship's actual TEU loading, two different estimation methods are used: (a), using the CCWG (Clean Cargo Working Group) published fleet average utilization, and, (b), using the Second IMO GHG Study 2009 assumption of 7 tonnes per TEU in conjunction with the cargo mass estimation. The Second IMO GHG Study 2009 assumption consistently produces better efficiency (lower EEOI) values. Explanations could be either that the average mass of a TEU is greater than the assumed 7 tonnes, or that this study's data is not representative of the fleet analyzed by CCWG. If the former, this suggests that estimating EEOI in units of TEU.nm is challenging using the data and method associated with this study.
12. For certain ship types, estimation of total transport supply obtained from this study's method, is compared against the published transport demand in UNCTAD's Review of Maritime Transport (2013). Some discrepancies can be observed and explained, although in many cases the discrepancy appears to be less than 20%.
13. The EEOI values calculated for the different ship types and sizes are compared with the equivalent data for road, rail (diesel only) and aviation (pure cargo aviation only). The results are presented in Figure 3. All transport modes show evidence of a correlation between the average carried load per vehicle and EEOI: EEOI improves (decreases) with an increase in average carried load per vehicle which in turn relates

to vehicle size. Across all modes, and consistent with this correlation, shipping achieves some of the best (lowest) EEOI values, because the average loads per ship are consistently greater than the average loads of other vehicles and transport modes.

14. Per unit of transport supply, shipping is at least an order of magnitude more efficient than aviation and, in many specific cases, an order of magnitude more efficient than road transport. At the same time, although the largest road vehicles have average carried loads that are over an order of magnitude smaller than ships with equivalent EEOI values, the least efficient ships have EEOIs equivalent to the most efficient road vehicles. Many ship types and sizes also appear to have worse (higher) EEOIs than rail vehicles.

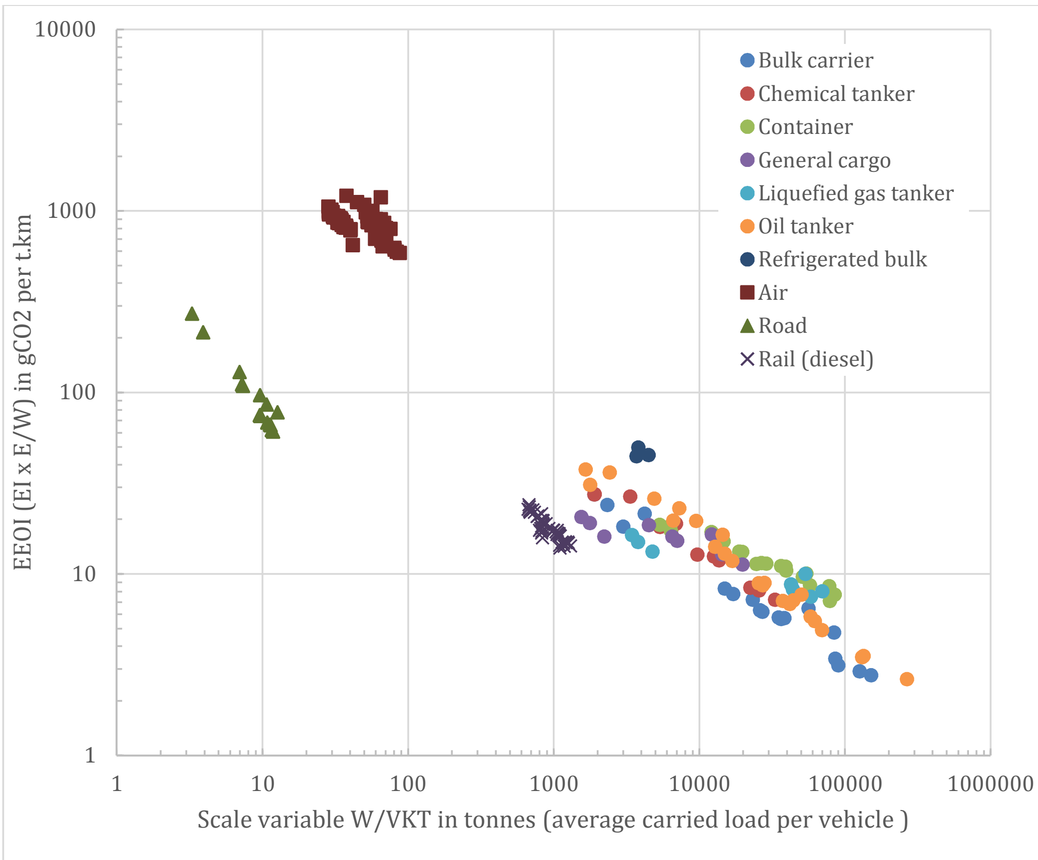


Figure 3: Comparison of EEOI for different modes of transport

Method

1. This analysis builds on the method development work undertaken for the Third IMO GHG Study 2014, which saw the use of large amounts of AIS data to estimate annual fuel consumption and transport supply for individual ships at up to an hourly resolution. This substantially progresses the state of the art , improving the rigor in the analysis of CO2 efficiency of the global fleet and the robustness of the conclusions that can be drawn from the analysis.
2. A novel approach for estimating cargo mass from draught is derived, and is shown in the section on quality assurance to provide a generally high standard of agreement with a number of validation data—including port lineups, fixtures, and noon report data.

3. The estimated data is filtered to remove EEOI values associated with spurious draught data. The remaining sample is typically approximately 10% of the active fleet. The potential for the filtered sample to be a biased representation of the total fleet is tested using ship technical parameters; the levels of bias on the basis of these technical parameters are found to be negligible for the majority of ship types and sizes.
4. Container ship transport supply is estimated using both draught derived t.nm and average utilization derived TEU.nm.
5. Data for different vehicle's EEOI is estimated from a variety of sources and the drivers of differences in EEOI between similar vehicles are discussed in order to identify both common and dissimilar challenges for different transport modes.

1. Introduction

Shipping is commonly cited as the most efficient transport mode. When expressed as a generalization (across all ship types) this is rarely disputed, however as evidenced in the Second IMO GHG Study 2009 (Bauhaug et al. (2009)), there can be large variations in efficiency from one ship type and size and another. In January 2013, the EEDI (Energy Efficiency Design Index) came into force, requiring all newbuild ships to meet a minimum energy efficiency standard. In the same regulation's annex, the SEEMP (Ship Energy Efficiency Management Plan) recommends the use of the EEOI (Energy Efficiency Operational Indicator) for estimating the efficiency of existing ships. A similar calculation to the EEOI was estimated for each of the ship types and sizes listed in the Second IMO GHG Study 2009: Total Efficiency (Table 9-1).

In the Third IMO GHG Study 2014 (MEPC 67/Inf.3, Smith et al. (2014)), building on the method used in the Second IMO GHG Study 2009, estimates of the GHG emissions of the global fleet were presented. Central to this study was a model (the bottom-up model) that estimated the fuel consumption of the individual ships in the global fleet from AIS (Automatic Identification System) data.

Although not included in the Terms of Reference for the Third IMO GHG Study 2014, the results from the combination of an AIS data source and the bottom-up model had the potential to be applied in an estimation of total efficiency of the existing fleet. This potential was demonstrated in a study done in 2013 for the ICCT (Smith et al. 2013), although at the time this study's results could not be validated due to a lack of a source of real-world data.

Access to validation data sources have improved since the study carried out for the ICCT, particularly the assembly of an extensive dataset of ship operator's data for the Third IMO GHG Study 2014 which provides a good source of information with which to understand the validity and uncertainty of AIS derived estimates of efficiency.

1.1. Efficiency definitions

There are many different definitions of shipping's efficiency. Table 2, a modified version of a table originally from Smith et al. (2013), provides descriptions of various efficiency-related terms.

As shown in Table 2, no single definition provides all the information that might be wanted to understand energy efficiency or carbon intensity. Definitions that might be useful for some stakeholders can obscure information that might be useful to others. For example, ship owners and charterers might be most interested in understanding the performance of a ship in a reference condition and therefore may find the different types of 'technical efficiency' most useful, whereas a regulator or a shipper who wants to understand the carbon intensity of shipping as a mode of transport might be more interested in 'total efficiency'.

In the Second IMO GHG Study 2009, the terms 'loaded efficiency' and 'total efficiency' were used (Table 9-1). Estimates were applied for the average mass of a container and a vehicle, so that ship types with capacities less appropriately expressed as mass (e.g.

container ships and vehicle carriers) could be translated into an equivalent unit (gCO_2/t.km). In order to obtain estimates of Total Efficiency, assumptions for the ship's utilization were applied in combination with the estimates of the ship's emissions, cargo capacity, at sea speed and time spent at sea.

Table 2: Different definitions of energy efficiency

Term	Description	Practical Considerations
As-designed technical efficiency	The efficiency of a ship in its as-designed condition (straight from the yard) in ideal conditions.	This is what is captured in the EEDI when it is applied to newbuild ships.
Technical efficiency in real operating conditions	The efficiency of a ship in real conditions (wind and waves etc.).	Careful attention to the hydrodynamics of a ship in waves can save significant fuel consumption in actual use, but such benefits are not captured in the present EEDI formulation.
Technical efficiency at a point in time	The efficiency of a ship of a certain age, following wear, deterioration and fouling, benchmarked to ideal conditions.	As ships deteriorate through life, they may consume greater quantities of fuel to travel at the same speed, reducing their efficiency.
Voyage efficiency (Loaded efficiency in Second IMO GHG Study 2009)	In combination with the ships fuel consumption and emissions, this embodies the relationship between the transport demand (e.g., tonnes of a commodity shipped), with actual capacity-distance (e.g., dwt x nm sailed).	Often, this assumes 100% capacity utilization on the loaded leg and ignores the backhaul voyage emissions (regardless of ship loading).
Achieved operational efficiency (Total efficiency in Second IMO GHG Study 2009)	The total operation emissions or energy consumed to satisfy a supply of transport work, this is usually quantified over a period of time which encompasses multiple voyages (e.g. a year).	This could be considered the ultimate measurement of a ship's estimated real-world efficiency in that it incorporates all of the components listed above, emissions when the ship is in port/anchor etc. This is what the EEOI metric is attempting to measure.

Abbreviations: dwt = dry weight tonnage; nm=nautical miles

In practice, there are restrictions in the availability of data that limit the ability to calculate the different definitions, many required details are commercially sensitive e.g. voyage fuel consumption and payload, and therefore difficult to obtain or infer from publicly available data. The Third IMO GHG Study 2014, accepted by MEPC at its 67th meeting, pioneered the use of AIS data coupled to a bottom-up model and demonstrated through extensive quantitative quality and uncertainty analysis the credibility of estimates of shipping activity and its associated emissions. This study builds on that work, adding further analysis of that study's results to estimate the components and the specific total efficiencies of the different ships that make up the global fleet (using the EEOI formula). Analysis of the quality of the estimated data and discussion of the results are also included.

In academic literature, although EEOI has been around for some time, papers presenting estimates of EEOI remain scarce. Acomi & Acomi (2014) and Ma (2014) are perhaps the only two notable publications in this milieu. The former utilizes data logged onboard a single handysize Tanker operating in the voyage market to estimate EEOI, while the latter uses a sample of a few bulk carriers operating on time charters. Under the assumption that data logged onboard the ship are valid, Acomi & Acomi (2014) show that the predicted (pre-voyage) estimate of EEOI is likely to be an underestimate of achieved EEOI. Ma (2014) makes a similar argument insofar as to suggest that the often unpredictable navigational behavior exhibited by ships under time charters is likely to be the biggest driver of achieved EEOI; that is, a ship type's predisposition to a particular contract type may skew the distribution of EEOI for that fleet. However, neither paper addresses a sufficiently large or diverse sample to permit their rudimentary findings to possibly be assumed to be norms.

1.2. Aim and approach

It is proposed that many of the shortcomings of existing analyses of total efficiency can be addressed by bringing together the following elements:

1. attention to the underlying physics that influence the performance of ships;
2. attention to the uncertainties associated with input data sources and the sensitivity of efficiency quantifications to the different input parameters;
3. incorporation of new and far richer data sources (i.e. Satellite Automatic Identification System, or S-AIS) to describe the real-world operational variables of shipping.

The analysis method produces results which, as in the case of the CO_2 emissions estimates in the Third IMO GHG Study 2014, when taken for an individual ship are uncertain, but which when aggregated to a population's average, provide a reliable estimate and an increased level of rigor over previous analyses.

The analysis is used to improve the data describing different portions of the world fleet (e.g. different ship type and size categories) and to provide an understanding of the variability of energy efficiency and its drivers. All analysis is carried out using datasets that are publicly available, albeit in some cases at a cost.

The report is structured as follows:

Section 1 – Introduction
Section 2 – Method
Section 3 – Estimates of shipping's EEOI (total efficiency)
Section 4 – Quality assurance of the EEOI estimates
Section 5 – Comparison of shipping's efficiency relative to the efficiency of other modes of transport

2. Method

2.1. Definition of the metric used for energy efficiency and the existing data.

The metric used for quantifying the efficiency of shipping is the EEOI and can be found in IMO MEPC.1/Circ.684 (2009).

$$EEOI = \frac{\sum_i \sum_j (F_{ij} C_{Fj})}{\sum_i (m_{cargo,i} \times D_i)}$$

Where:

i = the voyage number
j = the fuel type
F_{ij} = the mass of fuel consumed for the voyage i and fuel type j
C_{Fi} = the fuel mass to CO_2 mass conversion factor for fuel type j
$m_{cargo,i}$ = cargo carried (tonnes) or work done (number of TEU) for voyage i
D_i = distance in nm corresponding to the cargo carried or work done voyage i

The formula can be applied to discrete voyages or over a period of time that covers multiple voyages. In this study, the formula is applied over the course of a year (from 1st Jan to 31st Dec) to produce an annualized average. The fuel consumed and therefore CO_2 is inclusive of both the sea and port (anchoring) time associated with the year's voyages, and includes the consumption of fuel from the main propulsion engines, the auxiliary machinery and a boiler if one is fitted.

For the Third IMO GHG Study 2014, estimates of annual fuel consumption (main, auxiliary and boiler) and associated CO_2 emissions were produced; this data is used without modification for the numerator of the EEOI calculation.

The fuel consumption was estimated from activity data that included observations of the speed and draught of a ship at hourly intervals, it is also possible to readily estimate distance travelled. The only missing component of the calculation is the cargo carried, which, because it is not commonly reported as a field in AIS data, needs to be estimated separately.

2.2. Approach for estimating cargo carried

The general approach to estimating the amount of cargo carried is to represent the cargo as a mass. Mass carried by a ship affects its displacement and therefore the draught at which the ship's buoyancy and weight are in equilibrium. The total of mass of a ship at its design draught can be expressed as:

$$m_T = m_l + dwt$$

Where:

m_T = the ship's total mass
m_l = the ship's lightweight mass
dwt = the ship's deadweight

For the ship to be floating in equilibrium at this draught, the total buoyancy must equal the total weight so:

$$m_T = \rho V$$

Where:

$\boldsymbol{\rho}$ = the density of seawater
V = the volumetric displacement of the ship

The volumetric displacement of the ship is a function of the geometry of the hull. Furthermore, the variation of a ship's displacement as a function of draught is a relationship that can be expressed using a few principles of naval architecture. Combining those principles with the lightweight (lwt) of the ship calculated at its reference condition (fully laden with payload = deadweight, and draught = reference draught) enables a ship's instantaneous payload (or variable mass m_{var}) to be expressed as a function of its instantaneous draught T_{op}.

$$m_{var} = C_{b,op} L B T_{op} \rho - lwt$$

Where:

$C_{b,op}$ = the instantaneous block coefficient
L = the length (approximated as the length in the loaded condition)
B = the beam (approximated as the beam in the loaded condition)

The final step is to decompose the ship's instantaneous payload between cargo mass, m_{cargo}, and other payload. This decomposition is needed because a ship's payload includes all variable loads (cargo, fuel, ballast water, consumables etc.) and only the payload due to cargo mass is required for this study. The cargo mass when the ship is loaded is isolated by subtracting estimates of the fuel mass, m_{fuel}, and ballast mass, $m_{ballast}$, (only for ships that carry ballast when loaded), such that the final equation becomes:

$$m_{cargo} = m_{var} - m_{ballast} - m_{fuel}$$

Most of the data that is required for these calculations can be taken from the Third IMO GHG Study 2014. The instantaneous draught, T_{op}, is taken from that study's AIS datasets (it is reported alongside operating speed, V_{op}, and is also used in the calculation of instantaneous fuel consumption). Methods for estimating a ship's hull form particulars and lightweight are described in Section 2.6 and 2.7 respectively, whilst the assumptions for mass of fuel and mass of ballast when loaded are described in Sections 2.4 and 2.5 respectively. The approach for the identification of whether the ship is loaded or in a ballast condition (not carrying cargo, just ballast water) is given in Section 2.3.

2.3. Determining whether loaded or in ballast

An added element of the application of the formula derived in Section 2.2 is that certain ships operate some of their voyages loaded and some of their voyages in the ballast condition. That is to say that instead of carrying cargo, they are empty and returning to pick up more cargo from another port. For safety and stability reasons, it can be necessary for a ship to be carrying ballast water on that voyage. There is no information explicit in the AIS data that can be used to classify whether the ship is loaded or in the ballast condition, therefore the draught must be used to apply this judgment. For a ship that carries a large amount of ballast water as a proportion of its dwt, or a ship that is frequently part-loaded, care needs to be applied when identifying a threshold draught at which the transition from loaded to ballast occurs.

For the distinction between loaded and ballast voyages, it is assumed that there are two categories of ships:

1. ships that operate part of the time loaded and part of the time in ballast (category 1 in Figure 4)
2. ships that operate most of the time between part-loaded and fully loaded (category 2 in Figure 4)

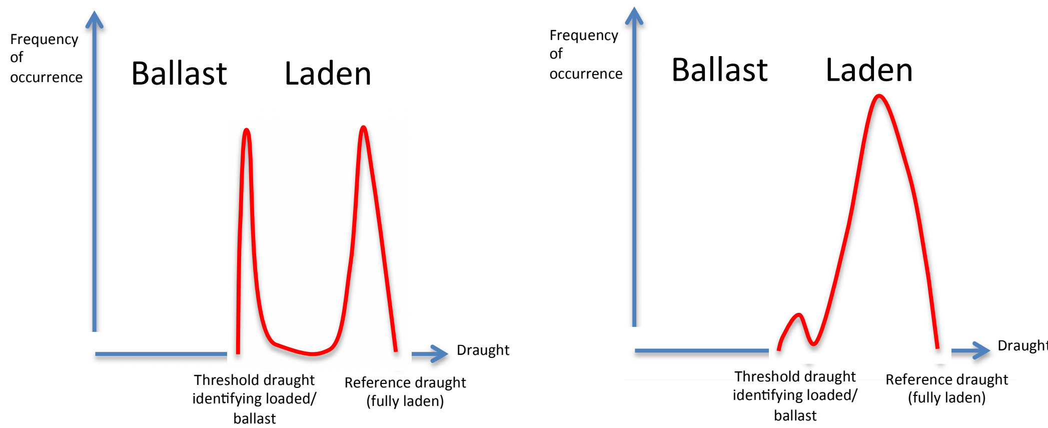


Figure 4: representative draught histograms for category 1 (left) and category 2 (right) ship types

The category 1 ships have a clearly identifiable peak in the frequency of occurrence associated with both their laden draughts and their ballast draughts. The category 2 ships often do not have such a clearly identifiable peak associated with ballast draughts (or in many cases may have no operation with no cargo). As a result it is harder to identify the threshold between loaded and ballast using the AIS reported draught alone and an alternative method is required. This categorization is applied to the ship types that are the subject of this study, listed in Table 3. Ro-ro ships, vehicle carriers and other liquids tankers were also considered for this study, but were not included in the results due to a shortage of validation data.

Table 3: Categorisation of ships for loaded/ballast classification

Category 1	Category 2
Bulk carriers	Chemical tankers
General cargo	Container ships
Liquefied gas tankers	Refrigerated bulk
Oil tankers	

For category 1 ships, the draught histogram is used to identify the ballast voyages. An algorithm detects the lower draught peak corresponding to ballast draught and then uses the corresponding draught to set a threshold draught (at a value 10% greater than the draught at which the peak occurred). In the event that there is no detectable ballast draught peak, a series of default threshold draughts are applied. The default thresholds come from the median of the distribution of draughts successfully detected and are listed in Table 4. For category 2 ships, no attempt is made to identify a threshold draught from the AIS data. Instead, assumptions taken from literature for the mass of ballast water expressed as a percentage of a ship's dwt are deployed. These values set a threshold of variable mass either side of which the ship is identified to be either laden or in ballast. These threshold values are also included in Table 4.

Table 4: List of default draughts used for Category 1 ships for which no ballast draught peak is detected

Type	Size	Draught threshold (decimal % of reference draught)	Variable mass threshold (found from draught/mass relationship and expressed as % of dwt)
Bulk carrier	0-9999	0.6429	-
	10000-34999	0.6179	
	35000-59999	0.5476	
	60000-99999	0.5365	
	100000-199999	0.5201	
	200000-+	0.5247	
Chemical tanker	0-4999	-	0.32
	5000-9999		
	10000-19999		
	20000-+		
Container	0-999	-	0 (assumed always loaded with some TEUs)
	1000-1999		
	2000-2999		
	3000-4999		
	5000-7999		
	8000-11999		
	12000-14500		
	14500-+		
General cargo	0-4999	0.6479	-
	5000-9999	0.6477	
	10000-+	0.6219	
Liquefied gas tanker	0-49999	0.6109	-
	50000-199999	0.6610	
	200000-+	0.6931	
Oil tanker	0-4999	0.6634	-
	5000-9999	0.6604	
	10000-19999	0.6153	
	20000-59999	0.6305	
	60000-79999	0.5844	
	80000-119999	0.5714	
	120000-199999	0.5510	
	200000-+	0.5206	
Refrigerated bulk	0-1999	-	0.33

2.4. Estimate of mass of ballast when loaded

For most ship types, the ballast mass when loaded was assumed to be negligible; this was tested and confirmed by analyzing noon report data from 25 oil tankers and assuming that these ships are typologically similar to bulk carriers, chemical tankers, general cargo carriers and liquefied gas carriers and refrigerated bulk carriers. However, for container ships, this is not always the case and ballast water can be used to retain stability and trim even when loaded.

To develop a method for estimating the term $m_{ballast}$ in Section 2.2, the ballast mass as a percentage of cargo mass was calculated from the noon report data of 95 ships and 610 observations. A judgment was required to apply a cut-off for defining that the ship was loaded and this was estimated to occur when the operational draught was greater than 65% of the design draught. The median of the percentage of ballast water was 13.25 % of the cargo mass. In the bottom-up model, this percentage was applied as a constant offset across all ships of this type.

2.5. Estimate of mass of fuel

To derive the cargo mass from the ship's estimated variable mass m_{var}, the mass of fuel and the ship's lightweight must be subtracted from the mass of water displaced. The mass of fuel was estimated from a sample of tankers with known deadweight and cargo capacity, (the total number of observations was 1902). An average oil density was set to 0.89 g/cm^3 and from this the cargo weight ascertained for a fully loaded ship. The difference between this and the deadweight gives an indication of the maximum possible fuel weight. There was a degree of variability in the result; this reflects the variability of factors such as the size of the ship's fuel tanks which may be designed for longer distances or for higher powered engines—both themselves a function of ship deadweight. There is also variability in the cargo density for which the ship is designed to carry. However, it was assumed that these variabilities will average out over a large enough sample such that a single value may hence be assumed to be representative. To apply a standard method for the calculation in Section 2.2, this estimated fuel mass is normalized by ship deadweight; the resultant mean of 3.4% (as a percentage of deadweight) is applied to all ship types and sizes.

2.6. Estimate of lightweight

Where possible, the ship's lightweight (lwt) was estimated from its deadweight in combination with a number of other principle characteristics; these relationships were based on regression formulae found in the literature. In the case of bulk carriers, container ships and oil tankers, the regression formulae of the studies presented in Kristensen (2012) and Kristensen (2013) were used. These formulae were derived from an IHS Fairplay database and were disaggregated by ship type as well as size. The regression of lightweight on deadweight for chemical tankers was based on the results of Anink and Krikke (2011) and for LNG tankers the results presented by Chadzynski (2010) were used. For other ship types, the 'at design' block coefficient was estimated directly from the Froude number, as described below, and this was used in combination with its length, beam, design draught and deadweight to ascertain its lightweight.

2.7. Estimate of ship parameters

When it was possible to estimate the lwt from the formulae described in the previous section then this was used to calculate each ship's block coefficient from its length, beam, design draught and deadweight. Where the lwt is unknown, then the C_b is estimated from its Froude number according to the equation by Townsin as described in Watson (1998).

$$C_{b,ref} = 0.7 + \left[\frac{1}{8}\operatorname{atan}\left(\frac{23 - 100Fn}{4}\right)\right]$$

Where:

Fn = Froude number

The estimation of a ship's C_b in its reference (assumed design) condition, $C_{b,ref}$ is also used to transform the ship's operational draught into a cargo mass (see Section 2.2). This is done by assuming that to a first approximation, beam and waterline length are constant, and that $C_{b,op}$ for a specific draught can be calculated from the Riddlesworth method quoted in MAN (2011):

$$C_{b,op} = 1 - \left[(1 - C_{b\_ref})\left(\frac{T_{ref}}{T_{op}}\right)^{1/3}\right]$$

3. Shipping's energy efficiency

Estimates of EEOI are presented as box plots by ship type and size categories. Sections 3.1 to 3.7 contain the graphs for 2012 broken down by ship type and size, whilst data for 2010 and 2011 are presented in Annex B and C. For each EEOI box plot, the blue box represents the interquartile range of the sample, the red line is its median (the value of which is labeled in red), the mean is marked as green diamond, and the purple dots are outliers. An EEOI value is considered an outlier if it is either 1.5 times the interquartile range above the upper quartile or 1.5 times the interquartile range below the lower quartile. The fraction beneath each box plot indicates the number of ships included in the sample over the total number of ships known to exist in the dataset.

Three plots follow each ship type's EEOI graph displaying:

- Average distance steamed (laden and ballast distance) and average tonnes of CO_2 emissions
- Average payload utilization (the average cargo mass when loaded, expressed as a percentage of the ship's dwt)
- Average at sea operating speed

These plots quantify some of the key components that determine a ship's EEOI and can explain some of the variability across size categories. Tabular results are presented in Section 3.8 of both EEOI and the parameters related to EEOI for all years and all ship types included in this study.

Plots showing time-series trends in efficiency and transport supply are presented and discussed in Section 3.9, and plots showing a power-law fit through the per-ship EEOI data are found in Section 3.10. In Section 3.11, estimates are made of container ship EEOI with units of gCO_2/TEU.nm. In Section 3.12, the data are aggregated to produce total transport supply and the supply-weighted average EEOI for each of the major ship and commodity types (oil, bulk, containers and gas). These aggregation categories are also matched to transport demand data and the quality of agreement is estimated and discussed.

Some groupings of ship types and sizes show that all ships have very similar efficiency, whereas for other ship type and size have significant variability. For example container ships in the 5000-8000 TEU size range have an inter-quartile range of EEOI that is 25% of the median, whereas the 80-120,000 dwt tankers have an inter-quartile range of EEOI that is 66% of the median.

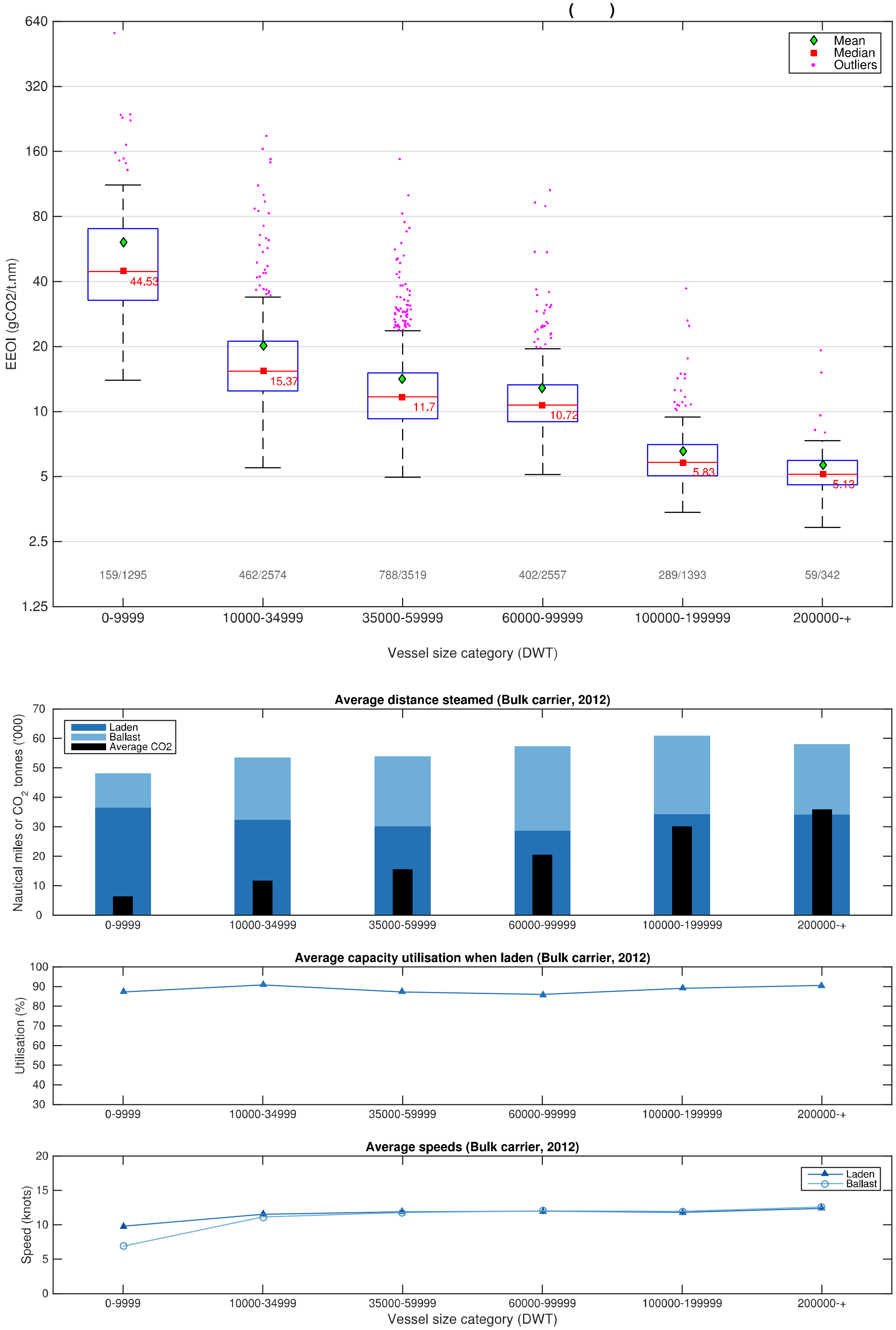
Lowest (best) EEOIs are achieved by the largest bulk carriers and tankers. In nearly all ship types, the EEOI trend reduces with ship size. The exception to this rule is the liquefied gas tanker fleet where the largest ship size category has a marginally higher (worse) EEOI than the next smallest size category.

The drivers of EEOI are also calculated and presented in graphical and tabular format in the main body of the study. Utilization is quantified: both allocative utilization (the distance travelled loaded vs. the total distance travelled) and payload utilization (the average payload mass relative to the dwt of the ship). Overall utilization is the product

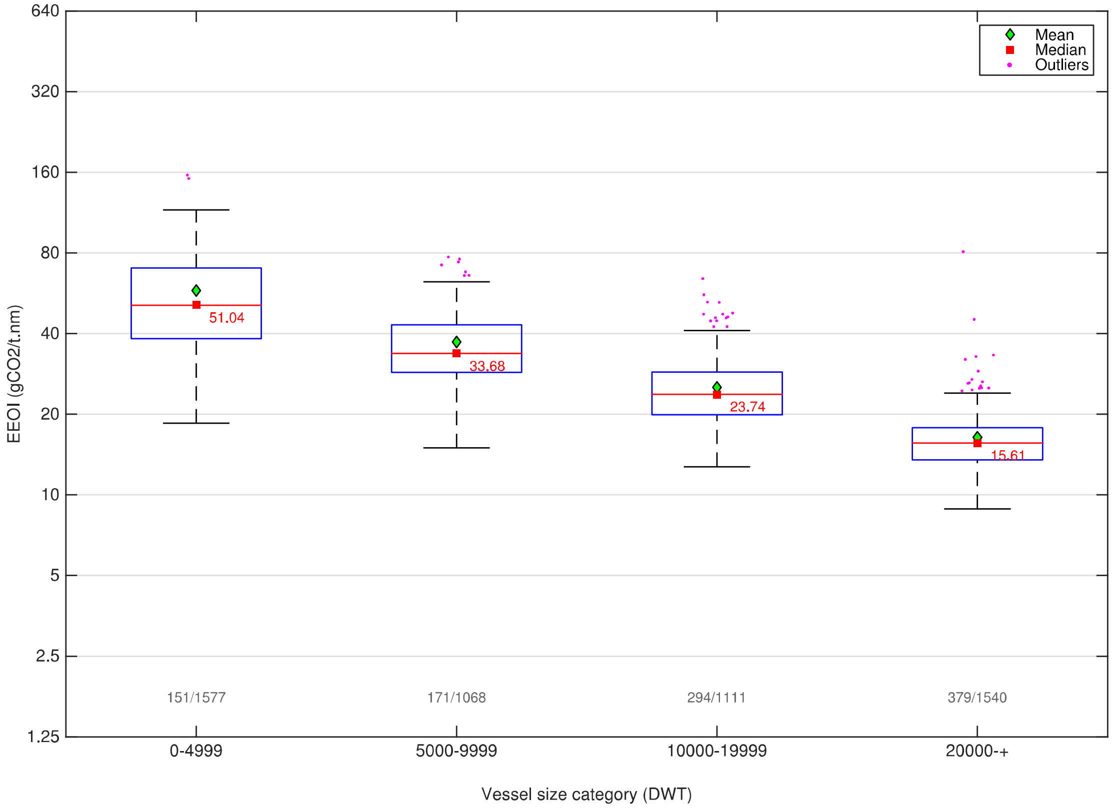
of both payload and allocative utilization. Variations in utilization explain some of the differences in EEOI between ship type and size categories.
For some of the ship types (particularly bulk carriers and oil tankers), the largest ships have higher utilization than some of the smaller ships. However, in other instances, utilization reduces with ship size (e.g. container and general cargo ships).

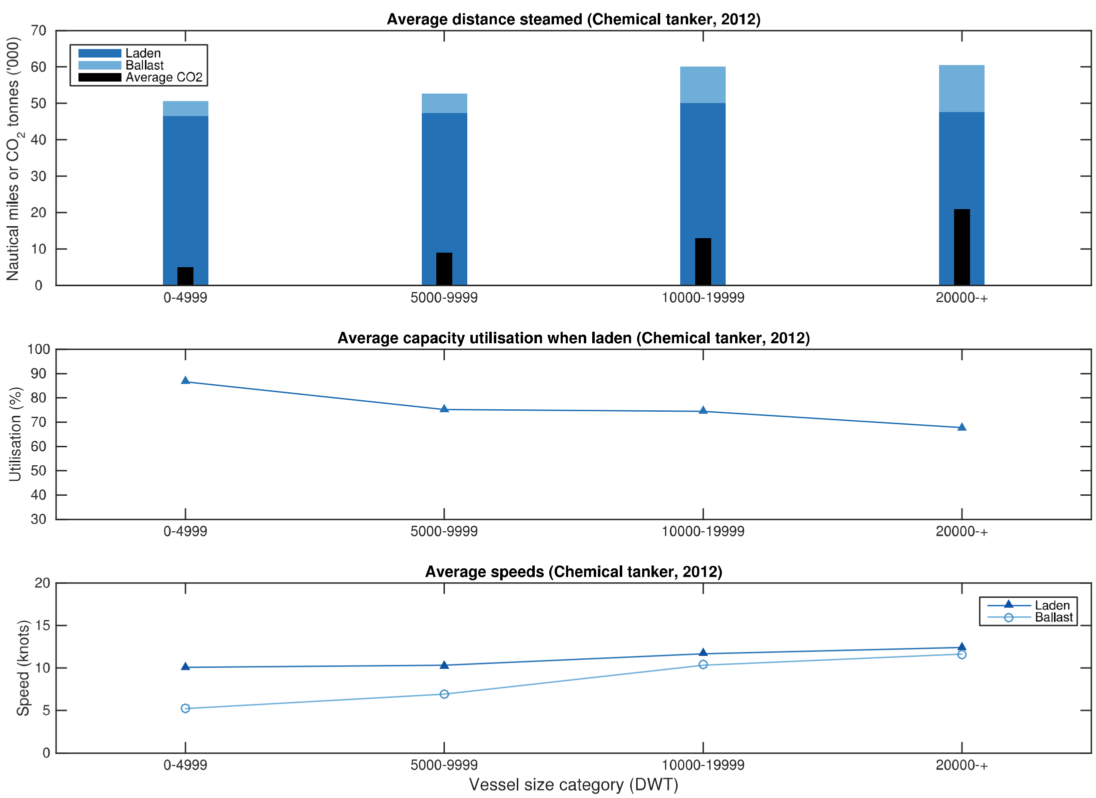
The figures present quantifications of loaded and ballast speeds for the different ship types and sizes. For many of the smaller ship sizes, the ballast speed sometimes reduces to a value which from judgment appears too small to be credible. A possible explanation is that the sample size of ballast speed for these ship types and sizes, particularly given their high allocative utilization, is too small to extract meaningful quantifications of speed.

3.1. Bulk carriers

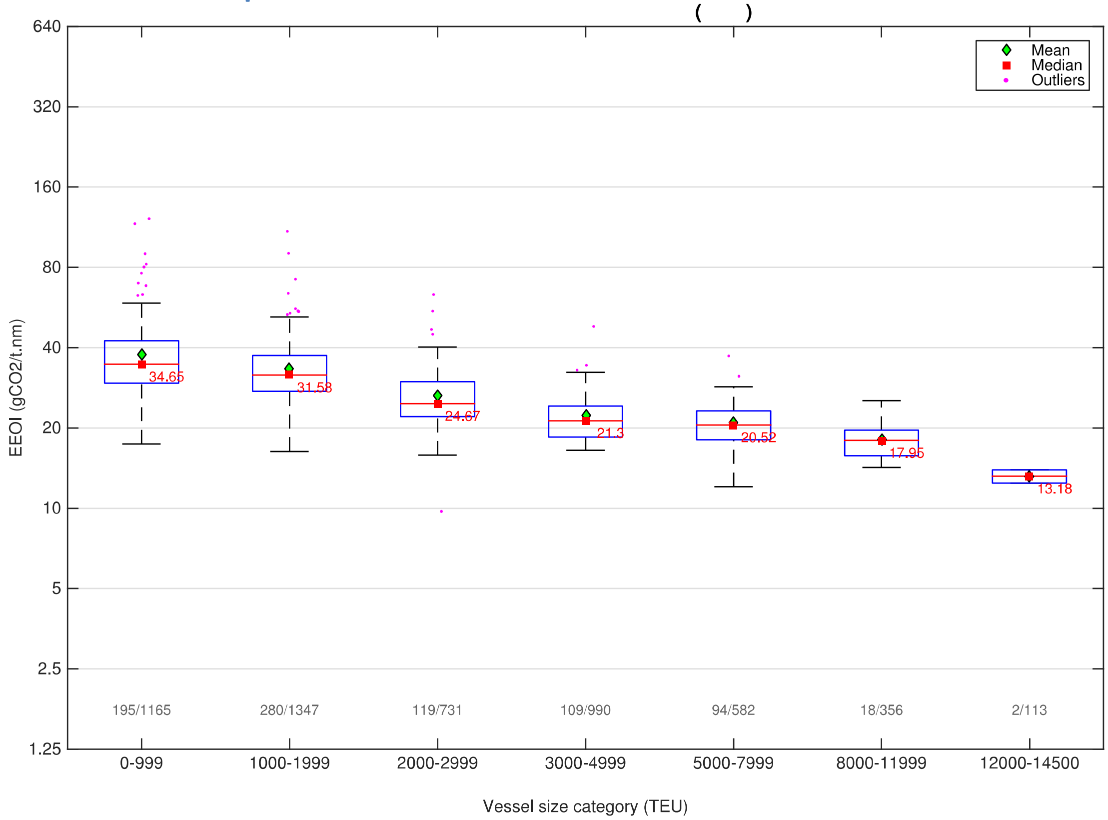


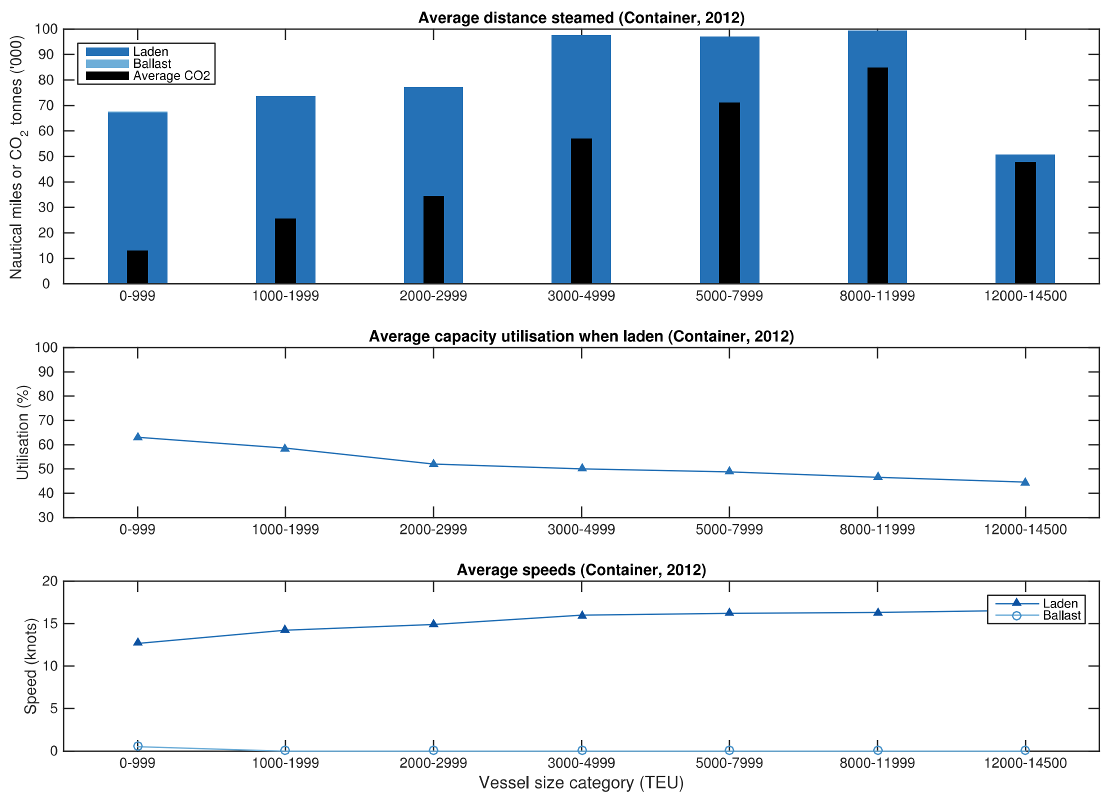
3.2. Chemical tankers



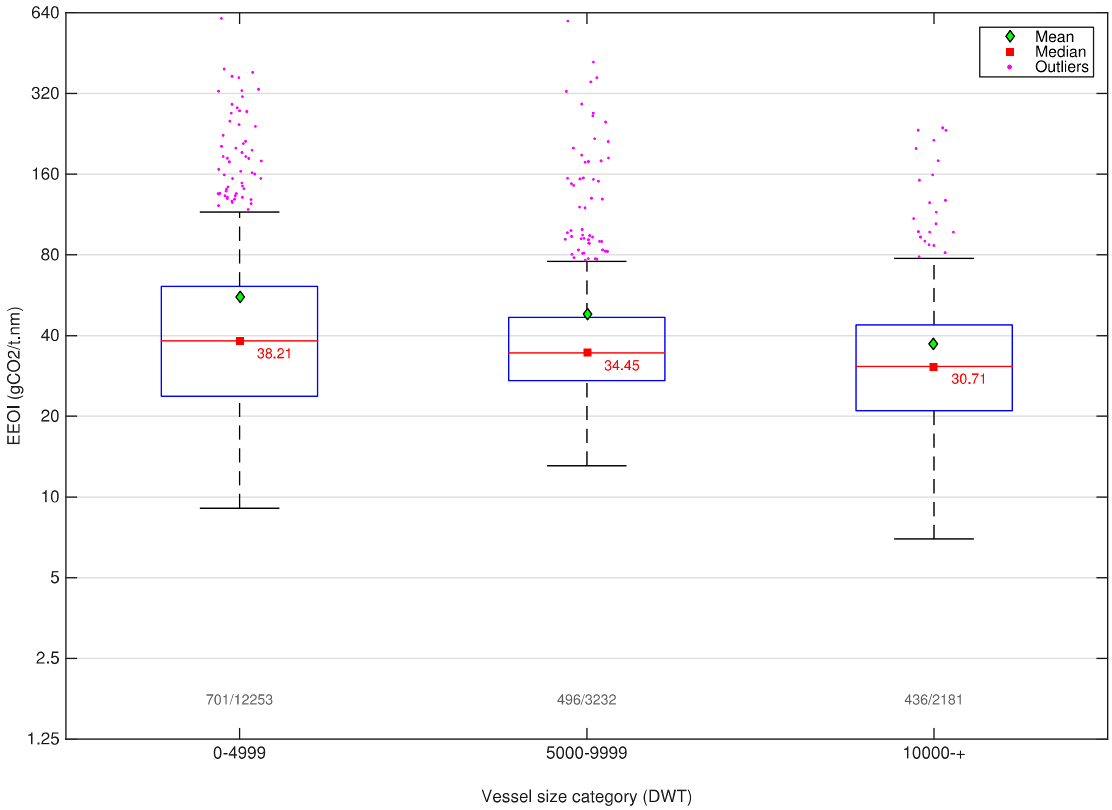


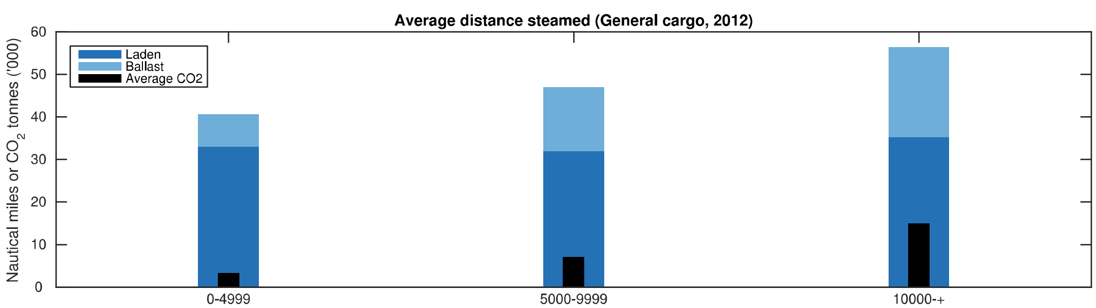
3.3. Container ships

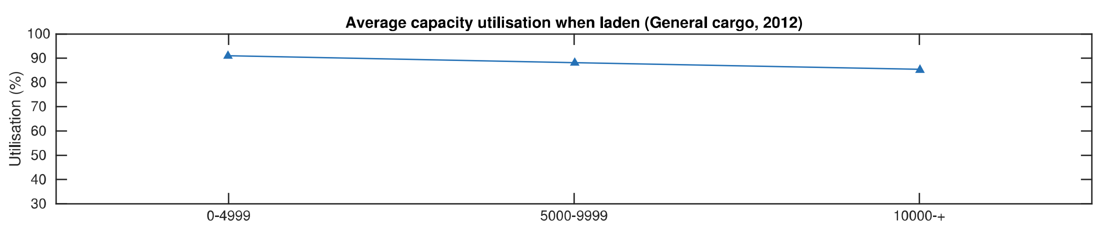


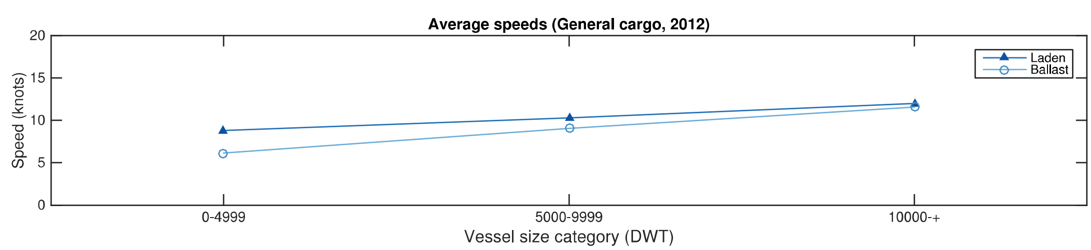


3.4. General cargo

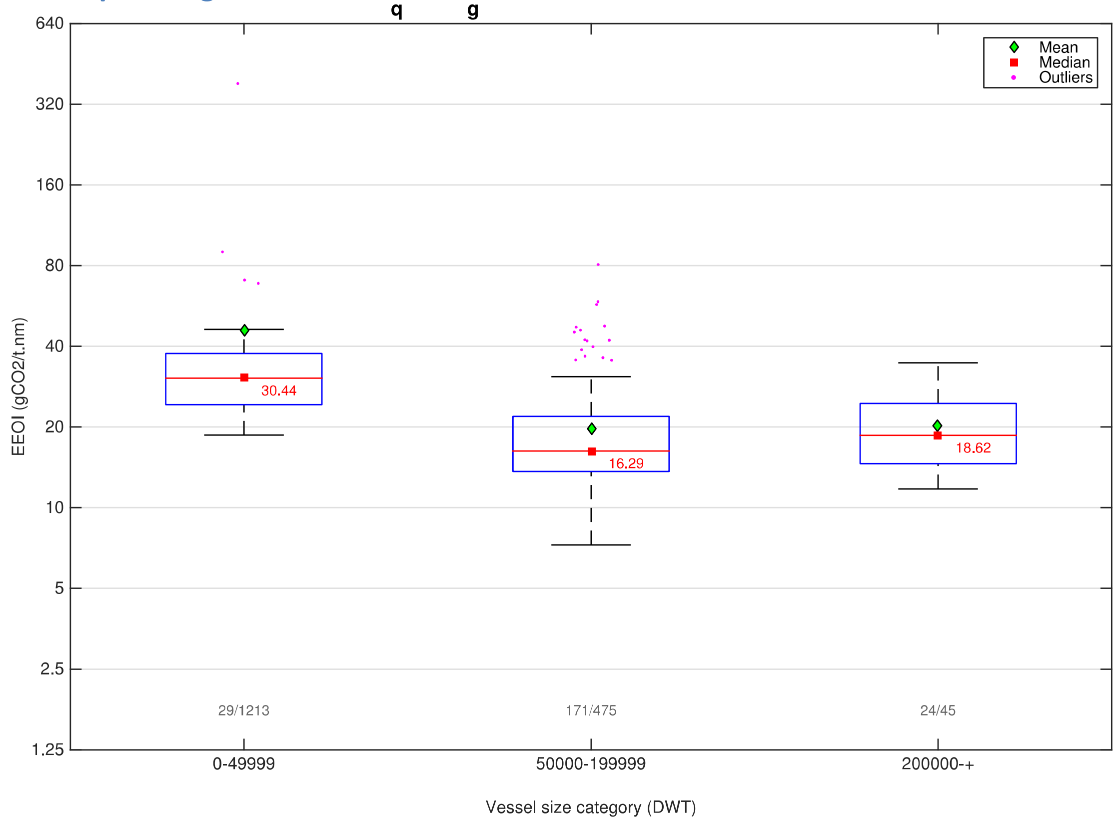


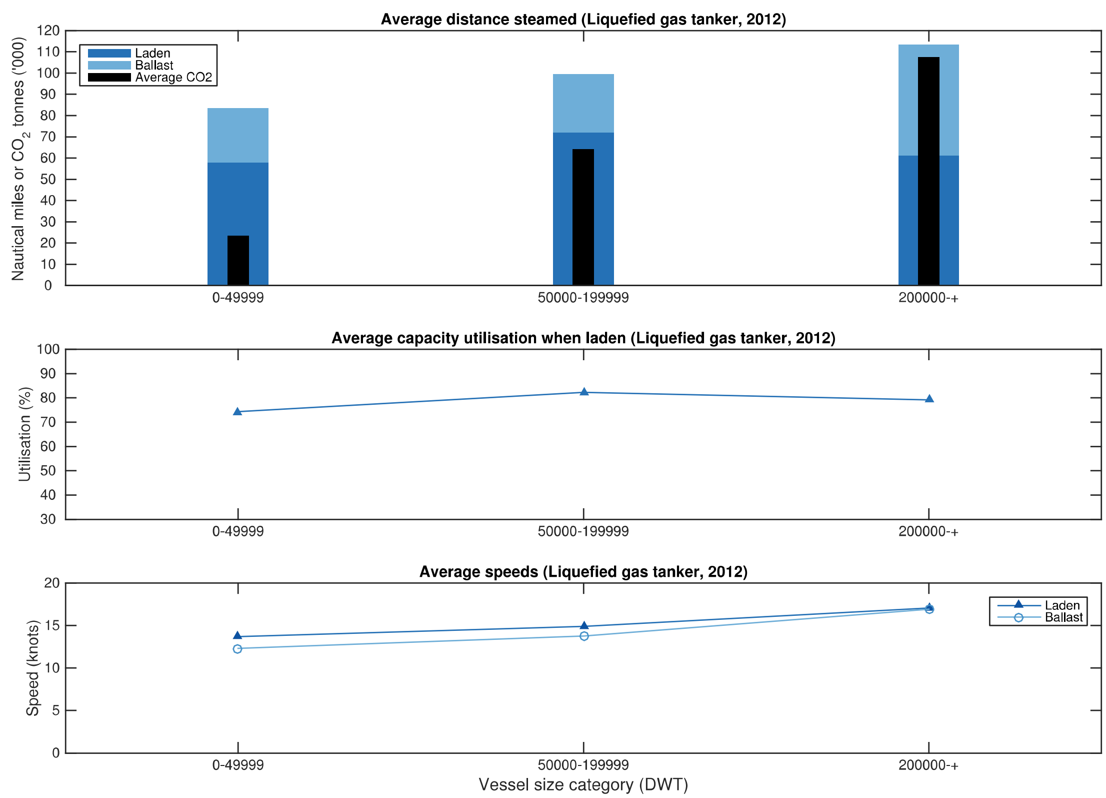




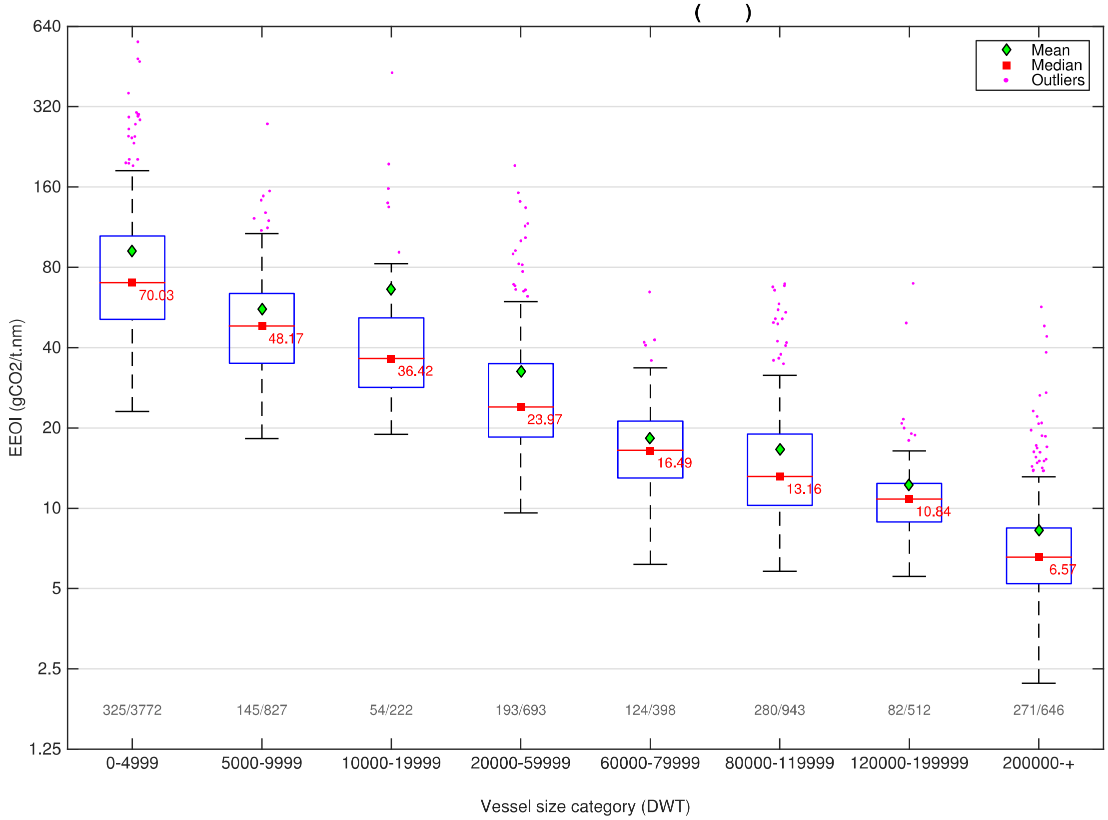


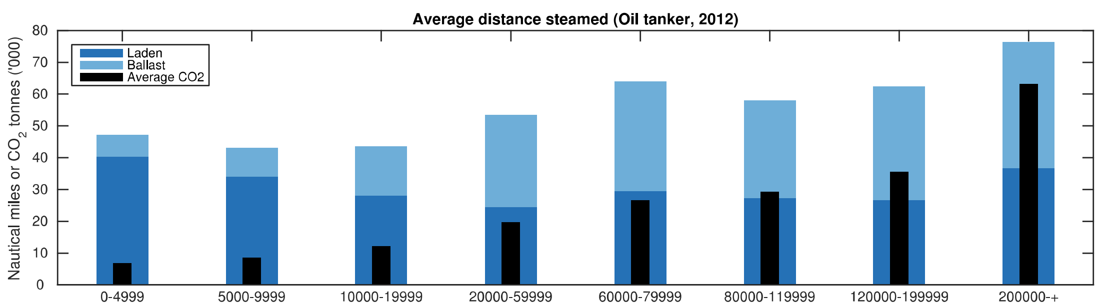
3.5. Liquefied gas tankers

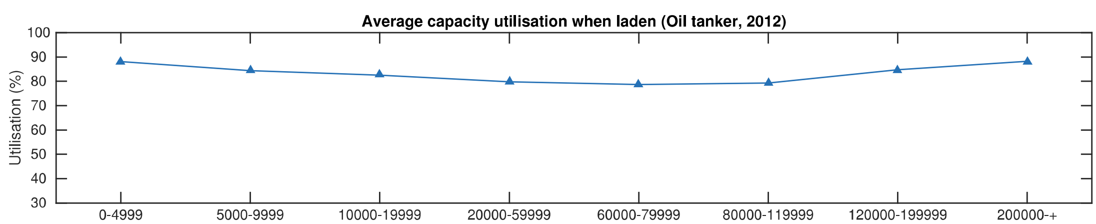


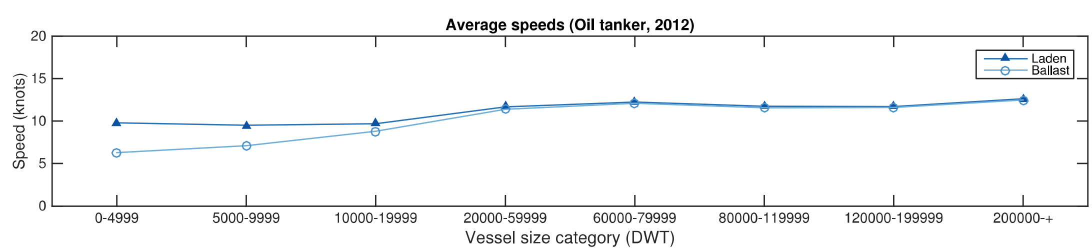


3.6. Oil tankers

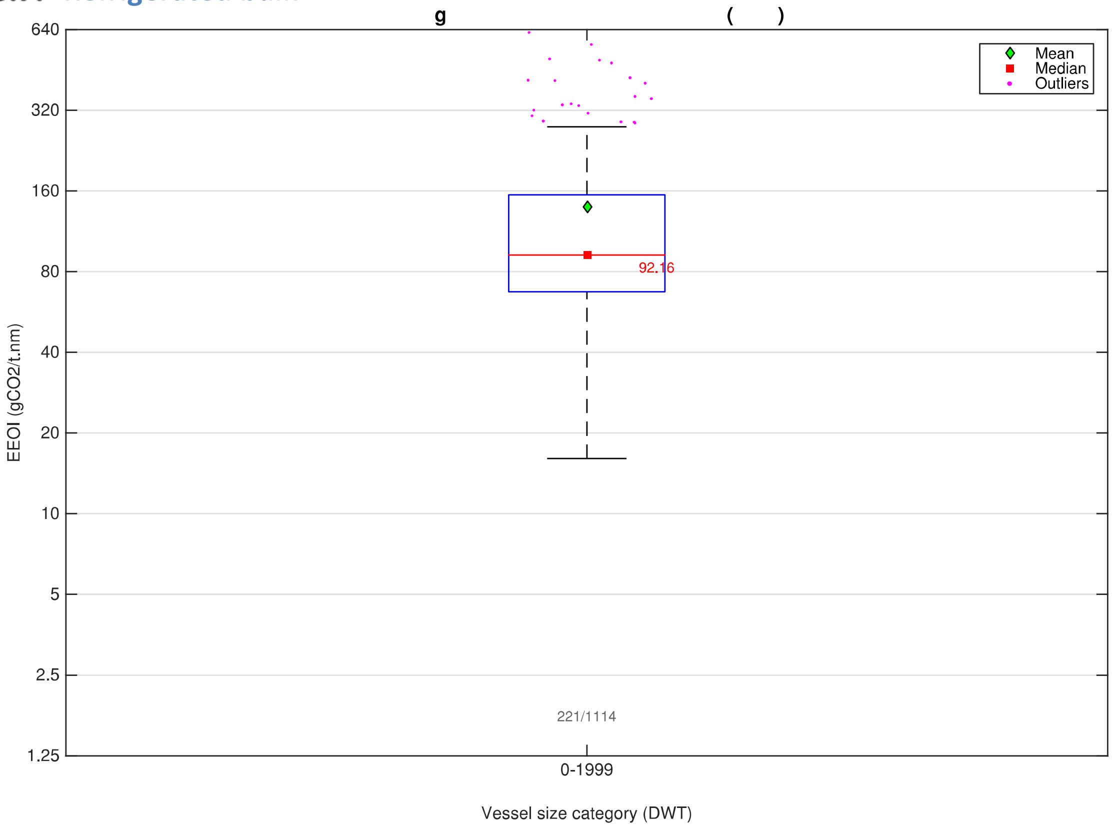


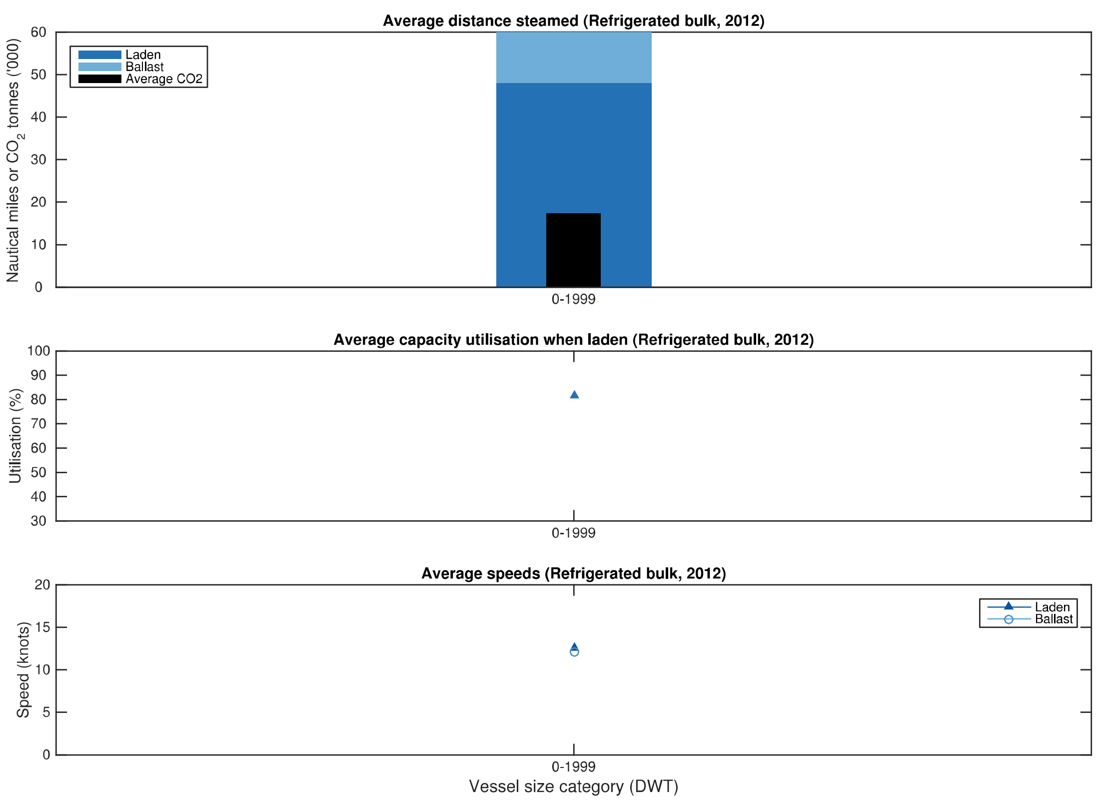






3.7. Refrigerated bulk





3.8. Tabular results, all years

Table 5: 2012 Summary

Type	Size	Fleet size		Mean dwt (tonnes)	Mean days at sea	Mean at sea speed (knots)	Filtered fleet size	EEOI ($gCO_2/t.nm$)			Median allocative utilisation (%)	Median payload utilisation (%)	Mean transport work per ship (billion t.nm)
		IHSF Active	AIS Active					Median	Lower quartile	Upper quartile			
Bulk carrier	0-9999	1216	670	3341	167	9.41	159	44.5	32.8	70.4	77.9	89.7	0.162
Bulk carrier	10000-34999	2317	2131	27669	168	11.4	462	15.4	12.5	21.2	58.8	91.8	0.771
Bulk carrier	35000-59999	3065	2897	52222	173	11.8	788	11.7	9.27	15.1	56.9	87.8	1.32
Bulk carrier	60000-99999	2259	2145	81876	191	11.9	402	10.7	8.99	13.3	49.7	86.1	1.92
Bulk carrier	100000-199999	1246	1169	176506	202	11.7	289	5.83	5.04	7.04	56.6	89.9	5.14
Bulk carrier	200000-+	294	274	271391	202	12.2	59	5.13	4.58	5.95	60.1	92.5	6.96
Chemical tanker	0-4999	1502	893	2158	159	9.81	151	51	38.2	70.2	99.9	88.1	0.107
Chemical tanker	5000-9999	922	863	7497	169	10.6	171	33.7	28.6	43.1	95.2	75.2	0.27
Chemical tanker	10000-19999	1039	1004	15278	181	11.7	294	23.7	19.9	28.8	84.7	75	0.571
Chemical tanker	20000-+	1472	1419	42605	183	12.3	379	15.6	13.5	17.8	78.4	66.9	1.36
Container	0-999	1126	986	8634	190	12.4	195	34.6	29.4	42.5	100	61.9	0.386
Container	1000-1999	1306	1275	20436	200	13.9	280	31.6	27.5	37.4	100	59.4	0.829
Container	2000-2999	715	689	36735	208	15	119	24.7	22.1	29.8	100	51.2	1.39
Container	3000-4999	968	923	54160	236	16.1	109	21.3	18.5	24.2	100	49.4	2.71
Container	5000-7999	575	552	75036	246	16.3	94	20.5	18.1	23.2	100	48.5	3.55
Container	8000-11999	331	325	108650	256	16.3	18	17.9	15.7	19.6	100	47.3	4.83
Container	12000-14500	103	98	176783	241	16.1	2	13.2	12.4	13.9	100	44.5	3.61
Container	14500-+	8	7	158038	251	14.8	-	-	-	-	-	-	-
General cargo	0-4999	11620	5163	1925	161	8.75	701	38.2	23.7	61	87.7	91.5	0.0803
General cargo	5000-9999	2894	2491	7339	166	10.1	496	34.5	27.2	46.8	69.1	88.7	0.203
General cargo	10000-+	1972	1779	22472	174	12	436	30.7	21	43.8	63.2	85.8	0.582
Liquefied gas tanker	0-49999	1104	923	6676	180	11.9	29	30.4	24.2	37.6	70	73.7	0.797
Liquefied gas tanker	50000-199999	463	444	68463	254	14.9	171	16.3	13.6	21.9	75.5	82.2	4.05
Liquefied gas tanker	200000-+	45	43	121285	277	16.9	24	18.6	14.6	24.5	55.4	79.8	5.91
Oil tanker	0-4999	3500	1498	1985	144	8.72	325	70	51	105	93.7	89	0.108
Oil tanker	5000-9999	664	577	6777	147	9.13	145	48.2	34.9	63.8	85	85.1	0.189
Oil tanker	10000-19999	190	171	15129	149	9.63	54	36.4	28.4	51.7	76.4	82.2	0.346
Oil tanker	20000-59999	659	624	43763	164	11.7	193	24	18.5	34.9	42.7	80.1	0.846
Oil tanker	60000-79999	391	381	72901	183	12.2	124	16.5	13	21.2	44.9	78.1	1.68
Oil tanker	80000-119999	917	890	109259	186	11.6	280	13.2	10.3	19	43.5	78.9	2.32
Oil tanker	120000-199999	473	447	162348	206	11.7	82	10.8	8.88	12.4	41.9	85.4	3.51
Oil tanker	200000-+	601	577	313396	233	12.5	271	6.57	5.21	8.43	48.3	88.8	9.86
Refrigerated bulk	0-1999	1090	763	5695	173	13.4	221	92.2	67.2	155	82.8	80.8	0.239

Table 6: 2011 Summary

Type	Size	Fleet size		Mean dwt (tonnes)	Mean days at sea	Mean at sea speed (knots)	Filtered fleet size	EEOI ($gCO_2/t.nm$)			Median allocative utilisation (%)	Median payload utilisation (%)	Mean transport work per ship (billion t.nm)
		IHSF Active	AIS Active					Median	Lower quartile	Upper quartile			
Bulk carrier	0-9999	1283	605	5194	177	9.71	137	39.9	31.2	51	87.1	93.2	0.189
Bulk carrier	10000-34999	2328	2004	27366	178	11.6	642	14.4	12.2	19	66.6	93.5	0.941
Bulk carrier	35000-59999	2650	2423	51195	187	12.2	881	11.5	9.65	14.1	59.8	88.3	1.61
Bulk carrier	60000-99999	1951	1823	76913	194	12.3	538	10.5	8.74	12.7	54.9	86.2	2.31
Bulk carrier	100000-199999	1084	1006	167167	203	12.2	320	6.34	5.36	8.03	56.6	90.7	5.3
Bulk carrier	200000-+	206	196	244150	204	12.4	54	5.41	4.38	6.32	56.3	91.7	7.72
Chemical tanker	0-4999	1594	823	3937	163	9.94	170	49.5	33.9	72.5	100	85.2	0.114
Chemical tanker	5000-9999	884	778	8931	170	10.8	270	35.2	27.9	40.7	99.3	78	0.282
Chemical tanker	10000-19999	1033	954	17884	188	12	390	23.2	19.3	27.9	88	79.8	0.643
Chemical tanker	20000-+	1410	1275	42782	182	12.6	581	15.1	12.8	17.6	87.6	68.5	1.49
Container	0-999	1154	945	9676	197	12.6	322	34.1	29.6	41.6	100	65.3	0.426
Container	1000-1999	1277	1172	20723	206	14.4	401	31	26.5	36.7	100	59.5	0.881
Container	2000-2999	724	666	35764	222	16	180	24.6	21.3	28.9	100	55.1	1.73
Container	3000-4999	944	864	53951	241	16.9	201	21.2	19.4	24.4	100	53.4	3.13
Container	5000-7999	576	545	76981	246	17.2	148	20.4	17.5	23.1	100	50.8	4.22
Container	8000-11999	260	236	108236	250	17.4	42	16.1	15	17.4	100	53.2	6.14
Container	12000-14500	50	47	164333	240	16.9	5	14.3	13.2	15	100	51.6	7.84
Container	14500-+	-	-	-	-	-	-	-	-	-	-	-	-
General cargo	0-4999	12187	4760	2405	167	8.8	1169	29.9	22.3	44.6	99.6	92.8	0.131
General cargo	5000-9999	2936	2268	8441	178	10.3	779	29.8	23.2	40	83.5	92.5	0.299
General cargo	10000-+	2108	1776	22011	181	12.1	604	23.8	17.1	33.7	72.9	89.1	0.81
Liquefied gas tanker	0-49999	1088	833	7240	186	12	39	27.9	24.5	53.8	67.7	77.5	0.837
Liquefied gas tanker	50000-199999	448	416	68019	262	15.1	190	15.3	13.5	19.9	80	80.5	4.35
Liquefied gas tanker	200000-+	45	38	121270	297	16.6	33	14.9	12.5	17	71.1	81.1	8.01
Oil tanker	0-4999	3761	1419	2781	145	8.9	255	67.4	48.9	96	96.4	90.2	0.118
Oil tanker	5000-9999	681	529	9005	155	9.32	135	42.7	35.5	58	94.4	85.7	0.226
Oil tanker	10000-19999	215	172	20338	159	9.79	55	30.5	23.8	45.1	87.9	80.9	0.43
Oil tanker	20000-59999	681	623	43467	169	11.9	225	21.9	16.9	35	48.7	79.6	1.02
Oil tanker	60000-79999	397	356	72401	177	12.4	149	16.1	12.7	22.1	47.4	79.2	1.81
Oil tanker	80000-119999	878	795	106477	180	11.9	350	12.7	9.55	19	48.7	80.7	2.61
Oil tanker	120000-199999	417	380	154878	206	12.2	158	9.12	7.32	12.1	53.2	84.4	4.9
Oil tanker	200000-+	563	534	304656	222	12.9	249	6.47	5.09	9.57	48	89.6	10.3
Refrigerated bulk	0-1999	1126	802	5538	184	13.6	312	82.7	56	127	88.3	75.7	0.335

Table 7: 2010 Summary

Type	Size	Fleet size		Mean dwt (tonnes)	Mean days at sea	Mean at sea speed (knots)	Filtered fleet size	EEOI (gCO_2/t.nm)			Median allocative utilisation (%)	Median payload utilisation (%)	Mean transport work per ship (billion t.nm)
		IHSF Active	AIS Active					Median	Lower quartile	Upper quartile			
Bulk carrier	0-9999	1276	637	3313	174	9.85	86	33.9	27.5	47.1	100	90.5	0.222
Bulk carrier	10000-34999	2374	2122	28455	179	11.6	514	13.4	10.6	25.2	86.5	94.6	1.03
Bulk carrier	35000-59999	2487	2389	54546	188	12.2	707	10.6	8.22	22.8	78.1	89.9	1.69
Bulk carrier	60000-99999	1868	1833	81713	180	12.3	543	15.5	8.17	23.6	35.2	87.8	1.96
Bulk carrier	100000-199999	1008	994	198060	179	12.7	290	12	7.4	15.4	30.6	92.7	3.8
Bulk carrier	200000-+	211	210	284595	177	12.8	92	8.85	4.88	12.6	31.5	93.9	6.85
Chemical tanker	0-4999	1581	850	2153	163	9.94	97	51.1	37.3	72.5	100	88.7	0.133
Chemical tanker	5000-9999	892	807	8082	170	11	170	32.6	25.9	39.5	100	79.3	0.354
Chemical tanker	10000-19999	1018	967	16800	183	12.1	254	22.1	18.2	27.9	100	81.4	0.67
Chemical tanker	20000-+	1446	1381	45789	179	12.7	276	13.4	11.4	16.7	100	72.4	1.83
Container	0-999	1211	1023	9080	191	12.7	200	32.1	27	38	100	70.2	0.516
Container	1000-1999	1313	1264	21520	201	14.5	414	28.1	23.7	32.4	100	68.1	1.11
Container	2000-2999	759	725	37478	214	16.2	247	21.1	18.7	25.1	100	65.7	2.18
Container	3000-4999	949	922	58072	230	17.2	233	19.4	17.5	21.8	100	68	3.34
Container	5000-7999	564	564	81168	228	17.5	108	18.7	16.4	20.7	100	66.8	4.66
Container	8000-11999	242	241	119058	238	17.9	15	15.9	12.7	17.6	100	65.5	5.15
Container	12000-14500	37	36	283558	241	17	-	-	-	-	-	-	-
Container	14500-+	-	-	-	-	-	-	-	-	-	-	-	-
General cargo	0-4999	13021	5204	1913	161	8.85	478	35.4	24	55.4	100	92.6	0.106
General cargo	5000-9999	3009	2381	7534	180	10.4	367	28.3	22.5	37.1	99.7	93.8	0.309
General cargo	10000-+	2225	1865	23156	172	12.2	370	20.9	14.9	29.9	96.9	88.3	0.978
Liquefied gas tanker	0-49999	1102	872	7081	181	11.9	29	24.7	18.1	29.8	100	67.2	1.04
Liquefied gas tanker	50000-199999	464	449	72093	230	14.5	140	13.9	11.8	18.5	100	80.7	4.36
Liquefied gas tanker	200000-+	45	45	135581	251	15.5	0	0	0	0	0	0	0
Oil tanker	0-4999	3910	1450	1933	140	9.05	212	57.6	42	79.5	100	92	0.142
Oil tanker	5000-9999	666	520	7258	144	9.55	100	36.6	28.2	57.3	100	91.2	0.258
Oil tanker	10000-19999	227	175	16019	139	10.2	52	26.2	21.8	38.3	100	80.2	0.504
Oil tanker	20000-59999	744	679	46793	162	12	191	16.6	13	36.8	73.8	81	1.28
Oil tanker	60000-79999	405	389	78219	172	12.5	62	13.3	10.2	37.1	71.7	78.7	1.95
Oil tanker	80000-119999	895	869	115036	178	12.3	178	10.2	7.98	35.9	68.5	78.6	2.84
Oil tanker	120000-199999	423	410	169810	186	12.7	71	14.3	7.35	29.5	34.5	86	3.9
Oil tanker	200000-+	578	550	335961	187	13.3	211	4.89	4.19	9.18	87.9	90	13.2
Refrigerated bulk	0-1999	1226	874	5705	184	13.7	215	84.1	61.1	127	100	78.5	0.26

3.9. Trends over time

Data from 2007 on total efficiency[1] as measured in the Second IMO GHG Study 2009 is utilized to compare trends in efficiency between 2007 and the data estimated in this report for 2010, 2011, and 2012. Because the Second IMO GHG Study 2009 used slightly different ship size categories, current outputs were reaggregated to coincide with the older categorizations. The results are presented in Figure 5 to Figure 9. For each ship type, both the median EEOI and the average transport supply (the estimated actual t.nm of transport supply performed) per ship in each year and each size category are plotted. In many cases there are substantial differences between the 2007 data and the 2010, 2011 and 2012 data (which are similar to each other). This discrepancy could be because of changes in the operation of ships over that period, or it could be because of differences in the method – the reliable deployment of AIS data for this analysis has only really been viable since the advent of satellite AIS data from 2010. Unfortunately, it is impossible to identify the relative importance of these two possible explanations without additional data.

The results show that in many instances the transport supply in later years is lower than the value from 2007. This is consistent with the observation in the Third IMO GHG Study 2014 of lower operating speeds (slow steaming). A further explanation is that in many instances, there is also lower utilization (lower payload and/or allocative utilization) estimated in this study, than the utilization estimated in the Second IMO GHG Study 2009.

If all else is equal, a lower quantity of transport supply (the denominator in the EEOI equation) will result in a higher EEOI. However, all is not equal and the drivers of low utilization (particularly slow steaming) can also contribute to reducing fuel consumption. The 'net' effect of the various drivers can be seen in the EEOI trends. For larger dry bulk carriers, there is a gradually improving (lowering) trend observed in EEOI from 2010 to 2012. Significant differences can be observed between those years and the 2007 data – differences which can largely be attributed to the difference in the estimated transport supply. Trends in the median EEOI for oil tankers are less uniform: whilst the EEOI values for smaller tankers have generally increased between 2010 and 2011, the trends for the larger tankers are quite mixed.

For other ship types (e.g. container ships, general cargo ships and some sizes of chemical tankers), the EEOI appears to be moderately deteriorating (increasing) between 2010 and 2012. For containerships, this appears to be at least partly to do with the reduced average transport supply from a reduction in average utilization over the same period of time. Discrepancies can again be observed for these ship types and the 2007 data. For container ships, it was observed in the Third IMO GHG Study 2014 that over the period 2007-2010, these ships saw extensive uptake of slow steaming which dramatically reduced fuel consumption and provides a plausible explanation for the observed large reduction in EEOI. Differences for the other ship types (chemical tanker and general cargo) are subtle and can not be decisively attributed to any particular

[1] Total efficiency was measured in gCO_2 per tonne-kilometer in the Second IMO GHG Study 2009, and this has been converted to an approximation in terms of gCO2 per tonne-nautical mile by multiplying by 1.852 (1 nautical mile is approximately 1.852 kilometers).

factor due to differences in the method for estimating transport supply between the Second and Third IMO GHG Studies.

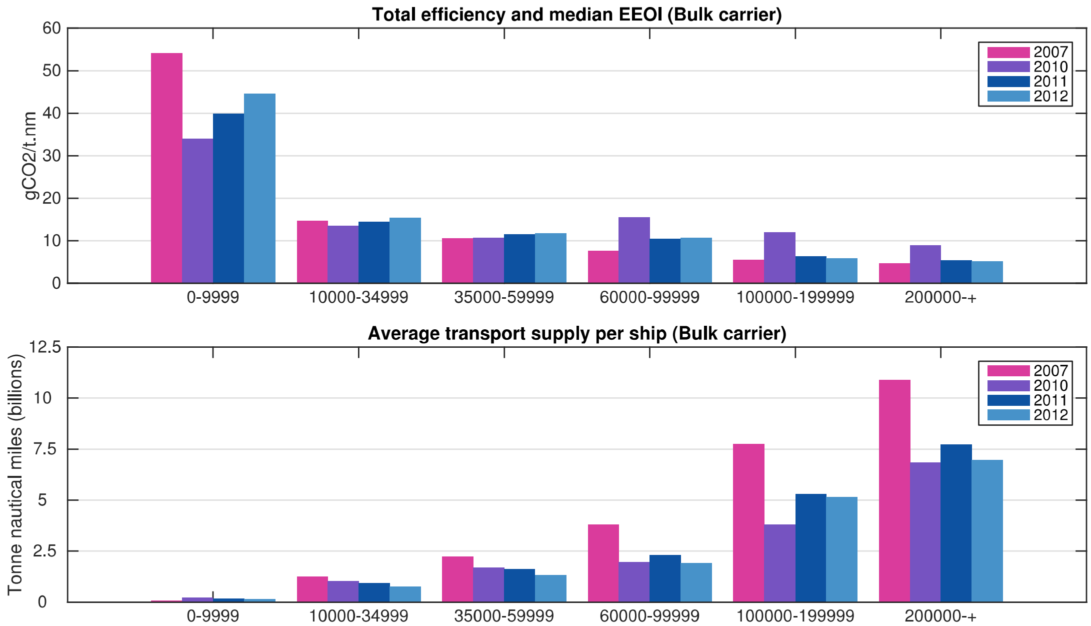


Figure 5: EEOI and transport supply 2007 to 2012, bulk carrier

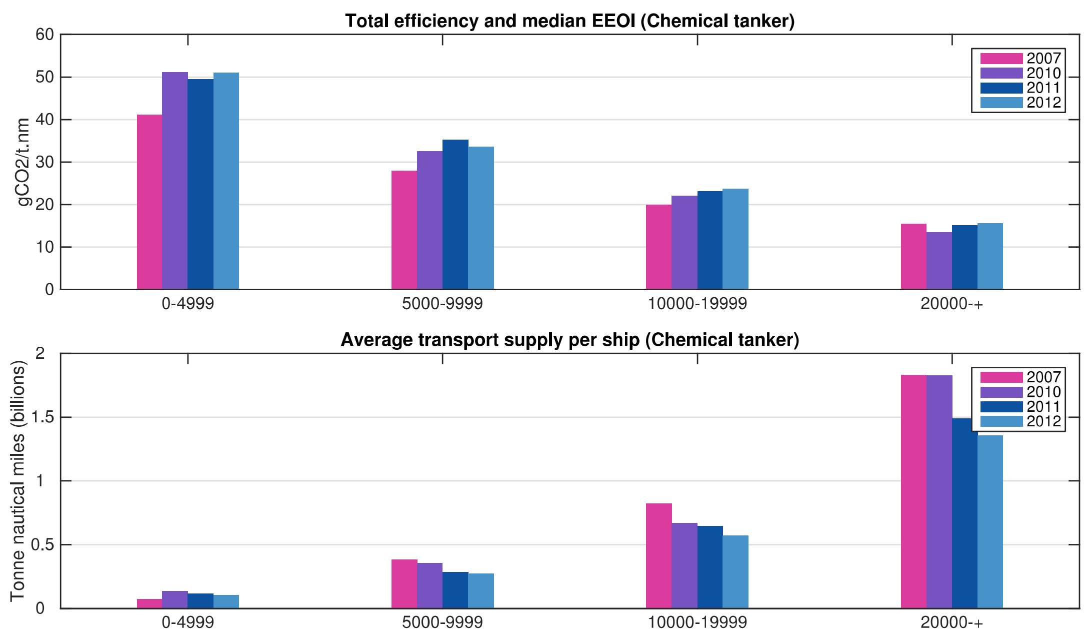


Figure 6: EEOI and transport supply 2007 to 2012, chemical tanker

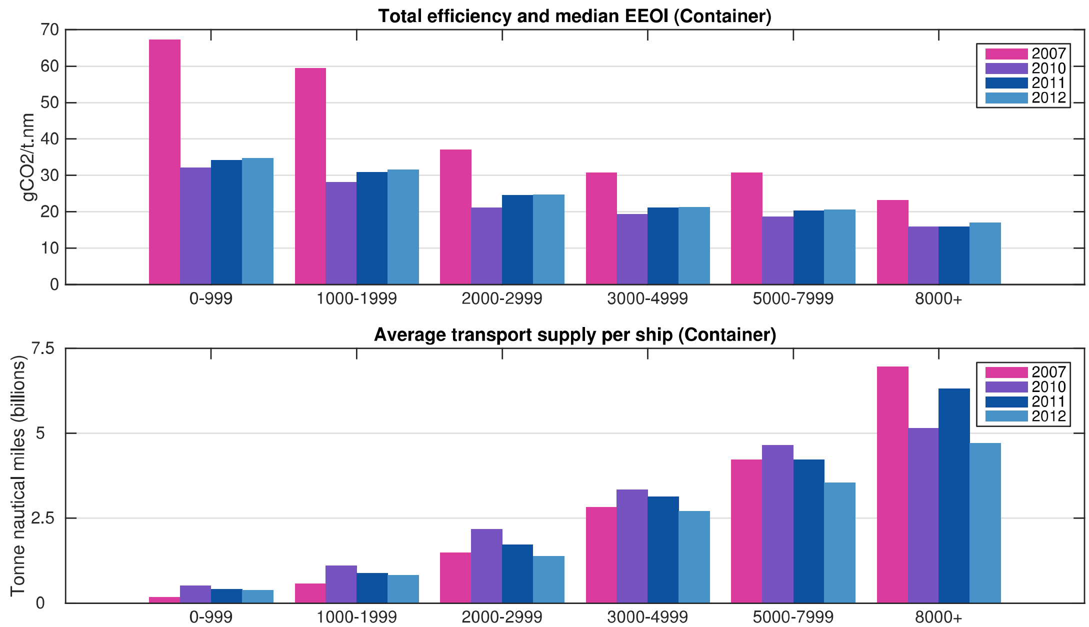


Figure 7: EEOI and transport supply 2007 to 2012, container ship

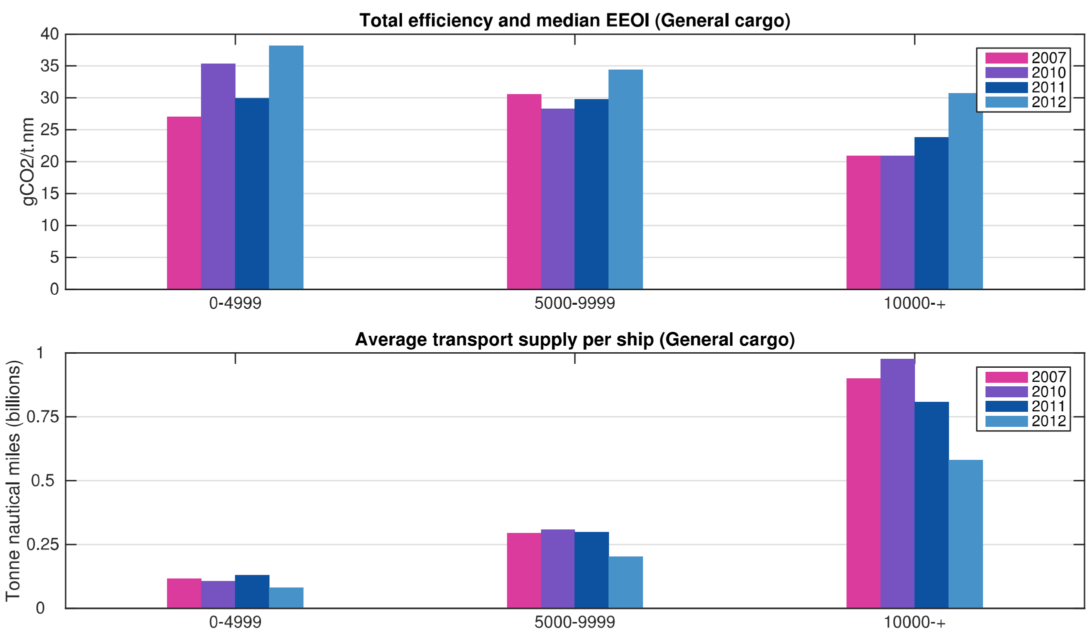


Figure 8: EEOI and transport supply 2007 to 2012, general cargo

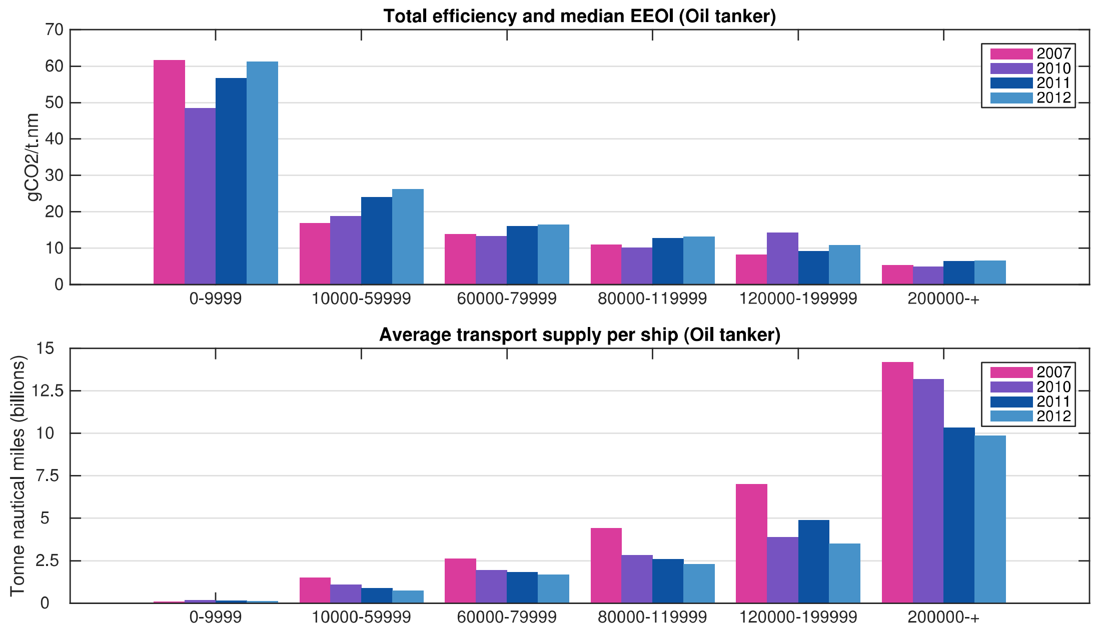


Figure 9: EEOI and transport supply 2007 to 2012, oil tanker

3.10. Power law fits for EEOI against dwt

Single term power law functions of the form $EEOI = \alpha dwt^{\beta}$ are fitted for each of the three years in the study. Only ships that pass the filters (see Section 4.1) are included. Table 8 below describes the estimated parameters for each year and type, while the figures that follow depict the scatter of EEOI values against dwt and the fitted power law functions.

Table 8: Single term power function parameter estimates

	2010		2011		2012	
	α	β	α	β	α	β
Bulk carrier	1430.963	-0.400	8568.621	-0.597	7770.516	-0.583
Chemical tanker	2505.115	-0.481	2175.134	-0.465	1937.875	-0.452
Container	1098.723	-0.371	722.603	-0.320	764.974	-0.324
General cargo	3582.609	-0.523	3040.665	-0.509	2070.986	-0.448
Liquefied gas tanker	3046.075	-0.445	8929.259	-0.544	6488.300	-0.517
Oil tanker	1522.565	-0.376	3506.085	-0.466	7575.529	-0.556
Refrigerated bulk	16479.498	-0.605	50928.661	-0.734	23585.282	-0.618

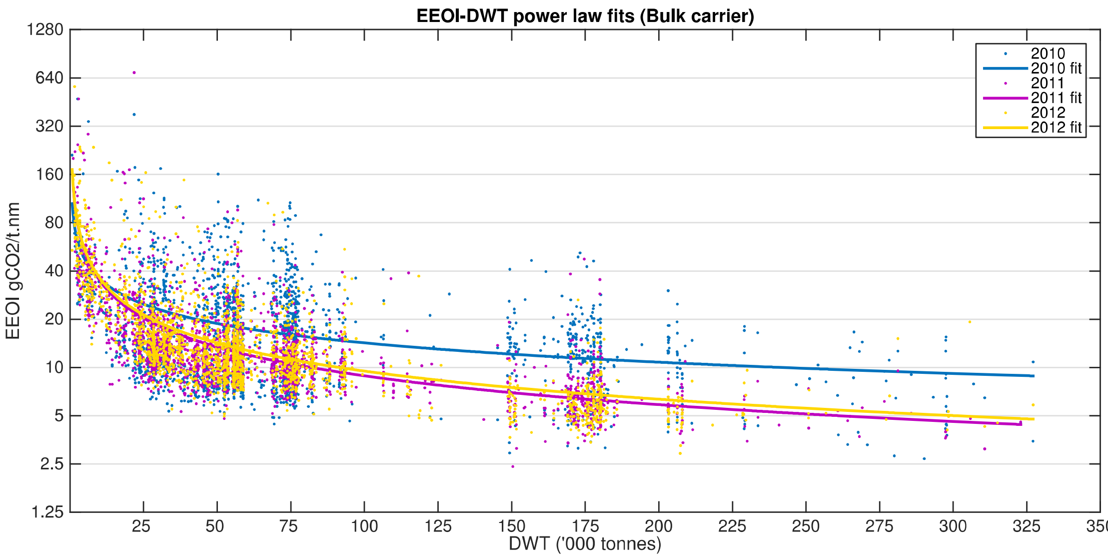


Figure 10: EEOI - dwt power law fits, bulk carrier

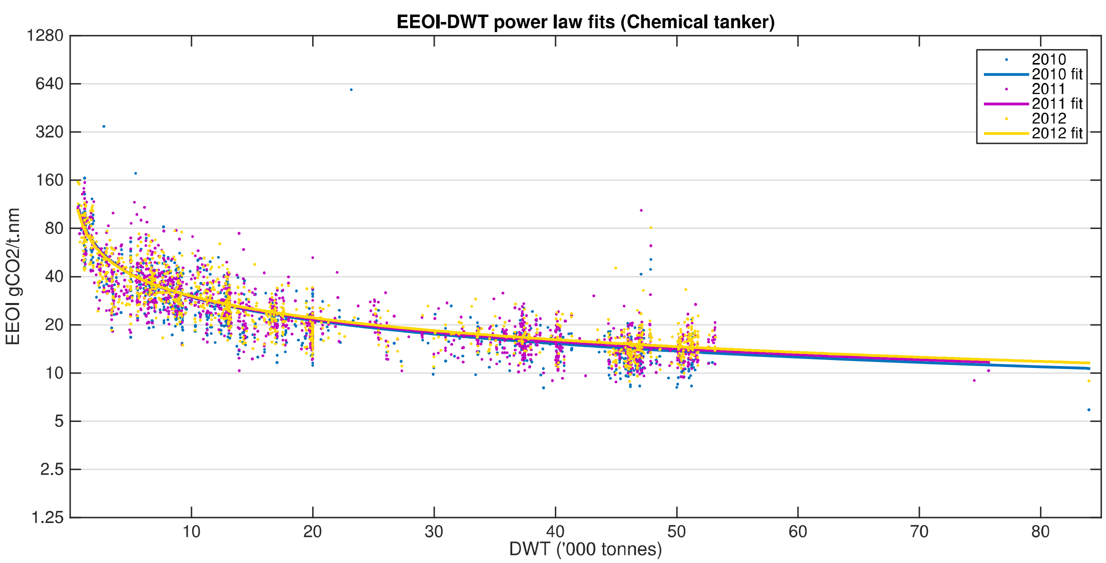


Figure 11: EEOI - dwt power law fits, chemical tanker

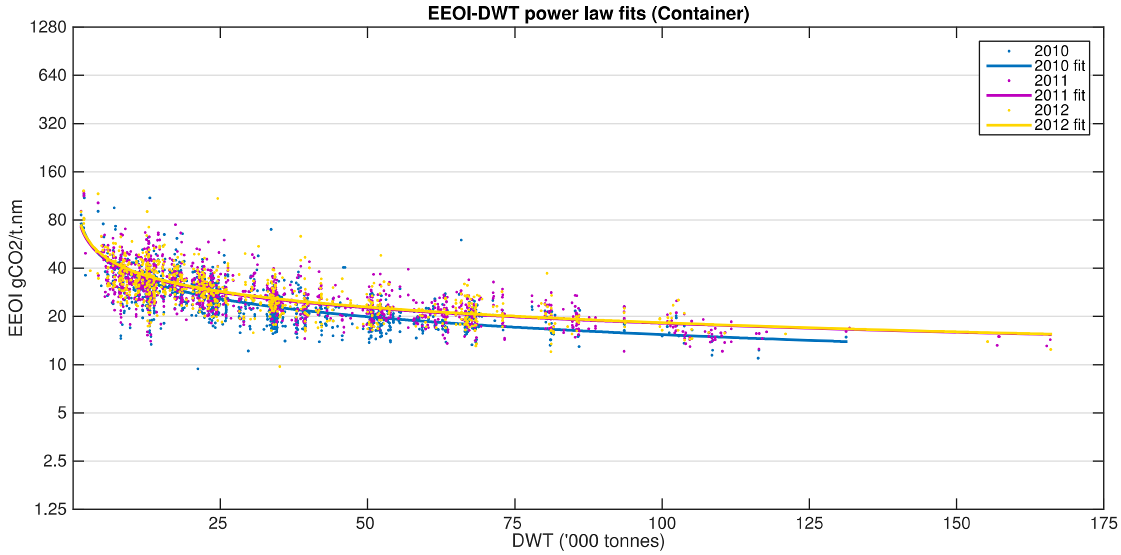


Figure 12: EEOI - dwt power law fits, container ships

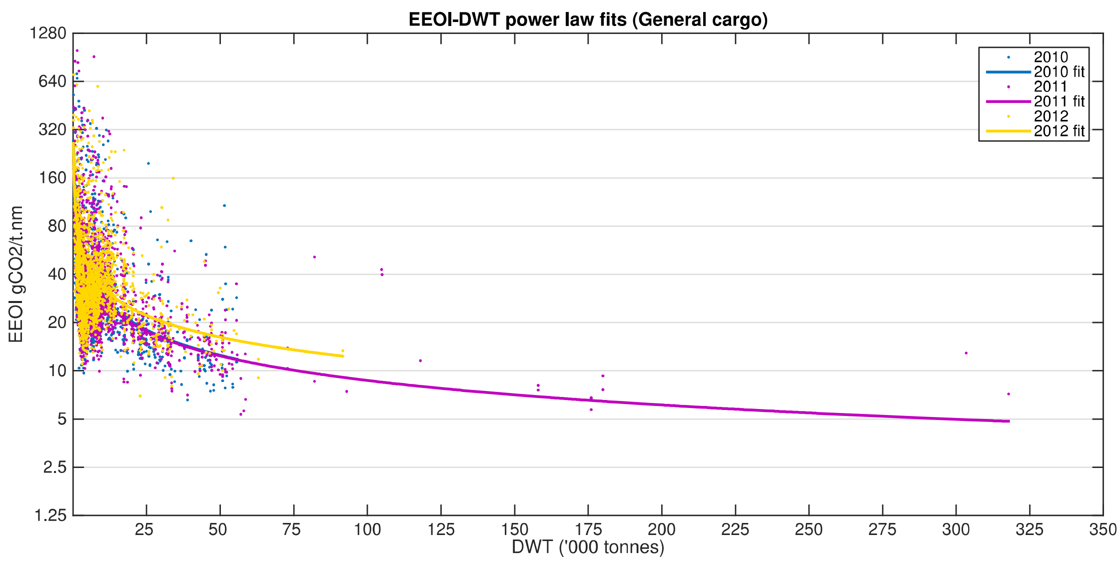


Figure 13: EEOI - dwt power law fits, general cargo

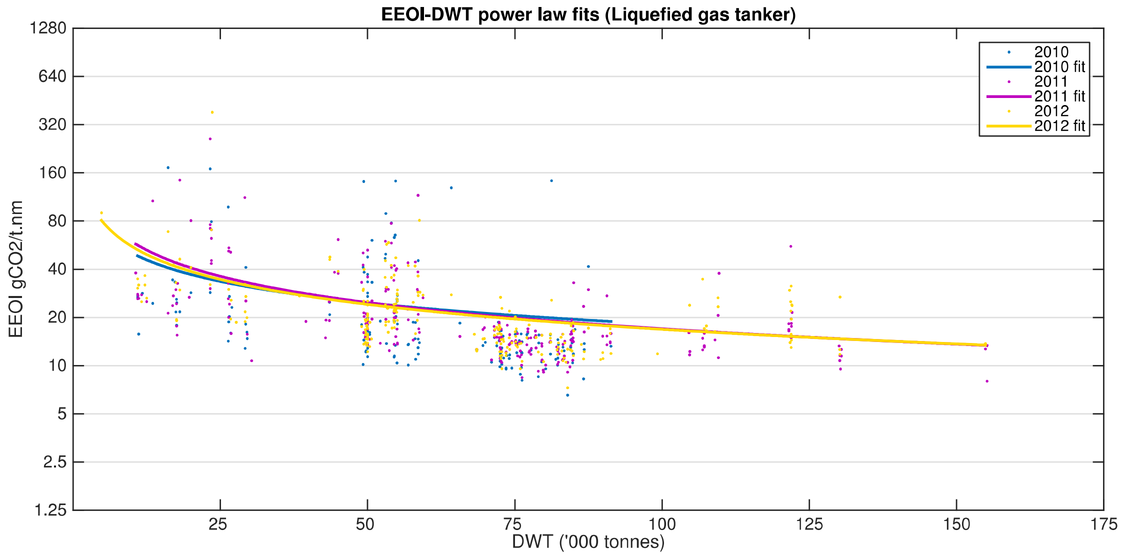


Figure 14: EEOI - dwt power law fits, liquefied gas tanker

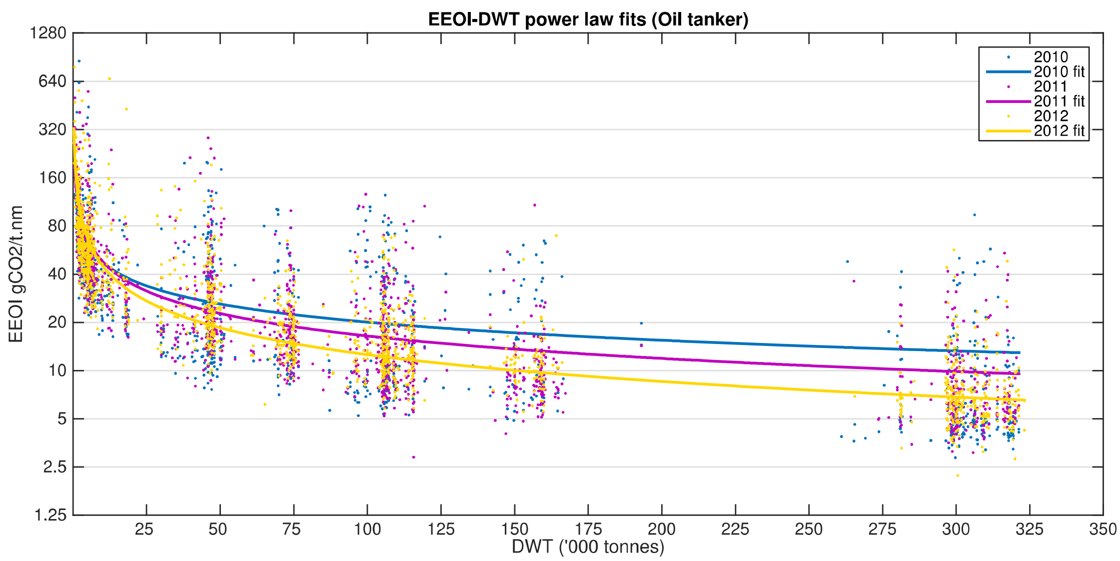


Figure 15: EEOI - dwt power law fits, oil tanker

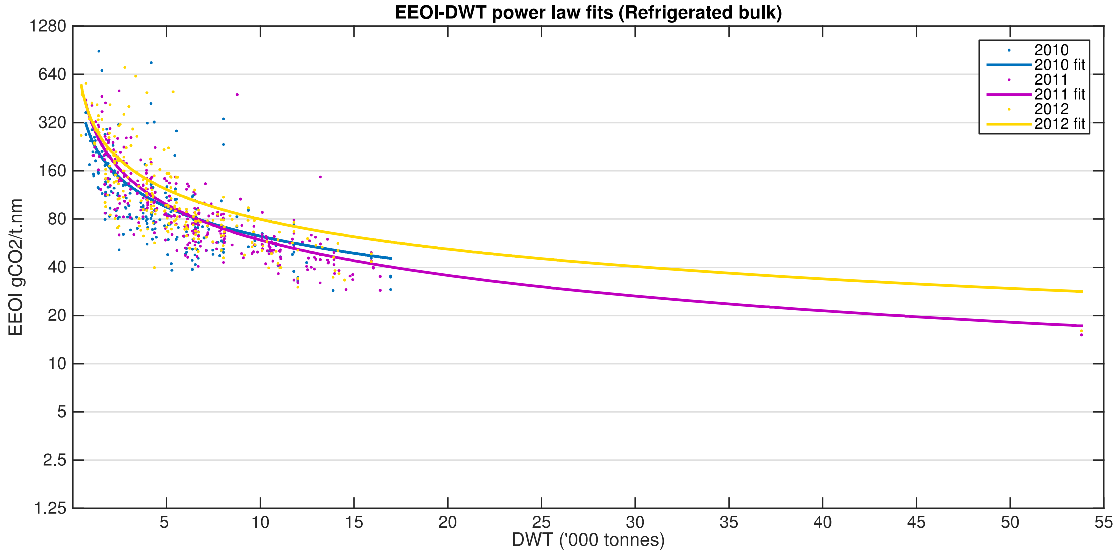


Figure 16: EEOI - dwt power law fits, refrigerated bulk

3.11. EEOI estimated with units gCO_2/TEU.nm

EEOI values computed for container ships throughout Section 3 are measured in units of gCO_2 per tonne nautical miles (t.nm). Because it is more common to express the capacity of a container ship in terms of the number of TEUs it can carry, estimates of EEOI in terms of gCO_2 per TEU nautical miles (TEU.nm) are also relevant and are made here.

Two methods for establishing this alternate representation are considered:

- using an assumption on the fleet-wide TEU utilization rate from the Clean Cargo Working Group's (CCWG) Global Maritime Trade Lane Emissions Factors (Annex III, p. 7, 2014), and,
- under the assumption that a container has an average constant mass of 7 tonnes as per the Second IMO GHG Study 2009 (p. 130, 2009).

CCWG's quoted fleet-wide average utilization rate is 73.7% for 2013 and 66% for 2012. These rates are shown to vary by around 10% or more across different trade routes. For this method, EEOI is computed as the ratio of total CO_2 emissions to the product of the ship's TEU capacity, the 2012 fleet-wide average utilisation rate, and distance travelled whilst laden.

The second method of estimating EEOI in gCO_2 per TEU.nm uses an assumption deployed in the Second IMO GHG Study 2009 that the average mass of a container (1 TEU) is 7 tonnes. This conversion is made by multiplying each ship's cargo mass EEOI by 7.

Whilst a certain amount of quantification of the variability in utilization can be established from CCWG's data variability by route, no equivalent bounds or variability in the average container mass can be established from the Second IMO GHG Study 2009.

Figure 17 displays the results for each size category of container ships (which assumes the constants for each method do not vary with ship size). Notably, the mean EEOI (per

TEU.nm) under the constant utilization of 66% of TEU capacity is consistently larger than the mean EEOI estimated via the 7 tonnes per container assumption.

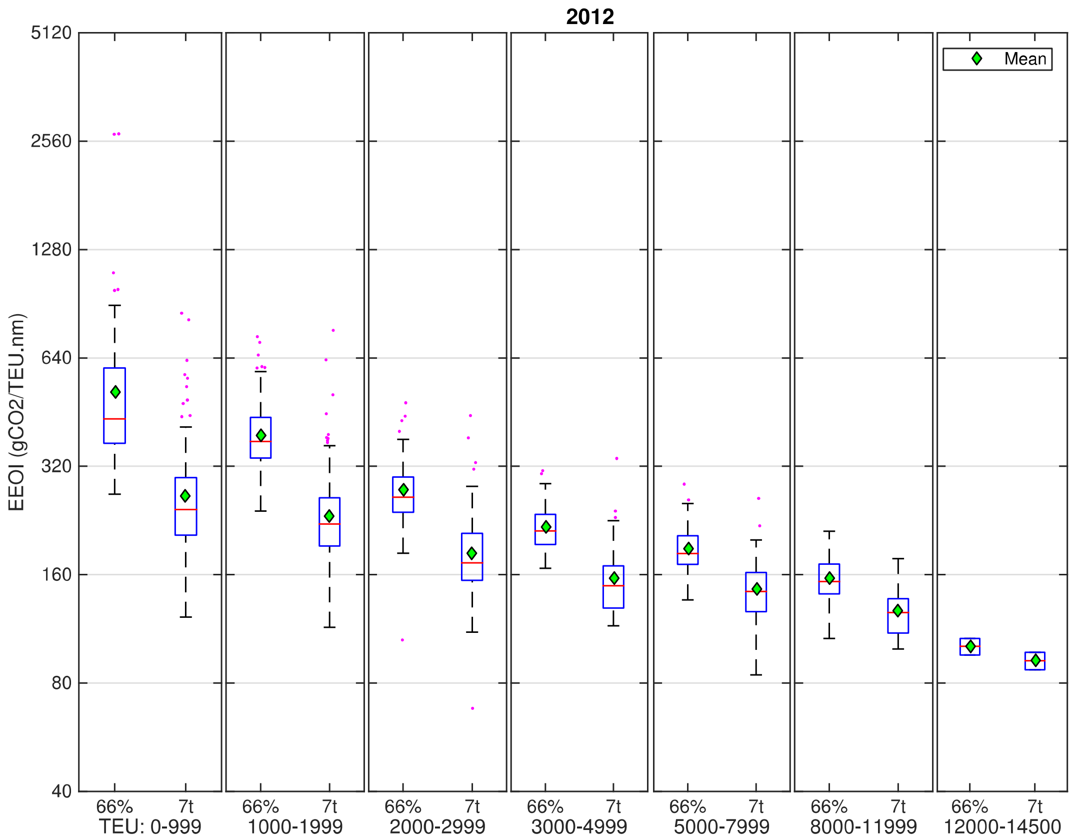


Figure 17: EEOI in gCO2/TEU.nm using two different methods

3.12. Fleet total transport work and fleet average EEOI

Throughout Section 3, results are presented broken down into ship type and size categories. This is useful in order to display differences between these categories and the impact of economies of scale on efficiency. However, this disaggregate perspective makes it difficult to track trends in a ship type's overall efficiency which can be influenced through a shift in the composition of the ship type from each ship size category, and their respective quantities of transport work.

In order to provide a quantification of a ship type's overall efficiency, Table 9 displays the supply-weighted ship type average efficiencies. These are obtained by weighting the EEOI with the ship size range's total supply and averaging. The ship size range's total supply is found by multiplying the average transport work per ship with the number of active ships in each ship type and size category (the IHSF active fleet data is used for the total number of active ships).

To provide some validation of whether the total supply calculated in this way, Table 10 quantifies the comparison between the calculated supply values with data for transport demand from UNCTAD Review of Maritime Transport (2013). To carry out this comparison, judgments are made about the matching between the ship type categories defined in this study and the ship type categories used by UNCTAD.

The results show that in many instances the agreement between total supply and total demand is good and predominantly within a discrepancy of approximately 20% (e.g. dry and oil). The supply of transport from the liquefied gas carrier fleet is consistently higher than the demand. A possible explanation in this instance is that the UNCTAD data only considers natural gas transport demand by ship, whereas the liquefied gas carrier fleet includes a number of ships carrying gaseous cargos other than natural gas.

The container ship supply also shows a consistent discrepancy with the UNCTAD container transport demand data. A possible explanation is that the transport supply method in this study includes the mass of the container (the structure of the container) in the estimate of the cargo mass, and the UNCTAD data may not. A plausible estimate for the container mass is 15-30% of the average combined mass of container and its contents which is similar to the observed discrepancy.

Table 9: Fleet supply-weighted average EEOIs

	Supply-weighted average EEOI (gCO_2/t.nm)		
	2010	2011	2012
Total dry (bulk carriers, general cargo and refrigerated bulk)	16.9	14.2	13.5
Total oil (oil tankers)	15.8	17.8	18.0
Total gas	17.8	18.8	20.6
Total container	21.0	22.1	22.4
Total all above ship types	17.6	17.1	16.9

Table 10: Transport demand and supply 2010-2012

	Estimated total transport demand (billion t.nm)			Estimated total transport supply (billion t.nm)			Discrepancy (%)		
	2010	2011	2012	2010	2011	2012	2010	2011	2012
Total dry (ship types: bulk carriers, general cargo and refrigerated bulk)	23388	24625	26010	20673	23101	21746	-12%	-6%	-18%
Total oil (ship type: oil tankers)	11018	11207	11471	14411	12244	11509	27%	9%	0%
Total gas (ship type: liquefied gas carriers)	1041	1069	1076	3169	3220	3021	101%	100%	95%
Total container (ship type: container ship)	6785	7383	7603	10781	10243	9146	45%	32%	18%
Total all above ship types	42232	44284	46160	49034	48808	45422	15%	10%	-2%

4. Quality assurance of estimation of work done and EEOI calculations

A number of inspections are undertaken to assess the quality of the calculated data. Some ships in the fleet have identifiably spurious draught data – for example a constant value of zero is transmitted as the draught, even whilst the ship is observed (from speed data) to be on a passage. Section 4.1 reviews the filters selected to correct this and presents the resulting sample sizes for the different ship type and size categories. Given those samples, Section 4.2 then undertakes a series of statistical tests on the filtered and unfiltered fleets to inspect for bias. Sections 4.3 to 4.6 compare the components of the EEOI estimates against a number of available datasets, including some of the noon report data (where relevant) that was assembled for the Third IMO GHG Study 2014.

4.1. Filtering of results

A set of filters is applied to the bottom-up model's output to discard spurious results and mitigate the likelihood of including EEOI estimates for ships with sparse or unreliable AIS data. Altering the filter parameters changes the diversity and coverage of the subset of ships deemed reliable. To test whether this filtering results in a biased representation of the global fleet, the filtered and unfiltered samples are subjected to a preliminary bias analysis.

The final filter set was chosen after measuring the sensitivities of each filter parameter, and renders a sample that is considered to be sufficiently diverse and well populated across as many ship types and sizes as possible. This set retains a ship (regardless of its type) in the sample if the following conditions are met:

- it is active and observed in AIS data,
- at least 62.5% of the ship's messages with draught values are valid and not spurious,
- the sum of the days it spends laden and in ballast is at least 100
- the ratio of the ship's distance travelled whilst laden to the sum of the distances travelled whilst laden and in ballast is at least 0.05.

This latter ratio is referred to as the ship's allocative utilization. An upper bound on allocative utilization of 0.95 is used as an additional condition if the ship is a bulk carrier, oil tanker, general cargo carrier, or a liquefied gas tanker.

Table 11 depicts the resulting changes in the total number of ships classed as reliable for each of the three years under consideration. The total ships column in each year is the sum of those that are deemed either active or inactive as per IHSF (IHS Fairplay, the database of ship particulars used in the Third IMO GHG Study 2014).

Table 11: Filter results for each year by ship type and size categories

		2012			2011			2010		
Type	**Size**	Total	Filtered	%	Total	Filtered	%	Total	Filtered	%
Bulk carrier	0-9999	1295	159	12.3	1403	137	9.8	1441	86	6.0
Bulk carrier	10k-34999	2574	462	17.9	2580	642	24.9	2726	514	18.9
Bulk carrier	35k-59999	3519	788	22.4	2940	881	30.0	3038	707	23.3
Bulk carrier	60k-99999	2557	402	15.7	2101	538	25.6	2122	543	25.6
Bulk carrier	100k-199999	1393	289	20.7	1242	320	25.8	1256	290	23.1
Bulk carrier	200k-+	342	59	17.3	214	54	25.2	222	92	41.4
Chemical tanker	0-4999	1577	151	9.6	1759	170	9.7	1811	97	5.4
Chemical tanker	5k-9999	1068	171	16.0	978	270	27.6	1055	170	16.1
Chemical tanker	10k-19999	1111	294	26.5	1126	390	34.6	1177	254	21.6
Chemical tanker	20k-+	1540	379	24.6	1455	581	39.9	1528	276	18.1
Container	0-999	1165	195	16.7	1198	322	26.9	1269	200	15.8
Container	1k-1999	1347	280	20.8	1324	401	30.3	1382	414	30.0
Container	2k-2999	731	119	16.3	744	180	24.2	783	247	31.5
Container	3k-4999	990	109	11.0	984	201	20.4	1008	233	23.1
Container	5k-7999	582	94	16.2	583	148	25.4	581	108	18.6
Container	8k-11999	356	18	5.1	265	42	15.8	265	15	5.7
Container	12k-14500	113	2	1.8	76	5	6.6	76	0	0.0
Container	14500-+	8	0	0.0	0	0	0.0	0	0	0.0
General cargo	0-4999	12253	701	5.7	25424	1169	4.6	20140	478	2.4
General cargo	5k-9999	3232	496	15.3	3213	779	24.2	3472	367	10.6
General cargo	10k-+	2181	436	20.0	2251	604	26.8	2487	370	14.9
Liquefied gas tanker	0-49999	1213	29	2.4	1158	39	3.4	1199	29	2.4
Liquefied gas tanker	50k-199999	475	171	36.0	470	190	40.4	481	140	29.1
Liquefied gas tanker	200k-+	45	24	53.3	45	33	73.3	45	0	0.0
Oil tanker	0-4999	3772	325	8.6	3947	255	6.5	4121	212	5.1
Oil tanker	5k-9999	827	145	17.5	763	135	17.7	785	100	12.7
Oil tanker	10k-19999	222	54	24.3	240	55	22.9	264	52	19.7
Oil tanker	20k-59999	693	193	27.8	731	225	30.8	813	191	23.5
Oil tanker	60k-79999	398	124	31.2	409	149	36.4	442	62	14.0
Oil tanker	80k-119999	943	280	29.7	910	350	38.5	939	178	19.0
Oil tanker	120k-199999	512	82	16.0	424	158	37.3	439	71	16.2
Oil tanker	200k-+	646	271	42.0	593	249	42.0	626	211	33.7
Other liquids tanker	0-+	149	1	0.7	152	6	3.9	168	4	2.4
Refrigerated bulk	0-1999	1114	221	19.8	1164	312	26.8	1261	215	17.0
Ro-Ro	0-4999	1504	131	8.7	1496	117	7.8	1533	90	5.9
Ro-Ro	5k-+	435	64	14.7	464	119	25.6	512	84	16.4
Vehicle	0-3999	287	59	20.6	306	94	30.7	351	85	24.2
Vehicle	4k-+	586	124	21.2	520	185	35.6	563	93	16.5
Total		**53755**	**7902**		**65652**	**10505**		**62381**	**7278**	
Average				**18.1**			**24.7**			**16.0**

4.2. Justification of representativeness of sample

The three tables in Annex A compare some of the key characteristics (dwt, TEU capacity, and main engine power) of the ships included in the filtered sample to those excluded for each year.

For most of the ship types and sizes, the two samples have properties that are very similar in mean and median of both size and main engine power in each of the three years. As expected, the smaller, filtered sample in general has a marginally smaller standard deviation in dwt. However, the difference in the standard deviation of main engine power is more pronounced relative to that of dwt, which is indicative of variability in design speed as well as ship size.

If the two samples were normally distributed, a two-sample *t*-test under the assumption that variances are equal (or unequal[2]) could determine whether the means between the two samples were significantly different. In each year and for each ship type and size pair common to both the filtered and unfiltered samples, dwt (TEU for containers) and main engine power are first standardized (centered). The Kolmogorov-Smirnov and Lilliefors tests are applied to these centered samples to determine whether they are normally distributed[3]; each test has a null hypothesis of normality (standard normality in the case of Kolmogoro-Smirnov).

Neither dwt (TEU) nor main engine power is found to follow a normal distribution before or after standardization in any of the years at the 5% significance level consistently across both[4] tests. Hence, it is no longer possible to assess bias in the sample using the means of dwt (TEU) or power. Instead, Wilcoxon's non-parametric rank sum test was applied to see if the medians of each sample[5] were significantly different from each other. This test assesses the null hypothesis that the medians are equivalent against the alternative that they are not (Mann-Whitney (1947), Wilcoxon (1945)), the results of which are shown in Table 12. A result of 1 that coincides with a *p*-value less that 0.05 indicates that the medians between the two samples are significantly different from each other at the 5% significance level—and that, potentially, on the basis of the variable used to test for bias (dwt (TEU) or main engine power), some caution may be required if assuming that the results for that particular type-size category is an unbiased representation of the entire fleet under that type-size category[6].

Although there are only a few indications of bias in dwt or main engine power, they are more common for the size categories without an upper limit, those where the number of ships included after the filter is close to the number excluded, and those where the number included is a lot smaller than the number excluded.

[2] See, for example, Welch (1947).
[3] Lehmann et al (2006)
[4] These tests could only be run on samples that had at least a few observations. Thus, particularly for the filtered samples, there were type-size categories where the normality of the distribution could not be tested. Further, those that were nevertheless tested with small samples may have unreliable results.
[5] The medians of the excluded subset of vessels are compared to the medians of the filtered subset, because the Wilcoxon rank sum test requires independent samples.
[6] Comparisons of medians are indicative but not conclusive measures of potential bias between samples.

Table 12: Wilcoxon rank sum test results

Type	Size	2012						2011						2010					
		Fleet size		dwt or TEU		Main engine power		Fleet size		dwt or TEU		Main engine power		Fleet size		dwt or TEU		Main engine power	
		Excluded	Filtered	Result	*p*-val	Result	*p*-val	Excluded	Filtered	Result	*p*-val	Result	*p*-val	Excluded	Filtered	Result	*p*-val	Result	*p*-val
Bulk carrier	0-9999	1136	159	0	0.705	0	0.218	1266	159	0	0.555	1	0.014	1355	86	0	0.711	0	0.130
Bulk carrier	10000-34999	2112	462	0	0.784	0	0.324	1938	462	1	0.000	0	0.989	2212	514	0	0.813	0	0.089
Bulk carrier	35000-59999	2731	788	0	0.081	1	0.000	2059	788	0	0.314	1	0.001	2331	707	0	0.633	1	0.039
Bulk carrier	60000-99999	2155	402	0	0.167	0	0.228	1563	402	0	0.559	0	0.962	1579	543	0	0.827	0	0.227
Bulk carrier	100000-199999	1104	289	0	0.470	1	0.000	922	289	1	0.016	1	0.000	966	290	0	0.071	1	0.000
Bulk carrier	200000-+	283	59	0	0.467	0	0.288	160	59	0	0.396	0	0.956	130	92	0	0.589	0	0.794
Chemical tanker	0-4999	1426	151	0	0.650	0	0.564	1589	151	0	0.964	0	0.957	1714	97	0	0.642	0	0.685
Chemical tanker	5000-9999	897	171	0	0.925	0	0.803	708	171	0	0.933	0	0.966	885	170	0	0.737	0	0.921
Chemical tanker	10000-19999	817	294	0	0.736	1	0.009	736	294	0	0.257	1	0.001	923	254	0	0.361	1	0.000
Chemical tanker	20000-+	1161	379	1	0.000	1	0.000	874	379	1	0.000	0	0.069	1252	276	1	0.000	0	0.502
Container	0-999	970	195	0	0.902	0	0.118	876	195	0	0.932	1	0.034	1069	200	0	0.927	0	0.164
Container	1000-1999	1067	280	0	0.361	0	0.926	923	280	0	0.938	0	0.893	968	414	0	0.536	0	0.574
Container	2000-2999	612	119	0	0.916	0	0.553	564	119	0	0.541	0	0.202	536	247	0	0.935	0	0.096
Container	3000-4999	881	109	0	0.430	0	0.868	783	109	0	0.548	0	0.537	775	233	0	0.983	0	0.061
Container	5000-7999	488	94	0	0.900	0	0.706	435	94	0	0.795	0	0.806	473	108	0	0.840	0	0.680
Container	8000-11999	338	18	0	0.951	1	0.002	223	18	0	0.952	1	0.000	250	15	0	0.601	0	0.061
Container	12000-14500	111	2	0	0.699	-	-	71	2	0	1.000	0	0.741	76	0	-	-	-	-
Container	14500-+	8	0	-	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-
General cargo	0-4999	11552	701	1	0.005	0	0.447	24255	701	1	0.000	0	0.446	19662	478	0	0.120	0	0.318
General cargo	5000-9999	2736	496	0	0.802	0	0.772	2434	496	1	0.021	1	0.006	3105	367	0	0.360	1	0.003
General cargo	10000-+	1745	436	1	0.000	0	0.187	1647	436	1	0.002	0	0.907	2117	370	1	0.000	0	0.829
Liquefied gas tanker	0-49999	1184	29	0	0.551	0	0.082	1119	29	0	0.324	0	0.192	1170	29	0	0.701	0	0.286
Liquefied gas tanker	50000-199999	304	171	0	0.380	0	0.718	280	171	1	0.048	0	0.307	341	140	0	0.538	0	0.401
Liquefied gas tanker	200000-+	21	24	0	0.371	0	0.092	12	24	0	0.830	0	0.791	45	0	-	-	-	-
Oil tanker	0-4999	3447	325	0	0.613	1	0.002	3692	325	0	0.756	1	0.024	3909	212	0	0.739	0	0.225
Oil tanker	5000-9999	682	145	0	0.950	0	0.595	628	145	0	0.087	0	0.627	685	100	0	0.973	0	0.454
Oil tanker	10000-19999	168	54	0	0.831	0	0.791	185	54	0	0.962	0	0.163	212	52	0	0.919	0	0.078
Oil tanker	20000-59999	500	193	0	0.750	1	0.000	506	193	0	0.793	1	0.000	622	191	0	0.457	1	0.000
Oil tanker	60000-79999	274	124	0	0.966	0	0.594	260	124	0	0.321	0	0.605	380	62	0	0.961	0	0.243
Oil tanker	80000-119999	663	280	0	0.078	1	0.007	560	280	0	0.059	0	0.412	761	178	0	0.252	0	0.776
Oil tanker	120000-199999	430	82	0	0.227	1	0.020	266	82	1	0.001	1	0.038	368	71	0	0.891	0	0.764
Oil tanker	200000-+	375	271	1	0.005	1	0.039	344	271	0	0.122	0	0.651	415	211	0	0.877	0	0.201
Refrigerated bulk	0-1999	893	221	0	0.552	0	0.106	852	221	0	0.575	0	0.292	1046	215	0	0.877	0	0.403

4.3. Draught

A quality analysis of the bottom-up model outputs was carried out by comparison with noon report data. Noon report data record daily information regarding the ship's operational performance and the environmental conditions in which it is operating. Fields such as speed, draught, wind speed, wind direction and fuel consumption are included. They also record the time stamp for the beginning and end of the voyage. The information, which details data for individual ships, is aggregated over quarters and is compared with the same data as output from the bottom-up model and matched to the same quarter of each year. The bottom-up model obtains a value for the ship's draught from the AIS dataset. The comparison for the aggregated data can be seen in Figure 18.

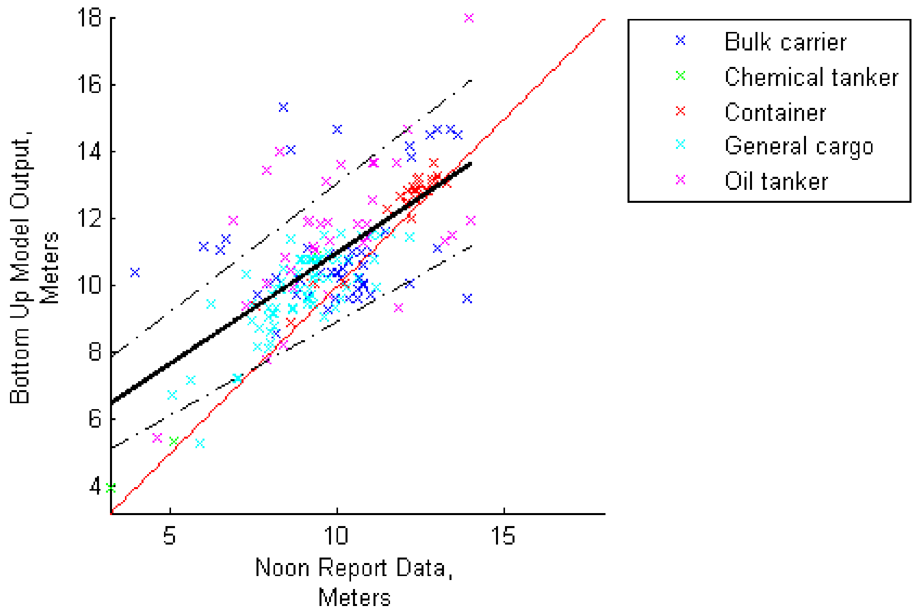


Figure 18. Comparison of at-sea and at-port days are calculated from both the bottom-up model output (y-axis) and the noon report data (x-axis) (2012).

The red line represents an equal relationship between the bottom-up model and the noon report model. The solid black line is the best fit through the data and the dotted black lines are the 95% confidence bounds of the fit. Each 'x' represents one ship categorized by ship type as described by the legend (no outliers are removed). This is the same data as presented in the Third IMO GHG Study 2014. It can be seen from the figure that there is a degree of scatter which demonstrates an over-estimation of draught by the bottom-up model. This is particularly true for lower draughts and for ship types with greater draught variability. A possible source of the discrepancy is the infrequency with which the draught data is reported to the AIS receiver, although it is more likely that the explanation is that the field is poorly updated by the crew since on many ships this field needs to be entered manually. For ship types of lower draught variability, such as container ships, the agreement is good.

As can be seen in the results presented in the Third IMO GHG Study 2014, the quality of the agreement between the bottom-up model estimates and the noon reported output improves over time from the 2007 data to the 2012 analysis.

4.4. Cargo mass

The draught parameter is used in the estimation of payload and cargo carried. There are several alternative sources of data indicating the cargo carried on a ship. For example, the data is reported in fixture datasets used by brokers (e.g. Clarkson's Shipping Intelligence Network) and in data from port lineup reports. A systematic analysis comparing these different sources of information on cargo size for one ship type and size category (capesize bulk carriers) was undertaken in Jia et al. (2015), some of the key results of which are presented in Figure 19. 'Lineup' (collected from port lineup reports) can be seen to compare favorably with 'variable lightweight' - data obtained from AIS observed draught that is converted to estimates of cargo mass using the formulae described in Section 2 of this report. Both the means and the medians are very close (less than 5% different). The fixtures results show the greatest discrepancy with these other two data sources, and are clustered around a few discrete values potentially representing standardized—and perhaps biased—reporting in this size class.

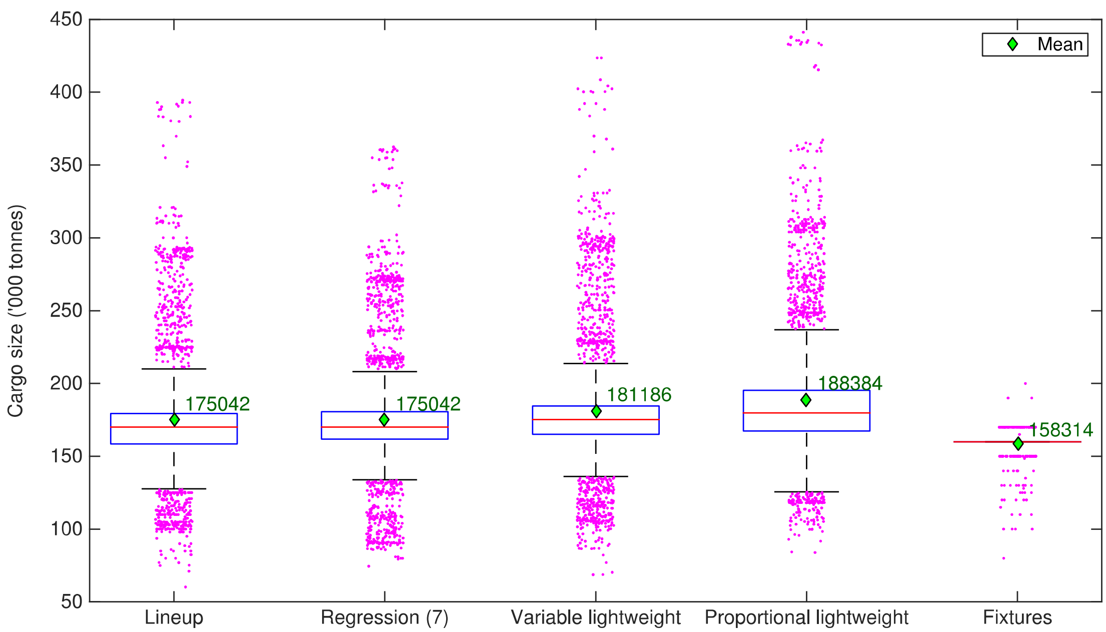


Figure 19: Cargo size on capesize ships, estimated or reported using different methods. Each box plot shows the interquartile range (blue box), median (red line), ±1.5 times the interquartile range (black line) and outliers in purple.

To extend beyond this single ship type and size category, for the larger sizes of dry bulk and oil tankers, estimated average payload is compared against cargo sizes reported in spot fixtures data[7]. As well as clarifying whether AIS data in combination with the method outlined in Section 2 can produce credible estimates of cargo mass, this analysis facilitates an assessment of the validity of the loaded-ballast draught thresholds, the block coefficients, and the lightweight estimates—all of which feed into the calculation of each ship's annual average loaded utilization.

Figure 20 below depicts box plots of these estimated average cargo sizes for the bulk fleet in 2011 and 2012 (that pass the filters) against the respective sets of cargo sizes

[7] Fixtures data are from Clarkson's Shipping Intelligence Network.

reported in spot fixtures. The number near the bottom of each box plot indicates the size of the sample for that particular box plot.

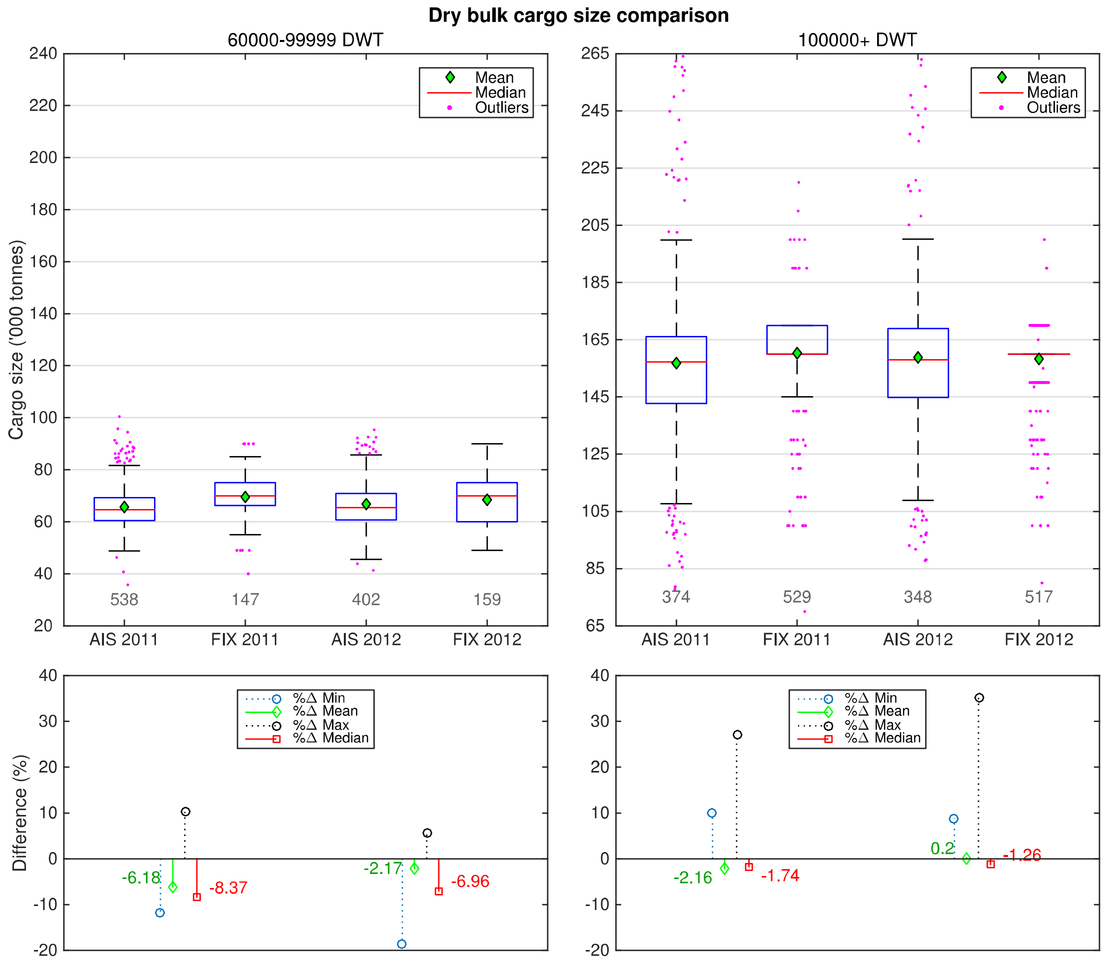


Figure 20: Comparison of cargo sizes reported in dry bulk spot fixtures to payload estimated from AIS. Diagram shows interquartile range (blue box), median (red line), ±1.5 times the interquartile range (black line) and outliers in purple.

The graphs below each of the two sets of box plots describes the percentage differences in the minimum, maximum, mean, and median between the AIS generated cargo sizes and the cargo sizes from fixtures. The percentage difference is defined as the AIS value minus the fixtures value all over the AIS value.

For example, the labeled difference in mean of -6.18% for the sample of 60,000 to 99,999 dwt ships in 2011 shows that the AIS generated average cargo size was 6.18% lower than the average from the fixtures data—in other words, the fixtures average was equal to 1.0618 times the AIS average.

The differences fall in percentage terms when moving from the smaller to the larger size category, and this pattern also coincides with a fall in terms of tonnes; in 2011, the 6.18% difference in the mean was equivalent to about 4500 tonnes for the lower size category, whilst, for the larger size category, a 2.16% difference was equivalent to about 3400 tonnes.

The differences in the mean and medians for both size categories are shown to be reasonably small in magnitude and therefore help reassure that the methods used for bifurcating draught into ballast and loaded conditions and the parameters underlying the lightweight and block coefficient estimations for the large bulk fleet are robust. A comprehensive comparison to cargo sizes reported in fixtures is however infeasible, because the fixtures dataset does not cover an equal range of cargo sizes and may only include fixtures from a limited sample of unique ships.

The discrepancy in the differences between the minima could be because cargo sizes reported in fixtures are indicative of the maximum cargo size agreed to, and, hence, actual, loaded cargo sizes may be smaller. The differences in the maxima could also be explained by considering the proportion of bulk fixtures likely to be represented as spot fixtures. Some proportion[8] of all bulk fixtures may be time or trip charters for which cargo sizes are not reported, but those ships are nonetheless captured in AIS. It is suggested that trip charters may, on average, have higher cargo sizes relative to dwt, because the charterers have the incentive to optimize cargo intake as they pay for the ship by the day and not per tonne of freight. If this hypothesis is true, this would explain the large positive percentage difference in the maximum for bulk ships of 100,000 dwt or more.

Similar trends can be noted for the large oil fleet in Figure 21. Estimated payloads from AIS are close to their counterparts from fixtures in terms of means and medians, and the percentage discrepancy falls when moving to the larger size categories.

[8] For bulk fixtures, the predisposition is suggested to be towards time chartering.

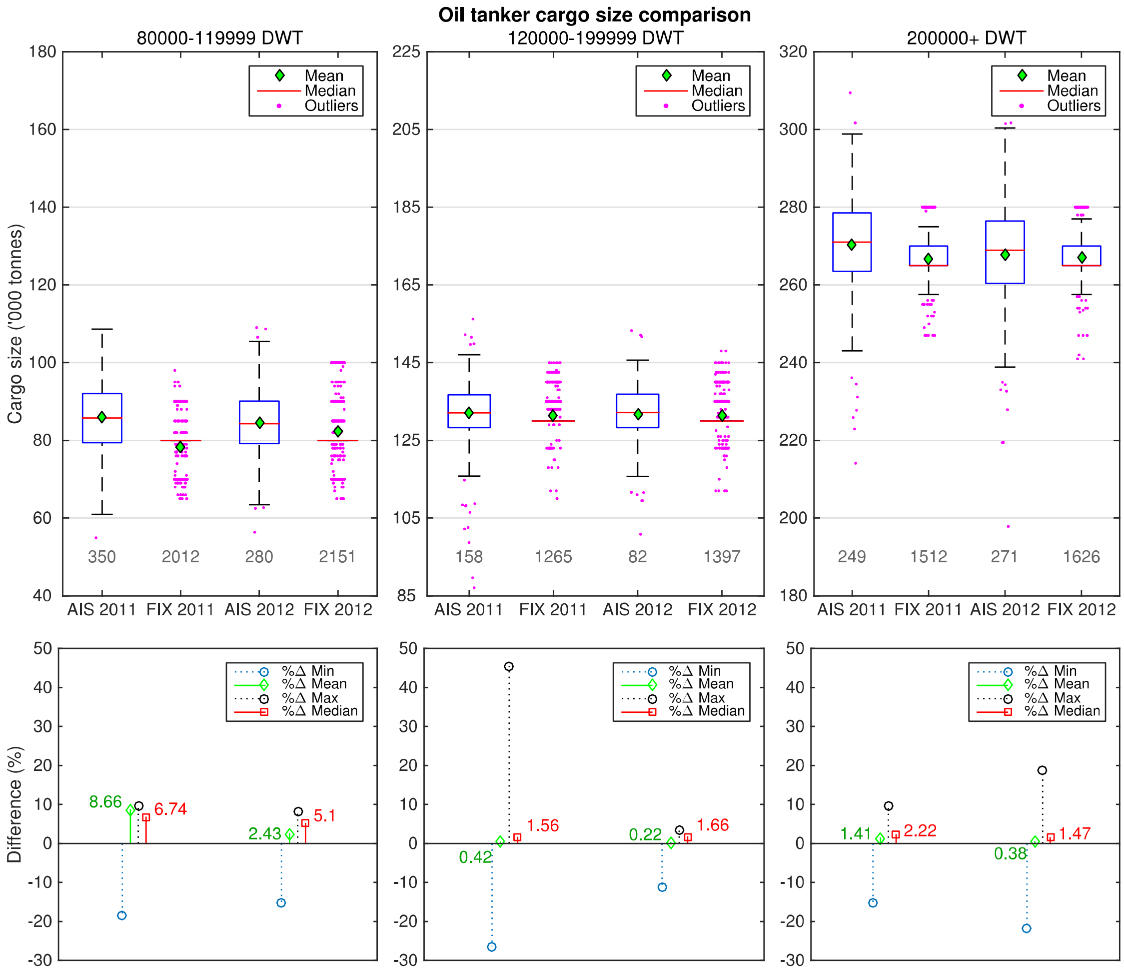


Figure 21: Comparison of cargo sizes reported in oil tanker spot fixtures to payload estimated from AIS

To further analyze the quality of the estimations of cargo mass carried, a small number of comparisons can be drawn as some noon reports also include this as a field. For the ship type and size categories for which noon report data were available, Figure 22, Figure 23 and Figure 24 present the average cargo mass carried as a proportion of average deadweight. All data is from 2012, and so can be compared against the data in Section 3. The sample size in this instance was small that nothing further than qualitative validation of the payload utilization can be undertaken, but in all cases the results for these samples lie within the inter-quartile range of the AIS derived results, thereby supporting the assessment that the AIS derived results are robust.

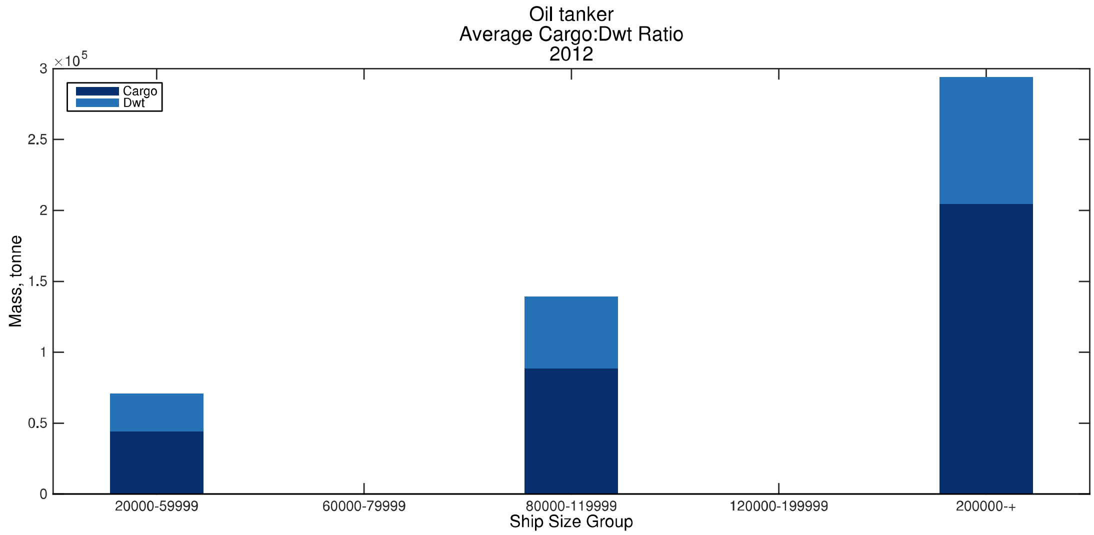


Figure 22: Data for the cargo carried and dwt as reported in noon reports for a small sample of oil tankers

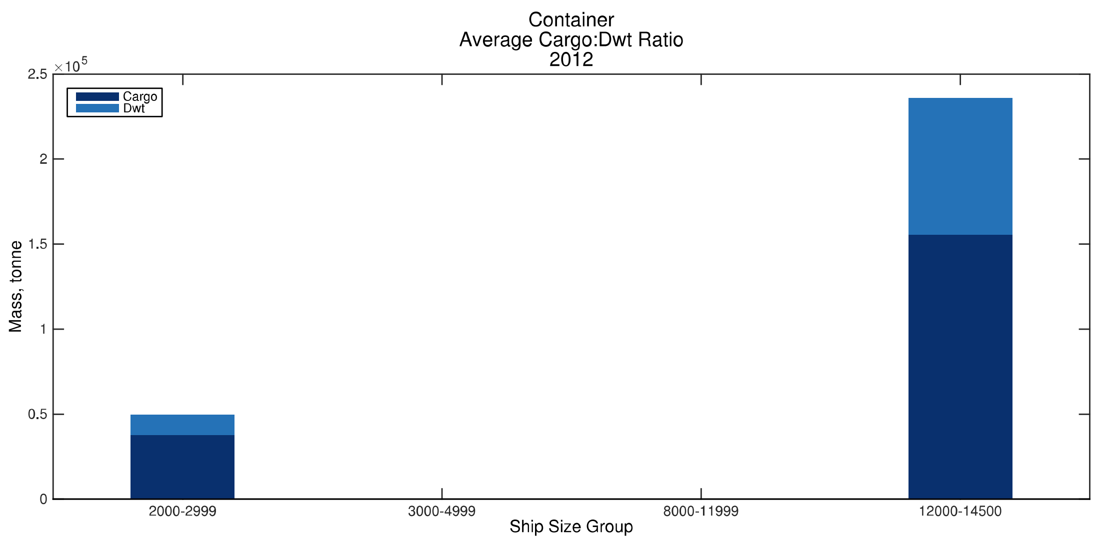


Figure 23: Data for the cargo carried and dwt as reported in noon reports for a small sample of container ships

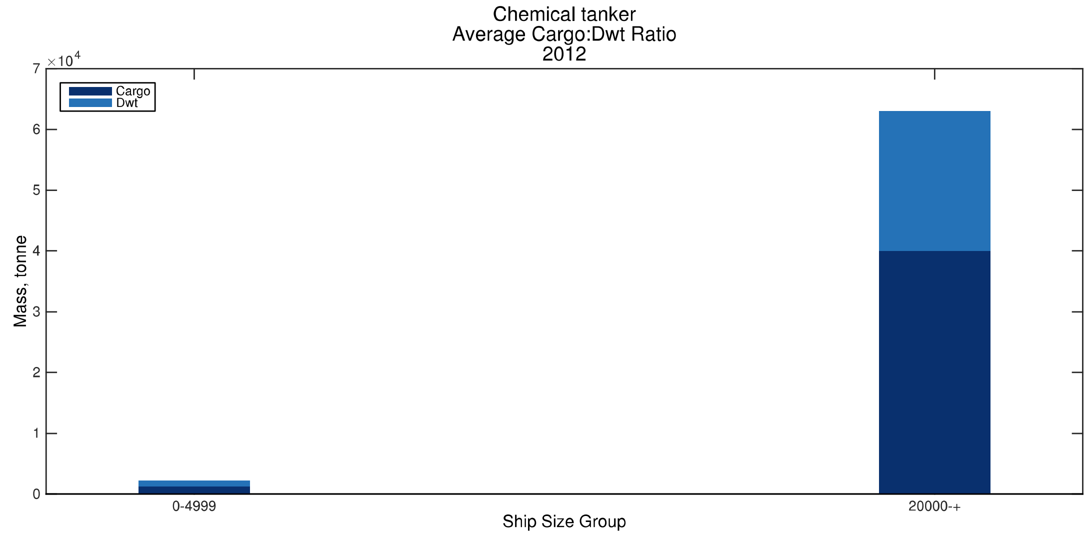


Figure 24: Data for the cargo carried and dwt as reported in noon reports for a small sample of chemical tankers

4.5. Distance

The noon report data from some ships include fields that specify if the ships are laden or in ballast. From this it was possible to ascertain trends in the ratio of total loaded distance to total distance (allocative utilization) for certain ship type and size categories. The results are shown for oil tankers, chemical tankers and liquefied gas tankers in Figure 25 to Figure 27. The distances are the averages of all ships within the ship type and size category estimated for one quarter and then extrapolated linearly to one year. Similar to the noon report data presented in Section 4.4, the sample is small and so can only be compared qualitatively against the results in Section 3; nevertheless, these results compare favorably with the AIS derived estimates of allocative utilization and total distance steamed and provide further confidence in the results of Section 3.

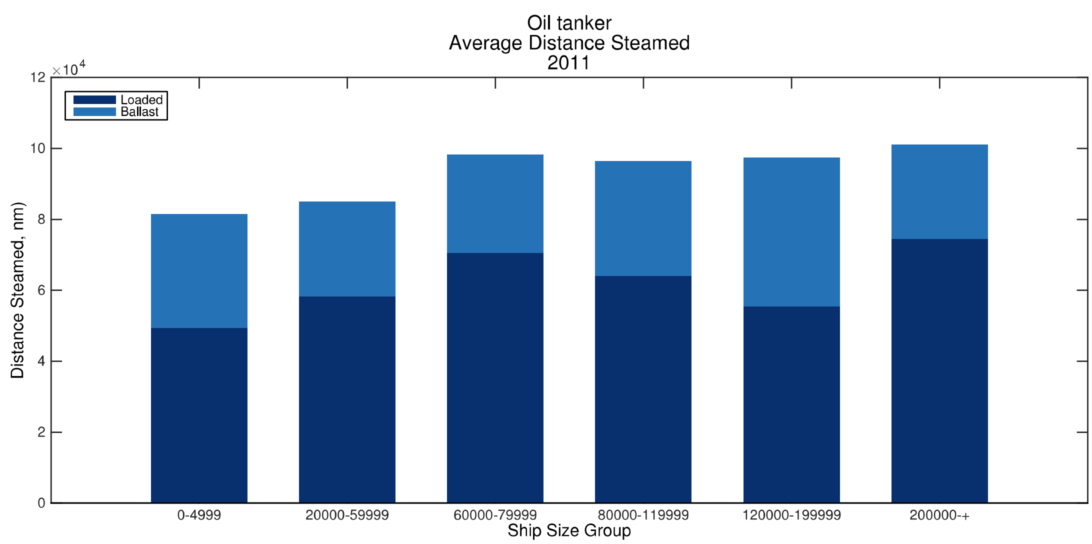


Figure 25: Data for the allocative utilisation as reported in noon reports for a small sample of oil tankers

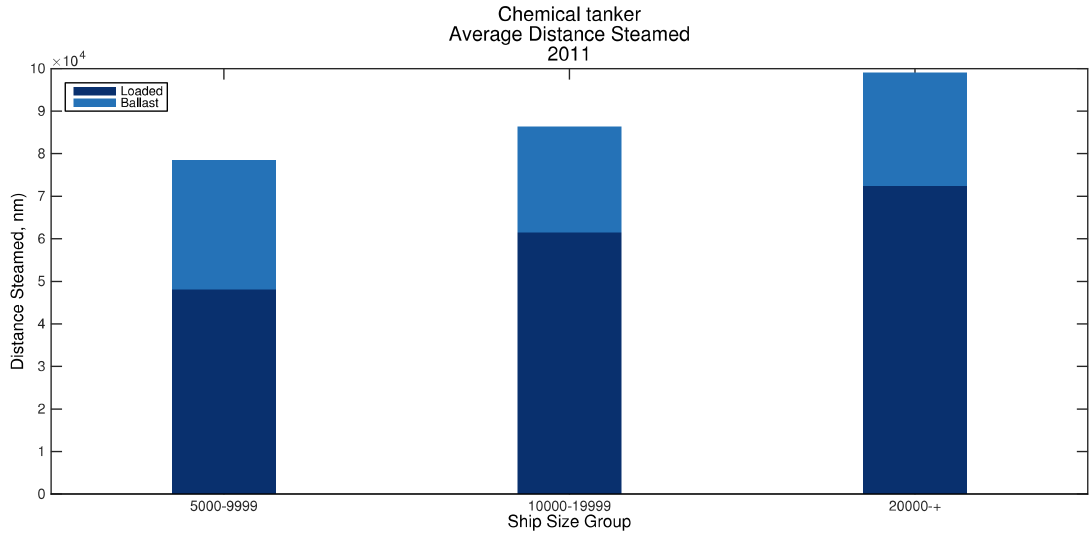


Figure 26: Data for the allocative utilisation as reported in noon reports for a small sample of chemical tankers

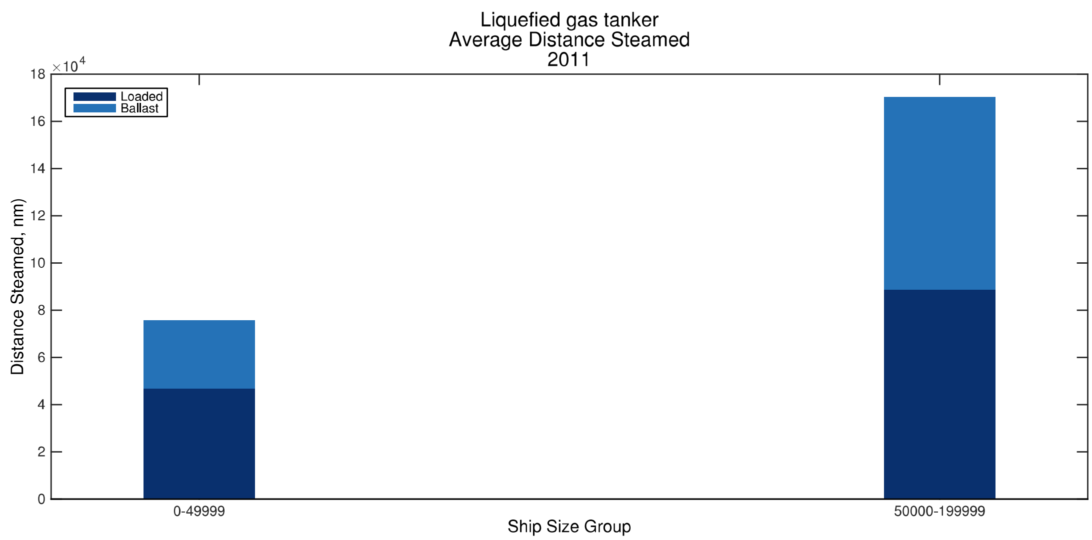


Figure 27: Data for the allocative utilisation as reported in noon reports for a small sample of liquefied gas tankers

5. Comparison of shipping's efficiency relative to the efficiency of other modes of transport

The equivalent data to shipping's EEOI for other transport modes is most commonly expressed in gCO_2/tonne-km. With only one fuel source (i.e. no hybrid vehicles are considered in this section), the quantity of emissions emitted is directly proportional to the amount of fuel or energy E consumed, usually expressed with an emission index EI in gC02/litres$_{\text{Fuel}}$ or gCO_2/MJ_{Fuel}. The EEOI can be expressed using E, EI and transport work W in tonne-km:

$$\mathrm{EEOI} = \mathrm{EI}\cdot\frac{E}{W} = \left[\frac{\mathrm{gCO_2}}{\mathrm{MJ_{Fuel}}}\cdot\frac{\mathrm{MJ_{Fuel}}}{\mathrm{t.km}}\right] = \left[\frac{\mathrm{gCO_2}}{\mathrm{t.km}}\right]$$

The energy intensity per t.km (E/W) is the product of energy use per vehicle-km travelled (E/VKT) and the inverse, distance-weighted, average carried load per vehicle (W/VKT) (Gucwa and Schäfer, 2013):

$$\mathrm{EI}\cdot\frac{E}{W} = \mathrm{EI}\cdot\frac{E}{\mathrm{VKT}}\cdot\frac{\mathrm{VKT}}{W}$$

with W/VKT as the scale variable in average tonnes [t], stemming from $\left(\sum_{\text{trips}}\text{Distance}\cdot\text{Payload}\right)$/Total Distance. Furthermore, it can be shown that this scale variable is in turn the product of vehicle capacity and payload utilisation (Gucwa and Schäfer, 2013), as well as allocative utilisation (Krammer et al., 2015):

$$\mathrm{EI}\cdot\frac{E}{W} = \mathrm{EI}\cdot\frac{E}{\mathrm{VKT}}\cdot\left(\frac{\mathrm{VKT}}{\mathrm{VKT_W}}\cdot\frac{\mathrm{VKT_W}}{\mathrm{W_{available}}}\cdot\frac{\mathrm{W_{available}}}{\mathrm{W}}\right)$$

with:

- EI, the CO_2 emission index in [gCO_2/MJ] that varies by fuel type,
- E/VKT, the energy intensity in [MJ/t.km],
- VKT_W/VKT, the vehicle allocative utilisation in [% of total vehicle-km travelled], where
  - VKT is total vehicle-km travelled (loaded and unloaded distance)
  - VKT_W is total vehicle-km travelled for which transport work is performed (loaded or partially loaded distance only)
- $W_{available}/VKT_W$, the vehicle capacity in [average tonnes], and
- $W/W_{available}$, the vehicle payload utilisation (aka freight load factor) in [% of total, available transport work], where
  - W refers to the actual transport work performed in [t.km], and
  - $W_{available}$ to the theoretical, maximum transport work in [t.km] if the vehicle would always travel fully loaded on routes, where it is non-empty (VKT_W).

The energy intensity E/VKT in turn is a function of many variables (Gucwa and Schäfer, 2013), including

$$\frac{\mathrm{E}}{\mathrm{VKT}} = \frac{1}{\mathrm{VKT}}\cdot f\left(\eta, V, \dot{V}, m, c_D, c_T, A_S, A\right) \quad \text{for ships,}$$
$$\frac{\mathrm{E}}{\mathrm{VKT}} = \frac{1}{\mathrm{VKT}}\cdot f\left(\eta, V, \dot{V}, m, c_D, c_R, A, \right) \quad \text{for trucks and railways, and}$$

$$\frac{\mathrm{E}}{\mathrm{VKT}} = \frac{1}{\mathrm{VKT}} \cdot f(\eta, m_{TO}, m_F, c_D, c_L) \qquad \text{for aircraft,}$$

where:

- η corresponds to the propulsion or drivetrain efficiency and to the product of thermal, propulsive, and combustion efficiency for aircraft,
- V to the vehicle speed and $\dot{V}$ to the vehicle acceleration,
- m to the vehicle mass (including payload), and m_{TO} and m_F to the aircraft take-off and fuel mass,
- c_D to the aerodynamic drag coefficient, c_T to the resistance coefficient, c_L to the aerodynamic lift coefficient, and c_R to the rolling resistance coefficient, and
- A and A_S to the cross sectional area of the vehicle (for aerodynamic resistance) and the wetted surface area of the submerged hull (for hydrodynamic resistance).

For aircraft, CL/CD equals the lift-to-drag ratio (L/D) and indicates the level of aerodynamic efficiency, and the fuel mass ratio of initial aircraft mass m_{TO} to final aircraft mass ($m_{TO} - m_F$) indicates the level of structural optimization.

The declining energy intensity with increasing scale (or capacity) can be attributed to the square-cube law, implying that the resistance relative to the total energy needed is decreasing with increasing vehicle size.

Irrespective of the mode of transport considered, the emission intensity of transporting freight is dependent on:

1. operational aspects (i.e. allocative utilisation, payload utilisation, vehicle capacity)
2. technical aspects (vehicle technology), and
3. fuel characteristics (emission index).

Table 13 gives an overview of each of those variables for the different modes of transport considered. For shipping, only the container ship type category is considered. This is partly because the cargo unit (a TEU) is commonly also moved on road and rail transport, and also because the types of container ship cargos are more similar than bulk shipping cargos to air freight cargos.

Table 13: Variables that influence the emission intensity of transporting freight (Source: using data as described in Section 5.3 or as indicated by footnotes)

Variable	Unit	Sea (Container)	Road	Rail	Air
Operational variables:					
payload times allocative utilisation	%	52	not avail.	61	59
av. carried load per vehicle W/VKT	av. tonnes	34,775	30	943[b]	47
Technical variables:					
speed	km/h	28	80[c]	38[d]	900
Emission index for the typical fuel type[e]**:**	gCO_2/kg_{Fuel}	3.114	3.230	3.230	3.156

a) usually, only the product of payload and allocative utilisation is reported in the data: for road transport, the utilisation is not stated explicitly.
b) on a per locomotive basis
c) depending on speed limits
d) average network velocity in the US and Canada
e) for sea transport: HFO (MEPC 63/23, Annex 8), for air: jet fuel (Penner et al., 1999), for road and rail diesel fuel (EIA, 2011)

From the equations above it can be seen that the EEOI is linearly dependent on payload utilisation, allocative utilisation and average vehicle capacity i.e. a 1% increase in payload utilisation lowers the EEOI by 1%. The values of overall utilisation (i.e. the product of payload and allocative utilisation) as shown in Table 13 indicate that a substantial reduction potential of emission would exist by increasing overall utilisation. However, transport demand is often unidirectional, implying empty or partially loaded voyages back to the origin. Furthermore, the overall level of transport demand varies with each origin-destination pair, implying that the most economical average vehicle size is not equivalent to the biggest vehicle available. Payload utilisation, allocative utilisation as well as the vehicle capacity are therefore dependent on the local market circumstances.

Most of the technical variables are characteristic for the transport mode and therefore vary widely across them. A comparison of the variables in Table 13 however indicates where discrepancies in emission intensity between transport modes stem from. For instance, average speed and the average carried load per vehicle vary widely across transport modes.

Opportunities for transport operators to influence the fuel emission index are limited, unless substituting existing fossil fuels with alternative low-carbon fuels. Some of the types of biofuels available are already classified as "drop-in" biofuels, as they can readily be used in existing vehicles without the need to change vehicle technology. Gucwa and Schäfer (2013) find that diesel engine trucks are 28% less energy intensive than all gasoline fleets, all else being equal.

In summary, the EEOI for different transport modes is dependent on overall utilisation, vehicle capacity, energy intensity and the type of fuel utilized. Transport operators are therefore left with the following options to reduce the emission intensity:

- optimize operational patterns (as far as possible) i.e. maximize allocative and payload utilisation as well as vehicle capacity,
- substitute old with new technology, and
- substitute fossil fuels with low-carbon fuels.

In the following subsections, emission intensity values are compared across transport modes. These values have been assembled from:

1. a literature review on mode and region-specific emission intensity studies,
2. a top-down calculation of energy efficiency values using global fuel and transport work data, and
3. a bottom-up calculation of energy efficiency values using firm-level or operational fleet level data.

The obtained results are then compared against each sample and transport mode and discrepancies are highlighted and discussed.

5.1. Sources of total efficiency of different transport modes from literature

The values of energy efficiency across transport modes obtained from the literature vary considerably by source and country (Table 14). Many operational variables affect the energy efficiency on a local level e.g. average speed on motorways and thus infrastructure as well as population density (long-distance vs. short-distance transport). Furthermore, the energy efficiency varies by vehicle size and category, the type of commodities transported and total utilisation.

Table 14: Data from literature on different modes of transport's energy efficiency

Mode	Country	EEOI (gCO_2/t.km)	Reference	Assumptions and comments
Road: heavy articulated truck (>44t)	EU	62 (59-109)	McKinnon and Piecyk (2011)	Literature review from various sources. Using 80% average load factor and 25% empty running gives 62gCO_2/t.km for chemical cargo only
Road: heavy truck > 40t	Germany	80	Leonardi and Baumgartner (2004)	Based on per vehicle data, including empty runs and load factors, conducted Q2 2003
Road: light truck < 40t	Germany	181.8		
Road	Germany	96.2		
Road	UK	130 (86-272)	Leonardi and Rizet et al. (2008)	Based on Road Goods Transport surveys which provide annualized statistics (DfT, ECMT, Eurostat, MTETM) 86: articulated 272: rigid
Road	France	97 (78 – 215)	Leonardi and Rizet et al. (2008)	
Road	Spain	109.3 (91 – 128)	Perez-Martinez (2009)	Spanish road freight sampling survey; random sampling on a per vehicle basis, 2003
Road	Japan	144	MLIT (2007)	
Road	US	153	Corbett and Eyring et al. (2009)	
Road	EU	156	EC (2006)	cited in Lindstad et al. (2012), 2004
Road	Turkey	61 – 75	Ozen and Tuydes-Yaman (2013)	Data from 2000 - 2009
Road	Denmark	105	Liimatainen and Arvidsson et al. (2014)	2010
	Finland	84		
	Norway	98		
	Sweden	68		
Rail	EU	7.3 – 55.0	McKinnon and Piecyk (2011)	Highly variable depending on diesel vs electric, chemical cargo only
Rail	EU	81	EC (2006)	cited in Lindstad et al. (2012), 2004
Rail	US	10-14	Corbett and Eyring et al. (2009)	2004 (for bulk trains) with data from U.S. Department of Transportation (2014)
Air: medium haul	EU	673 – 867	McKinnon and Piecyk (2011)	Chemical cargo only
Air	EU	570 – 1925	McKinnon and Piecyk (2011)	Chemical cargo only
Inland waterways	EU	68	EC (2006)	Cited in Lindstad et al. (2012), 2004
Sea	New Zealand	17	Fitzgerald and Howitt et al. (2011)	2007

For instance, the study by Leonardi and Baumgartner (2004) indicates the influence of vehicle capacity on the energy efficiency of trucks (180 gCO_2/t.km for light trucks in comparison to 80 gCO_2/t.km for heavy trucks). This correlation was also demonstrated in Leonardi and Rizet et al. (2008) in the comparison between the total efficiency of French and British road transport. In their study, the nature of the vehicle type mix (articulated or rigid) influences the efficiency of vehicle use; articulated trucks have higher vehicle use efficiency and therefore better total efficiency. The greater proportion of work carried out by articulated trucks relative to lighter, rigid vehicles in France leads to French trucks having, overall, a higher total than British trucks. This matches a corresponding improvement in energy efficiency despite total CO_2 emissions remaining relatively stable over the period.

EEOI values for each transport mode obtained from the literature therefore vary by study as the underlying data reflects the prevailing local transport characteristics the firm is operating in. The variation in EEOI values across transport modes is therefore expected.

5.2. Top-down estimates of aggregate average total efficiency

This section uses aggregated data on fuel consumed[9] and transport work generated on a global or international scale to arrive at a top-down total operational efficiency estimate for each transport mode.

Global CO2 emissions for air, rail, road and pipeline transport are taken from EIA (2010-14). For sea transport, global CO2 emissions are taken from the Third IMO GHG Study 2014 (top-down and bottom-up estimates). Transport work in t.km for air, rail, road and pipeline transport are taken from the OECD/ITF (2012) and the World Bank (2015) and for sea transport from Table 10 above. The top-down efficiency estimates in gCO_2/t.km are then calculated for each transport mode[10] and compared against each other in Figure 28.

The obtained results suggest an average value of 11 gCO_2\t.km for sea transport, 15 gCO_2\t.km for rail transport, 41 gCO_2\t.km for pipeline transport, 185 gCO_2\t.km for road transport and 570 gCO_2\t.km for air freight transport. The relatively short time period of the time series precludes robust inferences about year-over-year energy efficiency trends.

The numbers in Figure 28 represent a global average on a highly aggregated basis, and the calculation of transport work and CO_2 emissions is dependent on the data collection and aggregation method of the reporting organisation. The obtained energy efficiency values for each transport mode therefore also vary by reporting organisation.

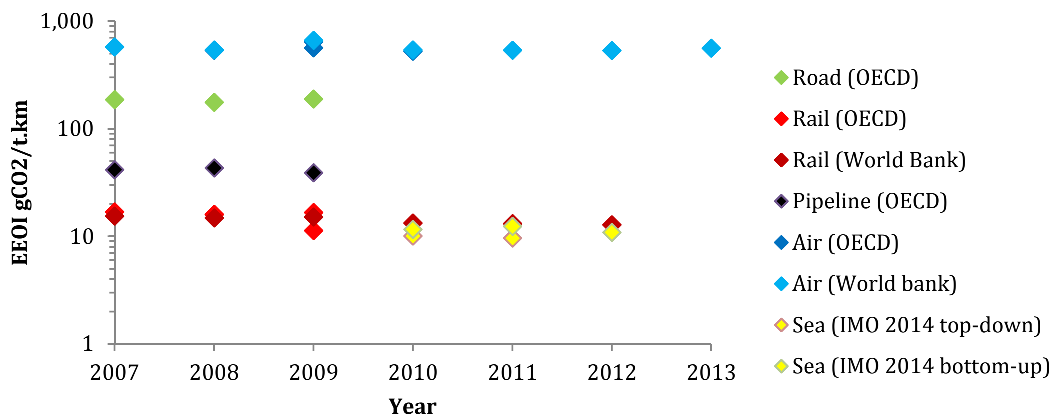


Figure 28: Top-down EEOI estimates for different modes of transport and years, using data from EIA (2010-14), OECD/ITF (2012), World Bank (2015), Smith et al. (2014) and data from this report (Table 9)

[9] Using efficiency indices, the total fuel consumed can be converted into gCO_2 emissions emitted.
[10] The information for the numerator (gCO_2) for air freight is taken from the International Energy Outlook reports prepared by the US Energy Information Administration. The energy related CO_2 emissions by end-use charts indicate the total aviation CO_2 emissions so these are converted to air freight values by calculating the proportion of air freight relative to the total as reported in the energy use by mode and type tables for the years 2006, 07 and 08 and, due to high variability in the data, assumed to be constant at the 06-08 average for the remaining years. The denominator, transport supply, is reported in the US transport statistics as compiled by the OECD and presented in the 'Trends in The Transport Sector' reports.

5.3. Bottom-up estimates of average total efficiency

For the bottom-up calculation of EEOI values mode-specific firm-level or operational fleet-level data is used. The data sources, calculation methods and presentation of results deployed in this Section build on the work of Gucwa and Schäfer (2013) who analysed the relationship between scale and energy efficiency across different transport modes. This study's extension to their work is in the incorporation of this study's AIS data derived estimates of EEOI for the different ship type and size categories.

For sea transport, data from Table 5 to Table 7 are used. Air transport data is taken from the U.S. Department for Transportation (2014). The dataset is filtered for air freight carriers only (i.e. United Parcel Service, Evergreen International Inc., Polar Air Cargo Airways, and Federal Express Corporation) so as to obtain a valid comparison with all other freight carriers by transport mode[11]. The rail data comes from Statistics Canada (1986-2009) and contains the railways Canadian National and Canadian Pacific. It should be noted that for railways, freight locomotive-kilometres instead of freight train-kilometres are used to measure VKT. The locomotives in the Canadian dataset are all powered by diesel fuel. The road data is taken from the literature using data from Leonardi et al. (2008), Ozen and Tuydes-Yaman (2013) and Perez-Martinez (2009).

At this aggregation level, it is possible to calculate the scale variable W/VKT for each transport mode. The energy intensity ($\mathrm{EI} \cdot E/W$) is therefore plotted against the average carried load per vehicle (W/VKT) in Figure 25 to control for the variation in energy efficiency stemming from economies of scale. Due to the scale of either variable, the data is plotted on a double-logarithmic scale.

Figure 29 compares the EEOI values across transport modes using the scale relationship as described above, indicating that much of the variation in energy intensity for a given mode of transport can be explained by the scale variable (W/VKT), which also includes allocative and payload utilisation (see equations above). The obtained result is very similar to the key finding in Gucwa and Schäfer (2013) as the transformation from energy intensity in Joules per t.km to emission intensity in gCO_2 per t.km is approximately linear across transport modes (see the similarity between emission indices for typical fuel types in Table 13).

[11] Mixed carriers report transport work in passenger-kilometres for transporting passengers, and transport work in t.km for transporting freight. For mixed carriers, it is therefore difficult to summarise total transport work in t.km.

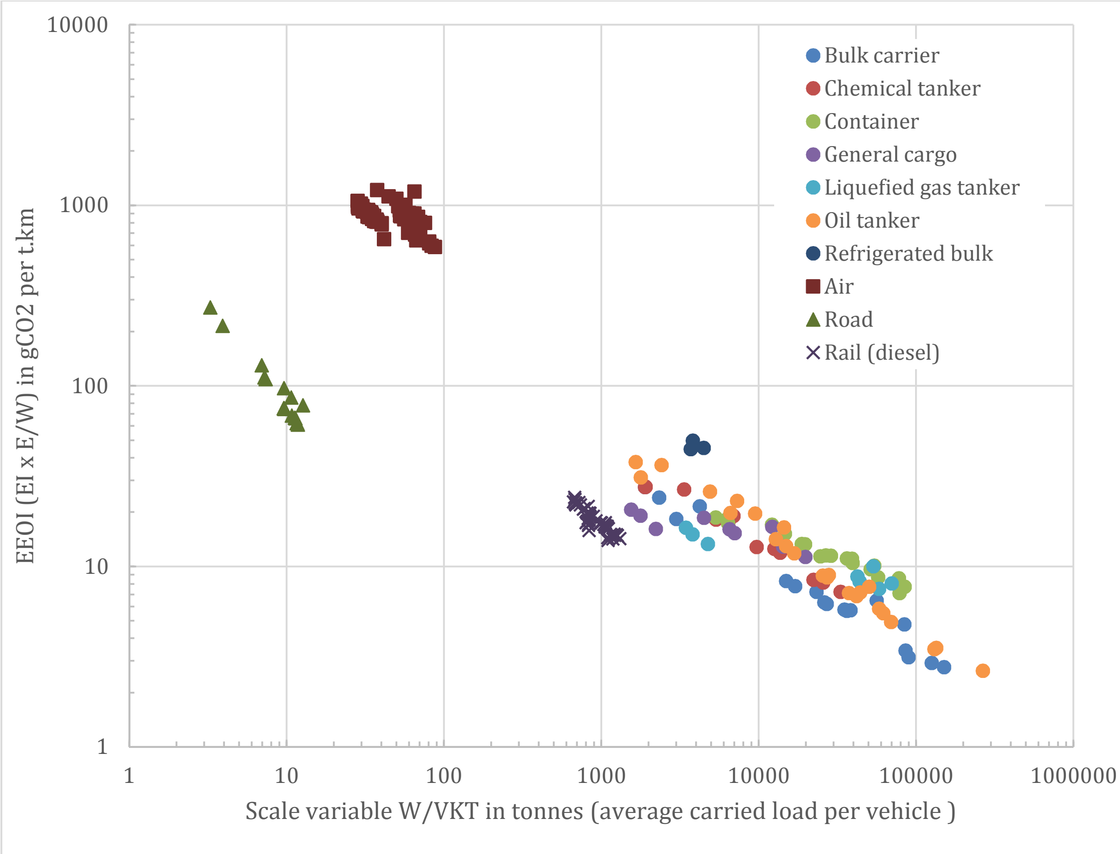


Figure 29: Bottom-up energy intensity estimates by transport mode over the scale variable W/VKT

The air transport data captures a time period from 1994 to 2012 over which all air freight carriers were able to drastically increase their average vehicle capacity of the aircraft fleet, explaining the downward trend in emission intensity (top left observations reflect 1994 data, bottom right observations 2012 data). Evergreen International Inc. and Polar Air Cargo Airways have, on average, a fleet consisting of larger aircraft (observations on the right hand side), in comparison to UPS and FedEx (observations on the left hand side), which explains the offset along the x-axis among these two groups.

The same effect also applies to the Canadian freight railways, which both increased their average vehicle capacity by 60% over a 1986-2009 period. The slight difference in energy efficiency between the two railways is hardly visible in the plot due to the logarithmic scaling of both axis to accommodate all data.

For sea transport, the variation along the x-axis stems from the different size categories (see Table 5 to Table 7). The sea transport data only includes the years 2010, 11 and 12 and is therefore inappropriate to infer about average fleet size growth. The data shows that on a per t.km basis, bulk carriers are more efficient in terms of CO_2 emitted than any other ship type across the entire average vehicle capacity range. The data also suggests that between 10,000 and 100,000 tonnes of average vehicle capacity, oil tankers have a lower EEOI than container ships.

For road transport, the data reflects the values found in the underlying survey from the literature, including average carried load per vehicle. The variation of energy efficiency (along the y-axis) in the road transport sample is attributable to different vehicle usage, including the transport of different cargo types. Due to legislation limiting the total weight of the truck and trailer, the payload capacity of the road unit is in general fully utilised, although this depends on the density of the commodity. Food for example is a relatively low density product and the load capacity tends to be volume constrained rather than weight constrained (Leonardi and Rizet et al., 2006). Other variables that might influence the emission intensity to a significant extent are average speed and average length of haul as well as other variables that vary by location and population topology. All of that variation is reflected in the road transport sample.

In summary, for air, road and rail transport, the scale variable therefore reflects the average vehicle capacity of the transport fleet; for sea transport, the scale variable reflects the average vehicle capacity of each size category of the transport fleet. Although the information is different, a comparison between them remains valid. For rail, road and air transport however, observations to the left (and less so to the right of the dataset) are missing in the plot, as only averaged vehicle capacities of the transport fleet are shown in the data (hence, EEOI values of very small and inefficient vehicles are missing in the plot for air and rail transport). These missing observations are however to be expected along the notional (OLS) regression line of each transport mode in the plot.

A comparison of the emission intensity across different transport modes can be done along the vertical line for a given average vehicle capacity. For instance, using 40 tonnes as the size category, road transport is as much as 10 times more efficient (in terms of CO_2) in comparison to air transport. In the 1500 tonnes category, rail transport (using diesel locomotives only) emits less than half of CO_2 emissions in comparison to general cargo ships, chemical tankers and oil tankers in that size category. Hence, rail transport can be more competitive with regards to emissions than sea transport due to the inefficiencies of smaller ships (< 5,000 dwt).

5.4. Summary and discussion

The emission intensity of rail, road, air and sea transport can be compared against each other on a per t.km basis. Irrespective of the mode of transport considered, the EEOI of transporting freight is dependent on operational aspects (i.e. allocative utilisation, payload utilisation, vehicle capacity), technical aspects (vehicle technology), and fuel characteristics (emission index).

As first demonstrated by Gucwa and Schäfer (2013), the data shows that much of the variation in the EEOI is attributable to the vehicle capacity (represented by average carried load per vehicle), which influences the energy intensity through economies of scale (square-cube law). Other variables such as utilization also scale linearly with the EEOI; a large variation in vehicle utilisation is however not depicted in the data due to more or less stable, exogenous demand. Influences of technology on emission intensity are difficult to capture from the data, as a long data time-series would be needed.

In this report, EEOI data from the literature are supplemented with a top-down and a bottom-up EEOI calculation, similar to MEPC 67/Inf.3 (Smith et al. 2014). The top-down calculation of energy efficiency values in this section is based on global fuel and transport work data; the bottom-up calculation on firm-level or operational fleet level data.

Using gCO_2/t.km as the metric for calculating emission intensities across transport modes in freight transport, the top-down calculations of EEOI's yield an average value of 11 gCO_2\t.km for sea transport, 15 gCO_2\t.km for rail transport, 41 gCO_2\t.km for pipeline transport, 185 gCO_2\t.km for road transport and 570 gCO_2\t.km for air freight transport. These values compare well with values obtained from the bottom-up calculation, except for air transport. Using highly aggregated global air transport (top-down) data, this discrepancy might originate from difficulties in calculating the energy (fuel) share of freight transport of airlines offering passenger and freight transport.

The bottom-up analysis shows evidence of a correlation between the average carried load per vehicle and EEOI (EEOI improves (decreases) with an increase in average carried load per vehicle which in turn relates to vehicle size). Across all modes, and consistent with this correlation, shipping achieves some of the best (lowest) EEOI values, because the average loads per ship are consistently greater than the average loads of other vehicles and transport modes.

Per unit of transport supply, shipping is at least an order of magnitude more efficient than aviation and in many specific cases, an order of magnitude more efficient than road transport. At the same time, the least efficient ships have EEOIs equivalent to the most efficient road vehicles (even though the largest road vehicles have average carried loads which are over an order of magnitude smaller than ships with equivalent EEOI values). Many types and sizes of ship have worse (higher) EEOIs than rail vehicles.

In international transportation, road and rail transport are often not available between city pairs (e.g. two cities not sharing the same landmass), and air transport therefore competes directly with sea transport. Although the energy intensity of air transport is significantly higher in comparison to sea transport, it should be noted that the aircraft energy intensity of new built aircraft declined by nearly two thirds between 1959 and 1995, primarily due to improvements in engine efficiency (Schäfer, 2009). Furthermore, air transport has a significant time advantage over shipping, which, for certain high-value commodities, gives air shipping a significantly higher economic value. Also, the emission intensity calculated on a per t.km basis does not account for the fact that ships usually travel longer distances than aircraft between a given city pair (Krammer et al., 2015). This effect does not change the difference in emission intensity between sea and air transport significantly. However, it should be noted, that for a comparison of sea transport with rail (and road) transport, results are depicted in favour of sea transport (hence assuming straight line distance between city pairs for all modes of transport).

Irrespective of the mode of transport considered, the emission intensity of transporting freight can be lowered by optimizing operational patterns (i.e. maximizing utilisation and vehicle capacity), substituting old with new technology, and substituting fossil fuels with low-carbon fuels (e.g. drop-in biofuels).

References

Acomi, Nicoleta, and Ovidiu Cristian Acomi (2014). "Improving the Voyage Energy Efficiency by Using EEOI." *Procedia-Social and Behavioral Sciences* 138: 531-536.

Anink, D. and M. Krikke (2011). Analysis of the effect of the new EEDI requirements on Dutch build and flagged ships. Commisioned by the Ministry of Infrastructure and the Environment, Centre for Maritime Technology and Innovation.

Carlton, J. T., D. M. Reid, et al. (1995). The Role of Shipping in the Introduction of Nonindigenous Aquatic Organisms to the Coastal Waters of the United States (other than the Great Lakes) and an Analysis of Control Options.

Chadzynski, W. (2010). "Some remarks on the estimation of design characteristics of membrane LNG carrier."

Corbett, J.J, Eyring, V., et al. (2009). Prevention of air pollution from ships, Second IMO GHG Study 2009, Update of the 2000 IMO GHG Study**:** 289.

EIA (2011). "Voluntary Reporting of Greenhouse Gases Program Fuel Carbon Dioxide Emission Coefficients)", U.S. Energy Information Administration [Online]. URL: http://www.eia.gov/oiaf/1605/coefficients.html#tbl2 [Accessed: 03.03.2015]

EIA (2010-14). "Annual Energy Outlook", U.S. Energy Information Administration [Online]. URL: http://www.eia.gov/oiaf/aeo/tablebrowser/ [Accessed: 03.03.2015]

EC (2006), "White paper on transport, time to decide." European Commission. Cited in Lindstad et al. (2012)

Fitzgerald, W. B., O. J. A. Howitt, et al. (2011). "Greenhouse gas emissions from the international maritime transport of New Zealand's imports and exports." Energy Policy **39**(3): 1521-1531.

Gucwa, M. and A. Schäfer (2013). "The impact of scale on energy intensity in freight transportation." Transportation Research Part D: Transport and Environment **23**: 41-49.

Jia, H., Prakash V. and Smith T. (2015). Estimating Ship Utilization in the Drybulk Freight Market: The Reliability of Draught Reports in AIS Data Feeds. (*in prep*)

Krammer, P., Schäfer, A. and Smith, T. (2015). "Costs in freight transportation". Working Paper. UCL Energy Insitute [Unpublished].

Kristensen, H. O. (2012). Determination of Regression Formulas for Main Dimensions of Tankers and Bulk Carriers based on IHS Fairplay data. Project no. 2010-56, Emissionsbeslutningsstøttesystem, Work Package 2, Report no. 02, Technical University of Denmark.

Kristensen, H. O. (2013). Statistical Analysis and Determination of Regression Formulas for Main Dimensions of Container Ships based on IHS Fairplay Data. Project no. 2010-56, Emissionsbeslutningsstøttesystem, Work Package 2, Report no. 03, Technical University of Denmark.

Larsson, S. (2011), "Commercial vehicles, fuel efficiency and CO2 - challenges and possible solutions. Presentation to the European Automobile Manufactures Association. [Online]. URL: http://www.iea.org/workshop/work/hdv/larsson.pdf [Accessed 6.3.2015]

Lehmann, E. L., & D'Abrera, H. J. (2006). *Nonparametrics: statistical methods based on ranks*. New York: Springer.

Leonardi, J. and M. Baumgartner (2004). "CO2 efficiency in road freight transportation - Status quo, measures and potential." Transportation Research Part D: Transport and Environment **9**(6): 451-464.

Leonardi, J., Rizet, C., Browne, M., Allen, J., Pérez-Martínez, P. J., & Worth, R. (2008). Improving energy efficiency in road freight transport sector: the application of a vechilce approach. In *Logistics Research Network Annual Conference, 10th–12th September, Liverpool*.

Liimatainen, H., N. Arvidsson, et al. (2014). "Road freight energy efficiency and CO2 emissions in the Nordic countries." Research in Transportation Business & Management **12**: 11-19.

Lindstad, H., Asbjornslett, B.E., and Pedersen, J.T. (2012). Green Maritime Logistics and Sustainability. In. Song, D. W., Panayides, P., & Panayides, P. M. (Eds.). (2012). *Maritime Logistics: Contemporary Issues*. Emerald Group Publishing.

Ma, F. Y. (2014). Analysis of energy efficiency operational indicator of bulk carrier operational data using grey relation method. *Journal of Oceanography and Marine Science*, *5*(4), 30-36.

MAN (2011). Basic Principles of Ship Design. Denmark.

Mann, H. B., & Whitney, D. R. (1947). On a test of whether one of two random variables is stochastically larger than the other. *The annals of mathematical statistics*, 50-60.

McKinnon, A. and M. Piecyk (2011). Measuring and Managing CO2 Emissions of European Chemical Transport, Logistics Research Centre, Heriot-Watt University, EDINBURGH, UK.

MLIT (2007), "The survey on transport energy, 2007", Japan Ministry of Land, Infrastructure, Transport and Tourism, Japan

OECD/ITF (2012), *Trends in the Transport Sector 2012*, OECD Publishing, Paris/ITF, Paris. DOI: http://dx.doi.org/10.1787/trend_transp-2012-en

Ozen, M., and Tuydes-Yaman, H. (2013). Evaluation of emission cost of inefficiency in road freight transportation in Turkey. *Energy Policy*, *62*, 625-636.

Penner, J. E. (Ed.). (1999). Aviation and the global atmosphere: a special report of IPCC Working Groups I and III in collaboration with the Scientific Assessment Panel to the Montreal Protocol on Substances that Deplete the Ozone Layer. Cambridge University Press.

Perez-Martinez, P. J. (2009). The vehicle approach for freight road transport energy and environmental analysis in Spain. *European Transport Research Review*, *1*(2), 75-85.

Schäfer, A. (2009). *Transportation in a climate-constrained world*. MIT press.

Statistics Canada (1986-2009). tables 404-0004, 404-0005, 404-0013, 404-275 0016 and 404-0019, CANSIM database [Online]. URL: http://www.statcan.gc.ca/tables-tableaux/sum-som/l01/cst01/trad46a-eng.htm [Accessed 17.12.2014]

U.S. Department of Transportation (2014). Bureau of transportation statistics, transtats. [Online] URL: http://www.transtats.bts.gov [Accessed 11.8.2014]

UNCTAD Review of Maritime Transport (2013, UNCTAD/RMT/2013).

Welch, B. L. (1947). The generalization of 'student's' problem when several different population variances are involved. *Biometrika*, 28-35.

Wilcoxon, F. (1945). Individual comparisons by ranking methods. *Biometrics bulletin*, 80-83.

World Bank (2015). "World Bank open data." The World Bank Group [Online]. URL: http://data.worldbank.org/ [Accessed 4.3.2015]

Annex A: Bias analysis

Table 15: Comparison of ship dwt and power between excluded and included ships (2010)

		Excluded ships						Included ships					
		dwt or TEU			Main engine power (kw)			dwt or TEU			Main engine power (kw)		
Type	Size	Mean	Std. dev.	Median	Mean	Std. dev.	Median	Mean	Std. dev.	Median	Mean	Std. dev.	Median
Bulk carrier	0-9999	2963	2665	2000	2434	3641	1324	5366	2114	5777	2426	968	2537
Bulk carrier	10000-34999	25149	6652	26799	6716	2501	6450	26682	5531	28347	5933	1254	5850
Bulk carrier	35000-59999	48145	7713	48275	8832	3134	8562	50181	6121	52301	8357	1049	8360
Bulk carrier	60000-99999	75912	8975	75229	10700	4325	10216	75849	6504	75100	9882	1291	9800
Bulk carrier	100000-199999	162297	22783	172571	17773	10124	16860	168458	14952	172375	16068	2049	16858
Bulk carrier	200000-+	260967	56494	244740	20482	5250	18899	242885	40111	229093	19971	3426	19297
Chemical tanker	0-4999	1967	1416	1337	1430	1209	1100	2730	1354	2593	1799	749	1618
Chemical tanker	5000-9999	7173	1230	6985	3264	983	3089	7713	1310	7860	3331	606	3250
Chemical tanker	10000-19999	15053	3095	14450	5609	3941	5180	14529	3080	13098	4792	953	4440
Chemical tanker	20000-+	51093	37243	43475	11254	9104	9480	42147	8054	45348	9086	1238	8948
Container	0-999	503	312	540	6294	4680	5782	708	219	720	6584	2329	6352
Container	1000-1999	1402	287	1388	12218	3669	11415	1452	290	1550	12695	3252	12269
Container	2000-2999	2527	268	2553	21187	3973	21560	2577	213	2556	22224	3235	21735
Container	3000-4999	3977	558	4051	35142	8511	36479	4176	374	4252	37270	5702	36559
Container	5000-7999	6078	716	5905	55261	7604	55569	6053	780	5896	57068	7628	57086
Container	8000-11999	8848	894	8500	67987	4049	68569	8761	968	8500	68454	1379	68529
Container	12000-14500	13251	682	13344	72318	5291	68519	0	0	0	0	0	0
Container	14500-+	0	0	0	0	0	0	0	0	0	0	0	0
General cargo	0-4999	1555	1392	1165	1136	1449	898	2659	1508	2464	1604	1478	1360
General cargo	5000-9999	6938	1341	6740	3379	2825	2942	7383	1860	7194	3492	1234	3236
General cargo	10000-+	43317	49972	25000	9131	8979	7723	22259	12029	17882	6863	3501	6230
Liquefied gas tanker	0-49999	7939	10820	3814	4077	4194	2700	21376	6360	23270	8695	1849	9480
Liquefied gas tanker	50000-199999	79891	23056	77217	25181	8992	26867	66145	13253	71737	21264	8775	21322
Liquefied gas tanker	200000-+	267217	57928	290085	23901	3589	25007	0	0	0	0	0	0
Oil tanker	0-4999	1733	1417	1266	1147	1256	883	3278	1301	3258	1995	881	1864
Oil tanker	5000-9999	6546	1195	6314	2880	1610	2700	6677	1361	6249	2955	628	2941
Oil tanker	10000-19999	14831	2992	14204	5882	5654	4531	15368	2930	16268	4512	1109	4591
Oil tanker	20000-59999	41368	8594	44555	9503	6676	8580	44230	5940	45975	8487	1271	8580
Oil tanker	60000-79999	71311	4334	73307	12221	4289	11444	72035	3112	72910	11394	1153	11299
Oil tanker	80000-119999	105108	8605	105857	13213	4006	13549	105761	5934	106045	13127	1603	13128
Oil tanker	120000-199999	154066	11329	157467	19372	9985	18623	152655	11964	153015	17679	2539	16916
Oil tanker	200000-+	299867	19752	300058	25507	4018	25487	303656	11841	304992	26917	2603	27160
Refrigerated bulk	0-1999	781	624	678	1083	954	883	5118	3329	4343	4224	2838	3310

Table 16: Comparison of ship dwt and power between excluded and included ships (2011)

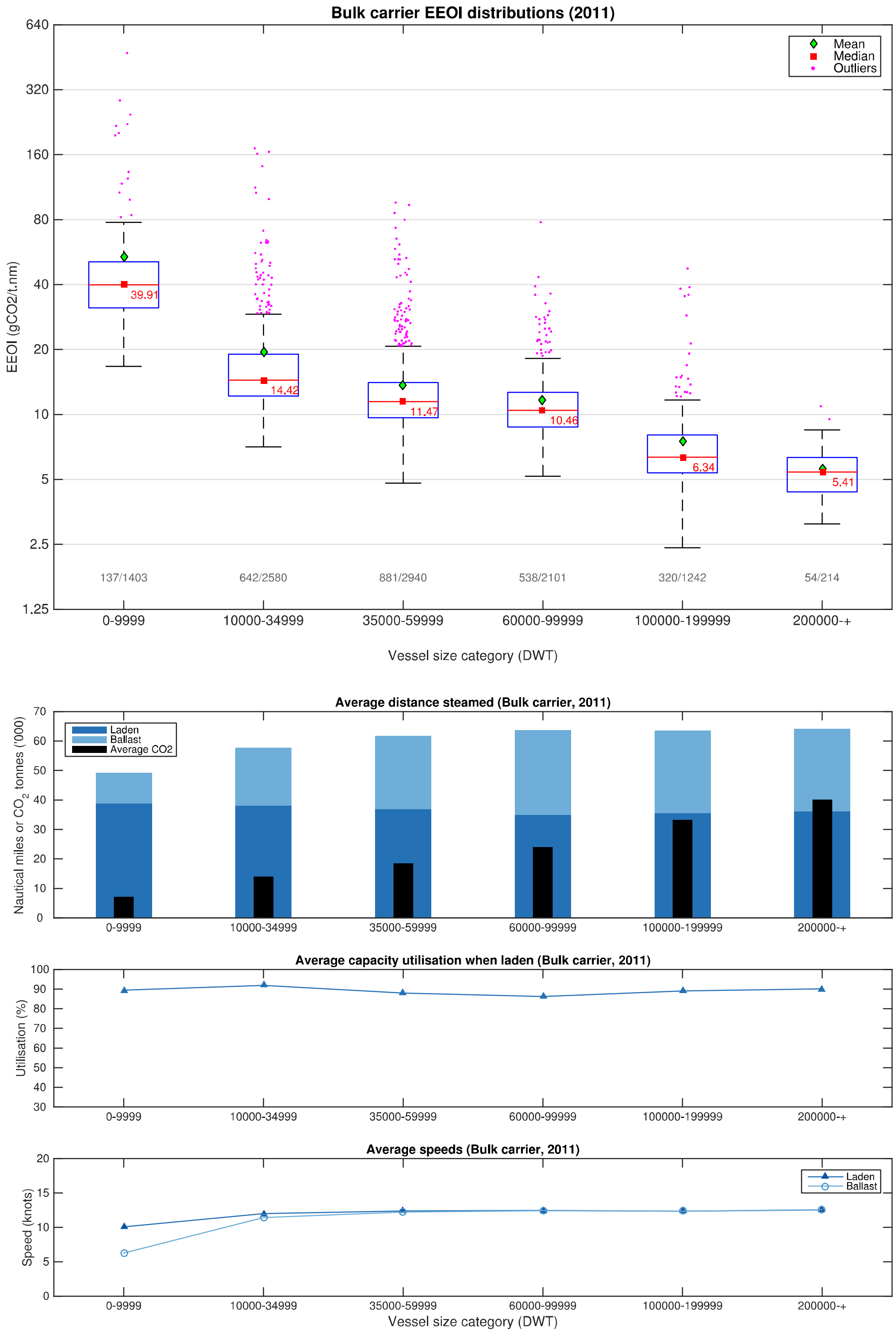
		Excluded ships						Included ships					
		dwt or TEU			Main engine power (kw)			dwt or TEU			Main engine power (kw)		
Type	Size	Mean	Std. dev.	Median	Mean	Std. dev.	Median	Mean	Std. dev.	Median	Mean	Std. dev.	Median
Bulk carrier	0-9999	2874	2633	1760	2447	3728	1324	5517	2099	5910	2377	856	2500
Bulk carrier	10000-34999	25105	6701	26723	6675	2591	6355	26985	8902	28201	6137	1698	5883
Bulk carrier	35000-59999	48173	7564	48772	8778	3217	8561	49980	6922	52248	8457	1164	8400
Bulk carrier	60000-99999	75710	8782	75200	10635	4388	10200	76232	7157	75253	10036	1411	9989
Bulk carrier	100000-199999	163484	21753	172612	17864	10404	16860	165738	20087	172689	16210	2096	16858
Bulk carrier	200000-+	260655	54438	254095	20762	4890	20028	234010	36356	208571	18785	3501	18629
Chemical tanker	0-4999	1914	1411	1285	1410	1170	1030	2788	1258	2974	1731	681	1650
Chemical tanker	5000-9999	7252	1283	7056	3256	1020	3089	7321	1245	7051	3317	641	3227
Chemical tanker	10000-19999	14876	3065	14019	5564	4412	4856	15334	4409	14298	5176	1139	4525
Chemical tanker	20000-+	54692	42028	45706	11977	10402	9480	41334	7927	40713	9081	1285	9450
Container	0-999	473	319	509	6276	5040	5710	697	207	704	6490	2158	6555
Container	1000-1999	1413	286	1429	12215	3653	11416	1427	290	1440	12546	3169	12260
Container	2000-2999	2529	257	2552	21386	3878	21660	2566	236	2556	21873	3196	21660
Container	3000-4999	3980	541	4143	35139	7760	36515	4237	409	4253	38718	7336	36559
Container	5000-7999	6040	725	5782	55026	7490	54941	6170	729	6350	57259	7829	57198
Container	8000-11999	8830	918	8500	67959	4113	68609	8912	781	8528	68303	2932	68519
Container	12000-14500	13216	698	13218	71897	5112	68519	13606	359	13344	76529	5776	80079
Container	14500-+	0	0	0	0	0	0	0	0	0	0	0	0
General cargo	0-4999	1357	1358	916	1150	1589	883	4075	12908	3201	1746	1836	1470
General cargo	5000-9999	6945	1350	6725	3541	3308	2942	8698	16145	7141	3583	2003	3120
General cargo	10000-+	47815	53605	29999	9306	8802	7980	22134	14693	17254	6966	3404	6360
Liquefied gas tanker	0-49999	7524	10388	3782	4004	4372	2648	20659	6132	23270	8732	1826	9480
Liquefied gas tanker	50000-199999	75806	20894	74028	23771	9025	26479	68014	14118	72545	21871	8300	23882
Liquefied gas tanker	200000-+	266013	51896	275040	22798	4196	22548	120069	12653	121843	36736	1674	37319
Oil tanker	0-4999	1721	1418	1250	1162	1367	883	3126	1358	2995	1961	957	1623
Oil tanker	5000-9999	6577	1175	6338	2959	2763	2648	7324	9488	6165	3126	1832	2942
Oil tanker	10000-19999	14762	2984	14102	6100	6045	4545	15277	2913	15761	4305	1164	4440
Oil tanker	20000-59999	41650	8615	45268	9611	7249	8580	44077	5966	45989	8556	1200	8580
Oil tanker	60000-79999	71349	4269	73307	12400	4774	11444	72459	3347	73611	12093	2188	11525
Oil tanker	80000-119999	104906	8734	105852	13137	4518	13534	106734	6307	106138	13422	1597	13560
Oil tanker	120000-199999	153233	12565	156829	20195	11481	18623	156474	15164	158059	17637	2006	18623
Oil tanker	200000-+	302311	19004	302159	26056	3871	26460	303448	10697	301171	26777	2368	27160
Refrigerated bulk	0-1999	774	619	663	1063	912	852	6807	4698	6120	6026	4253	5001

Table 17: Comparison of ship dwt and power between excluded and included ships (2012)

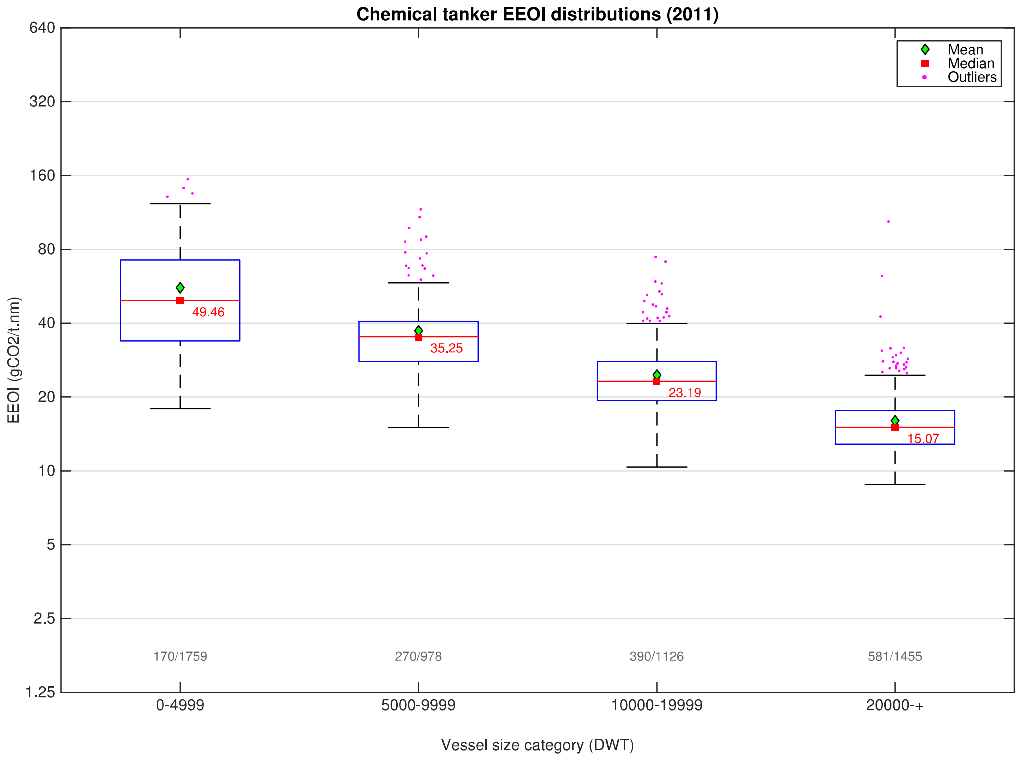
		Excluded ships						Included ships					
		dwt or TEU			Main engine power (kw)			dwt or TEU			Main engine power (kw)		
Type	Size	Mean	Std. dev.	Median	Mean	Std. dev.	Median	Mean	Std. dev.	Median	Mean	Std. dev.	Median
Bulk carrier	0-9999	2834	2620	1820	2579	3624	1324	5088	2198	5276	2234	945	2398
Bulk carrier	10000-34999	26097	6500	27915	6486	2431	6250	26363	6152	28270	5889	1108	5850
Bulk carrier	35000-59999	48743	7726	50300	8726	3280	8561	50640	7082	53100	8540	1096	8580
Bulk carrier	60000-99999	76876	8430	75928	10544	2940	10200	77703	8383	75921	10239	1580	10003
Bulk carrier	100000-199999	165388	22611	175744	17911	8714	16860	167359	19041	175607	16374	2251	16860
Bulk carrier	200000-+	263533	57963	260723	21811	4711	21910	228181	35494	207912	18767	4126	18629
Chemical tanker	0-4999	2013	1426	1365	1467	1611	1100	2657	1332	2507	1703	735	1618
Chemical tanker	5000-9999	7260	1265	7052	3233	755	3009	7495	1241	7415	3198	593	3089
Chemical tanker	10000-19999	15075	3097	14383	5284	1836	4891	15074	3095	13969	5018	1006	4457
Chemical tanker	20000-+	46746	29719	40218	10248	5961	9466	43135	8565	46162	9022	1214	9480
Container	0-999	539	307	614	6214	4540	5920	657	220	698	5987	2021	6150
Container	1000-1999	1419	291	1436	12283	3626	11457	1399	289	1348	12169	3023	11577
Container	2000-2999	2539	253	2553	21487	3685	21660	2549	235	2553	21481	3321	21594
Container	3000-4999	4058	531	4249	35293	7860	36526	4136	507	4252	36938	6794	36559
Container	5000-7999	5990	668	5782	54071	7515	54925	6010	741	5897	56852	8335	57074
Container	8000-11999	8900	872	8540	66359	6688	68519	8469	517	8320	67119	3523	68504
Container	12000-14500	13298	509	13092	70782	2950	71759	14037	52	14037	68519	0	68519
Container	14500-+	15673	210	15550	80754	334	80903	0	0	0	0	0	0
General cargo	0-4999	1748	1381	1450	1095	1168	883	2730	1766	2742	1519	1433	1324
General cargo	5000-9999	6942	1351	6763	3129	1402	2880	7203	1401	7124	3381	1322	3124
General cargo	10000-+	30766	33205	18731	8285	6739	6810	19615	11182	14397	6448	3361	5828
Liquefied gas tanker	0-49999	7490	10046	3811	3986	5308	2700	20391	7940	18110	8622	1557	9480
Liquefied gas tanker	50000-199999	80540	21254	77564	25549	12097	26802	66064	13863	69846	20963	8515	21322
Liquefied gas tanker	200000-+	307599	26616	319000	26952	5405	29340	119917	11220	121877	36918	2197	37319
Oil tanker	0-4999	1703	1442	1200	1211	1823	883	2984	1351	2903	1875	860	1618
Oil tanker	5000-9999	6588	1149	6380	2741	881	2643	6553	1285	6165	2930	862	2942
Oil tanker	10000-19999	14795	2938	13939	5268	4559	4440	14759	2852	13514	4098	1217	4101
Oil tanker	20000-59999	42593	8173	45740	9712	7572	8580	43897	6143	46101	8581	1119	8580
Oil tanker	60000-79999	72008	4251	73584	11895	4067	11500	72625	3337	73673	11802	1302	11447
Oil tanker	80000-119999	105605	8529	106005	14064	5444	13560	106669	6315	106140	13273	1583	13549
Oil tanker	120000-199999	155989	10853	158149	18002	2040	18624	155282	5534	156885	17384	1867	18080
Oil tanker	200000-+	301062	25264	302845	26319	5131	27160	304058	10220	301861	26874	2202	27160
Refrigerated bulk	0-1999	778	615	681	1080	1081	828	5772	4730	5035	4817	3519	3963

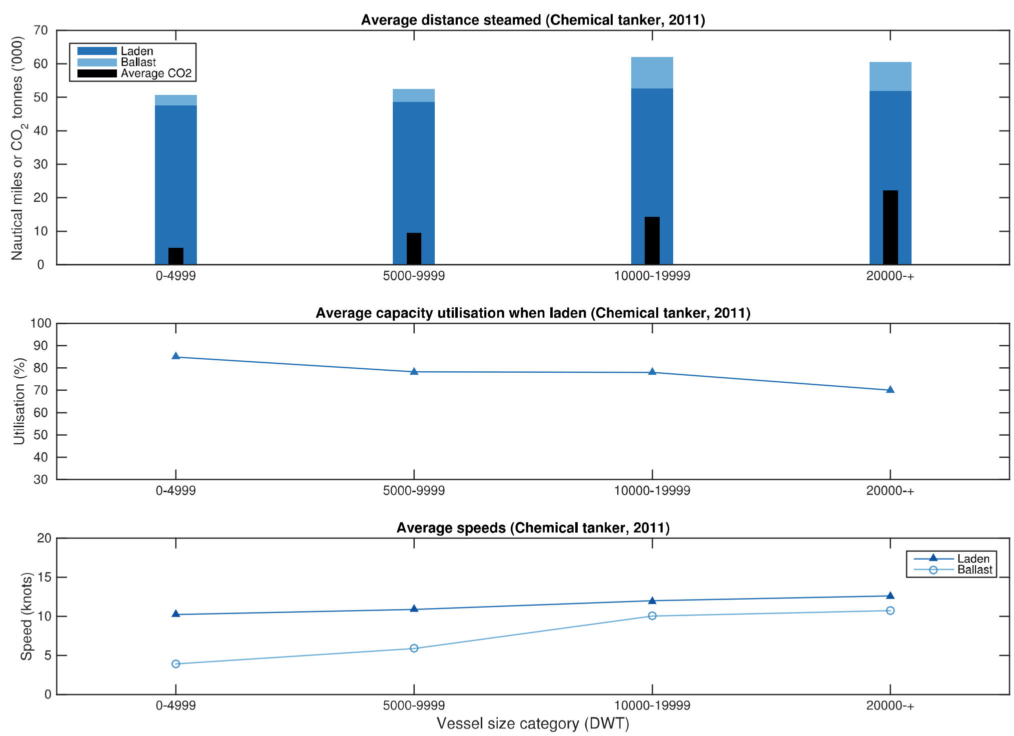
Annex B: 2011 detailed results

Bulk carrier

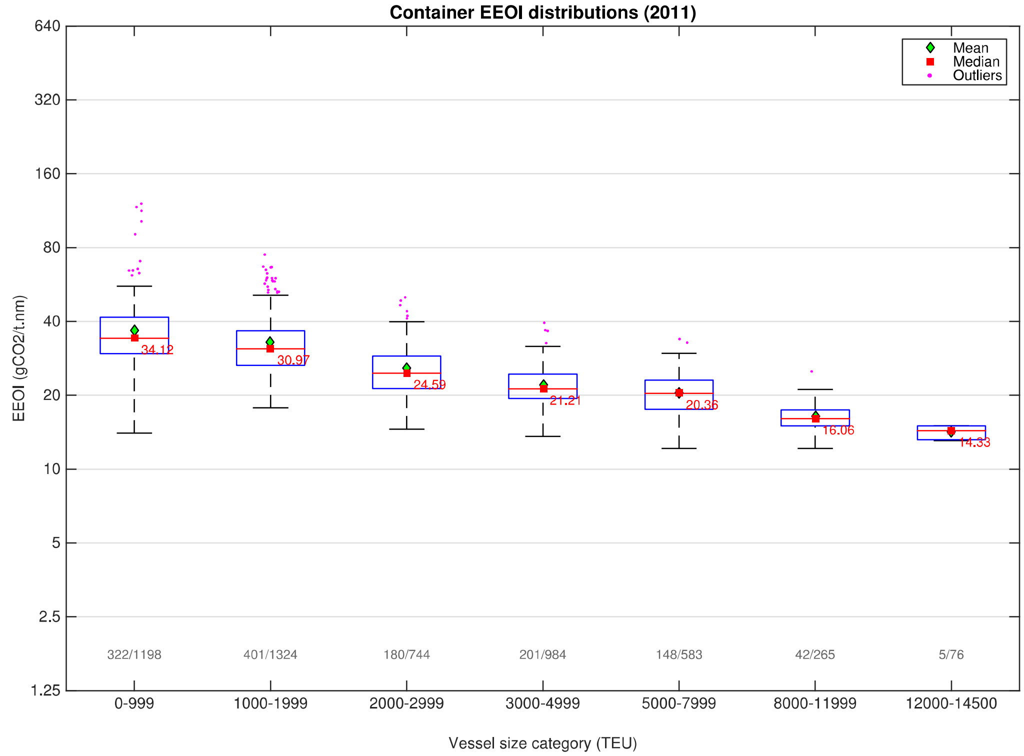


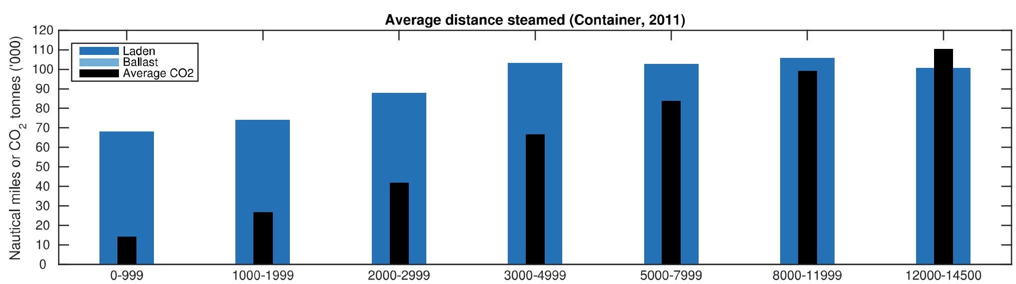
Chemical tanker

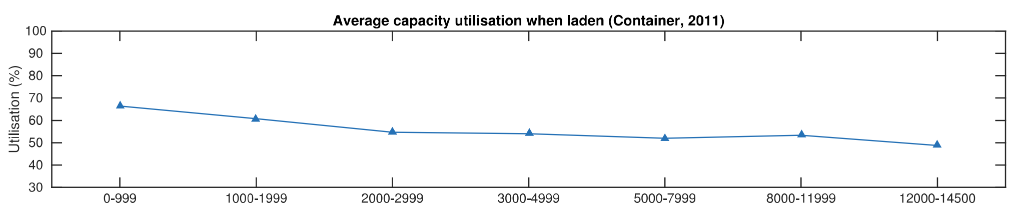


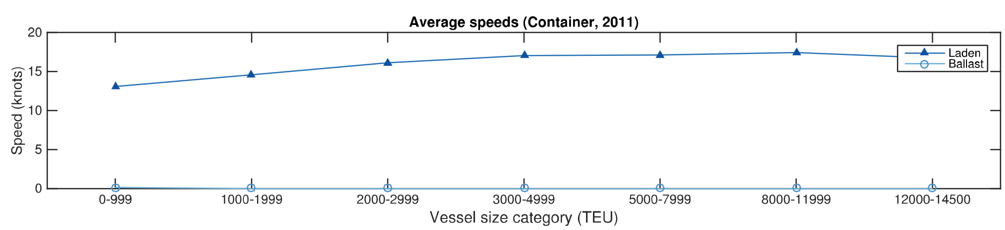


Container ship

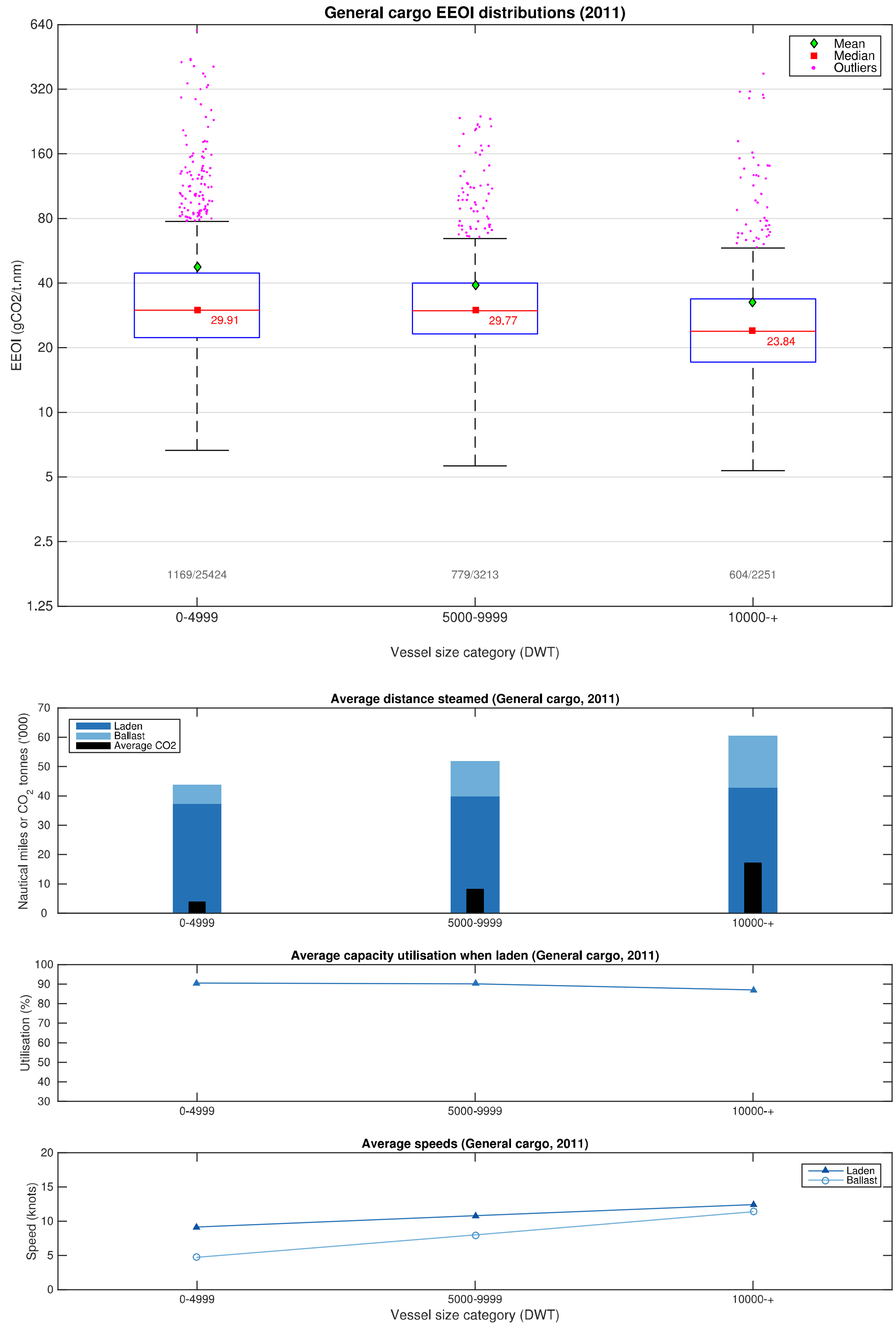




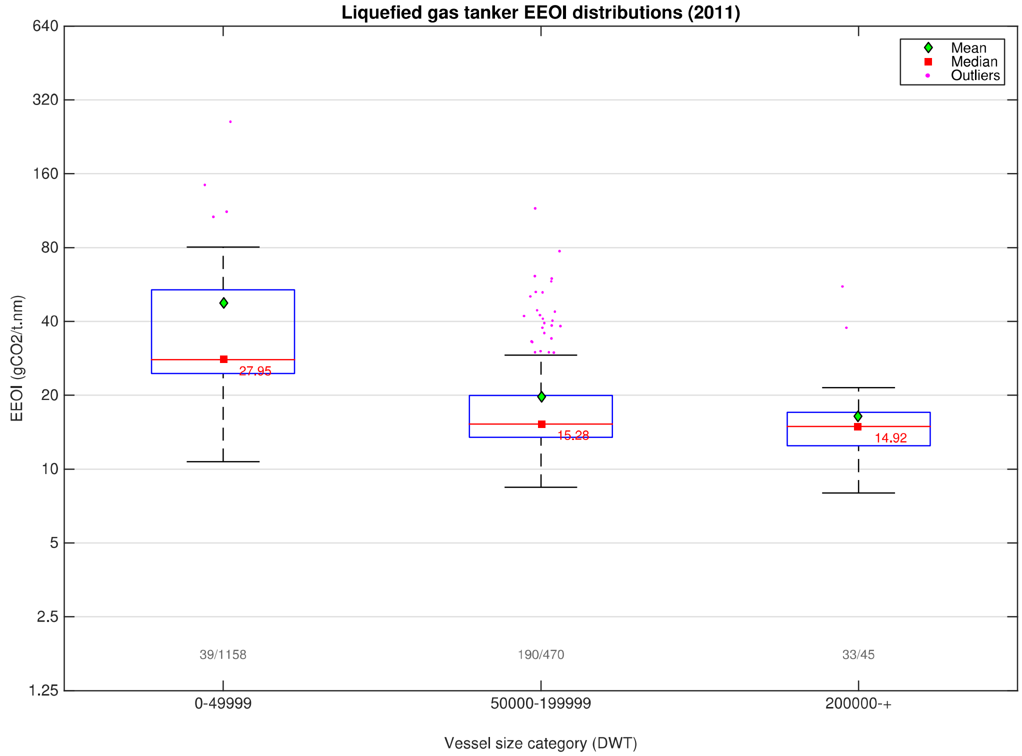


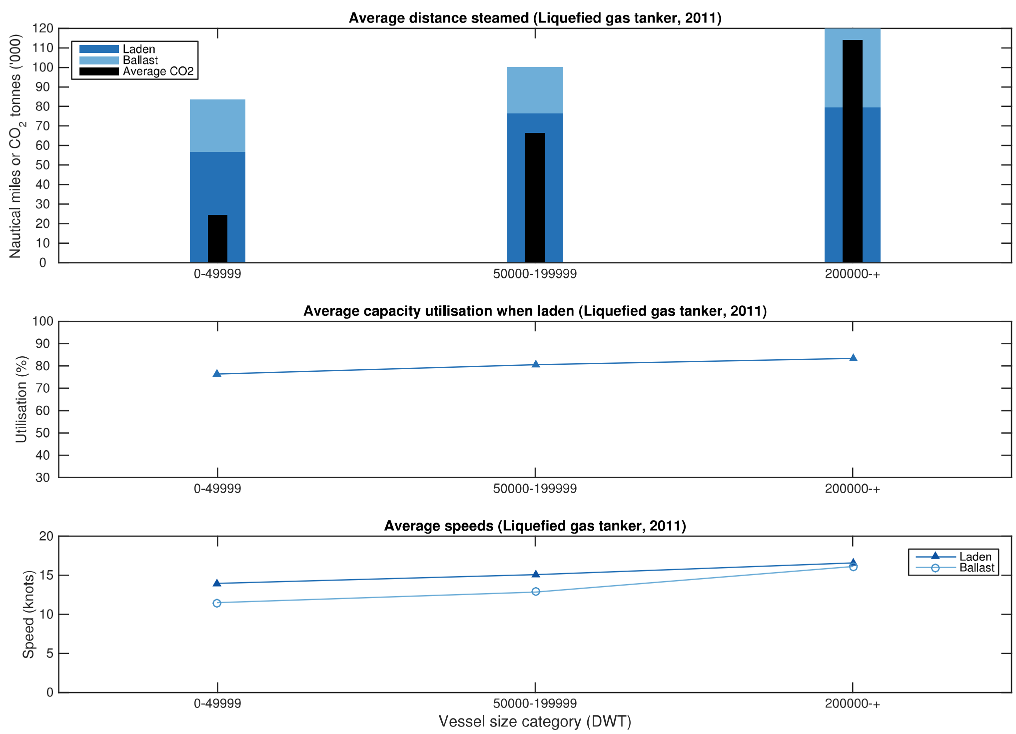


General cargo

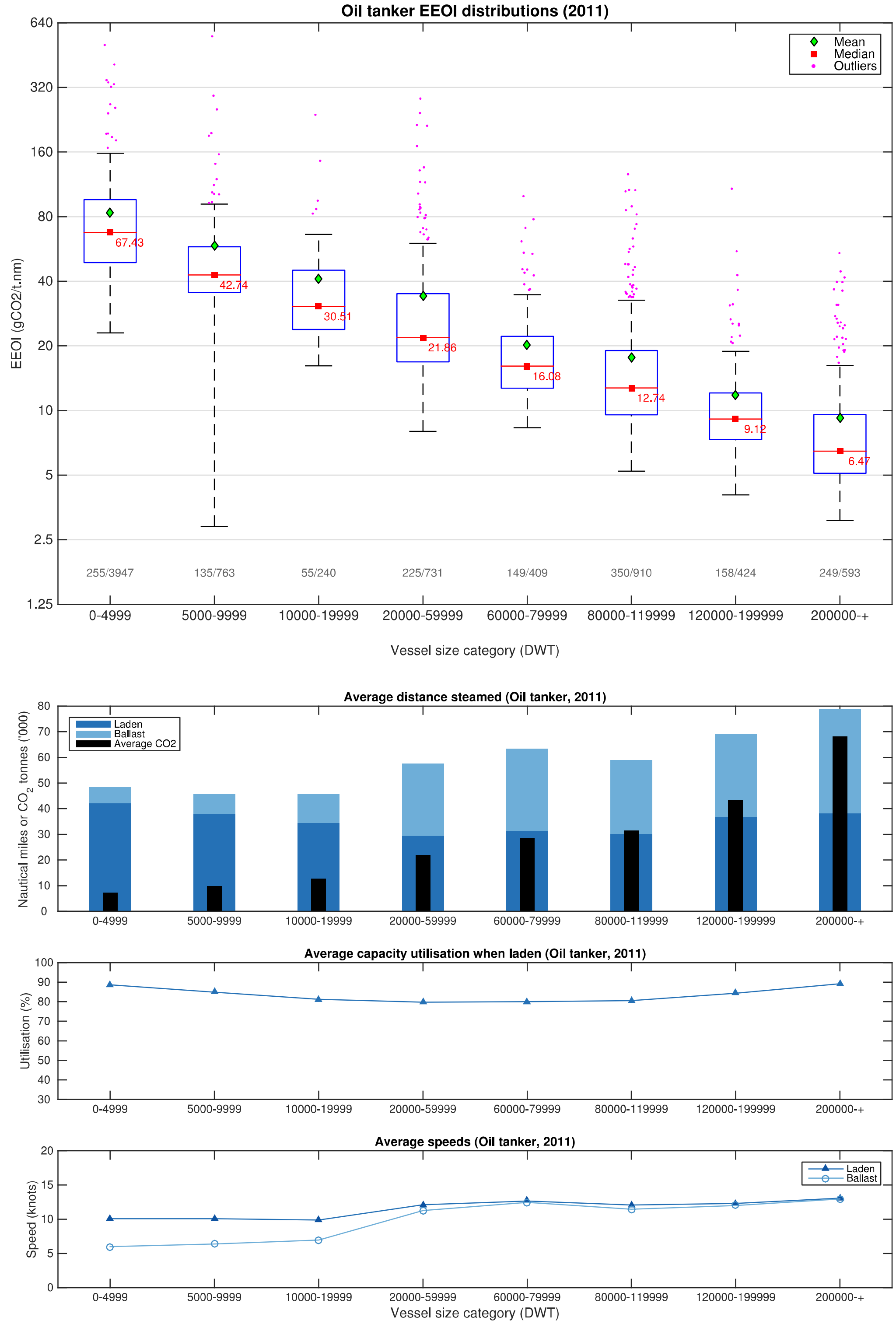


Liquefied gas tanker



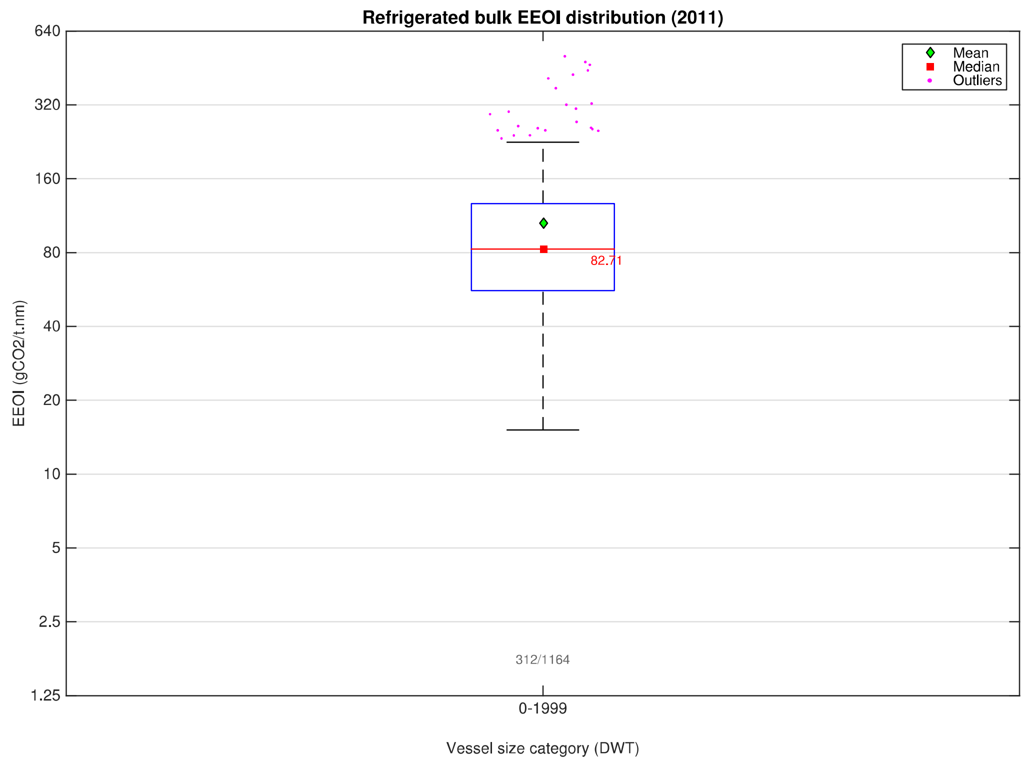


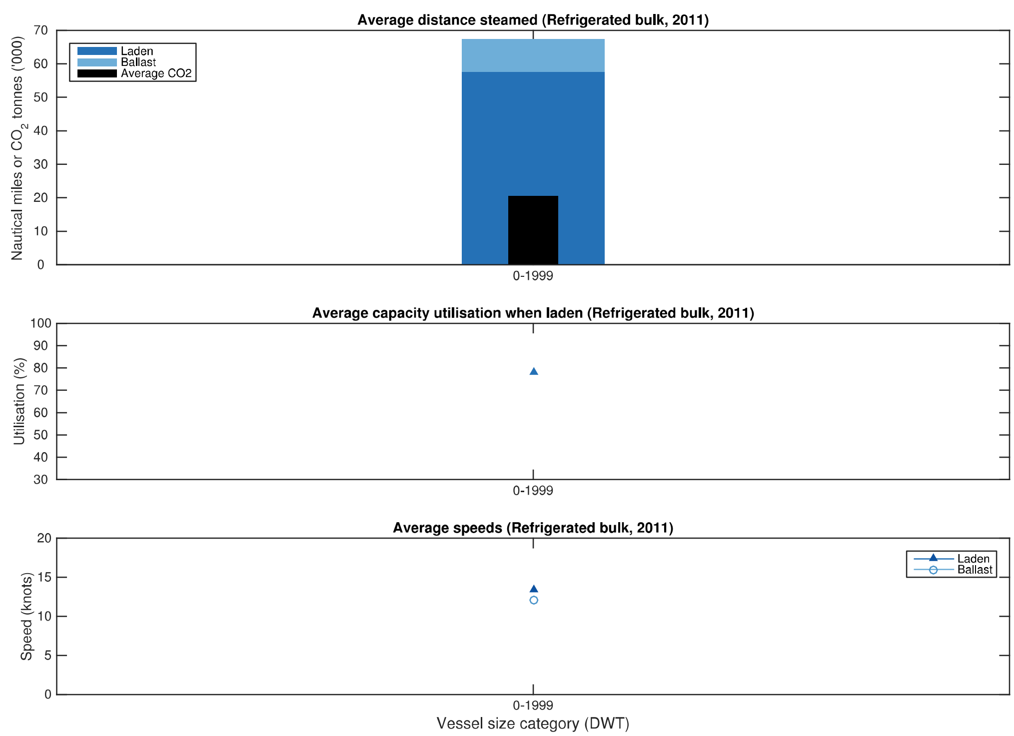
Oil tanker



Oil tanker EEOI distributions (2011)
Mean
Median
Outliers
EEOI (gCO2/t.nm)
640
320
160
80
40
20
10
5
2.5
1.25
67.43
42.74
30.51
21.86
16.08
12.74
9.12
6.47
255/3947
135/763
55/240
225/731
149/409
350/910
158/424
249/593
0-4999
5000-9999
10000-19999
20000-59999
60000-79999
80000-119999
120000-199999
200000-+
Vessel size category (DWT)
Average distance steamed (Oil tanker, 2011)
Laden
Ballast
Average CO2
Nautical miles or CO2 tonnes ('000)
Average capacity utilisation when laden (Oil tanker, 2011)
Utilisation (%)
Average speeds (Oil tanker, 2011)
Speed (knots)
Laden
Ballast
Vessel size category (DWT)

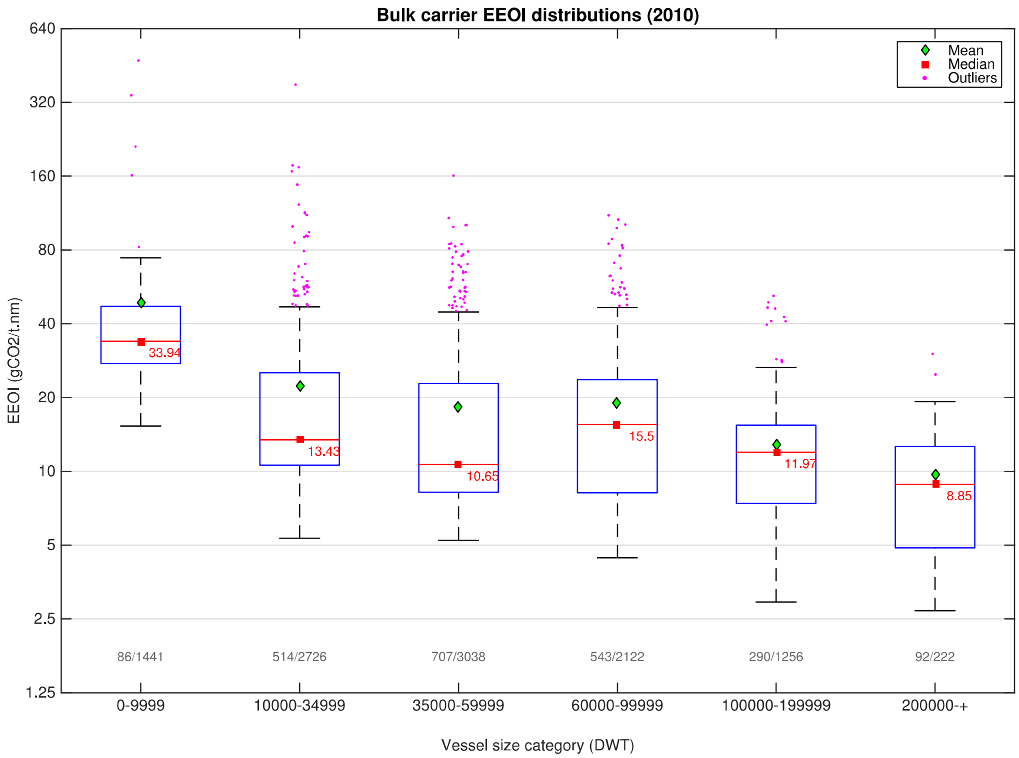
Refrigerated bulk

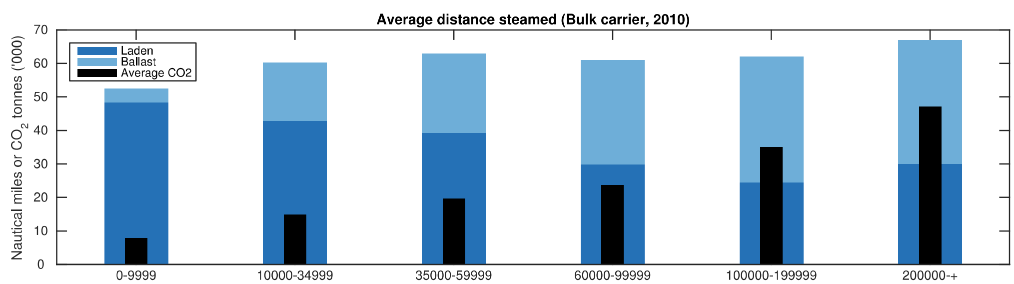


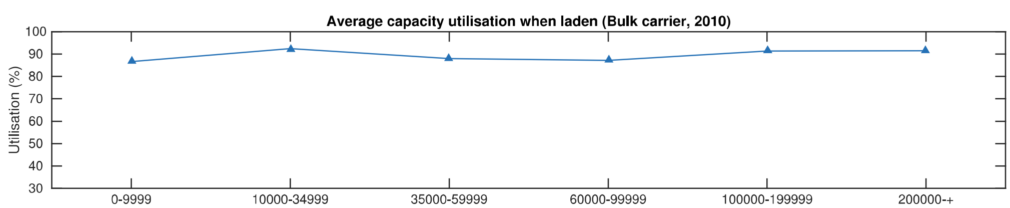


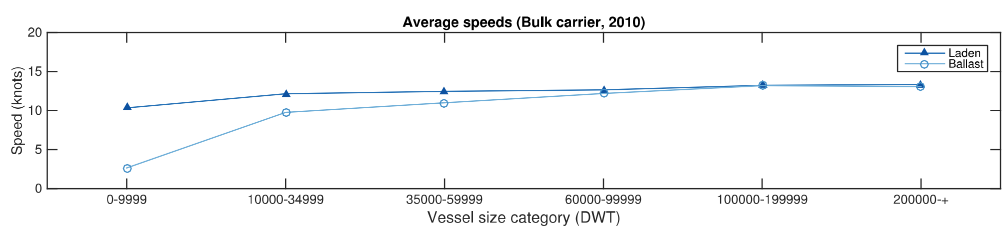
Annex C: 2010 detailed results

Bulk carrier

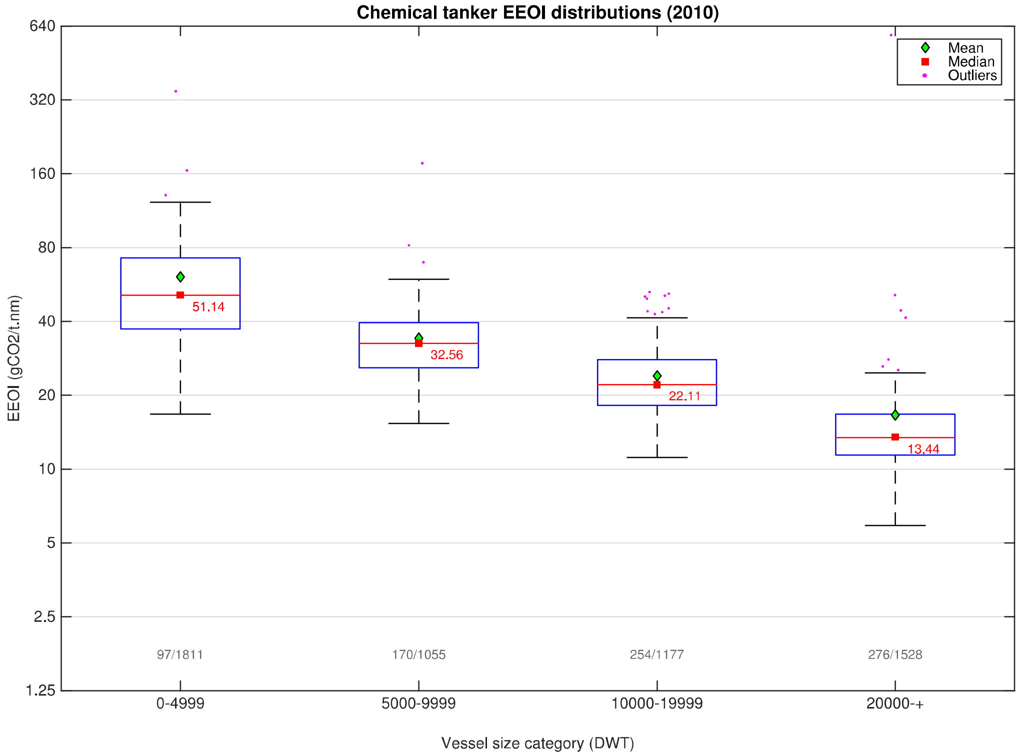


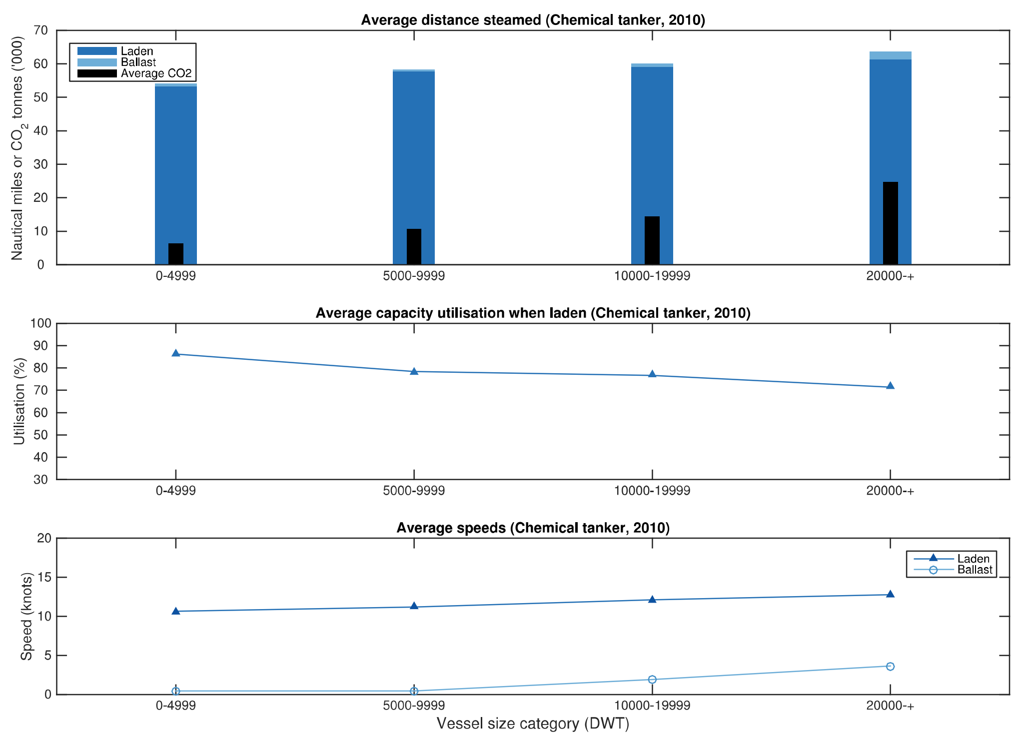




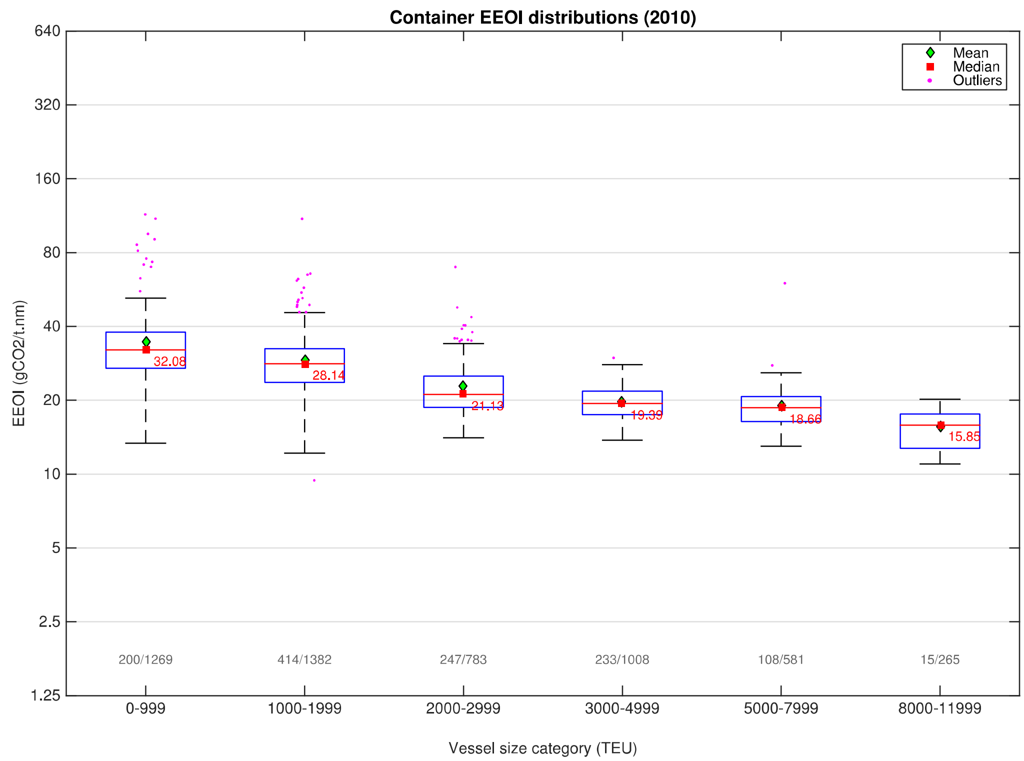


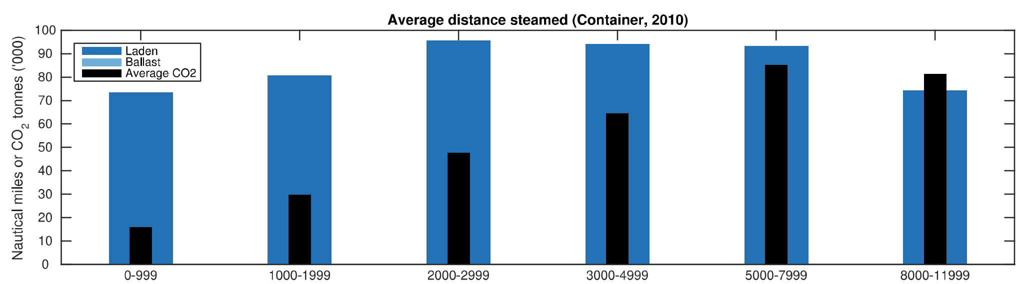
Chemical tanker

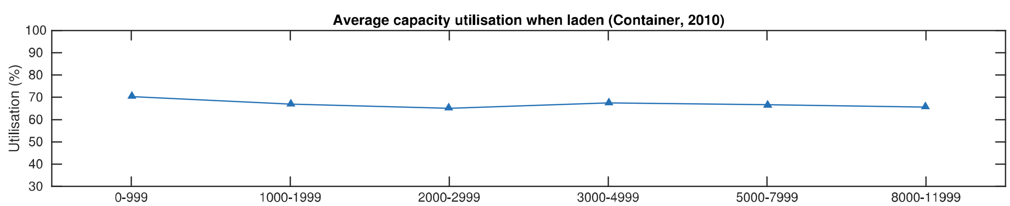


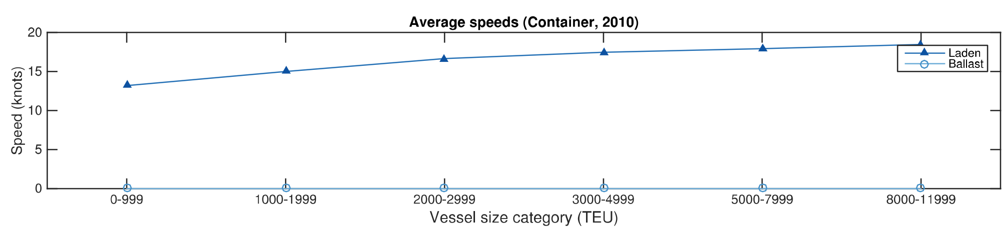


Container ship

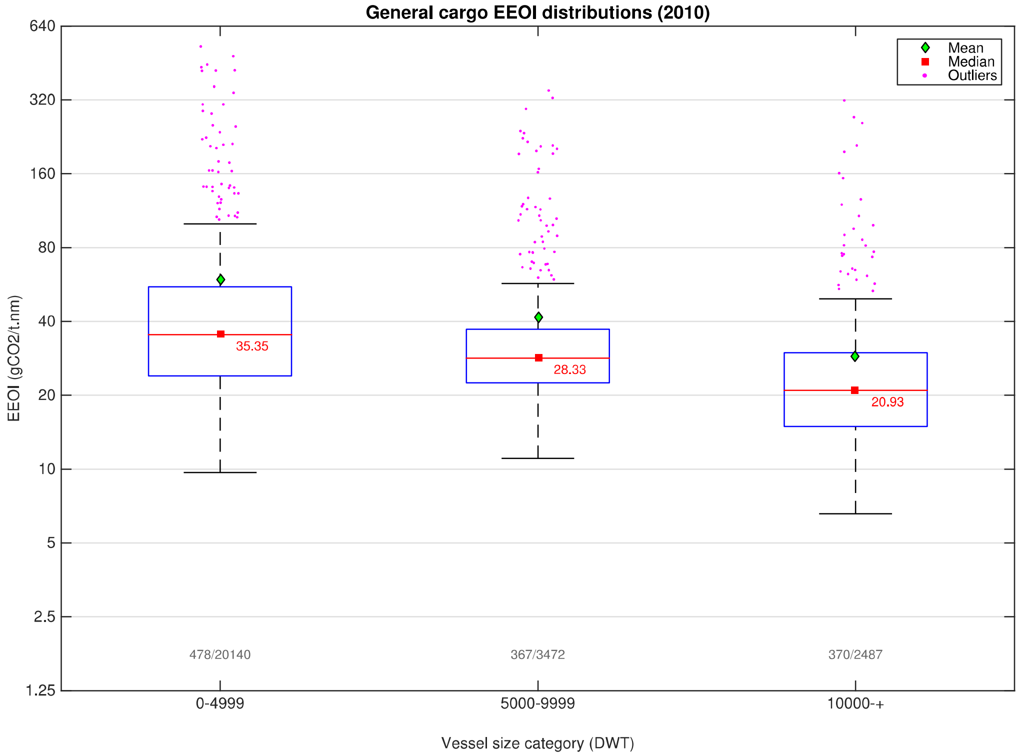


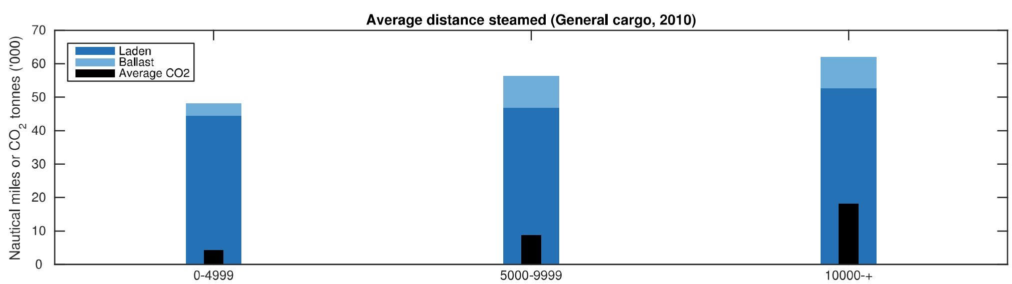


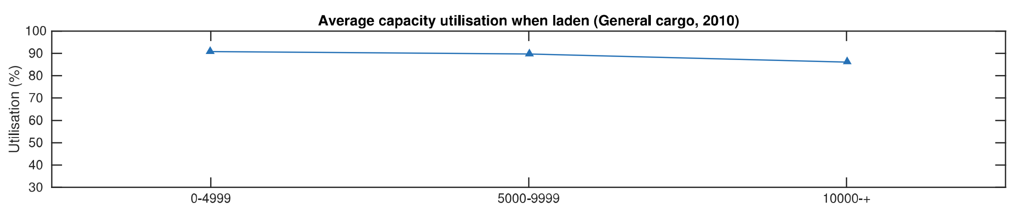


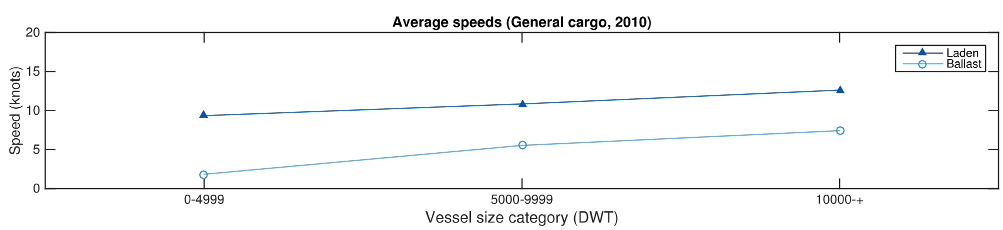


General cargo

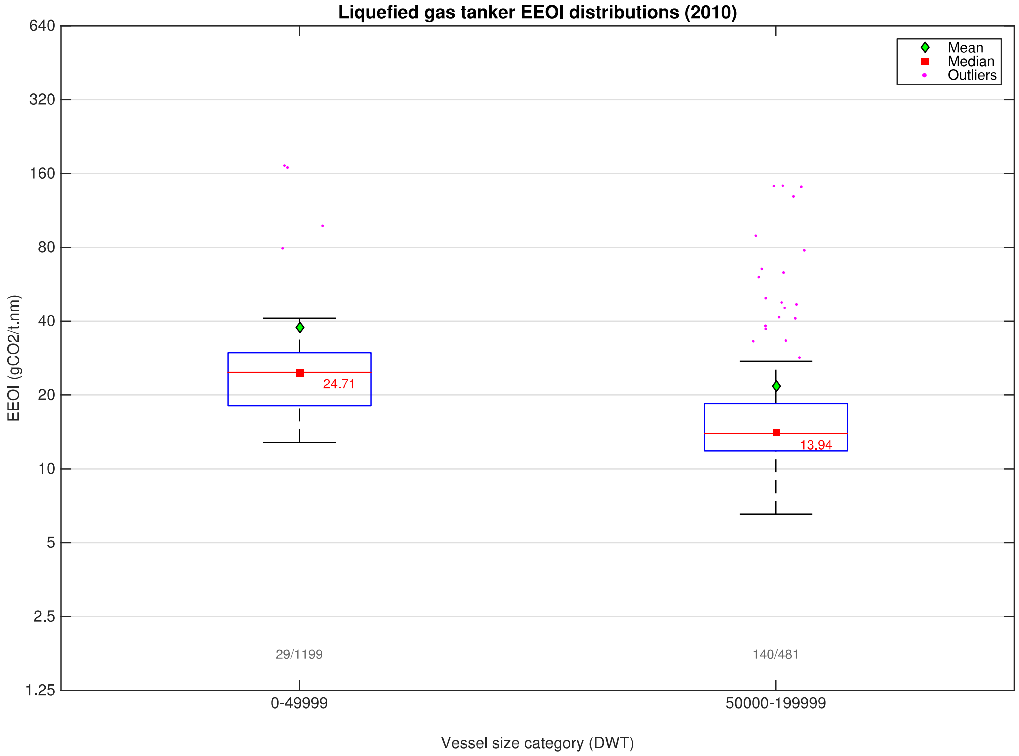


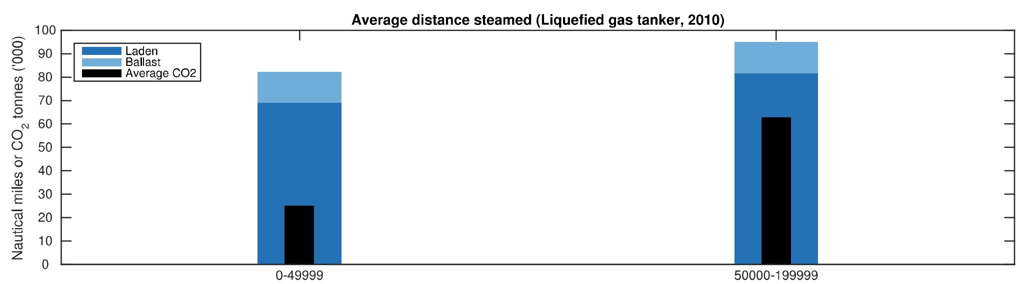


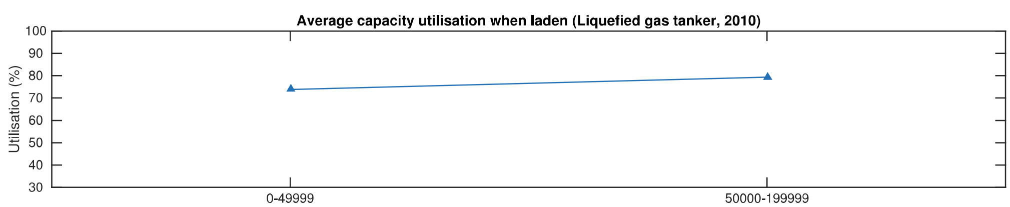


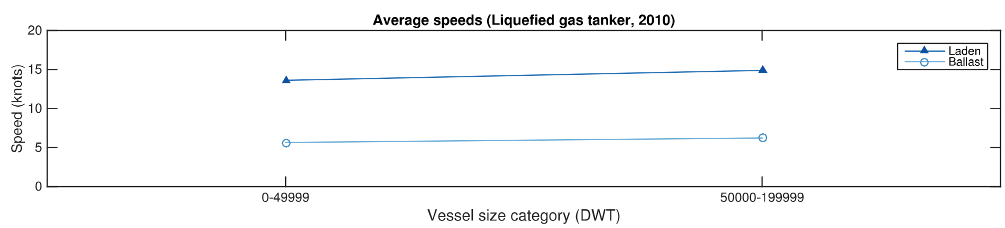


Liquefied gas tanker

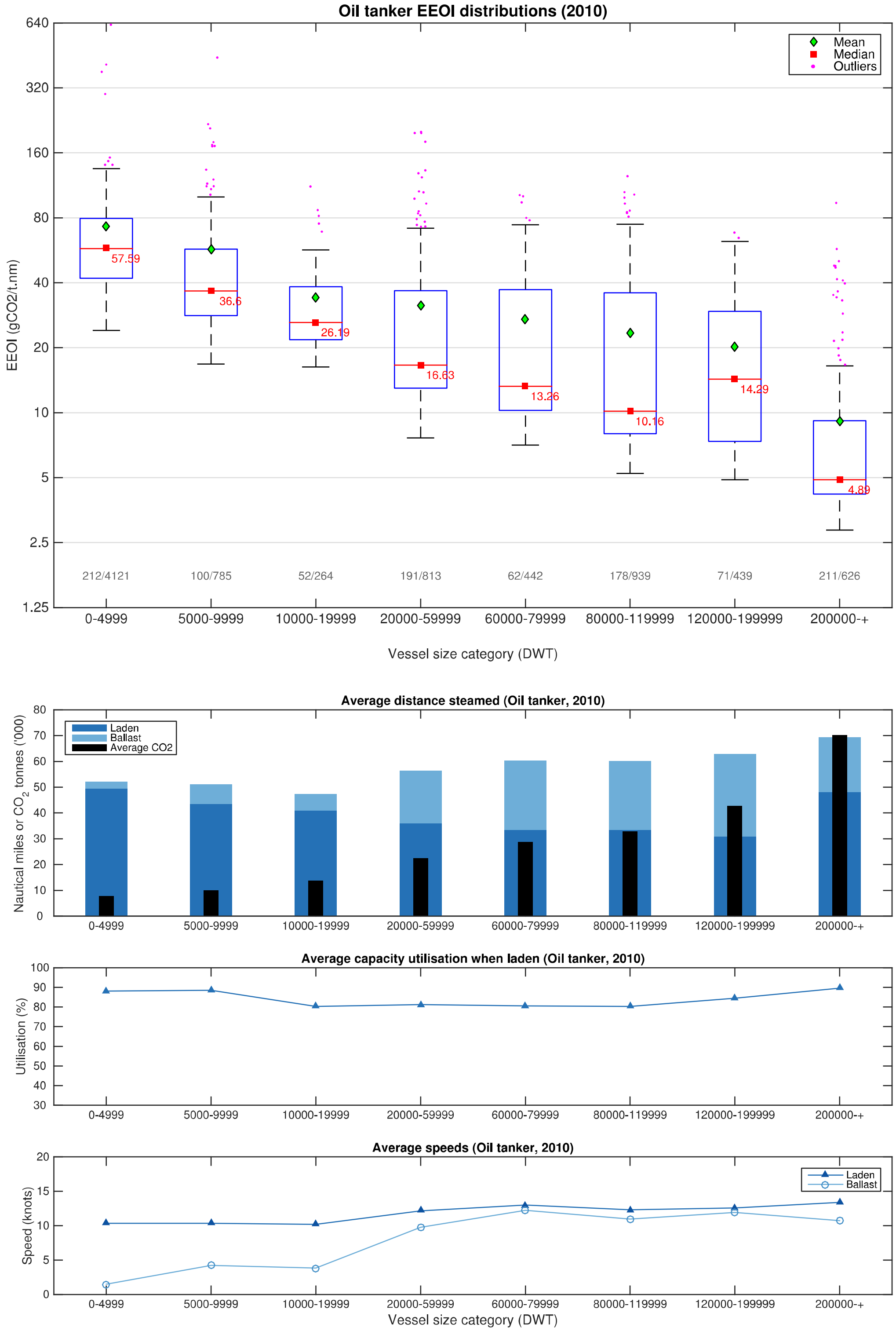








Oil tanker


Oil tanker EEOI distributions (2010)
Mean
Median
Outliers
EEOI (gCO2/t.nm)
640
320
160
80
40
20
10
5
2.5
1.25
57.59
36.6
26.19
16.63
13.26
10.16
14.29
4.89
212/4121
100/785
52/264
191/813
62/442
178/939
71/439
211/626
0-4999
5000-9999
10000-19999
20000-59999
60000-79999
80000-119999
120000-199999
200000-+
Vessel size category (DWT)
Average distance steamed (Oil tanker, 2010)
Laden
Ballast
Average CO2
Nautical miles or CO2 tonnes ('000)
Average capacity utilisation when laden (Oil tanker, 2010)
Utilisation (%)
Average speeds (Oil tanker, 2010)
Laden
Ballast
Speed (knots)
Vessel size category (DWT)

Refrigerated bulk