Empirical comparative analysis of energy efficiency indicators for ships

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Summary

In the discussion on further measures to enhance the energy efficiency of ships, four options for specific metrics for calculating operational efficiency have been proposed to MEPC, viz. the Annual Efficiency Ratio (AER, formerly Annual EEOI), the Individual Ship Performance Indicator (ISPI), the Fuel Oil Reduction Strategy (FORS) and an unnamed United States' proposal.
The respective Working Group of MEPC 66 agreed that further work was needed on all the metrics and that no metric should be excluded at that point in time (MEPC 66/WG.9). The Committee encouraged interested delegations to voluntary submit data resulting from monitoring programme and metric testing to the Committee (MEPC 66/21, Paragraph 4.1.5.3).

This study has been commissioned by Germany in order to contribute to the discussion on possible metrics and appropriate indicators for operational energy efficiency.

Data sources, method and aim of the study
The data used in this study comprises fuel, distance, and time data of 221 ships: 93 bulk carriers, 79 containerships and 49 tankers. For each ship, data was obtained for at least two and at most five consecutive years. In total, the analysis is based on 652 observations. The data were kindly provided by German shipowners and by an independent organisation.

This data was used to analyse the following indicators of energy efficiency:
1. DIST: CO_2 emissions per unit of distance (tonnes/nm).
2. cDIST: CO_2 emissions per unit of capacity and unit of distance (tonnes/tonne deadweight . nm).
3. TIME: the amount of energy used per unit of time (joules/hour).
4. FUEL: the annual fuel consumption (tonnes).

The study aims to analyse first whether there is a common element in the definition of operational efficiency that each of these indicators use. To that end, the correlation of changes in the indicators was analysed. Second, the study analyses whether it is possible to set an operational efficiency standard in practice using any of these four indicators. Regression curves were calculated and analysed.

Main results of the study
The results suggest that the four indicators are related, but the relations are not always significant. In general, an improvement in one indicator coincides with an improvement in another indicator. However, while for some specific indicator pairs and specific ship types, the relation is statistically significant, for other indicator pairs and ship types it is not. This means that the probability that the correlations are representative for the world fleet, and not just for the sample, vary per ship type. cDIST/DIST and TIME are significantly correlated for all ship types, but the correlation of FUEL with either of the two other indicators is significant for some ship types but not for others. The average annual speed of ships is significantly correlated with indicators for some ship types, but never for all ship types.

The study also calculates size-dependent regression curves for the cDIST/DIST, TIME and FUEL indicators, i.e. the curve that best describes the relation between the efficiency indicator and the size. The variation of observations around the curve is smallest for cDIST, and largest for FUEL.

In principle, a regression curve can serve as a basis for ship-specific targets. The effectiveness of such targets in improving efficiency depends on the share of ships that is not too far above the target, and on the share of ships that is below the target. For the former group of ships, it is conceivable that changes in operations could result in indicator values at or below the target. For the latter group, a target will not act as an incentive to change their operations.

4-11% of ships (depending on ship type) is more than 20% below the FUEL regression curve in every observed year; 5-6% more than 20% below the TIME curve and 1-3% more than 20% below the cDIST curve.

It is conceivable that ships of which the indicator is far above a target in every year cannot change their operational pattern sufficiently to meet the target.

Within the sample of ships analysed in this study, 8-19% of ships (depending on ship type) are consistently more than 20% above the FUEL regression curve (depending on ship type), 4-10% are more than 20% above the TIME curve and 3-4% are more than 20% above the cDIST curve.

1 Introduction

1.1 Policy context of this study

In the discussion on further measures to enhance the energy efficiency of ships, four options for specific metrics for calculating operational efficiency have been proposed to MEPC, viz. the Annual Efficiency Ratio (AER, formerly Annual EEOI), the Individual Ship Performance Indicator (ISPI), the Fuel Oil Reduction Strategy (FORS) and an unnamed United States' proposal.
The respective Working Group of MEPC 66 agreed that further work was needed on all the metrics and that no metric should be excluded at that point in time (MEPC 66/WG.9). The Committee encouraged interested delegations to voluntary submit data resulting from monitoring programme and metric testing to the Committee (MEPC 66/21, Paragraph 4.1.5.3).

Japan responded to this request and submitted an analysis based on actual data to MEPC 67 with the aim to analyse whether the AER could be an appropriate metric to capture and enhance energy efficiency from international ships (MEPC 67/5/4).

In this study we analyse four indicators of efficiency, using a large sample of empirical data of ocean going ships.

1.2 Objectives of this study

This study analyses four indicators of energy efficiency of ships using empirical data to answer the following two main questions:
1. Is there a common element in the definition of operational efficiency between the four indicators?
2. Is it possible to set an operational efficiency standard in practice?

1.3 Data

This study is based on operational data from a large number of ship operators, which has kindly been provided by German shipowners and an independent organisation. The operational data include the following information for each ship:
- fuel consumption per year (separately for HFO/IFO and for MGO/MDO);
- distance sailed per year;
- time in service per year;
- ship type;
- size of the ship (dwt);
- main engine power (kW);
- auxiliary engine power (kW);
- reference speed of the ship at 75% MCR.

In total, we have received data on 221 ships: 93 bulk carriers, 79 container ships and 49 tankers. The bulk carriers ranged in size from about 34,000 dwt to about 184,000 dwt (approximately 100,000 dwt on average); the containerships from 8,000 dwt to 127,000 dwt (about 52,000 dwt on average); and the tankers from 9,000 dwt to 310,000 dwt (average 112,500 dwt).
For each ship, data have been provided for 2-5 years in the period 2009–2014 (see Table 1).

Table 1 **Ships in the data sample**

Ship type	Number of ships	2009	2010	2011	2012	2013	2014
Bulk carrier	93	5	15	40	75	87	41
Containership	79	4	55	54	76	75	0
Tanker	49	25	32	32	38	39	17
Total	**221**	**34**	**102**	**126**	**189**	**201**	**58**

1.4 Methods

The report distinguishes four indicators of efficiency:
1. DIST: CO_2 emissions per unit of distance (tonnes/nm).
2. cDIST: CO_2 emissions per unit of capacity and unit of distance (tonnes/tonne deadweight . nm).
3. TIME: the amount of energy used per unit of time (joules/hour).
4. FUEL: the annual fuel consumption (tonnes).

To answer the two questions raised in Section 1.2 the empirical data is analysed as follows:
1. The consistency of the year-to-year changes of the different indicators are analysed per ship and the correlation of the year-to-year changes of the indicators are determined for the different ship types as well as for the total sample.
2. In order to determine whether an operational efficiency standard can be set in practice, the sample is analysed as follows:
   a Where applicable, it is established whether an industry regression curve can be set.
   b The possible regression curves are compared with the actual value of the indicators of the different ships.
   c The fluctuation of each indicator over the years is determined.
   d It is analysed whether the different indicators change in the way one would expect if the average speed of a ship has changed.

2 Analytical comparison of energy efficiency indicators

This chapter presents an analytical, theoretical comparison of the four energy efficiency indicators used in this study. It analyses how, in theory, the year-to-year changes of the indicators are related. The relationship is tested empirically in Chapter 3.

The four efficiency indicators analysed in this study are alternative bases for a potential measure to enhance the energy efficiency of international shipping.

For these measures to be effective, changes of the energy efficiency of a ship should be reflected by an corresponding change of the indicator.

The energy consumption of a ship depends on the technical efficiency of a ship as well as on the operational profile of a ship. The operational profile of a ship comprises many different parameters, such as speed, displacement, trim, environmental conditions (wind, waves, ice current), etc. Because many of these operational parameters change between voyages (or even during individual voyages), the average value of the indicators over a year.

2.1 Year-to-year percentage changes per ship

In the empirical analysis we present the year-to-year percentage changes of the annual averages of the four indicators. What results can we expect from this analysis regarding specific ships?

The year-to-year percentage changes of the four indicators are as follows:

$$\Delta DIST = \Delta cDIST = \frac{(1+\Delta fuel\ consumption) * (1+\Delta\ average\ emission\ factor)}{(1+\Delta\ distance)} - 1$$

$$\Delta TIME = \frac{(1+\Delta fuel\ consumption) * (1+\Delta\ energy\ content\ of\ fuel)}{(1+\Delta\ hours\ in\ service)} - 1$$

$$\Delta FUEL = \Delta fuel\ consumption$$

In these formulae, Δ signifies the percentage change of the variable.

The year-to-year percentage changes of DIST and cDIST are the same and will therefore be perfectly correlated, whereas the year-to-year percentage changes of DIST/cDIST, TIME and FUEL can have different values and signs (positive or negative).

The year-to-year changes of DIST/cDIST, TIME and FUEL will have the same sign if (see Table 2):

a the reduction in fuel consumption is smaller than the reduction in distance and service hours; or
b the increase in fuel consumption is larger than the increase in distance sailed and hours in service.

Table 2 **Necessary and sufficient conditions for the year-to-year percentage changes of the indicators to be consistent in terms of direction of the effect for a specific ship, given that the average fuel quality does not change**

	Necessary and sufficient conditions		Direction of consistent year- on-year change
a.	$\Delta\, fuel\ cons. < \Delta\, distance$ $\Delta\, fuel\ cons. < \Delta\, hours\ in\ s.$ $\Delta\, fuel\ cons. < 0$	$\Leftrightarrow$	Δ DIST and ΔcDIST < 0 Δ TIME < 0 Δ FUEL < 0
b.	$\Delta\, fuel\ cons. > \Delta\, distance$ $\Delta\, fuel\ cons. > \Delta\, hours\ in\ s.$ $\Delta\, fuel\ cons. > 0$	$\Leftrightarrow$	Δ DIST and Δ cDIST > 0 Δ TIME > 0 Δ FUEL > 0

In all other cases, the changes in the indicators will have different signs.
For example:

1. The change of DIST/cDIST will have a different sign than the change of the TIME, if the change of the fuel consumption is in between the change of the distance sailed and the change of the hours in service:

A)

$$\Delta\, distance > \Delta\, fuel\ cons. > \Delta\, hours\ in\ s. \Rightarrow \begin{cases} \Delta DIST\ and\ \Delta\, cDIST < 0 \\ \Delta TIME > 0 \end{cases}$$

B)

$$\Delta\, distance < \Delta\, fuel\ cons. < \Delta\, hours\ in\ s. \Rightarrow \begin{cases} \Delta DIST\ and\ \Delta\, \text{cDIST} > 0 \\ \Delta TIME < 0 \end{cases}$$

2. The change of FUEL will have a different sign than the change of TIME, if:

A) fuel consumption decreases and hours in service decrease to a greater extent:

$$0 > \Delta\, fuel\ cons. > \Delta\, hours\ in\ s. \Rightarrow \begin{cases} \Delta\, FUEL < 0 \\ \Delta\, TIME > 0 \end{cases}$$

B) fuel consumption increases and hours in service increase to a greater extent:

$$0 < \Delta\, fuel\ cons. < \Delta\, hours\ in\ s. \Rightarrow \begin{cases} \Delta\, FUEL > 0 \\ \Delta\, TIME < 0 \end{cases}$$

3. The change of FUEL will have a different sign than the change of DIST/cDISTin, if:

A) fuel consumption decreases and the distance sailed decreases to a greater extent:

$$0 > \Delta\, fuel\ cons. > \Delta\, distance \Rightarrow \begin{cases} \Delta\, FUEL < 0 \\ \Delta\, DIST\ and\ \Delta cDIST > 0 \end{cases}$$

B) fuel consumption increases and the distance sailed increases to a greater extent:

$$0 < \Delta\, fuel\ cons. < \Delta\, distance \Rightarrow \begin{cases} \Delta\, FUEL > 0 \\ \Delta DIST\ and\ \Delta cDIST < 0 \end{cases}$$

When ships are reducing their speed consistently between one year and the next, case 1 would not occur, because slow steaming results in a reduction in fuel consumption that is relatively larger than the reduction in distance, which in turn is larger than the reduction in hours in service.

Cases 2 and 3 illustrate the inherent difference between a relative (DIST, cDIST, and TIME) and an absolute indicator (FUEL):

- cases 2.B) & 3.B) are cases in which the efficiency improves in terms of the three relative indicators but more fuel is consumed (and consequently more greenhouse gases are emitted) due to more activity (more nautical miles sailed or more hours in service); and
- cases 2.A) and 3.A) are cases in which the efficiency deteriorates in terms of the three relative indicators but less fuel is consumed due to less activity (less nautical miles sailed or less hours in service).

Note that case 3.B) has been presented in MEPC 67/5/4.

In Table 3 the six possible situations are presented that would lead to different signs of the changes of the various indicators.

Table 3 Necessary conditions for the year-to-year percentage changes of the four indicators to have a different sign for a specific ship

1	$\Delta\, distance > \Delta\, fuel\ cons. > \Delta\, hours\ in\ s.$ $0 > \Delta\, fuel\ cons. > \Delta\, hours\ in\ s.$	$\Rightarrow$	Δ DIST and Δ CDIST < 0 Δ TIME > 0 Δ FUEL < 0
2	$\Delta\, distance > \Delta\, fuel\ cons. > \Delta\, hours\ in\ s.$ $\Delta\, distance > \Delta\, fuel\ cons. > 0$	$\Rightarrow$	Δ DIST and Δ CDIST < 0 Δ TIME > 0 Δ FUEL > 0
3	$\Delta\, hours\ in\ s. > \Delta\, fuel\ cons. > \Delta\, distance$ $\Delta\, hours\ in\ s. > \Delta\, fuel\ cons. > 0$	$\Rightarrow$	Δ DIST and Δ CDIST > 0 Δ TIME < 0 Δ FUEL > 0
4	$\Delta\, hours\ in\ s. > \Delta\, fuel\ cons. > \Delta\, distance$ $0 > \Delta\, fuel\ cons. > \Delta\, distance$	$\Rightarrow$	Δ DIST and Δ CDIST > 0 Δ TIME < 0 Δ FUEL < 0
5	$\Delta\, distance > \Delta\, fuel\ cons. > 0$ $\Delta\, hours\ in\ s. > \Delta\, fuel\ cons. > 0$	$\Rightarrow$	Δ DIST and Δ CDIST < 0 Δ TIME < 0 Δ FUEL > 0
6	$0 > \Delta\, fuel\ cons. > \Delta\, distance$ $0 > \Delta\, fuel\ cons. > \Delta\, hours\ in\ s.$	$\Rightarrow$	Δ DIST and Δ CDIST > 0 Δ TIME > 0 Δ FUEL < 0

2.2 Correlation between the year-to-year percentage changes of the indicators

Even if the year-to-year changes of the indicators have different signs for some ships, there could still be a positive correlation for the sample as a whole. This could, for example, be the case when the conditions specified in Table 3 are met by some ships but the conditions in Table 2 for most ships. What the empirical analysis should give in any case is a perfect correlation between the year-to-year percentage changes of DIST and cDIST, since these changes are inherently the same.

As a consequence the empirical data should also give:

1. the same correlation between the year-to-year percentage changes of DIST and FUEL on the one hand and between the year-to-year percentage changes of cDIST and FUEL on the other hand; and
2. the same correlation between the year-to-year percentage changes of DIST and TIME on the one hand and between the year-to-year percentage changes of cDIST and TIME on the other hand have to be the same.

2.3 Impact of speed on indicators

The empirical analysis also evaluates the relation between the change of the annual average speed of the ships and the change of the indicators. What is to be expected?

Starting point of the empirical analysis is to determine the annual average speed of the ships. Since the average service speed of the vessels is not included in the database, the average service speed is approximated by the average speed over ground. The change of the average speed over ground depends on the year-to-year change of the distance sailed and the year-to-year change of the hours in service as follows:

$$\Delta\, distance < \Delta\, hours\ in\ s. \Leftrightarrow \Delta\, average\ speed\ over\ ground < 0$$

$$\Delta\, distance > \Delta\, hours\ in\ s. \Leftrightarrow \Delta\, average\ speed\ over\ ground > 0$$

since $\Delta\, average\ speed\ over\ ground = \frac{(1+\Delta\, distance)}{(1+\Delta\, hours\ in\ service)} - 1.$

Following the logic of slow steaming one would expect the fuel consumption and the energy efficiency of a ship to decline/improve if the ship sails at a lower speed and vice versa for a ship that has sailed at a higher speed.

We know that:

$$\Delta\, fuel\ consumption > \Delta\, hours\ in\ s. \Leftrightarrow \Delta\, USP > 0$$
$$\Delta\, fuel\ consumption < \Delta\, hours\ in\ s. \Leftrightarrow \Delta\, USP < 0$$

and

$$\Delta\, fuel\ consumption > \Delta\, distance \Leftrightarrow \Delta\, AER\ and\ \Delta\, ISPI > 0$$
$$\Delta\, fuel\ consumption < \Delta\, distance \Leftrightarrow \Delta\, AER\ and\ \Delta\, ISPI < 0$$

and

$$\Delta\, fuel\ consumption > 0 \Leftrightarrow \Delta\, FORS > 0$$
$$\Delta\, fuel\ consumption < 0 \Leftrightarrow \Delta\, FORS < 0$$

Therefore, if a ship has sailed at a lower average speed one would expect:
- for TIME: $\Delta\, distance < \Delta\, hours\ in\ s.$ and $\Delta\, fuel\ consumption < \Delta\, hours\ in\ s.$
- for DIST/cDIST: $\Delta\, fuel\ consumption < \Delta\, distance < \Delta\, hours\ in\ s.$
- for FUEL: $\Delta\, distance < \Delta\, hours\ in\ s. \wedge \Delta\, fuel\ consumption < 0$

The empirical analysis could have different results for three reasons:
1. Although the average speed of a ship has decreased/increased, the ship may still have sailed on (parts of) trips at a higher/lower speed, and the effect of the change of the average speed may thus not be straightforward.
2. The average speed over ground may not be a sufficient approximation of the average service speed.
3. To establish the relationship of speed and the indicators, the change of the indicators should be determined for a change of the speed only, i.e. given that the other elements of the ship’s operational profile (like e.g. draft, currents, etc.) do not change - thus a counterfactual analysis.

3 Empirical analysis of operational efficiency

This chapter presents the empirical analysis of the operational efficiency of cargo ships. Section 3.1 presents a description of the data. Descriptive statistics of the year-to-year changes of the data are in Section 3.2, and Section 3.3 analyses the degree to which the different indicators of operational efficiency are correlated. Section 3.4 shows how industry regression curves can be set for all the indicators and analyses how far ships are removed from them. This chapter presents selected graphs and tables for illustrative purposes. The full set of graphs, tables and figures created and used as part of this study can be found in Annex A.

3.1 Description of data

The data received included data sets for 221 ships, for each ship ranging over several years. Almost all data records were complete, apart from the data for thirty of these ships for which the reference speed was unavailable and for one ship for which the hours in service were unavailable. As a result, FUEL and cDIST were calculated for 221 ships, TIME for 220 ships, and DIST for 191 ships.

Most data could be collected from the internal IT systems of the shipping companies. In some cases, the reference speed at 75% MCR was not available. Collection of data on hours in service was not straightforward. Some shipping companies included hours in port, others did not. Some included all the hours of voyages that started in a certain year, so that the total number of hours per year sometimes exceeded 8,760. In this case, the FUEL parameter for those ships was adjusted to the long term average of service hours for that ship.

All the data were checked for internal consistency. Some ships reported fuel consumption figures which were several orders of magnitude larger than could reasonably be expected, this was corrected in consultation with the data providers. Data of ships with exceptionally low or high average speeds (calculated as annual distance sailed divided by annual hours in service) were reported back to the data providers. In some cases, this led to data corrections. Also, since it appeared that hours in service were not reported consistently over the entire sample, we excluded the following cases from the analysis:

- TIME was excluded from the analysis for containerships with an apparent speed below 6 knots;
- TIME was excluded from the analysis for containerships with more than 8,760 service hours above (100% of all hours per year).

Table 4 shows the total number of ships in our dataset for each ship type, and per indicator the number of unique ships for which at least in one year the measure could be calculated.

Table 4 **Ships for which the different measures could be calculated**

Ship type	Number of ships	#FUEL	#cDIST	#DIST	#TIME
Bulk carrier	93	93	93	88	93
Containership	79	79	79	55	79
Tanker	49	49	49	48	48
Total	**221**	**221**	**221**	**191**	**220**

3.2 Year-to-year changes in indicator values

Year-to-year differences are used in this study to analyse the extent to which the four indicators are correlated. This cannot simply be done by analysing the values of the different indicators, because the lack of a baseline, target or reference for all indicators render it impossible to assess the quality of the value (in other words, to assess whether a value signifies an efficient or an inefficient ships). However, assuming that the reference lines or baselines remain constant over time, a decrease in the value of an indicator indicates a decrease in fuel use and emissions (per se or per unit of activity) and therefore an improvement in the score.

Table 5, Table 6 and Table 7 show the descriptive statistics of year-to-year changes of the four indicators and speed for bulkers, container ships and tankers, respectively. In general, the variation in FUEL is larger than of the other indicators, as shown by both the difference between the minimum and the maximum score and the standard deviation of the values. Surprisingly, the opposite is true for the tankers.

The largest year-to-year differences in FUEL occur when the number of hours in service and the distance sailed vary strongly between two years. This could be caused by the ship being inactive for a large part of one year but not in another, e.g. due to dry docking or to the ship being laid-up.

The largest year-to-year differences in DIST, cDIST and TIME occur for bulkers and tankers. The largest changes for containerships are an order of magnitude smaller. This probably reflects the more predictable operational profiles of liner ships. Chemical tankers and product tankers see their indicator values change by hundreds of percents due to large changes in the consumption of MDO/MGO. Variable MDO/MGO use is also a cause for large year-to-year differences for bulkers, but other bulkers in our sample had large changes in activities or simply had changes in fuel consumption that were smaller or larger than changes in distance or hours sailed, perhaps due to being active in different regions or because of different loading conditions.

Although for most ships, the year-to-year variation in FUEL is larger than in the other indicators, for some ships the reverse is the case. The causes are not always clear, but they are often similar to those mentioned in the previous paragraph.

Table 5 **Year-to-year changes of the four indicators for bulkers**

	FUEL	cDIST	DIST	TIME
Number of ships	93	93	93	93
#Data points	170	170	158	170
Min.	-99%	-45%	-45%	-50%
Max.	18298%	1560%	1560%	757%
Average	124%	16.2%	17%	6.0%
Median	-6%	-1%	0%	-4%
St dev.	14.0	1.3	1.3	0.7

Table 6 **Year-to-year changes of the four indicators for container ships**

	FUEL	cDIST	DIST	TIME
Number of ships	79	79	79	79
#Data points	185	185	113	185
Min.	-99%	-29%	-23%	-52%
Max.	11027%	63%	63%	76%
Average	244%	-1%	-1%	-2%
Median	0%	-2%	-2%	-3%
St dev.	13.3	0.1	0.1	0.1

Table 7 **Year-to-year changes of the four indicators for tankers**

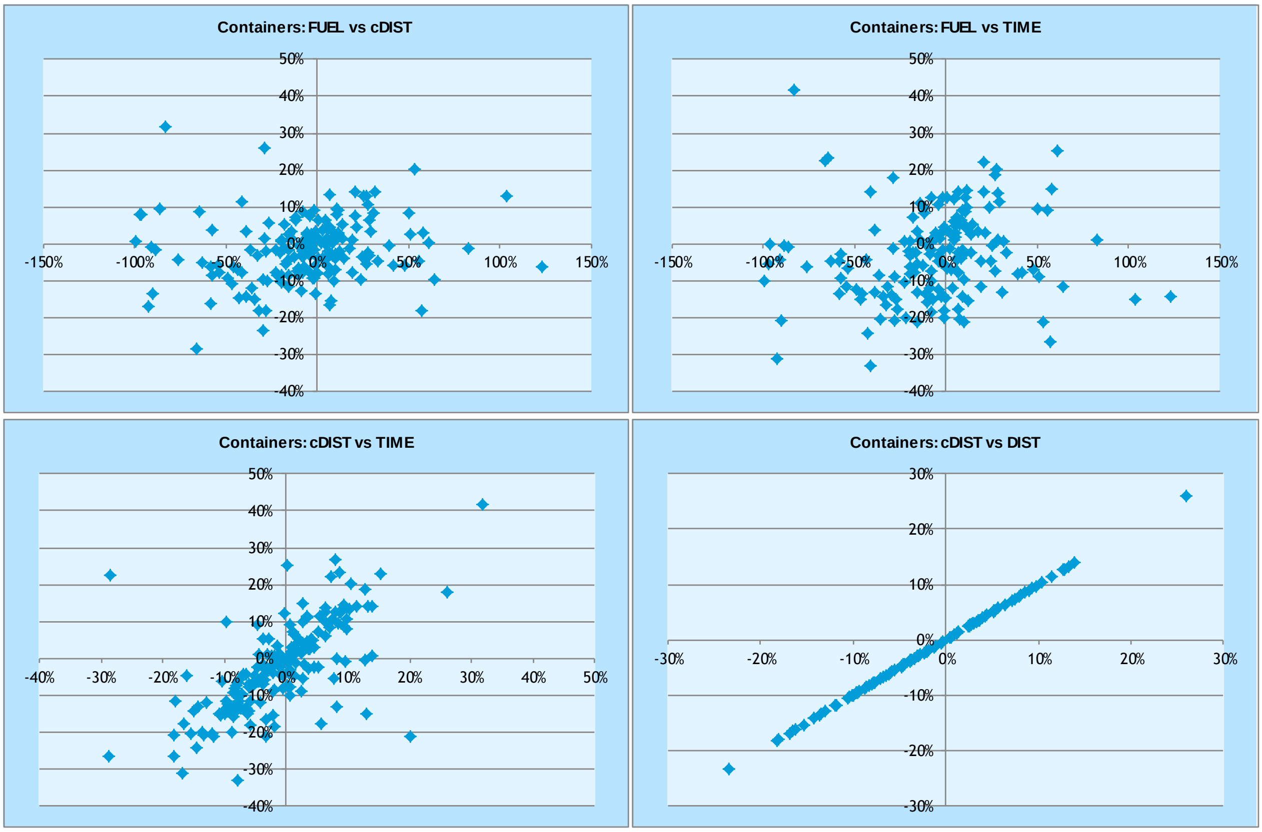
	FUEL	cDIST	DIST	TIME
Number of ships	49	49	49	49
#Data points	134	134	131	133
Min.	-89%	-81%	-81%	-87%
Max.	2084%	3160%	3160%	2530%
Average	68%	71%	72%	71%
Median	-4%	0%	0%	-1%
St dev.	2.6	3.3	3.4	3.1

3.3 Correlation between the year-to-year changes of the four indicators

This section analyses the correlation of the year-to-year changes in the indicators. The sign of the correlation coefficient indicates whether the values move in the same direction or not, i.e. whether an improvement in one indicator generally coincides with an improvement of another.

Figure 1 shows the correlation between the different indicators for container ships. All the correlation coefficients are positive, meaning that an increase in one indicator generally results in an increase in another indicator. As is apparent from the figure, the correlation between cDIST and DIST is perfect, as is to be expected (see Section 2.2). The graphs below also indicate that the correlation between cDIST (or DIST) and TIME is stronger than the correlation of FUEL with either of these indicators.

Figure 1 Correlation between the different indicators for container ships



The probability of these observed correlations being representative for the entire world fleet is indicated as the so-called ‘significance level’.
The significance of the correlation is presented in Table 8, Table 9 and Table 10 for bulkers, container ships and tankers, respectively.

DIST and cDIST are perfectly correlated, as is to be expected. The significance of the correlation between the other indicators varies between ship types. While for bulkers FUEL is not significantly correlated with any other measure, it has a correlation with TIME that is significant at the 5% level for containers, and for both DIST/cDIST and TIME for tankers at 5% and 1% significance level, respectively. DIST/cDIST and TIME are significantly correlated for all ship types at a 1% level. This suggests that the relative efficiency measures are strongly correlated, while the correlation of FUEL with either relative measure is less pronounced.

The following tables also show the significance of the correlation between the indicators and the average annual speed (distance sailed in nm divided by hours in service), which is the only observation we have of which we expect a relation to efficiency. We found different levels of significance for different ship types. None of the indicators was significantly correlated with the average speed for all the ship types in our sample.

Table 8 **Significance of correlation of the indicators for bulkers**

	DIST/cDIST	TIME	SPEED
FUEL	Not significant	Not significant	Not significant
DIST/cDIST		Significant at 1% level	Significant at 5% level
TIME			Not significant

Note: Association was estimated with fixed effects panel data that allows for ship ID specific heteroskedasticity and serial correlation. The table indicates the significance of the coefficient of the independent variable.

Table 9 **Significance of correlation of the indicators for containers**

	DIST/cDIST	TIME	SPEED
FUEL	Not significant	Significant at 5% level	Significant at 10% level
DIST/cDIST		Significant at 1% level	Significant at 1% level
TIME			Significant at 1% level

Note: Association was estimated with fixed effects panel data that allows for ship ID specific heteroskedasticity and serial correlation. The table indicates the significance of the coefficient of the independent variable.

Table 10 **Significance of correlation of the indicators for tankers**

	DIST/cDIST	TIME	SPEED
FUEL	Significant at 5% level	Significant at 1% level	Significant at 1% level
DIST/cDIST		Significant at 1% level	Not significant
TIME			Significant at 1% level

Note: Association was estimated with fixed effects panel data that allows for ship ID specific heteroskedasticity and serial correlation. The table indicates the significance of the coefficient of the independent variable.

3.4 Regression curves

This section calculates regression curves for each of the indicators and analyses to which extent these curves could be used as a reference curve, i.e. a basis to develop an emissions target for an operational efficiency standard.

This section analyses whether regression curves can be established that are:
- stable over time and do not change significantly depending on the particular year(s) in which the data were collected;
- useful as a basis for a ship-specific target, meaning that a target can be set that can reasonably be achieved by most, if not all, ships, yet results in an average improvement of efficiency.

3.4.1 cDIST regression curves

Figure 2 shows the cDIST industry regression curves for specific years and for all years combined for tankers. For bulkers and container ships, the regression curve is relatively insensitive to the choice of the year or years. However, this is not the case for our sample of tankers. The choice of 2013 as a reference year would yield a very different regression curve than the choice of other years. A 2014 regression curve looks more similar to a 2010, 2011 or 2012 regression curve, but the differences for smaller ships can be large.

Figure 2 **cDIST industry regression curves for tankers**

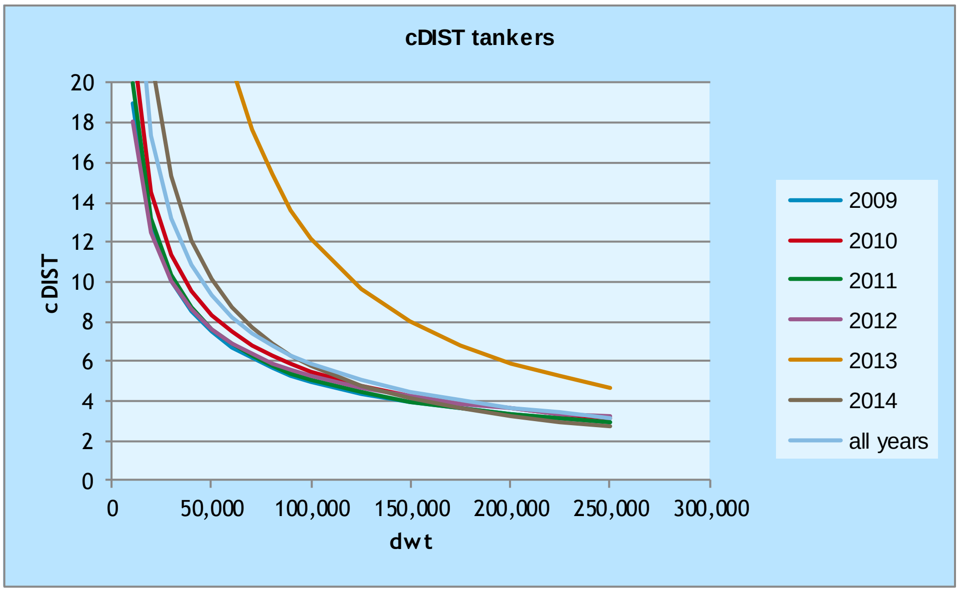


Table 11 presents the data for the tanker regression curves, as well as the number of observations that were used to calculate the curves and the coefficient of determination (R^2).[1] If an efficiency target was based on the regression curve, and assuming that ships can improve their operational performance by a certain percentage at most, a low R^2 could indicate that more ships would have difficulties to comply with the standard, as their efficiency lies too far from the curve.

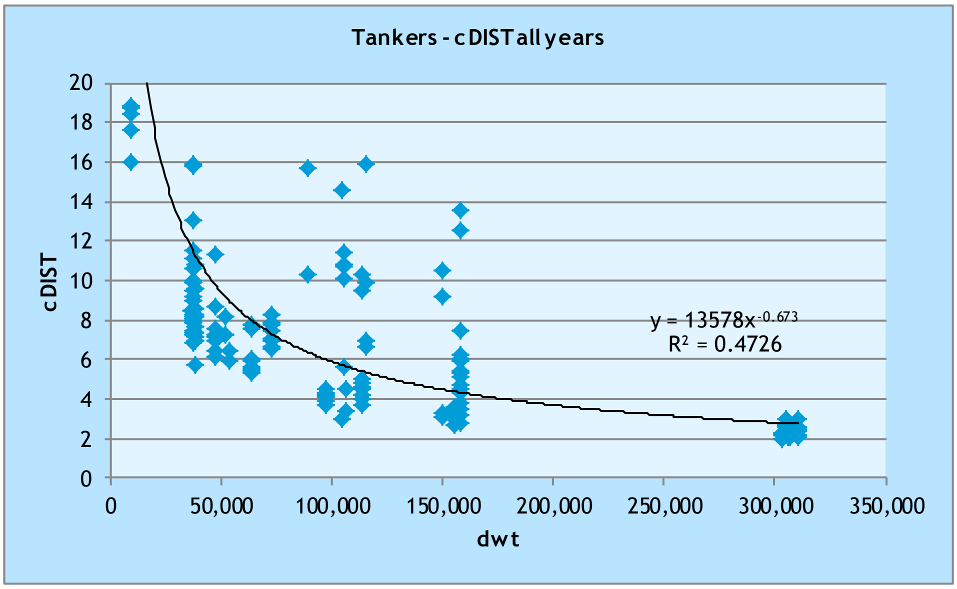
Table 11 **cDIST industry regression curve data for tankers with the formula cDIST = a.dwt^b**

	2010	2011	2012	2013	2014	All years
#data points	25	32	32	38	39	17
a	3967.3	5684	4988	2593.4	2000000	68942
b	-0.58	-0.603	-0.599	-0.539	-1.043	-0.816
R^2	0.837	0.4935	0.8244	0.5171	0.515	0.6026

Figure 3 graphically shows how the observations for bulkers relate to the regression curve.

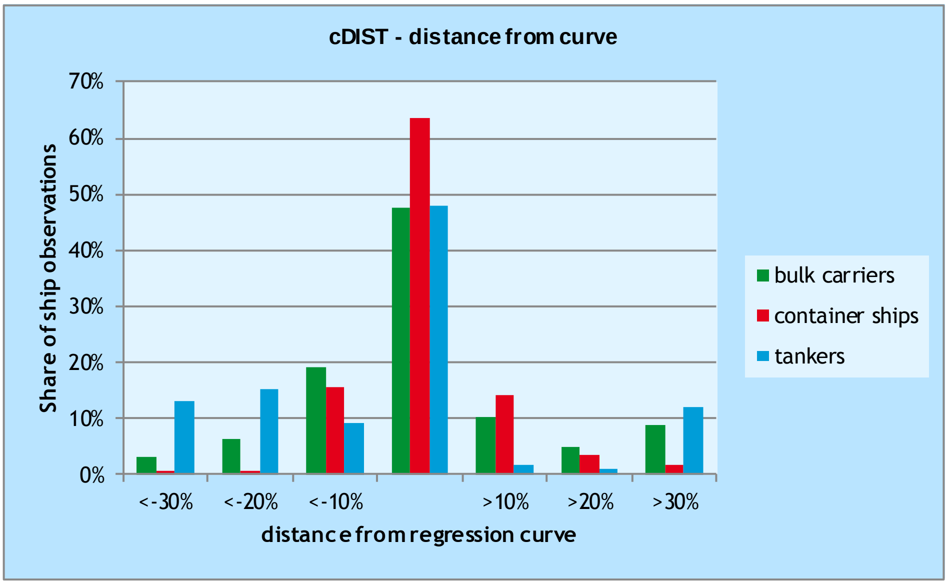
1 The coefficient of determination expresses the magnitude of deviation between the regression curve and the actual observations. The higher the value of R^2, the closer the observations are to the regression curve. If all the observations are on the curve, R^2 equals 1.

Figure 3 Average cDIST industry regression curve and cDIST values for tankers



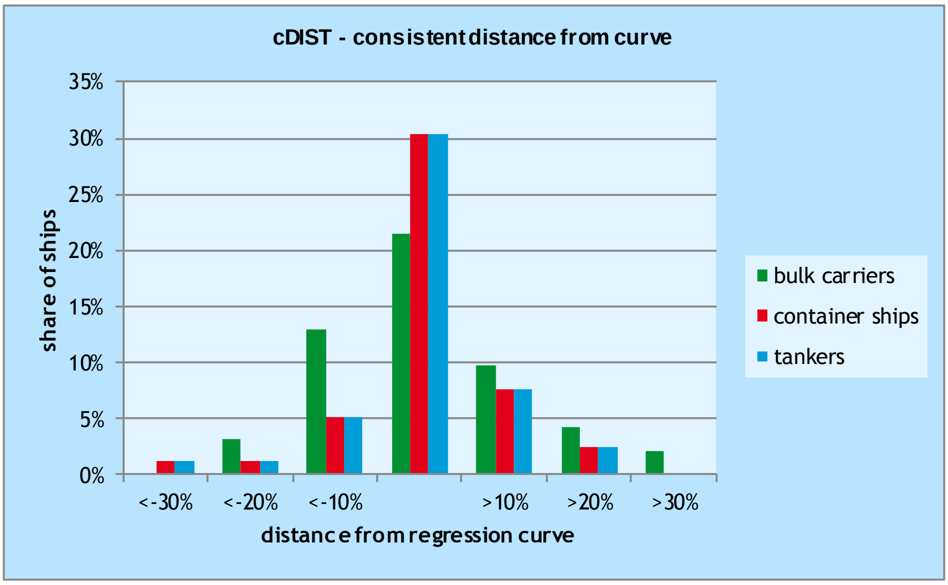
The further the ships find themselves above the regression curve, the more they will need to change their operational profiles to meet a target based on this curve. Similarly, the larger the share of ships well below the regression curve, the smaller the impact of a regression curve-based target on emissions, as ships that are well below the regression curve will not be required to change their operations in order to meet the target. Figure 4 shows the share of observations that is within a given distance from the regression curve. Over 60% of container ships, but less than 50% of the observations on bulkers and tankers are within a band from 10% below to 10% above the regression curve; just a few percent of container observations but approximately 10% of bulker and tankers are more than 30% above the regression curve.

Figure 4 Distance of observations of cDIST to regression curve



Ships that are consistently well above the regression curve may not be able to reach a target, while ships that are consistently below the regression curve may not be affected by an operational target and therefore not reduce their emissions as a result of it. Figure 5 shows that 8% of the container ships and tankers in our sample and 10% of the bulkers were at least 10% above the regression curve in every year in which they were observed.

Figure 5 Consistent distance of cDIST observations from the regression curve



3.4.2 TIME regression curves

The regression curve for TIME, which expresses efficiency in joules of energy per hour in service, slopes upward, as can be seen in Figure 6. In comparison to cDIST, the regression curves are more dependent on the choice of the reference year. Figure 6 shows that for capesize bulkers (175,000 dwt and above), the choice of reference year can make a difference of 20% in the regression curve. Note that for these ships and for container ships, the variation is larger for larger ships, in contrast to the cDIST regression curves, where the variation was larger for smaller ships.

Figure 6 **TIME industry regression curves for bulkers**

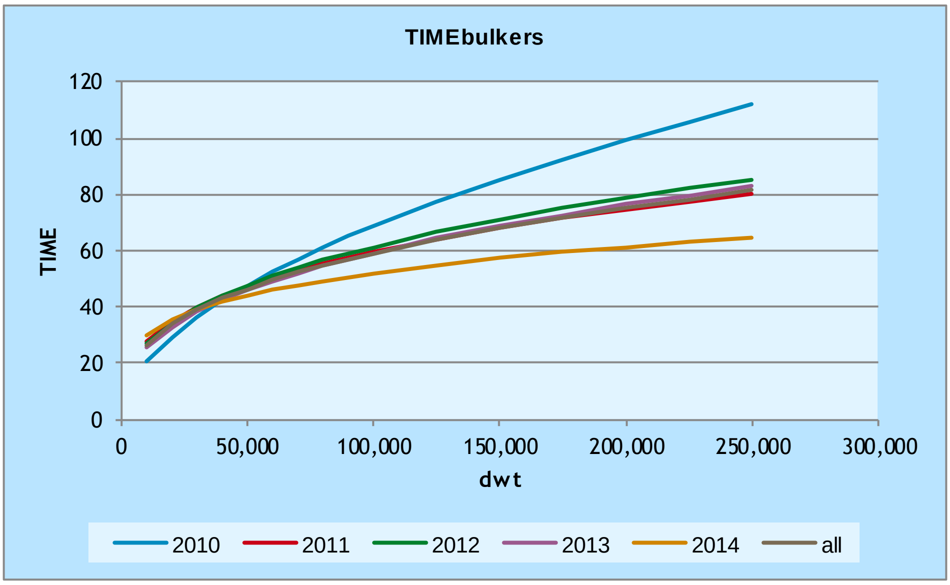


Table 12 presents the data for the TIME regression curves for bulkers, as well as the number of observations on which the lines are based and the coefficient of determination (R^2). The tables show that R^2 is larger for container ships than for tankers and bulkers.

Table 12 **TIME industry regression curve data for bulkers**

	2010	2011	2012	2013	2014	All years
#data points	15	40	75	87	41	263
a	0.1543	1.317	0.9746	0.867	3.3176	1.0779
b	0.5299	0.3307	0.3597	0.3669	0.239	0.3479
R^2	0.3478	0.1204	0.4632	0.2867	0.1447	0.2549

Figure 7 shows the average regression curves and the TIME values for all bulkers in our sample. The distance from the regression curve increases for the largest ships.

Figure 7 **Average TIME industry regression curve and TIME values for bulkers**

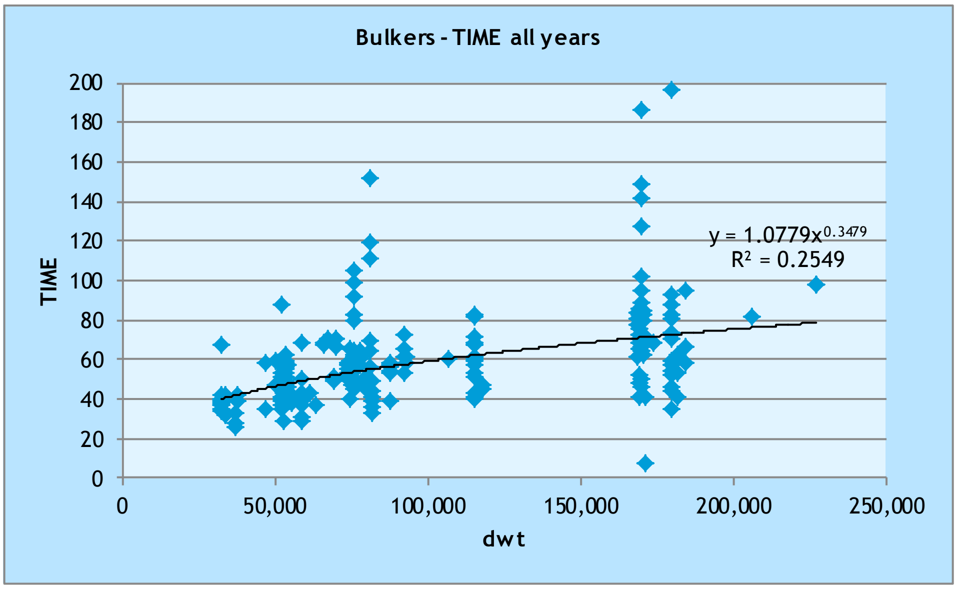


Figure 4 shows the distance of the observations to the regression curve. About 40% of the observations are within 10% from the regression curve; a little over 5% percent of container observations but over 10% of bulkers and 15% of tankers are more than 30% above the regression curve.

Figure 8 **Distance of TIME observations to regression curve**

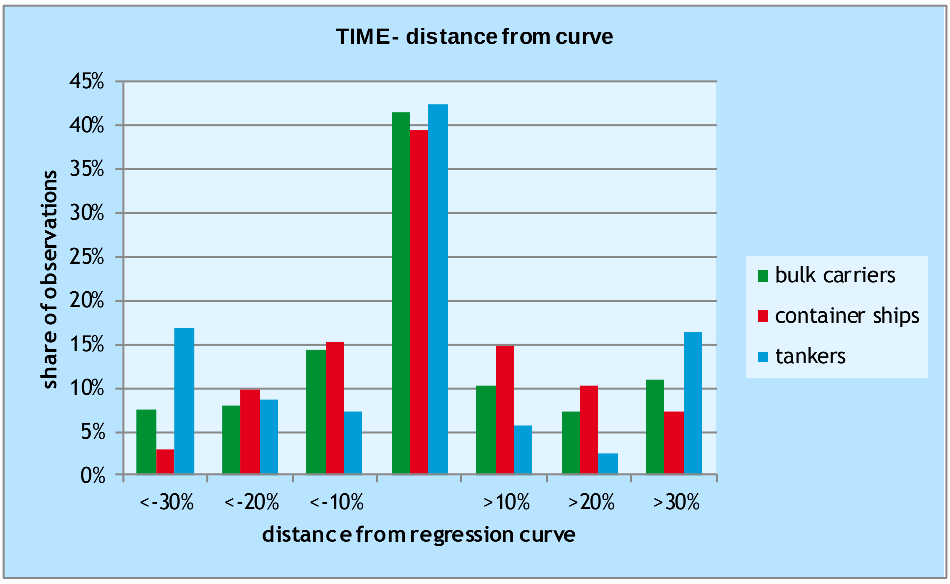
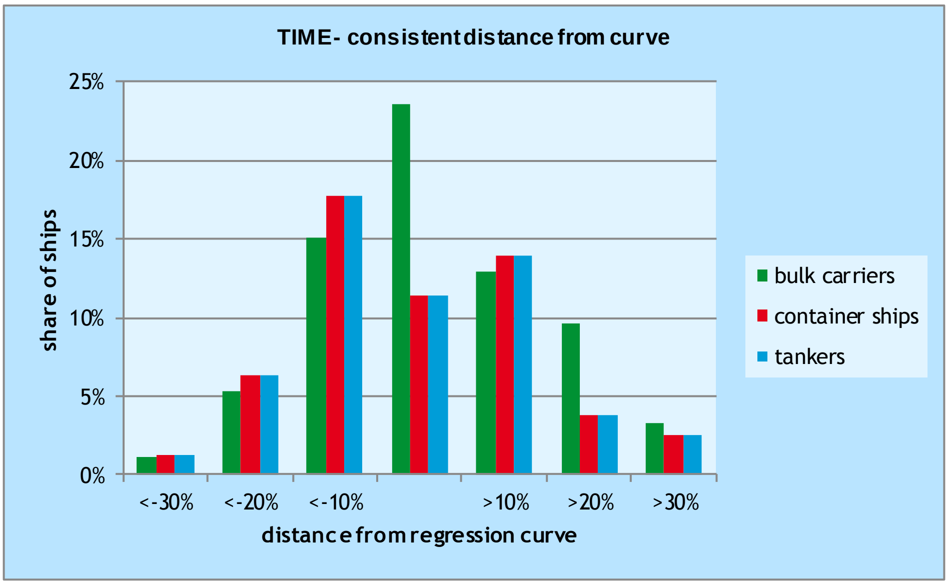


Figure 5 shows that between 13% and 14% of the ships in our sample (depending on their ship type) were at least 10% above the regression curve in every year in which they were observed. Between 15% and 18% of the ships were more than 10% below the curve.

Figure 9 Consistent distance of TIME observations from the regression curve



3.4.3 FUEL regression curves

The FUEL indicator regression curve could be based on fuel consumption estimates from existing studies, such as the 2nd IMO GHG Study (Buhaug et al., 2009) or it could be constructed in a similar way as the cDIST and TIME regression curve. Figure 10 shows what the empirical regression curves would look like. Both curves are based on the observations of the FUEL indicator for bulkers in our sample. One of the curves is a power function, but a logarithmic curve has a stronger correlation with the data.

Figure 10 FUEL industry regression curves for bulkers

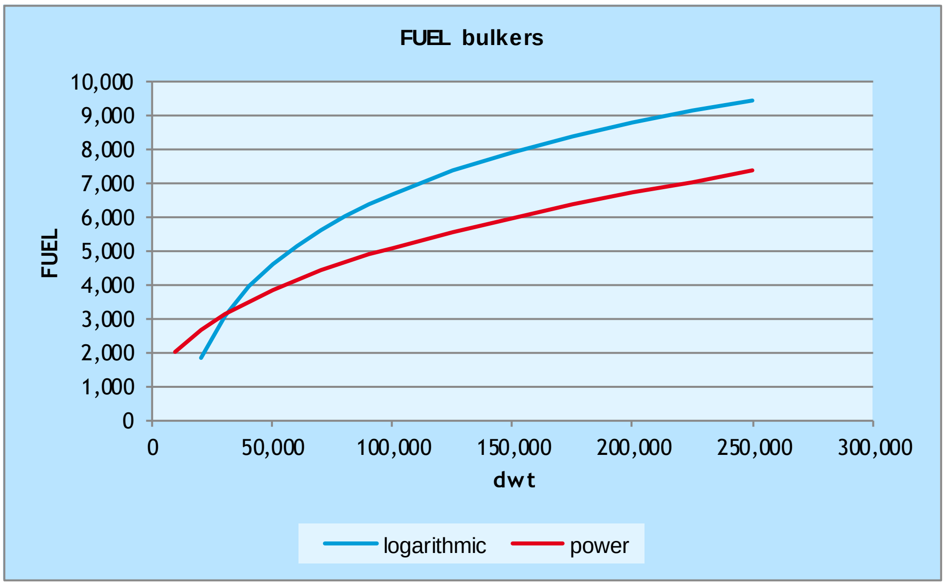


Table 13 presents the data for the FUEL regression curves for both power curves and logarithmic curves, as well as the number of observations on which the lines are based and the coefficient of determination (R^2). The tables show that R^2 is larger for the logarithmic curves.

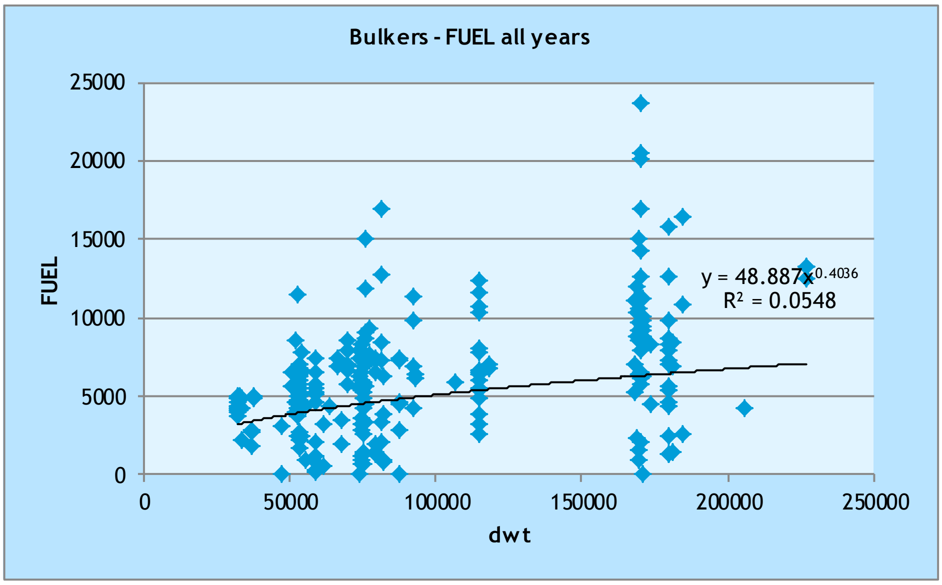
Table 13 **FUEL industry regression curve data**

	Bulker		Container ship		Tanker	
	Logarithmic	Power	Logarithmic	Power	Logarithmic	Power
# data points	263	263	264	264	183	183
a	3023.3	48.887	10273	2.316	4088.8	49.117
b	28096	0.4036	92889	0.8063	36279	0.446
R^2	0.1864	0.0548	0.4976	0.2766	0.211	0.2059

Note: The logarithmic function has the formula y = a.ln(dwt) – b; the power curve has the formula $y = a.dwt^b$.

Figure 11 shows the average regression curve and the FUEL values for all bulkers in our sample. There is a considerable spread in the observations.

Figure 11 **Average FUEL industry regression curves and FUEL values for bulkers**



The distribution of observations of FUEL in our sample around the regression curve are more disperse than in the cDIST and TIME indicators, as is shown in Figure 12. The very low values are ships that had little activity during the year in which they have been observed. The number of values far above the regression curve is large because the curve is lowered by the ships that have very low fuel consumption in some years.

Figure 12 Distance of FUEL observations to regression curve

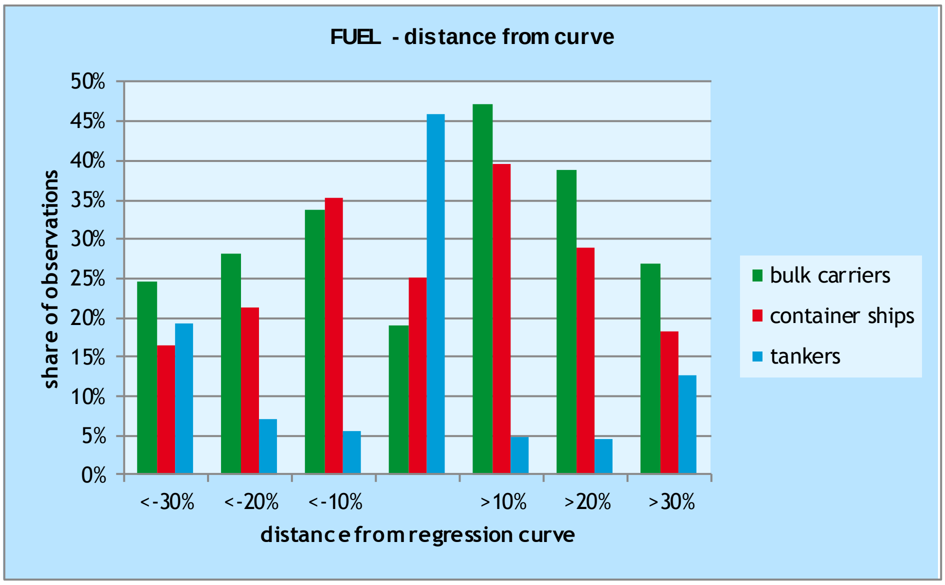
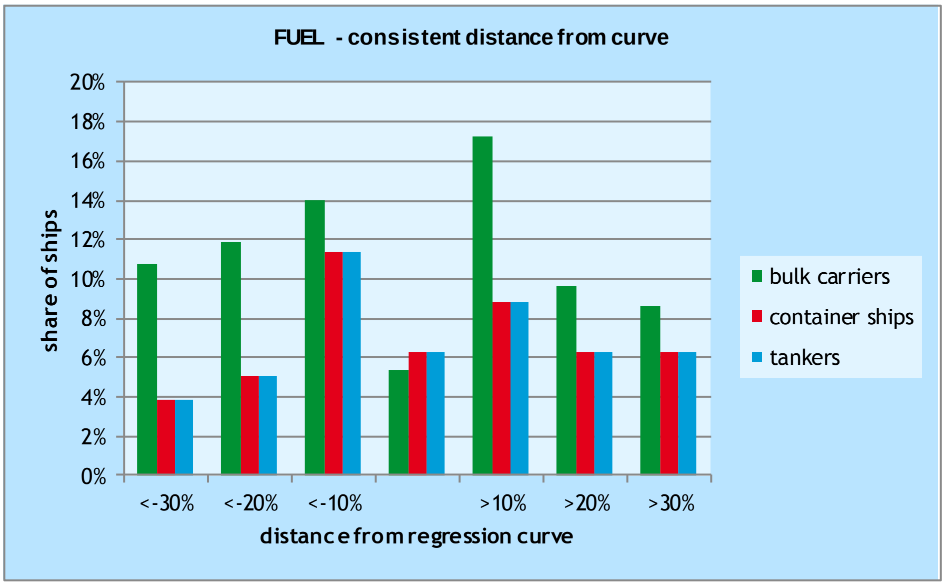


Figure 13 shows that the share of ships that are far above or far below the regression curve in all years is much smaller than the share of ships that are far above or below the line in any year.

Figure 13 Consistent distance of FUEL observations from the regression curve



4 Discussion of results

4.1 Feasibility of setting an operational efficiency target using any of the four indicators

It is generally possible to calculate industry regression curves that could be used to set an operational efficiency target. As curves vary from year to year, a target would ideally be based on several years of observations.

In order to be effective, an operational efficiency standard would need to induce operational changes on ships or encourage them to make technical retrofits that improve efficiency. For ships close to their target value, the changes would be relatively smaller than for ships that are further above their target.

Ships that are more efficient then would be required, would not be incentivised to change operations or ship design. Hence, when the share of ships that are much more efficient than the regression curve is larger, the effectiveness of standard is smaller.

For all indicators analysed in this report, a significant share of the observations is more than 10% above industry regression curves. Even for cDIST, where the observations are relatively closest to the curve, 5-12% of ships (depending on the ship type) are more than 10% below curve, and 10-25% are more than 10% above the curve. For the other indicators, the shares are higher.

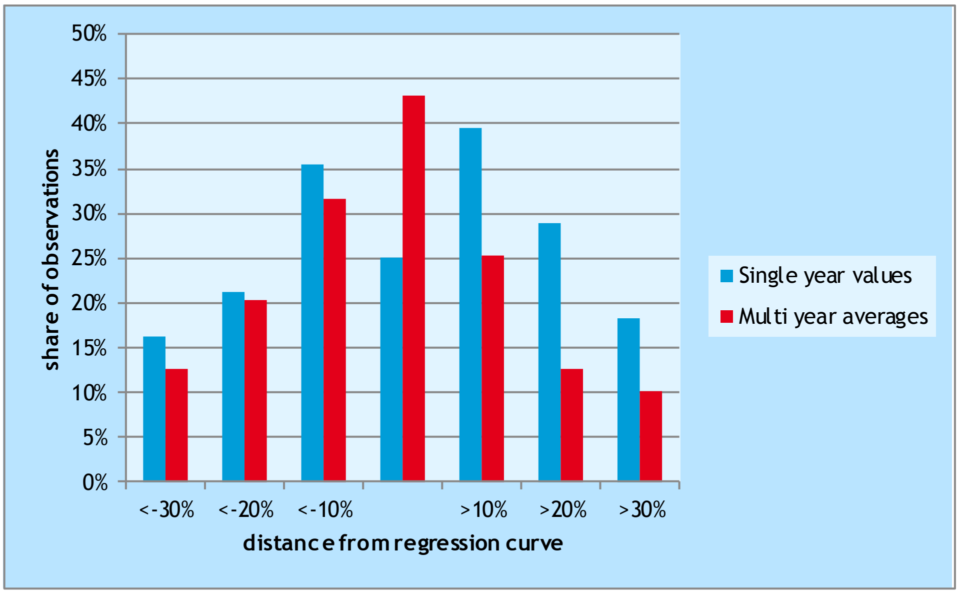
4.2 Possible flexibility mechanisms

For all indicators, the year-to-year variations are often large, especially for bulkers and tankers. The variations are largest for FUEL, but also for cDIST/DIST and TIME. Large year-to-year variations in one indicator are not necessarily reflected in other indicators. Our data sample includes ships with year-to-year variations of several hundreds of percents for one indicator, but nor for one of the other two. The most likely cause is a sudden change in the operational pattern of a ship.

To avoid that ships cannot meet a set efficiency target, flexibility mechanisms may be needed. These could involve pooling compliance for several ships, averaging compliance over several years, or even other mechanisms.

Figure 14 shows an example of the impact of averaging across years on compliance. The blue columns indicate the share of observations of FUEL of container ships that are more than 10%, 20% and 30% above or below the regression curve *in any year*. The red columns indicate the share of ships that are *on average* so far removed from the curve. When multi-year averages are used instead of values for a single year, the share of ships close to the regression curve increases considerably, while the share ships on extreme sides of the regression curve is much smaller.

Figure 14 The impact of averaging on compliance (FUEL, container ships)



5 Conclusions

The analysis suggests that the four indicators are related, but the relations are not always significant. In general, an improvement in one indicator coincides with an improvement in another indicator. However, while for some specific indicator pairs and specific ship types, the relation is statistically significant, for other indicator pairs and ship types it is not. cDIST/DIST and TIME are significantly correlated for all ship types, but the correlation of FUEL with either of the two other indicators is significant for some ship types but not for others. The average annual speed of ships is significantly correlated with either indicator for some ship types, but not for all ship types.

The study calculates size-dependent regression curves for the cDIST/DIST, TIME and FUEL indicators, based on the best fit curve through the observations. The variation of observations around the curve is smallest for cDIST, and largest for FUEL.

In principle, a regression curve can serve as a basis for ship-specific targets. The effectiveness of such targets in improving efficiency depends on the share of ships that is above the curve, but not too far removed from it. For these ships, it is conceivable that changes in operations could result in indicator values at or below the target. Ships that score consistently better than a target will not be incentivised to change their operations.

4-11% of ships (depending on ship type) are more than 20% below the FUEL regression curve in every observed year; 5-6% more than 20% below the TIME curve and 1-3% more than 20% below the cDIST curve.

It is conceivable that ships for which the indicator is far above a target in every year cannot change their operational pattern sufficiently to meet the target.

Within the sample of ships analysed in this study, 8-19% of ships (depending on ship type) are consistently more than 20% above the FUEL regression curve (depending on ship type), 4-10% are more than 20% above the TIME curve and 3-4% are more than 20% above the cDIST curve.

Annex A Graphs and tables

This Annex includes the full set of graphs and tables on the correlation between year-to-year changes of the indicators and on regression curves. Some of the graphs and tables are included in Sections 3.3 and 3.4 of the main report. For an introduction of the graphs and tables, please refer to those sections. By including all graphs and tables in this Annex, we hope to facilitate their comparison.

A.1 Correlation between year-to-year changes

Figure 15 Correlation between the different indicators for bulkers

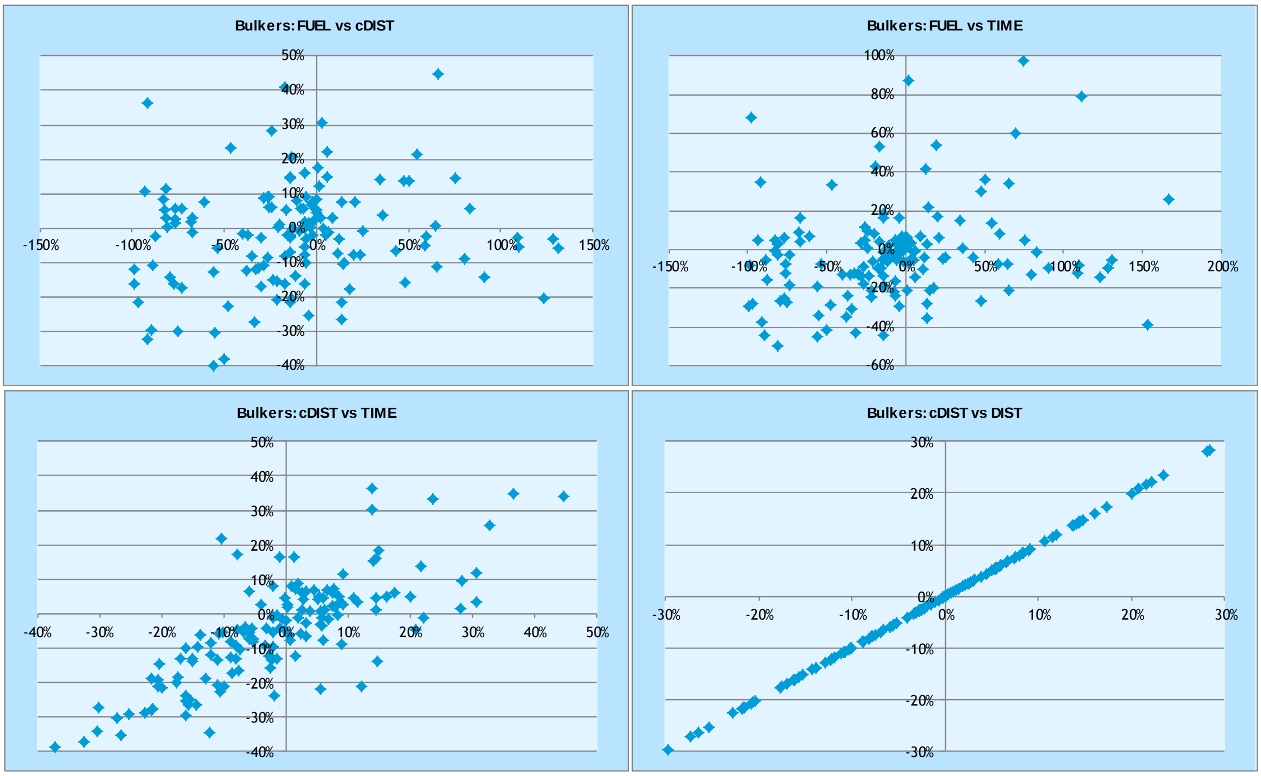


Figure 16 Correlation between the different indicators for container ships

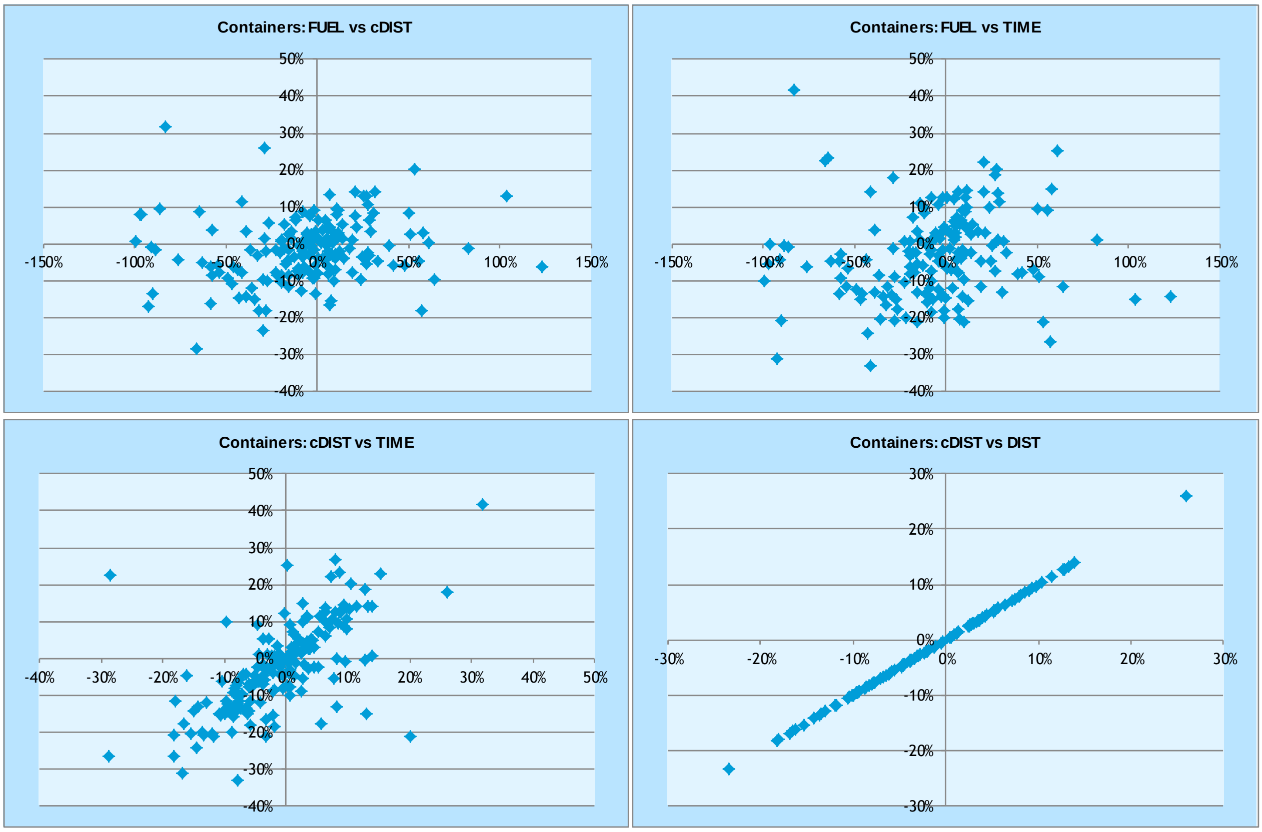


Figure 17 Correlation between the different indicators for tankers

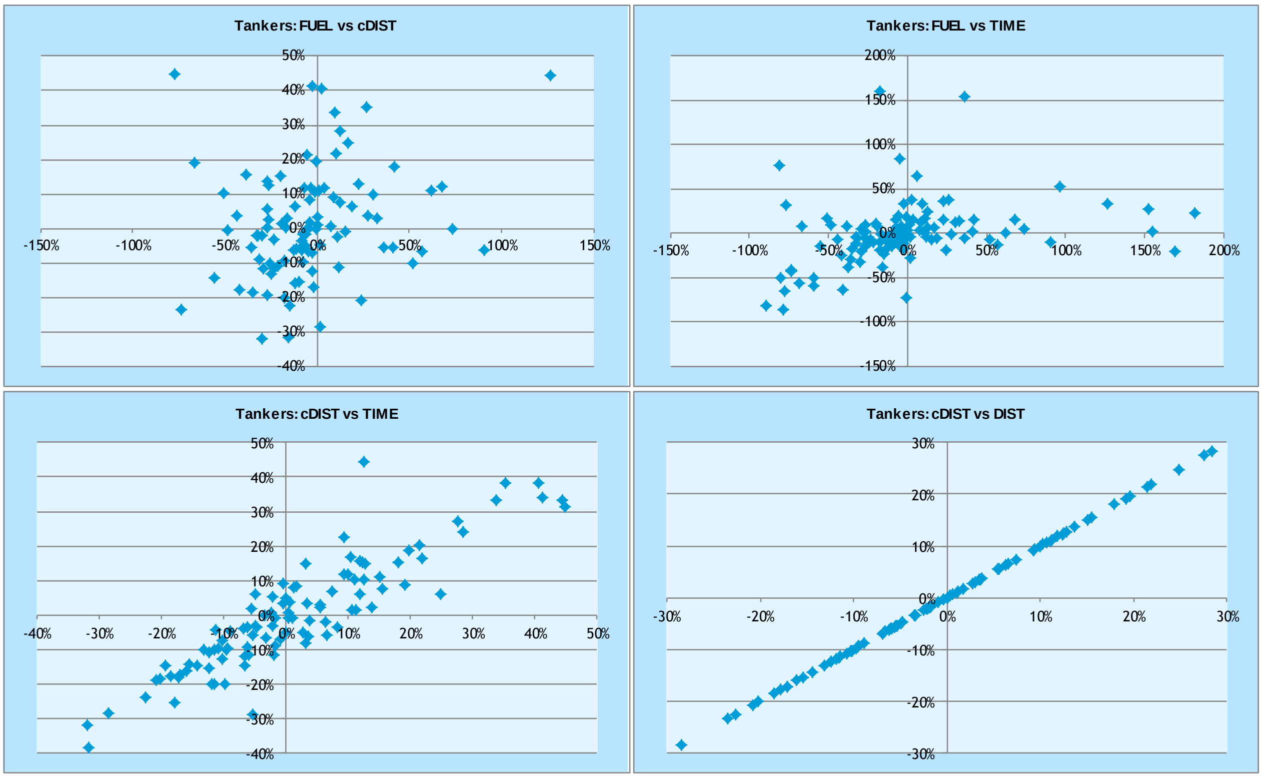


Table 14 Correlation coefficients between year-to-year changes of different indicators for bulkers

	cDIST	DIST	TIME
FUEL	0.92	0.92	0.78
cDIST		1.00	0.96
DIST			0.96

Table 15 Correlation coefficients between year-to-year changes of different indicators for container ships

	cDIST	DIST	TIME
FUEL	0.10	0.10	0.11
cDIST		1.00	0.74
DIST			0.74

Table 16 Correlation coefficients between year-to-year changes of different indicators for tankers

	cDIST	DIST	TIME
FUEL	0.28	0.28	0.35
cDIST		1.00	0.98
DIST			0.98

A.2 Regression curves

A.2.1 cDIST

Figure 18 cDIST industry regression curves for bulkers

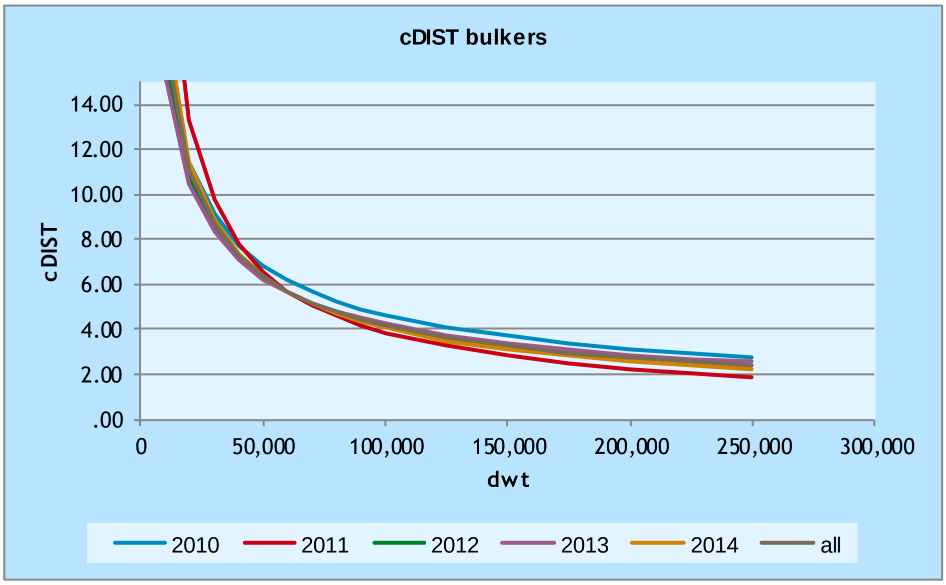


Table 17 cDIST industry regression curve data for bulkers with the formula cDIST = $a.dwt^b$

	2010	2011	2012	2013	2014	All years
#data points	15	40	75	87	41	263
a	2897	27639	3599.8	2621.7	6967	4675.3
b	-0.559	-0.771	-0.587	-0.558	-0.647	-0.61
R^2	0.3643	0.3626	0.7405	0.5031	0.6241	0.5134

Figure 19 Average cDIST industry regression curve and cDIST values for bulkers

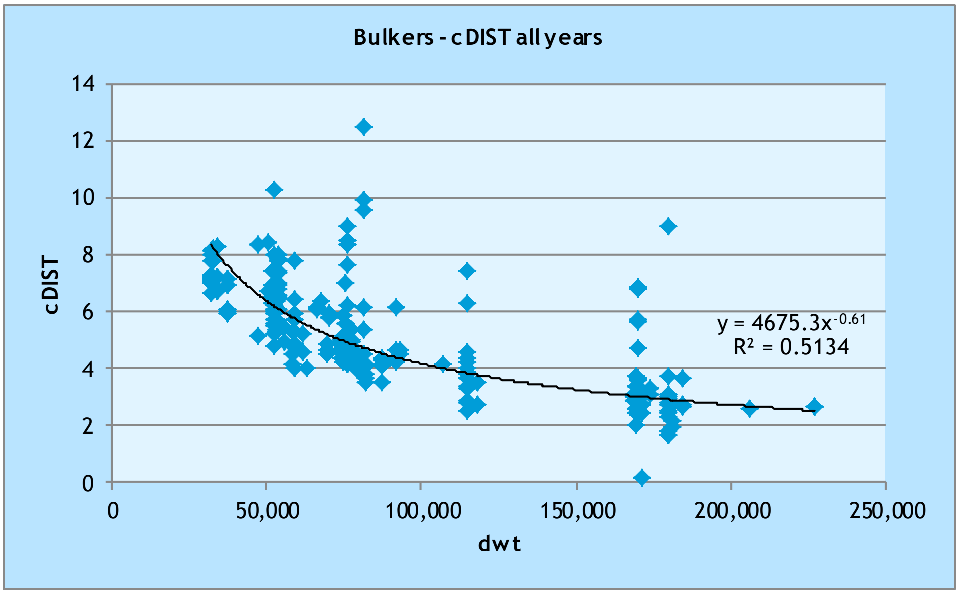


Figure 20 cDIST industry regression curves for container ships

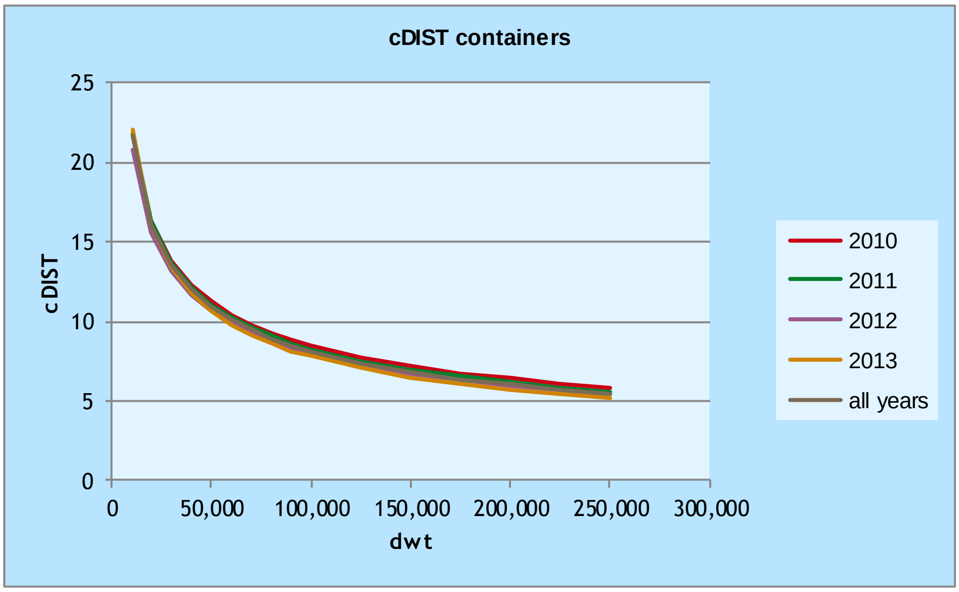


Table 18 cDIST industry regression curve data for container ships with the formula cDIST = $a.dwt^b$

	2010	2011	2012	2013	All years
#data points	55	54	76	75	264
a	910.18	1064.9	941.01	1401.9	1119
b	-0.406	-0.422	-0.414	-0.451	-0.428
R^2	0.791	0.8247	0.7545	0.8795	0.8119

Figure 21 Average cDIST industry regression curve and cDIST values for container ships

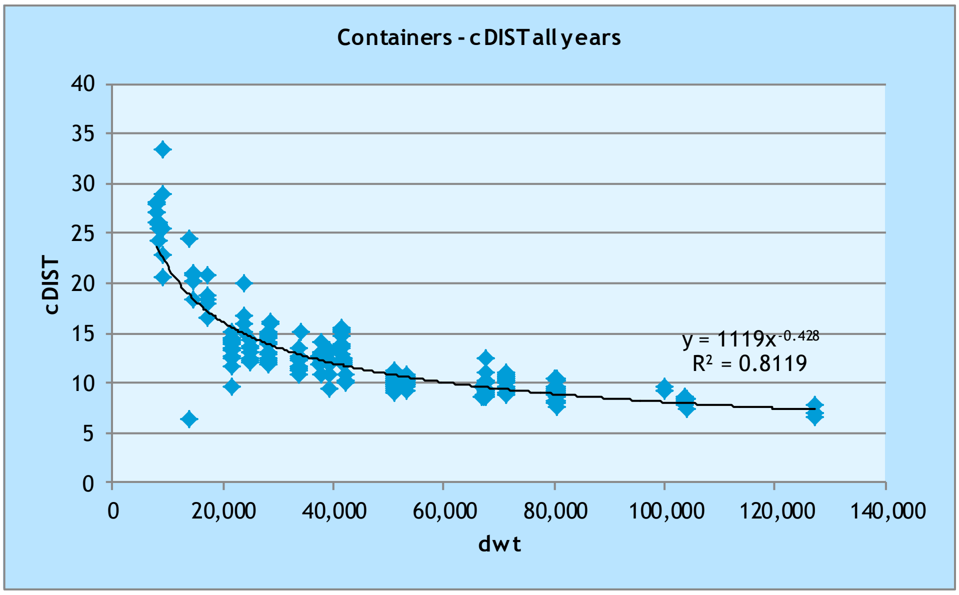


Figure 22 cDIST industry regression curves for tankers

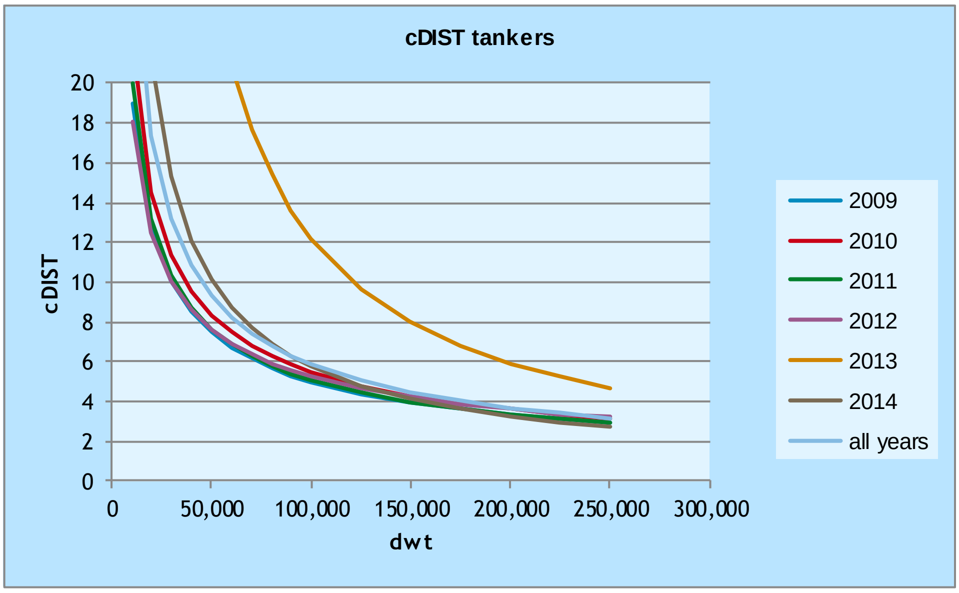
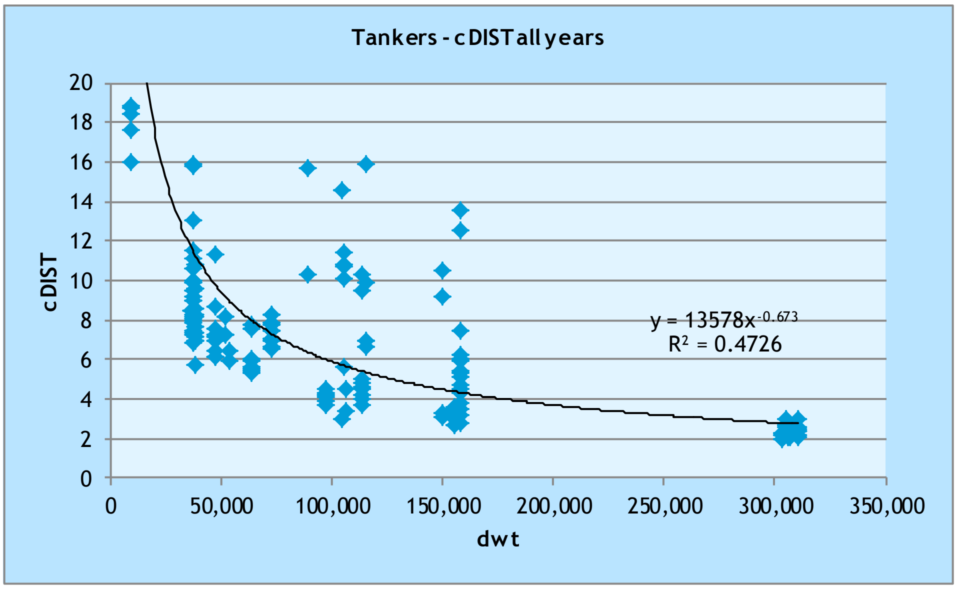


Table 19 cDIST industry regression curve data for tankers with the formula cDIST = $a.dwt^b$

	2009	2010	2011	2012	2013	2014	All years
#data points	25	32	32	38	39	17	183
a	3967.3	5684	4988	2593.4	2000000	68942	13578
b	-0.58	-0.603	-0.599	-0.539	-1.043	-0.816	-0.673
R^2	0.837	0.4935	0.8244	0.5171	0.515	0.6026	0.4726

Figure 23 Average cDIST industry regression curve and cDIST values for tankers



A.2.2 TIME

Figure 24 TIME industry regression curves for bulkers

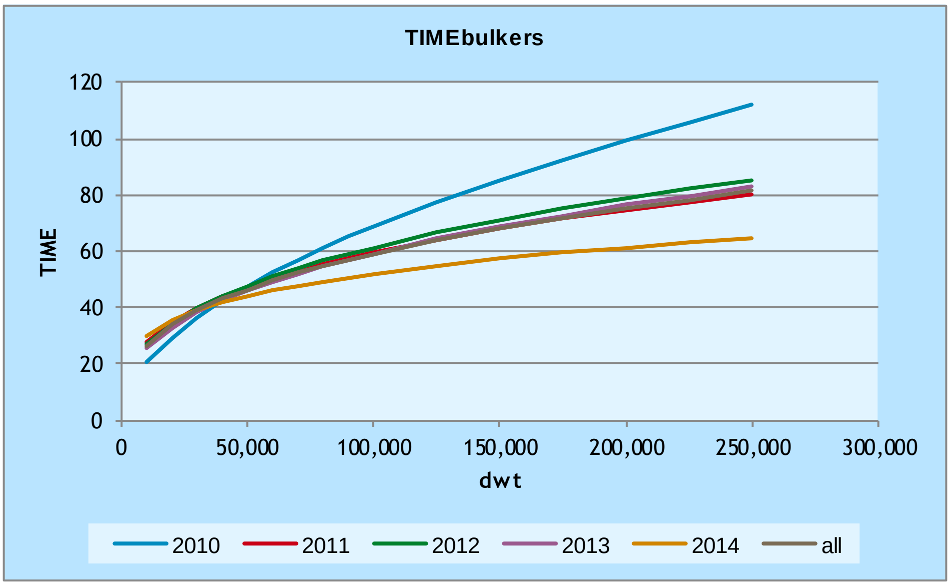


Table 20 TIME industry regression curve data for bulkers

	2010	2011	2012	2013	2014	All years
#data points	15	40	75	87	41	263
a	0.1543	1.317	0.9746	0.867	3.3176	1.0779
b	0.5299	0.3307	0.3597	0.3669	0.239	0.3479
R^2	0.3478	0.1204	0.4632	0.2867	0.1447	0.2549

Figure 25 Average TIME industry regression curve and TIME values for bulkers

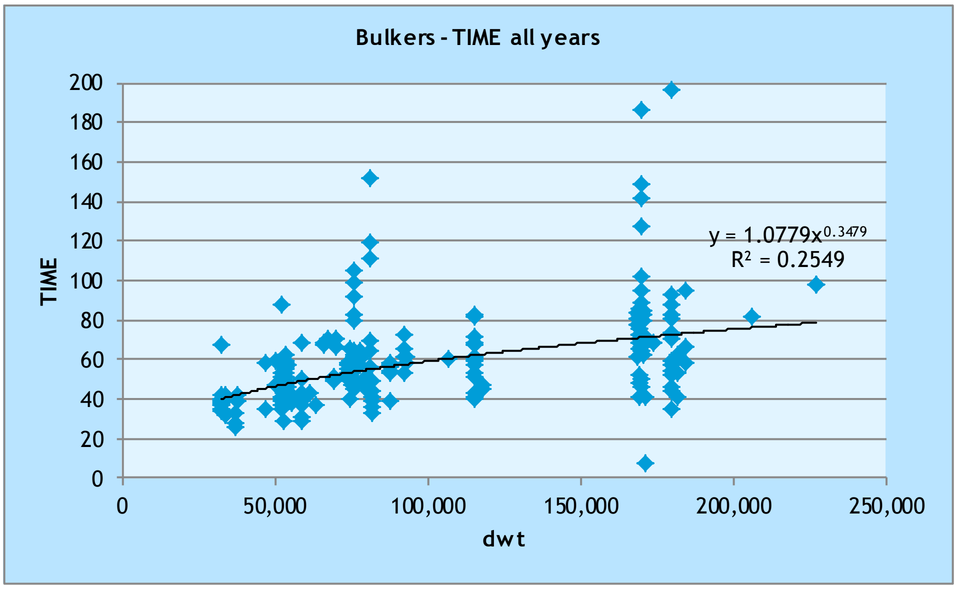


Figure 26 TIME industry regression curves for container ships

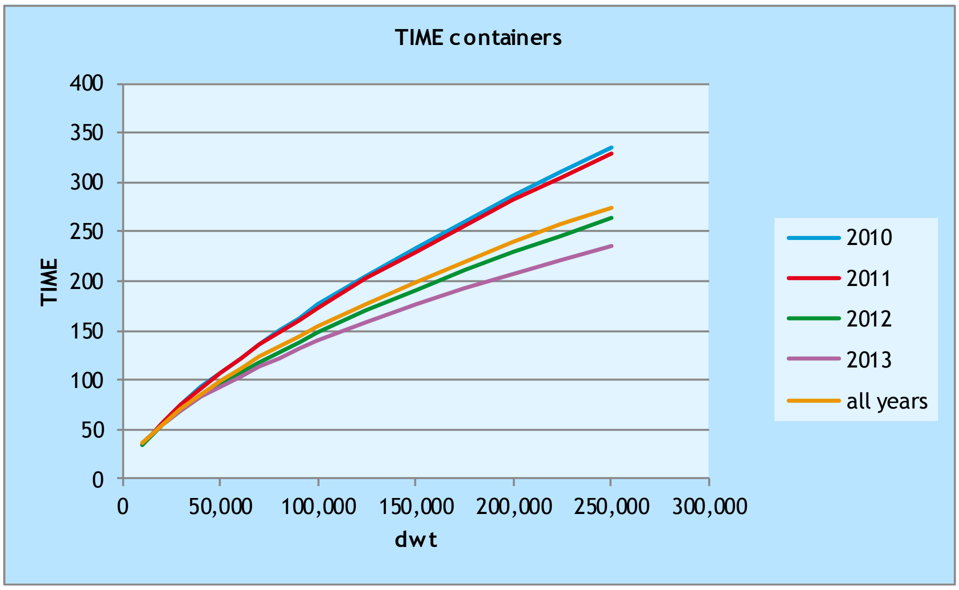


Table 21 TIME industry regression curve data for container ships with the formula TIME = $a.dwt^b$

	2010	2011	2012	2013	All years
#data points	55	54	76	75	264
a	0.0538	0.056	0.1065	0.1896	0.1049
b	0.7028	0.6982	0.6286	0.5732	0.6333
R^2	0.8255	0.8889	0.7728	0.8115	0.8016

Figure 27 Average TIME industry regression curve and TIME values for container ships

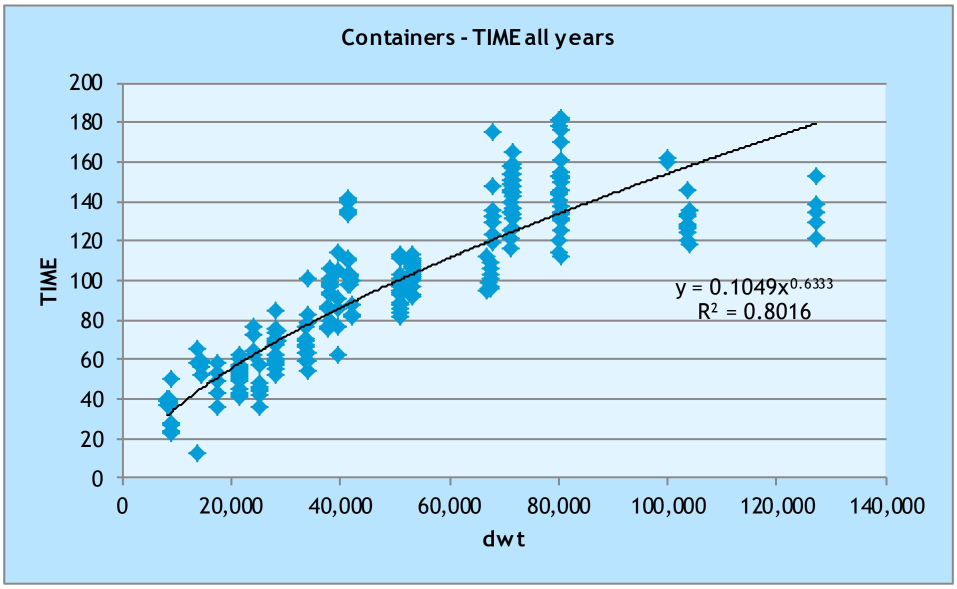


Figure 28 TIME industry regression curves for tankers

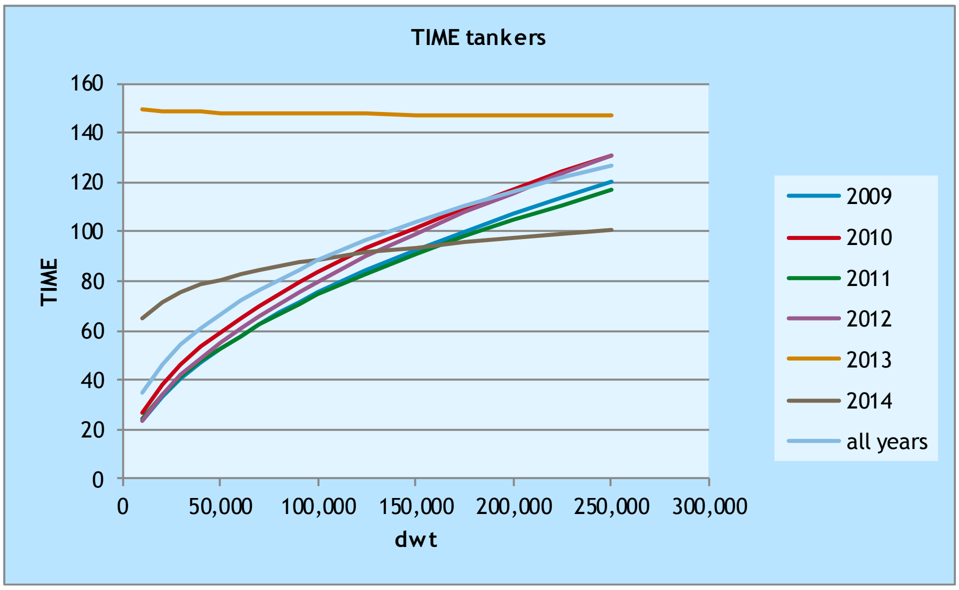
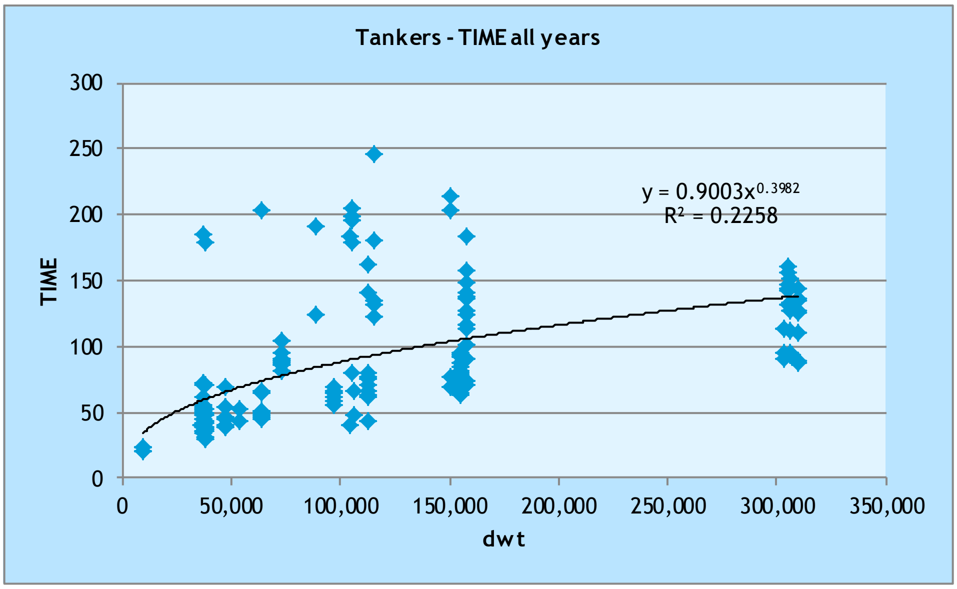


Table 22 TIME industry regression curve data for tankers with the formula TIME = a.dwt^b

	2009	2010	2011	2012	2013	2014	Tanker
#data points	25	32	32	37	38	17	181
a	0.2108	0.3011	0.2617	0.168	156.38	18.544	0.9003
b	0.5105	0.4886	0.4908	0.5354	-0.005	0.136	0,3982
R^2	0.834	0.353	0.6932	0.4731	3.00E-05	0.035	0,2258

Figure 29 Average TIME industry regression curve and TIME values for tankers



A.2.3 FUEL

Figure 30 FUEL industry regression curves for bulkers

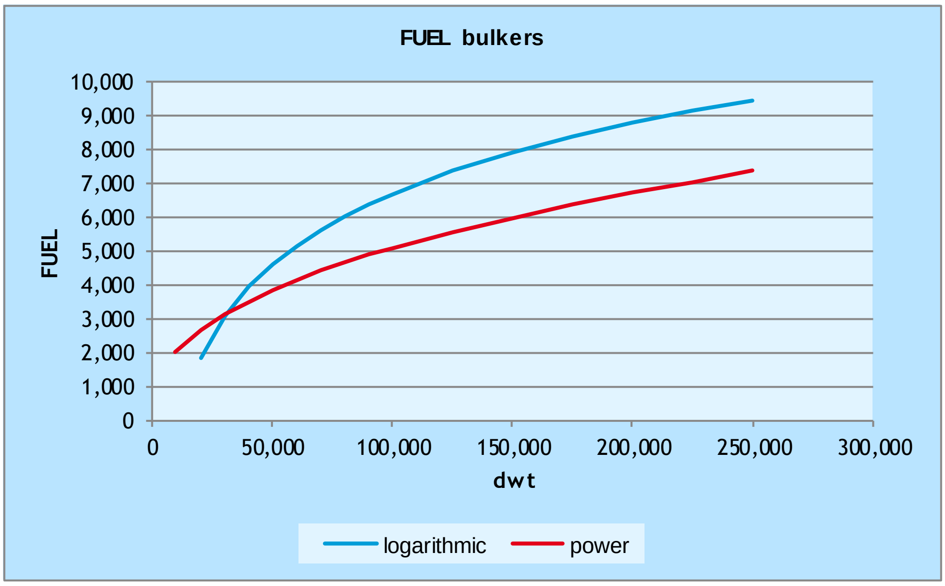


Table 23 FUEL industry regression curve data

	Bulker		Container ship		Tanker	
	Logarithmic	Power	Logarithmic	Power	Logarithmic	Power
# data points	263	263	264	264	183	183
a	3023.3	48.887	10273	2.316	4088.8	49.117
b	28096	0.4036	92889	0.8063	36279	0.446
R^2	0.1864	0.0548	0.4976	0.2766	0.211	0.2059

Note: The logarithmic function has the formula y = a.ln(dwt) - b; the power curve has the formula $y = a.dwt^b$.

Figure 31 Average FUEL industry regression curves and FUEL values for bulkers

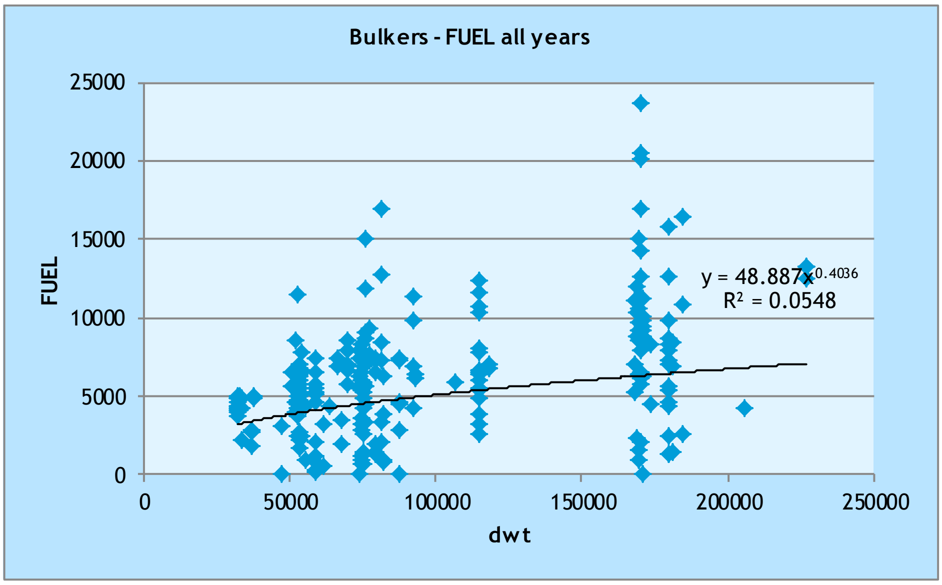


Figure 32 FUEL industry regression curves for container ships

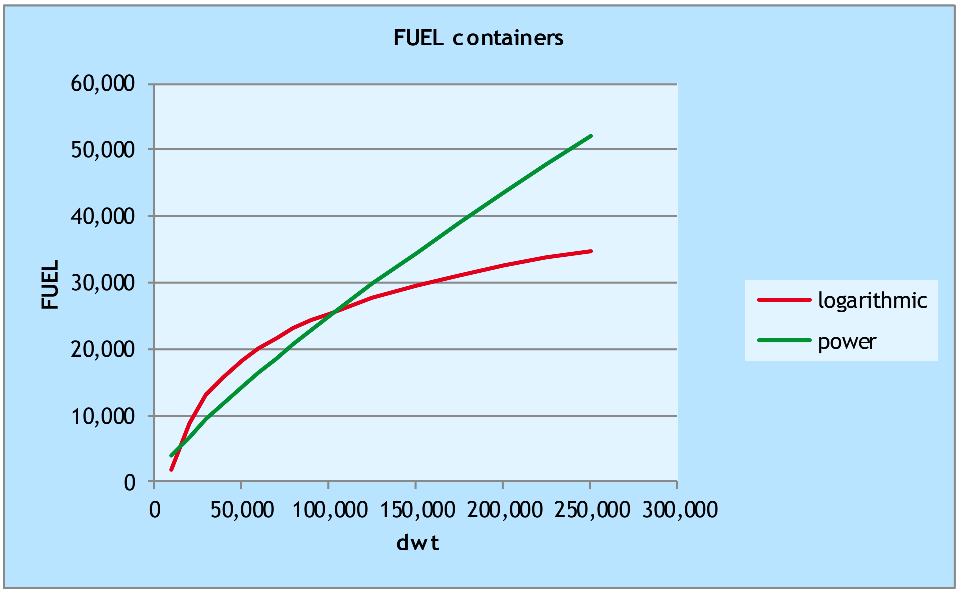


Figure 33 Average FUEL industry regression curves and FUEL values for container ships

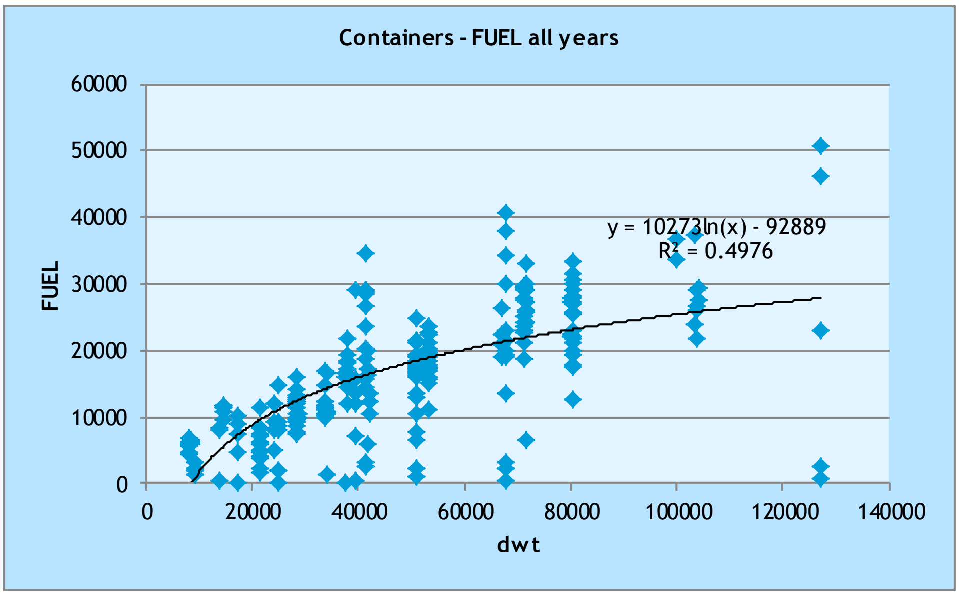


Figure 34 FUEL industry regression curves for tankers

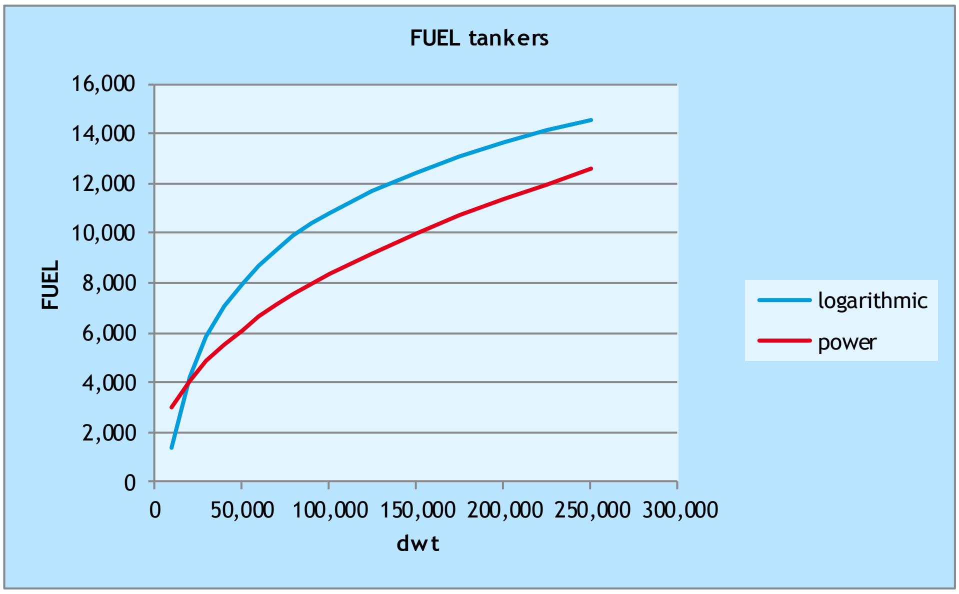


Figure 35 Average FUEL industry regression curves and FUEL values for tankers