REPORT

EEDI TESTS AND TRIALS
FOR
EMSA

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0. INTRODUCTION

This study has been conducted by Deltamarin at the request of European Maritime Safety Agency (EMSA).

The main objective of the study is to provide EMSA with tests and trials on Energy Efficiency Design Index (EEDI) for a number of different ship types.

The study consists of two tasks:

1) Tests of EEDI formula on conventional ship types

Conventional ship types include general cargo carriers, tankers, container vessels, bulk carriers and gas tankers. Representative sample of ships delivered after 2007 or currently under construction has been indentified and analyzed. EEDI has been calculated for the vessels and trends have been compared between different shipbuilding locations. Conclusions from the analysis have been drawn regarding applicability of formula, the general efficiency situation with modern ships as well as improvement possibilities.

2) Tests of EEDI formula on RoRo and RoPax ships

Representative sample of RoRo and RoPax ships being built after 2007 or currently under construction has been identified and analyzed. EEDI has been calculated for the vessels and trends have been compared between different shipbuilding locations. Conclusions from the analysis have been drawn with respect to applicability of the formula to RoRo and RoPax ships as well as on general efficiency situation and improvement possibilities.

1. EXECUTIVE SUMMARY

The main objective of this study has been to provide EMSA with tests and trials on Energy Efficiency Design Index (EEDI) for a number of different ship types in order to evaluate applicability of the index.

EEDI represents ship transportation CO_2 efficiency at a single design point. Calculation method is simple and the index can be calculated for most ship types. However, it is important to understand that the calculated index value does not express the actual transportation efficiency of a ship since it is only calculated for a single design point and not for the complete operation and loading profile. For the same reason it has to be noticed that index values of different types of ships are not directly comparable with each other.

Implementation of regulatory framework for EEDI needs to be carefully considered. It is essential to identify clearly the ship types where EEDI actually is a comparable measure of efficiency and to recognize the consequences of establishing limitations for index value.

Within this study it has been demonstrated through examples that EEDI would practically mean power limitation for new ships. This would, in turn, standardize design speeds for a certain level depending on ship type and size.

Regarding applicability of EEDI it has been concluded that the current approach could be feasible, with certain reservations, for oceangoing cargo ships which have uniform design criteria. In practice this means tankers, bulkers, container ships, LNG-carriers, LPG carriers, RoRo vehicle carriers and largest general cargo ships. These ships account for majority of CO_2 emissions from shipping.

Generally speaking, the current EEDI approach is very questionable for short sea shipping. Ships in short sea service are usually designed for a certain route or special purpose and many of them are also sailing in scheduled traffic. Within each ship type the actual design criteria can be very diverse and ships are difficult to categorize for good correlation of EEDI value. This means that in many cases the individual ships are not comparable with each other in index point of view. Therefore, limitation of the index value should not be made as it could finally lead to undesired sub-optimization of bigger transportation chains.

It has been concluded that the current EEDI methodology is not suitable for short sea shipping in general, including: all small ships, RoRo-, RoPax- and passenger ships as well as other special ships.

The calculation of reliable baselines according to the current average index value method is very difficult. This is mainly because the database values are not consistent with the actual values to be used in EEDI calculation. The verification of baselines should be made with accurate and reliable ship information once the basic EEDI calculation method is agreed.

2. BASIS OF THE STUDY

2.1 Basis of selected approach in calculating EEDI values

For calculation of accurate EEDI value, detailed information about the ship needs to be available. The essential details are speed, deadweight, engine power and specific fuel oil consumption, power take out and special design criteria such as ice class. Most importantly the speed needs to be consistent with capacity and main engine power that is used in the calculation. This would mean that instead of general ship datasheet, a complete model test report of the ship needs to be available when calculating the EEDI value. The report is needed in order to find out speed corresponding to 75% shaft power and maximum design draft.

In general, some values for required EEDI parameters are available in different ship databases. The challenge is that the consistency of data with EEDI calculation conditions can not be verified. Based on a brief cross-checking of database values and actual figures needed for EEDI calculation, it seems that often speed and capacity are not registered in same point in the databases, at least not in the point required for EEDI calculation.

Since detailed ship related information is needed to calculate accurate EEDI values, the original approach for the EMSA study was to collect ship data for latest newbuildings and ships currently under construction directly from shipyards and ship owners.

This approach was tested by sending about 50 inquiries to various yards and ship owners. In the inquiry purpose of EMSA study was explained and data request was specifically pointed to one or more vessels from the current yard or owner. Needed information was identified in detail, and purpose of use for the data was explained.

The results from the test were not too encouraging, since only four of the inquiries were replied to. Therefore it was concluded that data collection directly from yards or shipowners will not provide sample big enough needed for EMSA EEDI study.

Based on the fact that yards and owners treat certain information needed for EEDI calculation as confidential and are not willing to distribute it, an alternative method for compiling the needed data for EEDI calculation has been used. The approach is based on database values and additional assumptions, calculations and regressions to make the obtained index value more accurate.

Due to the simplifications in calculating the index value, the obtained EEDI values are not accurate, and thus can not be directly compared with the baseline. However, since same assumptions are made for all vessels, EEDI values are comparable with each other.

2.2 EEDI formula (IMO MEPC.1/Circ.681)

The latest version of EEDI (as defined in MEPC.1/Circ.681) is applied in this study. The formula is expressed as follows:

$$\frac{\left(\prod_{j=1}^{M} f_j\right)\left(\sum_{i=1}^{nME} P_{ME(i)} \cdot C_{FME(i)} \cdot SFC_{ME(i)}\right) + \left(P_{AE} \cdot C_{FAE} \cdot SFC_{AE}*\right) + \left(\left(\prod_{j=1}^{M} f_j \cdot \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{neff} f_{eff(i)} \cdot P_{AEeff(i)}\right) C_{FAE} \cdot SFC_{AE}\right) - \left(\sum_{i=1}^{neff} f_{eff(i)} \cdot P_{eff(i)} \cdot C_{FME} \cdot SFC_{ME}\right)}{f_i \cdot Capacity \cdot V_{ref} \cdot f_w}$$

Where:

C_F = non-dimensional conversion factor between consumed fuel and emitted CO_2. Subscripts $_{ME(i)}$ and $_{AE(i)}$ refer to main- and auxiliary engines.

V_{ref} = ship speed, measured in knots, in maximum design load condition (capacity), assuming deep water and calm sea and no wind.

Capacity = for conventional vessel types deadweight and gross tonnage for passenger ships and RoRo passenger ships.

$P_{ME(i)}$ = power of main engines measured in kW at 75% MCR having deducted shaft generators.

$P_{AE(i)}$ = auxiliary engine power in kW, the electrical load required to supply normal maximum sea load.

$P_{PTO(i)}$ = shaft generator power in kW at 75% output of each installed shaft generators.

$P_{PTI(i)}$ = shaft motor power in kW at 75% output of installed shaft motors.

$P_{eff(i)}$ = 75% of the main engine power reduction (kW) due to innovative mechanical energy efficient technology.

$P_{AEeff(i)}$ = auxiliary power reduction (kW) due to innovative electrical energy efficient technology measured at $P_{ME(i)}$.

SFC = specific fuel oil consumption of engines, measured in g/kWh, of the engines. Subscripts $_{ME(i)}$ and $_{AE(i)}$ refer to main- and auxiliary engines.

f_j = non-dimensional correction factor to account for ship specific design elements.

f_w = non-dimensional coefficient indicating the decrease of speed in representative sea conditions.

$f_{eff(i)}$ = availability factor of each innovative energy efficiency technology.

f_i = capacity factor for any technical or regulatory limitation on capacity.

General calculation guidelines described in IMO MEPC.1/Circ681 have been used.

2.3 Basis of data used in EEDI calculations for EMSA study

Basis of compiling the EEDI dataset is described in the following:

a) List of vessels is extracted from Lloyds Register Fairplay database:
- Ships delivered from 01/2007 or currently under construction included
- Ships distinguished to different categories regarding ship types
- Ships distinguished to different subcategories regarding building country

b) For each of the vessels an EEDI index has been calculated based on:
- Lloyds Register Fairplay database values
- Calculations, assumptions and regressions for certain parameters
- Fixed parameters

Basis for selecting each parameter for EEDI calculation is illustrated in the following.

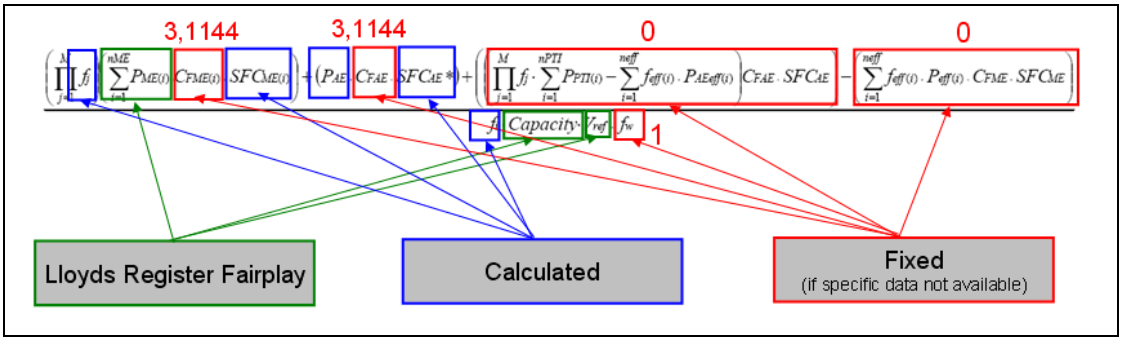

Figure 1 – Basis for calculating EEDI within EMSA study

Lloyds Register Fairplay database values that have been directly used in the EEDI calculation are P_{ME}, Capacity and V_{ref}. The biggest error margin in the absolute index value comes from the possible inconsistency of these three values. However, accurate values are impossible to define without ship model test report.

Values calculated based on database information include SFC_{ME}, P_{AE}, SFC_{AE}, and P_{PTO}. Specific fuel consumption of main and auxiliary engines have been calculated based on type and size of main engine as reported in the database with a regression curve prepared for this purpose. Existence of power take-out has been identified based on ship type, main engine type and propeller type and size of the PTO has been then calculated by using regression analysis. Auxiliary engine power has been calculated from main engine power as instructed in EEDI calculation guidelines. Ice class information has been obtained from the database and factors f_i and f_j have been calculated according to calculation guidelines.

Fixed values in EEDI calculation include C_{FME}, C_{FAE}, f_w and the factors indicating P_{PTI}, P_{eff} and P_{AEeff}. Fuel for main- and auxiliary engines has been assumed to be HFO, which fixes the carbon conversion factors to 3,1144. Innovative technologies for reducing main- and auxiliary engine power are not very common and thus these values are assumed to be zero. Same is assumed with power in-take. Coefficient f_w is set to 1 since calculation guidelines are not available

Basis of calculated values is explained in more detail in Appendix 10 of this report. Due to the above described simplifications and assumptions and other sources of errors, the accuracy in absolute EEDI value is in approximately in range of +-5...10%.

2.4 Baselines (IMO GHG-WG 2/2/7)

Baselines used in this study are from IMO GHG-WG 2/2/7. However, since calculation of the EEDI within this study is not based on accurate data and there is a certain error margin, the baseline is not perfectly comparable with the calculated EEDI values.

The currently available baselines cover: bulk carriers, tankers, gas carriers, container ships, general cargo ships and ro-ro cargo ships (not further divided into the three categories).

Therefore, certain simplifications and assumptions have been made in order to demonstrate the baselines for the ship types which have not been covered in GHG-WG 2/2/7 paper.

The basic principle of GHG-WG 2/2/7 baseline calculation method has been described in section 6 of this report.

3. EEDI CALCULATIONS FOR CONVENTIONAL SHIP TYPES

3.1 Introduction to tests on EEDI formula on conventional ship types

EEDI calculation has been made for more than 6000 ships delivered after 01/2007 or currently under construction, covering the following ship types and building locations.

Table 1 – Number of conventional ships analysed

Conventional ships	**Number of ships by building location**				
	EU	China	South-Korea	Japan	Total
Tankers	53	445	826	401	1725
Bulk carriers	13	745	278	748	1784
Container ships	212	479	590	119	1400
General cargo ships	249	553	16	147	965
Gas tankers	21	13	165	63	262
Total	548	2235	1875	1478	6136

EEDI has been calculated for each ship by applying the method described in section 2.3. For each ship type the ships are assorted with respect to their building location. Ships having index value deviating more than 10 units from the baseline have been excluded from the final data.

The results of calculation are discussed with respect to correlation of index values and differences between building locations.

Correlation level of index values illustrates the similarity of ships within each ship category. This is an important consideration since the ships being regulated by the same baseline should be uniform in design criteria point of view. Too wide categorisation of ships will lead to unreasonable penalisation of certain sub-types of ships. Therefore correlation of the index values is addressed separately in order to have an understanding which ship types or size classes are problematic from this point of view.

Differences between different building locations have been analysed based on the country specific graphs and curves. Conclusions on EEDI performance of ships being built in different locations have been made when possible. IMO baselines are visualized in each comparison graph. However, since the EEDI values produced by the calculation are not absolutely accurate, explicit comparison with the baselines can not be made. Applicability of baselines is discussed separately in section 6.

Finally, applicability of EEDI for the analysed ship type has been discussed. Special features of each ship type and possible differences in design criteria or operational requirements have also been discussed and conclusions on the general suitability of the calculation have been made.

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3.2 Tankers

3.2.1 Summary of EEDI calculations for tankers

Following table summarizes EEDI calculation for tankers grouped by ship building location. World refers to Europe, China, South-Korea and Japan together and does not include ships built outside of these countries.

Table 2 – Tanker EEDI summary table

Tankers		Europe	China	S-Korea	Japan	World
Sample size	(pcs)	53	445	826	401	1725
Avg. DWT	(t)	20783,98	57779,20	74099,74	66675,50	66525,54
Avg. ME MCR power	(kW)	5968,34	7826,42	10048,46	8785,33	9056,25
Avg. speed	(kn)	14,31	13,59	14,75	14,58	14,40
Avg. EEDI	(g/t*nm)	**9,99**	**9,986**	**6,56**	**8,848**	**8,08**
Avg. deviation from baseline		**-3,06**	**-1,55**	**-0,79**	**-1,60**	**-1,24**

Calculated EEDI values for tankers by ship building location are presented in the below figure. The graph shows EEDI regression line for each country and world as well as IMO EEDI baseline curve.

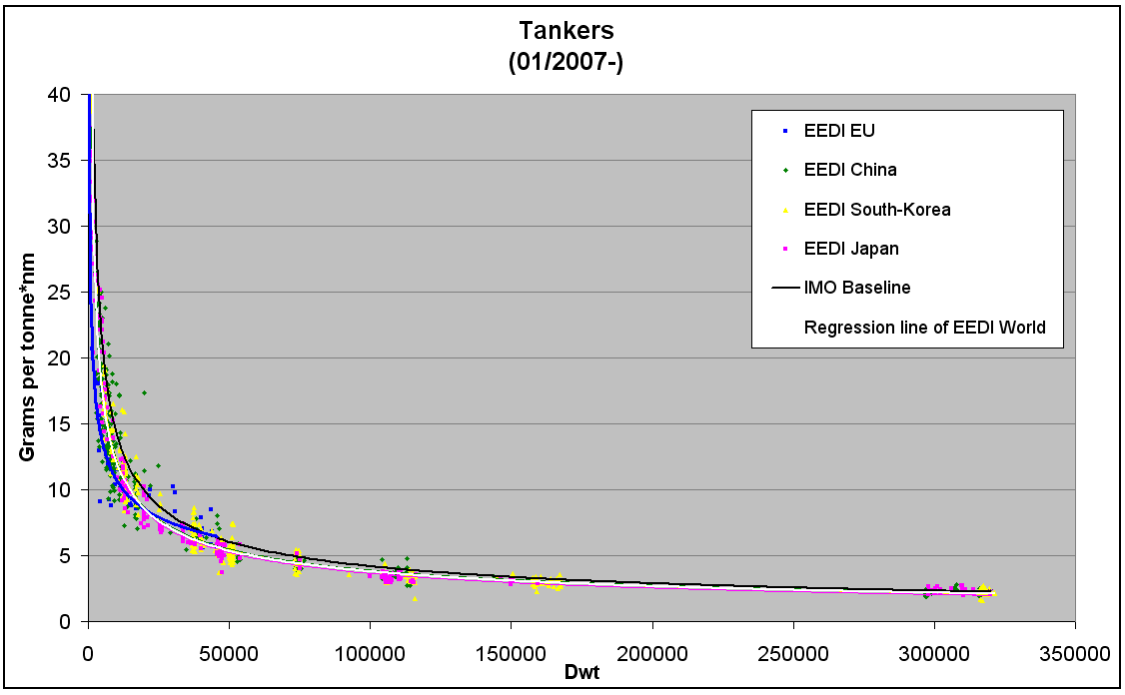


Figure 2- EEDI for tankers delivered after 1/2007 or currently under construction

3.2.2 Conclusions on EEDI calculations for tankers

Different tanker size classes can clearly be seen from the data. Tanker classes such as Panamax (<75000 dwt), Aframax (~120000 dwt), Suezmax (~150000 dwt) and Capesize/VLCC (~300000 dwt) can be seen as separate data clouds. For these larger tankers there is quite good correlation of index values.

Tankers smaller than 50000 dwt include mainly chemical tankers, product tankers and other smaller and special tanker types. For these ships scatter in index values is considerably bigger than for the bigger ships.

Country-specific trendlines for China, Japan and South Korea are very close to each other. For each of these far eastern builders the data consists of whole size scale of different types of tankers.

Trendline shape for EU is different from other countries since it is composed of limited data sample of chemical- products and special tankers smaller than 50000 dwt. Firm conclusions on relative efficiency of Far-Eastern builders cannot be made. Comparing EU against Far-East is also very difficult due to limited data sample.

However, at first look it seems that European built tankers perform rather well in EEDI point of view in the smallest size below 10000 dwt, but sizes from 30000 to 50000 dwt have higher index value than vessels built in Far East.

The exact reason for good performance below 10000 dwt can not be clearly identified. One possible reason is that majority of EU-built small tankers are ice-classed and Far-Eastern built are usually not. In EEDI point of view ice-class factors seem to give quite good compensation for small vessels. For 30000-50000 dwt European-built tankers there seems to be special tankers such as a juice tanker and ice classed tankers with speed higher than 15 knots exceeding the current baseline.

3.2.3 Applicability of EEDI for tankers

Tankers include several subtypes of ships designed to transport liquids in bulk. These are for example crude tankers, product tankers, chemical tankers, shuttle tankers and other special tankers.

Design speeds of tankers are in general between 14 and 16 knots, with exception of tankers smaller than 25000 dwt which have higher variation. In general, the correlation of main engine power to capacity of the ship is quite good and this results in rather limited scatter in EEDI values.

Design criteria of tankers are in general rather congruent when ships of similar subtype and capacity are examined. Considering capacities of ships there are few different size-classes such as Panamax and Suezmax, which are limited in main dimensions or other design criteria to be able to access certain locations. There are also certain sub-types of tankers which have special design criteria due to special operation. Shuttle tankers for example are equipped with dynamic positioning capability, redundant systems as well as cargo off-loading equipment.

The basic philosophy of EEDI should be quite well applicable for ocean going tankers bigger than 25000 dwt. Practically this would mean limitation of installed main engine power to a certain level depending on the capacity of the vessel. This would, in turn, even further flatten the variation in design speeds of tankers in the future. Reduction of operation speeds should however not compromise safety aspects. There should always be enough reserve power for safe navigation in rough seas.

It should also be ensured that special purpose ships like shuttle tankers are treated correctly. Alternatives are to exclude these ships from the current EEDI philosophy or to develop fair correction factors for these special cases.

Tankers smaller than 25000 dwt have more diverse design criteria and therefore there is also bigger scatter in index values. Limiting power of these ships with EEDI is problematic since that could make designing certain special purpose tankers in practice impossible. Therefore the basic approach of EEDI is less feasible for small tankers.

Considering baselines for tankers, it should be studied whether the baseline should be defined separately for the different size classes such as Panamax, Suezmax, and VLCC’s. This is since in the current definition of baselines ships bigger or smaller than the examined category affect on baseline value. This could make the requirement too easy or too tight in some cases.

3.3 Bulk carriers

3.3.1 Summary of EEDI calculations for bulk carriers

Table 3 summarizes EEDI calculation for bulk carriers by ship building location.

Table 3 – Bulk carrier EEDI summary table

Bulk Carriers		Europe	China	S-Korea	Japan	World
Sample size	(pcs)	13	745	278	748	1784
Avg. DWT	(t)	102058,69	88721,80	127672,76	79872,82	91178,47
Avg. ME MCR power	(kW)	11210,69	10216,18	13256,49	9694,49	10478,46
Avg. speed	(kn)	14,80	14,20	14,52	14,45	14,36
Avg. EEDI	(g/t*nm)	**5,12**	**4,645**	**3,76**	**4,713**	**4,54**
Avg. deviation from baseline		**0,04**	**-0,23**	**-0,17**	**-0,33**	**-0,26**

Calculated EEDI values for bulk carriers by ship building location are presented in below figure. The graph illustrates EEDI regression line for each country and world as well as IMO EEDI baseline curve.

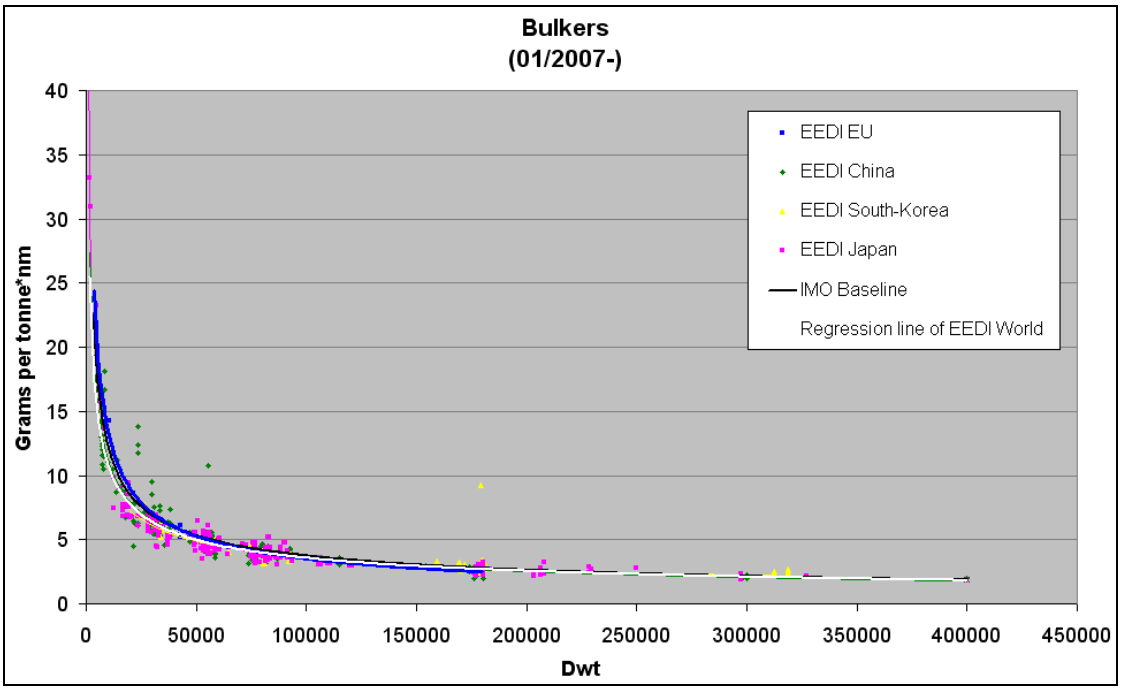


Figure 3 – EEDI for bulk carriers delivered after 1/2007 or currently under construction

3.3.2 Conclusions on EEDI calculations for bulk carriers

For bulk carriers there is in general quite good correlation of index values. Similarly as for tankers, different size-classes such as handymax and panamax can be separated from the data as they form clear data-clouds around certain deadweight ranges.

Since there is quite good correlation of index values and Far-Eastern yards are building all different size classes of ships, their trendlines are practically on top of each other. Data sample from EU is very limited and therefore shape of the trendline is different from others. It is in practice impossible to find identifiable differences in EEDI performance of bulk carriers built in different parts of the world.

There are few Chinese-built small bulk carriers at about 20000-30000 dwt range which differ considerably form other ships. For these vessels the reason behind high index value seems to be primarily higher design speed. In these cases the speed is around 14…16 knots, as other ships of that size are typically in range of 11...13 knots.

3.3.3 Applicability of EEDI for bulk carriers

Bulk carriers include ships that transport unpackaged cargo such as coal, grains, ore and cement. Design criteria of these ships are quite convergent. Optimization of bulk carriers means in general maximization of payload and at the same time minimization of fuel consumption. Therefore EEDI should be quite a good measure of bulker efficiency since it expresses finally emissions per carried cargo tonne over a nautical mile.

In today's bulkers the optimization of these design criteria has lead to quite constant design speed of the vessels, which varies typically between 14 and 16 knots. The tendency for ships smaller than 25000 dwt is similar as in tankers. In smallest ships the design speed varies from 11 to 16 knots and therefore also installed engine power and thus EEDI value have higher scatter.

Also within the bulk carrier category there are several special sub-types. These include for example self unloading bulk carriers, self packaging bulkers and ships operated on lakes. These ships differ in terms of light weight, powering and sometimes also main dimensions. Therefore it is important that they are fairly treated in EEDI point of view, either by excluding them from the scheme or by defining suitable correction factors.

Conclusions on EEDI for bulk carriers are very similar to conclusions for tankers. The basic philosophy would limit installed power of ships and should be applicable for ships bigger than about 25000 dwt with certain limitations. Special ships should be fairly treated and baseline definition could be made also separately for different size classes of ships in order to avoid nonconformity of regulatory requirements.

3.4 Container ships

3.4.1 Summary of EEDI calculations for container ships

Table 4 summarizes EEDI calculation for container ships by ship building location. Capacity of container ships is taken in 100% dwt in order to make the index values more comparable with IMO baseline.

Table 4 – Container ship EEDI summary table

Container Ships		Europe	China	S-Korea	Japan	World
Sample size	(pcs)	212	479	590	119	1400
Avg. DWT	(t)	35068,17	29637,30	78061,16	51677,45	52740,30
Avg. ME MCR power	(kW)	20284,25	18713,98	44922,18	35011,04	31381,90
Avg. speed	(kn)	20,91	20,53	24,01	22,55	22,22
Avg. EEDI	(g/t*nm)	**12,79**	**13,816**	**10,94**	**13,162**	**12,39**
Avg. deviation from baseline		**-2,75**	**-2,15**	**-1,68**	**-1,03**	**-1,95**

Calculated EEDI values for container ships by ship building location are presented in the below figure. The graph shows EEDI regression line for each country and world as well as IMO EEDI baseline curve.

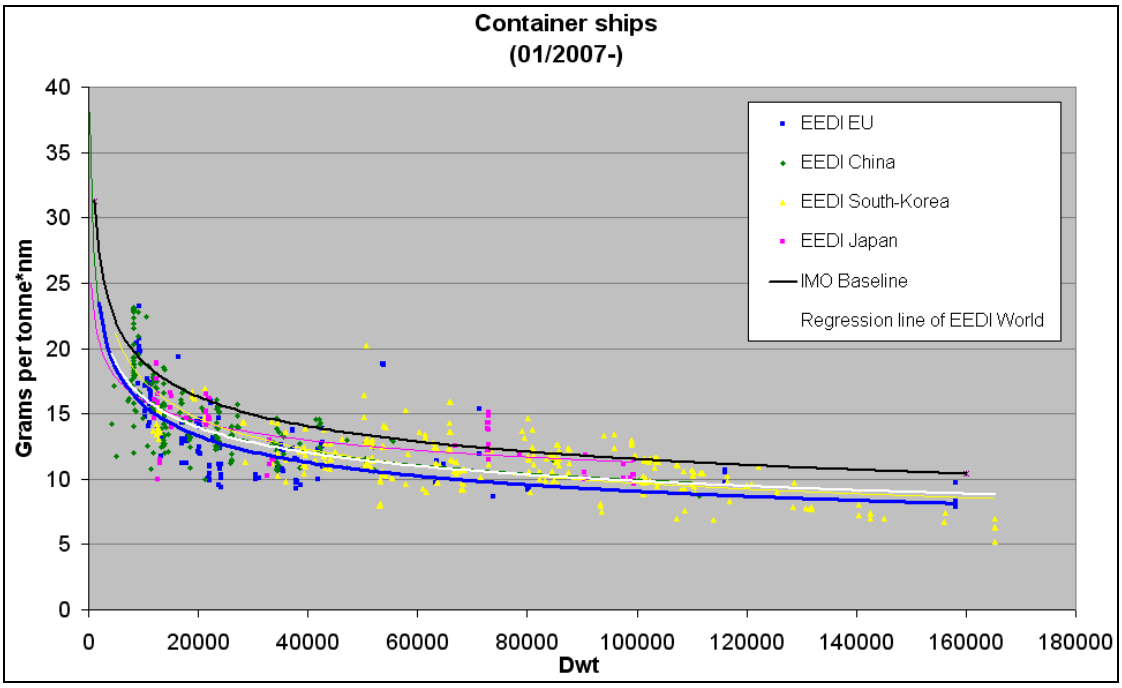


Figure 4 – EEDI for container ships delivered after 1/2007 or currently under construction

3.4.2 Conclusions on EEDI calculations for container ships

For container ships there is rather big scatter in index values through the whole capacity range. This can be explained by spread in design speeds of the ships.

First of all the speeds are high compared for example with tankers and bulk carriers. Propulsion resistance curve is in general very steep above 20 knots where container ships are designed to operate, and therefore also the installed power varies considerably more as function of design speed than for the previous two ship types.

Secondly, in addition to high level in speeds, the variations in speeds are also big. For example in 60000 dwt size range the highest speed in data was 28 knots and the lowest was 21 knots. These two issues translate to big spread in EEDI values for container ships.

Trendlines for different building countries are a bit difficult to compare due to low correlation of index values and differences in sizes of the vessels built in each country.

China is mainly building vessels smaller than 50000 dwt and all vessels built in Japan are smaller than 100000 dwt. Only South Korea and Europe are building vessels of all sizes; however the number of large container ships built in Europe is very limited.

There seems to be also some regional differences in container ship design speeds. For example South-Korean built vessels have average design speed of 24 knots, as average for the whole data sample is 22 knots. This is obviously the main reason for high index values for South-Korean built vessels in 50000 – 100000 dwt size range.

Maybe the only trend which can be seen from the graphs is that European built container vessels 20000 – 50000 dwt have rather good index values compared to other countries, which pulls EU trendline well below other countries. A clear explanation for this can not be identified from the data.

3.4.3 Applicability of EEDI for container ships

Application of EEDI for container ships would practically have the same effect as for the other two ship types discussed earlier; power of ships would be limited to certain level depending on capacity. This would correspondingly mean that design speeds of the container ships would become equalized, assumingly to about 24 knots for biggest container ships and to capacity dependent level between 15...24 knots for ships smaller than 60000 dwt.

The key question is: how would this affect on container ship traffic and business in general?

During the last few years many container ship operators have slowed down their oceangoing ships considerably due to high cost of bunker fuel. In order to maintain the same transportation capability, the companies have added more ships to transoceanic routes. Higher number of slower ships or few bigger ships on the same route have in general brought along smaller fuel and operational costs for shipowners. Obviously there is a limit for slowing down the ships since at some point the other operational costs and ship investment costs become determinant in the overall costs of transporting containers on a certain route.

From this background slowing down container ships already from design point of view could be justified as long as safety at heavy seas is not compromised.

The analogy in CO_2 emission point of view is basically the same. Many slow speed ships have in general smaller carbon emission than few fast ships with same overall transport capability. Same applies with having one big ship instead of few small ships. However, when the overall carbon footprint including the building and scrapping of the vessels is included, the final result could be different. Therefore, conducting of a comprehensive carbon footprint study of different kind of container trading schemes would be recommendable.

Similarly to tankers and bulkers the special cases and small ships need to be carefully considered. One example is feeder container ships, which are usually the last and first link in the sea transportation chain of containers. These ships are designed to access ports with limitations on draught or other main dimensions. Infrastructure in these ports can also be limited and therefore feeder ships are often geared with deck cranes. Therefore it needs to be considered that this type of ships with special design criteria are not unreasonably treated in index point of view since they may be limited in design criteria and also sometimes need to sail according to certain schedules and therefore there is need for higher need power for operational flexibility.

3.5 General cargo ships

3.5.1 Summary of EEDI calculations for general cargo ships

Table 5 summarizes EEDI calculation for general cargo ships by ship building location.

Table 5 – General cargo ships EEDI summary table

General Cargo Ships		Europe	China	S-Korea	Japan	World
Sample size	(pcs)	249	553	16	147	965
Avg. DWT	(t)	5939,58	11811,37	19640,25	18191,87	11398,02
Avg. ME MCR power	(kW)	2661,46	4843,97	6104,00	4244,37	4210,37
Avg. speed	(kn)	12,98	14,22	15,56	13,61	13,83
Avg. EEDI	(g/t*nm)	**14,43**	**13,588**	**12,06**	**16,253**	**14,19**
Avg. deviation from baseline		**-2,60**	**-0,59**	**-0,62**	**0,83**	**-0,89**

Calculated EEDI values for general cargo ships by ship building location are presented in below figure. The graph shows EEDI regression line for each country as well as IMO EEDI baseline curve.

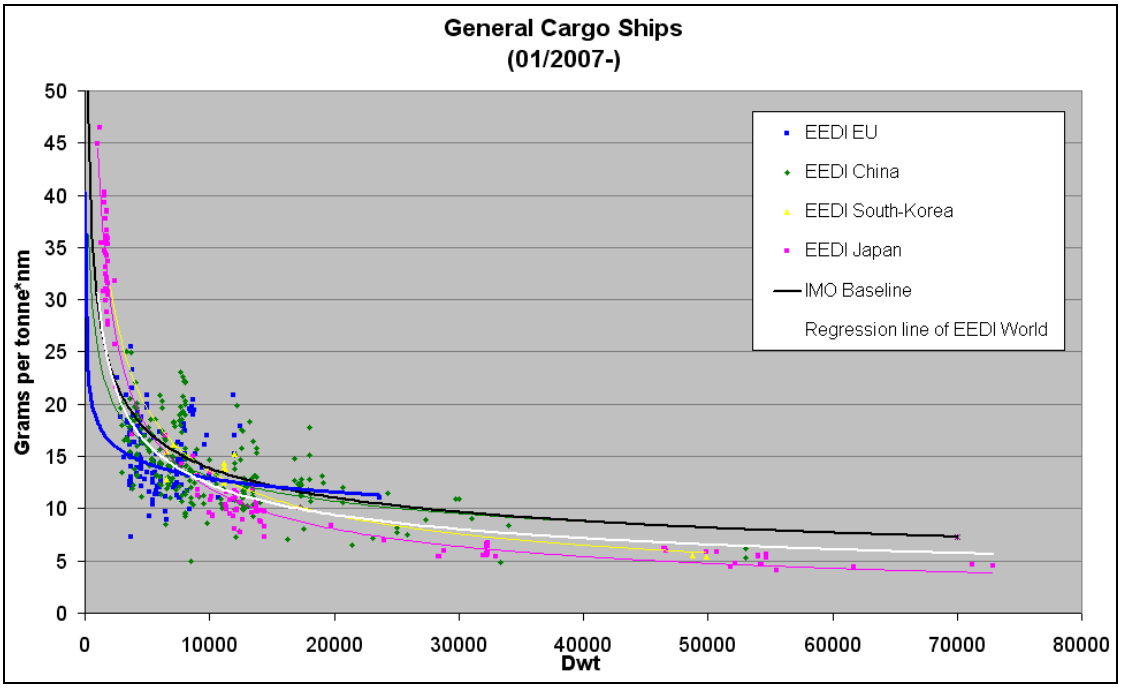


Figure 5 – EEDI for General cargo ships delivered after 1/2007 or currently under construction

3.5.2 Conclusions on EEDI calculations for general cargo ships

For general cargo ships there is considerable scatter in index values. Especially with ships smaller than 20,000 dwt there is very difficult to draw a representative regression line through the dataset. General cargo ships bigger than 50000 dwt are correlating rather well.

Only ships built in Japan seem to have reasonable level of correlation to draw a trendline. EEDI values for ships built in China and EU have too big spread to make a clearly representative trendline. The trouble with South Korea is that there are only 16 data samples, which is not enough to make a fair comparison with others.

Since majority of the ships are smaller than 20000 dwt and in ships of this size the index values are very much scattered, a reasonable comparison in EEDI performance of ships built in different locations can not be made based on trendlines.

However, if trendlines are neglected and the comparison is aimed only on EU- and Chinese built ships where data sample is remarkable, there seems to be a clear difference in EEDI performance of ships built in EU and China in capacity range between 2000 and 8000 dwt. The blue dots representing EU-built ships seem to be lower than the green dots representing China-built. Reason for this can not be clearly identified from the data. Average design speed is equal within that size range and both countries build ships with ice class. Also the main dimensions and Froude number are very similar. The only identifiable difference is that EU ships have higher ice-class compared to Chinese and it could be that they get more benefit from correction factors in this size range. Another possibility is that EU-ships are more custom made and carefully designed where as Chinese ships are more standard design type.

3.5.3 Applicability of EEDI for general cargo ships

General cargo ships are multi-purpose vessels, designed to handle and stow a variety of freight. The cargo can include steel, forest products, manufactured goods, heavy equipment, machinery, bagged goods, food and containers. General cargo ships are often equipped with their own cargo handling facilities, requiring cranes with a range of lifting capacities and outreach ratings, which can be equipped to handle any type of cargo. Also, some specialised general cargo ships combine have capabilities for transporting large, awkwardly shaped components to refinery, chemical processing and other construction projects.

There is also remarkable variation in design speeds of these ships. For example in 12,000 dwt sized ships the variation is from 7 knots up to 20 knots. It is very clear that the ships at the ultimate ends are designed for very different transportation tasks.

Applying EEDI on general cargo ships is very questionable since the design criteria of the ships varies way too much. Only ships bigger than 50000 dwt seem to be similar enough for comparing them with each other. Further categorisation of general cargo ships is possible, but probably a very challenging task.

3.6 Gas carriers

3.6.1 Summary of EEDI for gas carriers

Table 6 summarizes EEDI calculation for gas tankers by ship building location. Diesel-electric LNG carriers have been removed from the data. For steam turbine driven LNG carriers it has been assumed that fuel is 50/50 between HFO/LNG and that specific fuel oil consumption of the steam plant is 280 g/kWh.

Table 6 – Gas carriers EEDI summary table

Gas Carriers		Europe	China	S-Korea	Japan	World
Sample size	(pcs)	21	13	165	63	262
Avg. DWT	(t)	13873,14	13700,31	59324,99	41365,79	49099,65
Avg. ME MCR power	(kW)	6695,90	6122,92	18488,13	13316,75	15685,91
Avg. speed	(kn)	15,87	14,32	17,67	16,82	17,16
Avg. EEDI	(g/t*nm)	**13,20**	**28,216**	**9,55**	**14,598**	**11,98**
Avg. deviation from baseline		**-6,24**	**-1,03**	**-0,60**	**-1,00**	**-1,17**

Calculated EEDI values for gas carriers by ship building location are presented in below figure. The graph shows EEDI regression line for each country and world as well as IMO EEDI baseline curve.

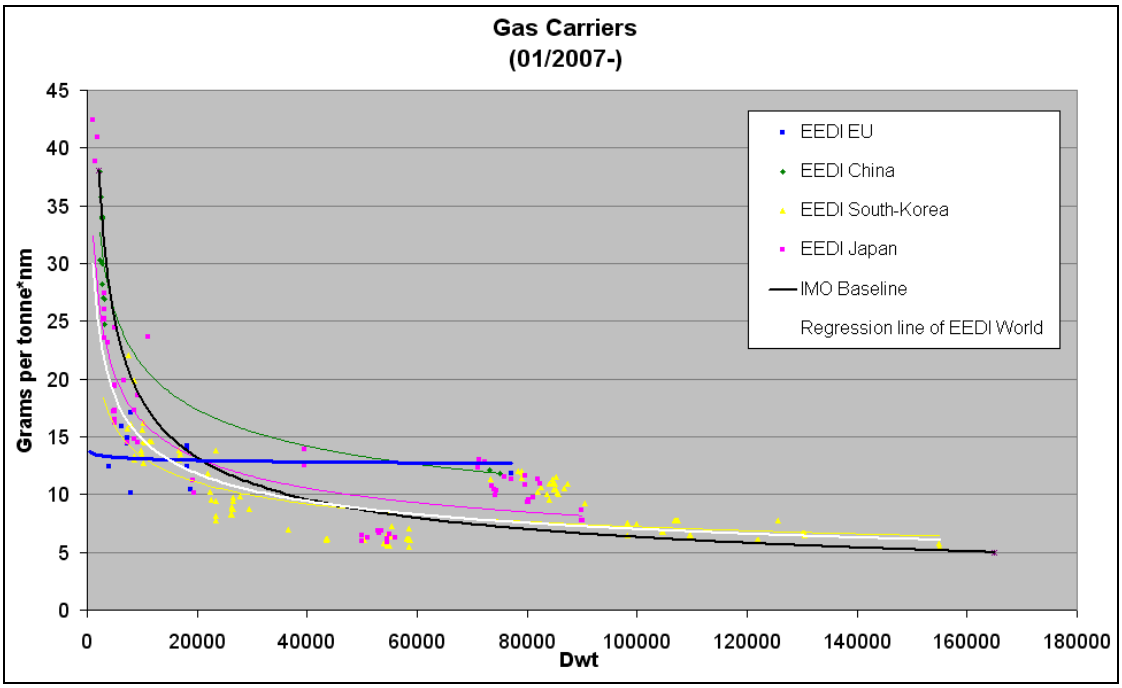


Figure 6 – EEDI for gas carriers delivered after 1/2007 or currently under construction

3.6.2 Conclusions on EEDI calculations for gas carriers

The two different subtypes of gas carriers can clearly be distinguished from the graph. These are liquefied petroleum gas (LPG) carriers and liquefied natural gas (LNG) carriers. Generally speaking ships smaller than 60000 dwt are LPG carriers and bigger ships are LNG carriers.

For LPG carriers there seems to be reasonable correlation of index values. There are few Japanese built small LNG carriers clearly deviating from the LPG carriers in index point of view. Also for LNG carriers the correlation of index values is quite reasonable if they are examined separately from LPG carriers. At size of about 80000 dwt the index values are quite high since practically all of the ships of that size are steam turbine driven LNG carriers.

Country specific trendlines can not be compared with each other since they consist of data sample combining LPG and LNG carriers.

3.6.3 Applicability of EEDI for gas carriers

The main problem for this category of ships is the two different sub-types of gas carriers; LPG and LNG carriers.

LPG carriers are designed to carry butane, propane, propylene and other gas types. They can be further categorized according to cargo storage system to fully pressurized, semi-pressurized and fully refrigerated ships. Depending on the type of the ship the structure and insulation of the tank system varies. Some of the ships are equipped with gas reliquefaction plant and some are not. Size of LPG carriers currently under construction varies from about 1000 dwt up to 60000dwt and the average size is 22500 dwt. Design speed varies from 12 to 21 knots and the median design speed for 22500 dwt LPG carrier is around 16 knots.

LNG carrier is a ship designed to transport liquefied natural gas at about -163°C temperature. There are four cargo containment system types in use for the newbuildings. Traditionally LNG carriers have been propelled by steam propulsion, but during the last few years there has been a shift towards diesel-electric and two stroke slow speed installations. Typical size of LNG carriers is around 70,000 – 150,000 dwt but there are also few smaller ships at 40000 dwt, 10000 dwt and 2000 dwt size range. Design speed of LNG carriers is typically around 19-20 knots.

Considering the different sizes of the two different ship types, gas carriers are divided so that vast majority of ships smaller than 60000 dwt are LPG carriers and practically all ships bigger than 70000 dwt are LNG carriers. It would be reasonable to develop own category for both of the ship types since if a LNG carrier is smaller than 60000 dwt it is in practice compared against LPG carriers. If one decides to build a large LPG carrier, it would be compared against LNG carriers.

The current methodology of calculating baselines is not very suitable for LNG carriers. Many LNG ships are using cargo as their fuel which would drop C_{FME} factor from 3,13 to 2,75. Also, the traditional solution in LNG carrier machinery is steam propulsion which has SFC of around 280g compared to 190 g/kWh used in the baseline formula. Today the machineries and utilization of cargo varies and therefore attention should be paid in fair definition of the baseline for different sizes of LNG carriers.

4. EEDI CALCULATIONS FOR RORO AND ROPAX SHIPS

4.1 Introduction to tests on EEDI formula on RoRo and RoPax ships

EEDI calculation has been made for about 300 RoRo and RoPax ships delivered after 01/2007 or currently under construction. The calculation has been divided into following subtypes and building locations.

Table 7 – Number of RoRo and RoPax ships analysed

RoRo and RoPax ships	**Number of ships by building location**				
	EU	China	South-Korea	Japan	Total
RoRo vehicle carrier	8	35	28	101	172
RoRo weight carrier	18	3	10	2	33
RoRo volume carrier	25	5	0	0	30
RoPax ships	64	5	2	6	77
Total	115	48	40	109	312

The latest calculation guidelines of EEDI (MEPC.1/Circ.681) divide RoRo ships into three categories: RoRo vehicle carriers, RoRo volume carriers and RoRo weight carriers.

RoRo vehicle carriers are multi deck RoRo cargo ships designed for the carriage of empty cars and trucks.

The difference between RoRo weight and volume carriers is made on the basis of deadweight per lane meter. RoRo weight carriers have more than 4t/lm and volume carriers have less than 4t/m.

RoRo passenger (RoPax) ships are passenger ships equipped with RoRo car deck.

EEDI has been calculated for each of these ship types by applying the approach described in section 2.3. For each ship type the ships are assorted with respect to their building location.

The results of calculation are analysed on a similar way as for the conventional ship types. Ship type specific considerations and conclusions on applicability of the current EEDI approach have also been made.

IMO baseline for RoRo's is visualized in each comparison graph. However, direct comparison can not be made since the EEDI values produced by the calculation are not absolutely accurate, and also the baseline is the generic RoRo baseline as defined in GHG WG 2/2/7 before further categorisation of RoRo ships.

4.2 RoRo vehicle carriers

4.2.1 Summary of EEDI for vehicle carriers

Following table summarizes EEDI calculation for RoRo vehicle carriers by ship building location. World refers to Europe, China, South Korea and Japan together and does not include ships built outside of these countries.

Table 8 - Summary of EEDI calculations for RoRo vehicle carriers

RoRo Vehicle Carriers		Europe	China	S-Korea	Japan	World
Sample size	(pcs)	8	35	28	101	172
Avg. DWT	(t)	16083,38	11624,40	22148,68	16880,39	16631,41
Avg. ME MCR power	(kW)	11939,25	11343,63	13917,93	12197,49	12291,80
Avg. speed	(kn)	19,95	19,36	20,11	19,92	19,84
Avg. EEDI	(g/t*nm)	**16,86**	**22,467**	**14,97**	**17,061**	**17,81**
Avg. deviation from baseline		**-5,97**	**-3,10**	**-1,94**	**-3,86**	**-3,49**

Calculated EEDI values for RoRo vehicle carriers by ship building location are presented in below figure. The graph shows EEDI world regression and IMO EEDI baseline curve. It is worth noticing that baseline for RoRo vehicle carriers has not been defined and therefore the baseline shown here is the generic RoRo baseline.

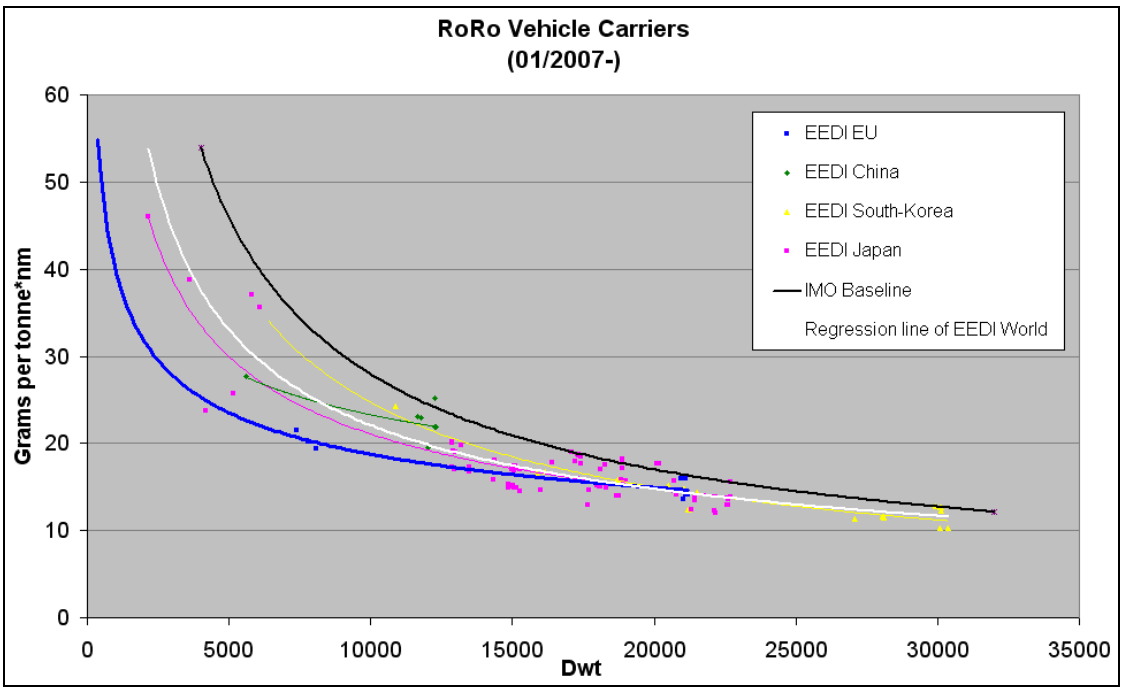


Figure 7 – EEDI for RoRo weight carriers delivered after 1/2007 or currently under construction

4.2.2 Conclusions on EEDI calculations for RoRo vehicle carriers

Correlation of index values is reasonable due to rather constant design speed for the vessels.

Only Japanese trendline is based on reasonable amount of data, as number of vessels built in other countries is rather limited. In general the trendlines are quite close to each other.

4.2.3 Applicability of EEDI for RoRo vehicle carriers

RoRo vehicle carriers are simple ships designed mainly for transportation of cars and trucks. These ships include pure car carriers (PCC's) and their close relatives, the pure car / truck carriers (PCTC's). Vehicle carriers usually have box-shaped superstructure fully enclosing and covering the cargo and a stern and a side ramp for loading and unloading of thousands of vehicles during port calls.

Design criteria of the ships are rather uniform if ships of similar capacity, which is commonly measured in lane meters or number of cars, are examined. Design speed of vehicle carriers is typically between 19 and 20 knots and machinery is based on slow speed two stroke engine. Vehicle carriers are typically designed for worldwide transoceanic operation, but there are certain limitations for main dimensions, such as maximum LOA for piloting to Japanese ports.

Since vast majority of RoRo vehicle carriers are quite similar ships, EEDI could be considered as a feasible approach for measuring their energy efficiency. However, it should be considered whether capacity could be measured in lane meters or with a specific capacity factor indicating number of cars and trucks carried instead of deadweight for even higher correlation rate of index values.

Safety aspect is also quite essential for this kind of ships. Due to large superstructure transversal area PCTC ships have sometimes challenges in course keeping for heavy seas and windy conditions. Therefore it should be considered that there is always enough power margin for safe operation.

4.3 RoRo weight carriers

4.3.1 Summary of EEDI for RoRo weight carriers

RoRo weight carriers are RoRo ships with deadweight per lane length higher than 4t/lm. Following table summarizes EEDI calculation for RoRo weight carriers by ship building location.

Table 9 - Summary of EEDI calculations for RoRo weight carriers

RoRo Weight Carriers		Europe	China	S-Korea	Japan	World
Sample size	(pcs)	18	3	10	2	33
Avg. DWT	(t)	13434,78	8099,67	10800,00	15734,50	12290,73
Avg. ME MCR power	(kW)	14712,78	4946,67	17059,00	6083,50	14012,94
Avg. speed	(kn)	18,98	14,57	22,30	16,15	19,42
Avg. EEDI	(g/t*nm)	**23,85**	**18,932**	**31,24**	**10,121**	**24,81**
Avg. deviation from baseline		**-2,72**	**-13,94**	**4,79**	**-10,37**	**-1,93**

Calculated EEDI values for RoRo weight carriers by ship building location are presented in below figure. The graph shows EEDI world regression and IMO EEDI baseline curve for RoRo's. It is worth noticing that baseline for RoRo weight carriers has not been defined yet and therefore the baseline shown here is the generic RoRo baseline.

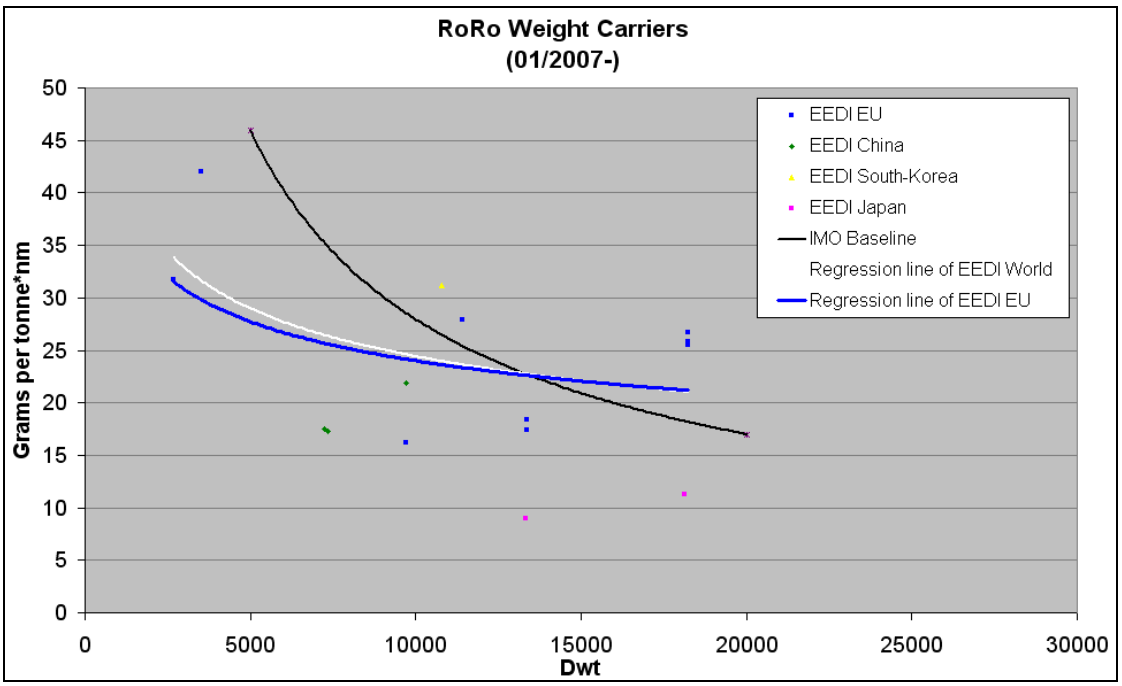


Figure 8 – EEDI for RoRo weight carriers delivered after 1/2007 or currently under construction

4.3.2 Conclusions on EEDI calculations for RoRo weight carriers

Data sample for RoRo weight carriers is only 33 ships and the scatter in calculated index values is very big.

The building activity of RoRo weight carriers built after 2007 has been concentrated to Europe. Therefore it is impossible to draw reliable trendlines for the shipbuilders in Far East.

The average size of the ships, measured in deadweight, is bigger in Japan and Europe compared to South Korea and China. Also speed of the vessels seems to vary quite a lot between the building locations.

Currently there are no ice-class correction factors defined for RoRo ships and thus this result in a high EEDI value for some of the European built ships. For example, the European built 18250 dwt vessels with high index value are the Transfennica vessels built in Poland. These vessels are built to ice class 1A super, and the installed power is based on operating in ice and not for achieving the service speed.

4.3.3 Conclusions on applicability of EEDI for RoRo weight carriers

Generally speaking there seems not to be any other unifying feature for RoRo weight carries, except that deadweight per lane meter exceeds 4 tons. Design speed, powering, selected main dimensions etc. seem to vary considerably case-by-case.

Most of European-built RoRo weight carriers are designed for transportation of paper products. For some of the ships, the design speed of the vessel is determined from a sailing schedule on a certain route. A typical example is a 7 day roundtrip between Finland and UK. Ship size is determined by available cargo volumes. For the cargo capacity, dwt is a suitable measure.

The current EEDI philosophy is not applicable for schedule defined transport systems. In this kind of ships, application of EEDI could easily lead to sub optimization, and probably also use of oversized vessels. A strict EEDI approach would concentrate the cargo to big hubs thus increasing the size of vessels used.

For regular and scheduled transportations, total CO_2 emissions per tonne of product and total distance, door to door, is perhaps a more rational way to calculate the transportation efficiency. Establishing a regulatory framework around this is most likely impossible.

4.4 RoRo volume carriers

4.4.1 Summary of EEDI for RoRo volume carriers

RoRo volume carriers have deadweight per lane meter less than 4t/m. Following table summarizes EEDI calculation for RoRo weight carriers by ship building location.

Table 10 - Summary of EEDI calculations for RoRo volume carriers

RoRo Volume Carriers		Europe	China	S-Korea	Japan	World
Sample size	(pcs)	25	5	0	0	30
Avg. DWT	(t)	9790,60	10144,60	0,00	0,00	9849,60
Avg. ME MCR power	(kW)	16042,04	15001,20	0,00	0,00	15868,57
Avg. speed	(kn)	21,39	18,50	0,00	0,00	20,91
Avg. EEDI	(g/t*nm)	**38,79**	**31,664**	**0,00**	**0,000**	**37,60**
Avg. deviation from baseline		**7,71**	**3,06**	**0,00**	**0,00**	**6,93**

Calculated EEDI values for RoRo weight carriers by ship building location are presented in below figure. The graph shows EEDI world regression and IMO EEDI baseline curve for RoRo's. It is worth noticing that baseline for RoRo weight carriers has not been defined yet and therefore the baseline shown here is the generic RoRo baseline.

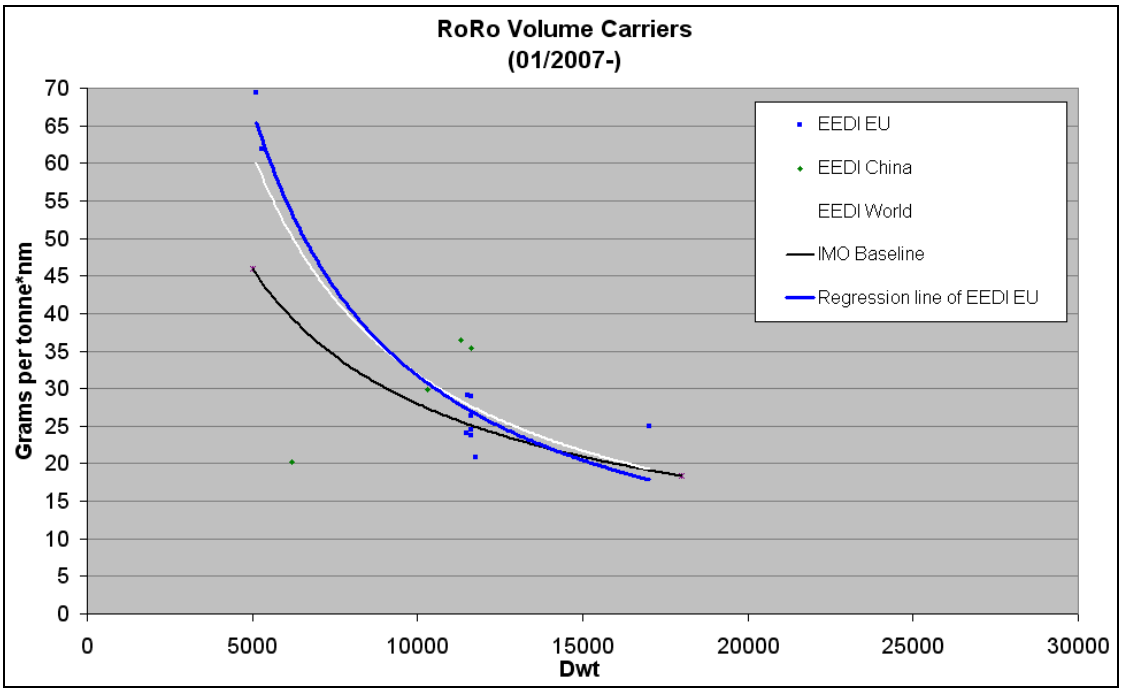


Figure 9 – EEDI for RoRo volume carriers delivered after 1/2007 or currently under construction

4.4.2 Conclusions on EEDI calculations for RoRo volume carriers

Size of data sample is very small and also the scatter in values is very big.

4.4.3 Applicability of EEDI for RoRo volume carriers

The European built RoRo volume carriers are mainly built for transportation of trucks and trailers. The design speed of the vessels is mainly determined from sailing schedule for which the ship is designed to. Typical examples are short UK to the Continent lines.

For measuring cargo capacity of RoRo volume carriers, deadweight, lane length or cargo volume could be used. Lane length or cargo volume is a more logical cargo measure than deadweight for these vessels. RoRo volume carriers have higher speeds than RoRo weight carriers as the cargo is more valuable, and cost of speed is lower for lighter cargo. RoRo vessels are also often designed for effective harbor operation and for diverse operation profile, not necessarily to be optimally efficient on long legs with constant speed as other type of cargo vessels. Some RoRo's may also be designed for transoceanic voyages and thus the whole design criterion is different.

A strict EEDI approach for RoRo volume carriers is a bit questionable since it would reduce operation speeds on certain routes and thus make short sea shipping schedule wise less attractive compared with road transportation. This again could lead shifting of cargo from ships to roads, which would assumingly have higher overall transportation emissions. From the overall emission point of view the whole transportation chain has to be considered for trucks and trailers including different distances and specific emissions on sea and road routes.

Finally, instead of comparing RoRo ships with each other they should actually be compared against other means of transportation in their actual route. However, setting a regulatory framework for comparisons between different means of transportation makes no sense.

4.5 RoPax ships

4.5.1 Summary of EEDI calculations for RoPax ships

According to calculation guidelines of EEDI, RoRo passenger (RoPax) ships are passenger ships as defined in SOLAS chapter II-1, Part A regulation 2.23. This means a ship which carries more than 12 passengers and is equipped with RoRo car deck. Following table summarizes EEDI calculation for RoPax ships by ship building location.

Table 11 - Summary of EEDI calculations for RoPax ships

RoPax Ships		Europe	China	S-Korea	Japan	World
Sample size	(pcs)	64	5	2	6	77
Avg. Gt	(t)	28171,94	14689,60	34700,00	9529,50	26013,36
Avg. ME MCR power	(kW)	24150,72	8921,60	21600,00	9972,17	21990,74
Avg. speed	(kn)	21,93	19,80	22,20	20,87	21,71
Avg. EEDI	(g/t*nm)	**21,87**	**30,331**	**11,98**	**30,721**	**22,86**
Avg. deviation from baseline		**-3,07**	**-11,01**	**0,52**	**-14,42**	**-4,38**

Calculated EEDI values for RoPax ships by ship building location are presented in below figure. Baseline curve for RoPax ships is not currently defined. Therefore, a separately calculated baseline curve for ships being built from 1995 to 2007 has been used for comparison purposes.

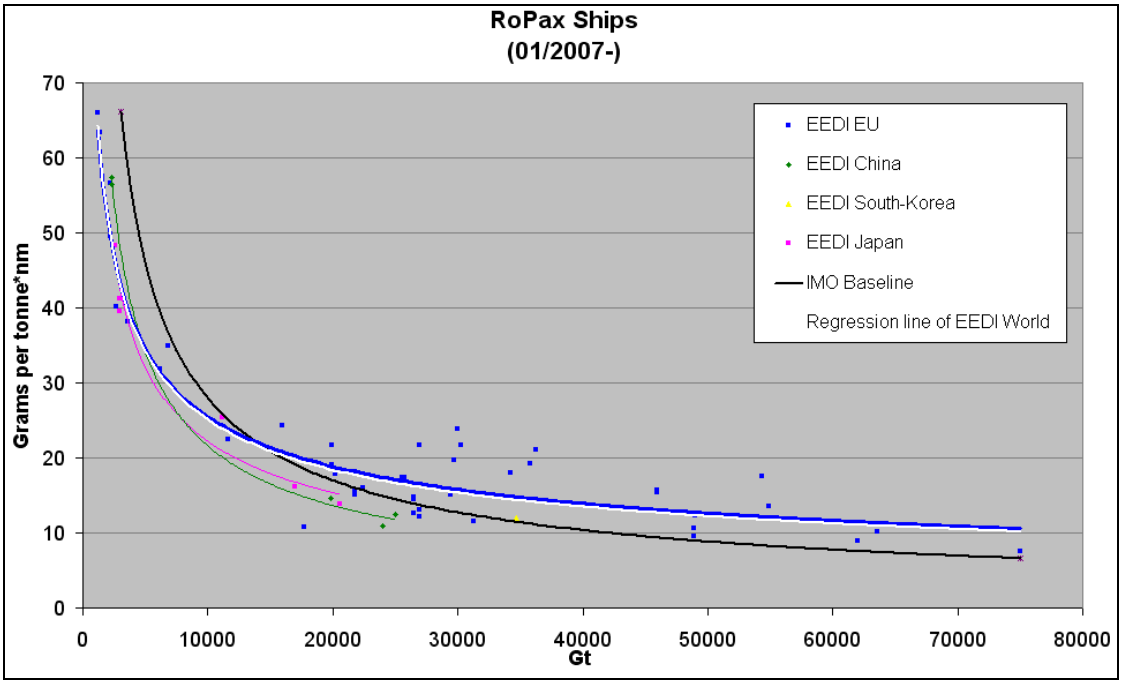


Figure 10 – EEDI for RoPax ships delivered after 1/2007 or currently under construction

4.5.2 Conclusions on EEDI calculations for RoPax ships

RoPax ship building is dominated by Europe with more than 80% market share calculated based on number of ships. Therefore it is possible to draw a trendline only for European-built RoPax vessels and thus trendline comparison between different building locations can not be made. The trouble is also the scatter in EEDI values for all different sizes of ships. China and Japan built ferries have rather low EEDI, and the reason is lower speed compared to European built ferries.

4.5.3 Applicability of EEDI for RoPax ships

RoPax ships include all ferries with a car deck and passenger carrying capability. These ships are specially designed for certain routes and schedules and therefore it is very difficult to compare them directly against each other.

One of the main problems is the definition of the capacity of the vessels. Cargo is RoRo cargo, trucks and cars, but the ship also carries passengers. Trailer capacity could be measured by deadweight but car capacity is volume related. Volume needed for passenger capacity is different on day ferries and night ferries, and different for short and long routes. The only easy way to calculate the capacity is to use gross tonnes as proposed by the current calculation guidelines of EEDI. However, this again does not make any difference between spaces actually used for transportation and for example machinery spaces. A more sophisticated approach would be to develop a capacity index, taking into account deadweight, RoRo deck volume, max passenger capacity and cabin number.

Another problem with RoPax vessels is the big scatter in powering and speed, as the vessels are design for specific routes, and the speed is dimensioned for reasonable schedules on that route. The 30000 GT vessels having an EEDI value above 20 have for example a service speed of 26 knots, whereas the typical speed value for this vessel size traditionally has been 21 to 22 knots. RoPax ships typically have a considerable of margins in engine power for different purposes. The reason can be maintenance of engines, redundancy, safety or ice-class related issues. Also the auxiliary engine power is considerably higher than what is calculated with the current EEDI approximation.

The problem with capacity definition together wit big scattering in speed and powering makes the whole EEDI approach to this vessel type very questionable since the ships are not practically comparable with each other with such an simple approach as the current EEDI.

The current EEDI approach would limit the design speed of new vessels. That again could make newbuildings on some route, where high speed vessels are practical, less feasible. The end result would then be either use of older vessels or a shift to road or air transportation since in many cases RoPax ships are actually competing against other means of transportation.

A very rigid EEDI approach could in the end lead to transition of the cargo flow away from RoPax vessels. The cargo could be shifted to container vessels or general cargo vessels and the passengers to airplanes. This is of course possible, but not certainly desirable from the industry point of view.

5. EVALUATION OF THE CURRENT EEDI FORMULA

5.1 Basics of the EEDI formula

The basic principle of the index is to represent ship CO_2 efficiency at design point. The simplest way of presenting EEDI formula is:

$$EEDI = \frac{\text{Impact to the environment}}{\text{Benefit for the society}} = \frac{\text{Ship } CO_2 \text{ emissions}}{\text{Performed work}}$$

On top of the division line there are CO_2 emissions of main- and auxiliary engines at certain power, defined by the ships operation speed. This is divided with “benefit for the society”, which is transportation of capacity at certain reference speed (V_{ref}). The simplified formula can be further written into form:

$$EEDI = \frac{CO2_{ME} + CO2_{AE}}{Capacity \cdot V_{ref}}$$

The main- and auxiliary engine emissions are calculated from fuel consumption of the main- and auxiliary engines (*FC*) and a carbon conversion factor (C_F), which connects the consumed fuel to the amount generated of CO_2 emissions. Adding in these factors further opens the formula as follows:

$$EEDI = \frac{(FC_{ME} \cdot C_{FME}) + (FC_{AE} \cdot C_{FAE})}{Capacity \cdot V_{ref}}$$

Fuel consumption of an engine depends on the power produced by the engine and on efficiency of the engine. Consumed fuel can be calculated as a product of produced power (*P*) and specific fuel consumption (*SFC*). When these factors are placed into the formula, the expression can be further written as:

$$EEDI = \frac{(P_{ME} \cdot SFC_{ME} \cdot C_{FME}) + (P_{AE} \cdot SFC_{AE} \cdot C_{FAE})}{Capacity \cdot V_{ref}}$$

Some ships are fitted with power take in electrical motors (P_{PTI}) on propeller shaft and the environmental impact of these devices needs to be included into the formula. It is also possible that ship is equipped with innovative energy saving technologies, such as sails, solar panels or a waste heat recovery system, which reduce the power required either from main- or auxiliary engines (P_{eff} and P_{AEeff}). These matters are taken into consideration in the formula by the subtracting the emission reduction due to innovative technologies with aid of additional factors. The EEDI formula then has additional elements and can be written as:

$$EEDI = \frac{(P_{ME} \cdot SFC_{ME} \cdot C_{FME}) + (P_{AE} \cdot SFC_{AE} \cdot C_{FAE}) + ((P_{PTI} - P_{AEeff}) \cdot SFC_{AE} \cdot C_{FAE}) + (P_{eff} \cdot SFC_{ME} \cdot C_{FME})}{Capacity \cdot V_{ref}}$$

Ships with special design elements (e.g. ice-class) may require additional installed main engine power. This is taken into consideration by introducing a power correction factor *(f_j)* which is used to normalize the installed main engine power. It is also possible that capacity of the ship is limited due to technical or regulatory reasons, and therefore a capacity correction factor *(f_i)* is included in the formula. As ships are designed for various operation conditions of wave height, wave frequency and wind speed, a weather correction coefficient (f_w) is also included for normalizing speed of the ship. When these non-dimensional factors are added to the formula, the expression is:

$$EEDI = \frac{f_j \cdot (P_{ME} \cdot SFC_{ME} \cdot C_{FME}) + (P_{AE} \cdot SFC_{AE} \cdot C_{FAE}) + ((f_j \cdot P_{PTI} - P_{AEeff}) \cdot SFC_{AE} \cdot C_{FAE}) + (P_{eff} \cdot SFC_{ME} \cdot C_{FME})}{f_i \cdot Capacity \cdot V_{ref} \cdot f_w}$$

Finally, as mathematical symbols for taking into consideration multiple engines and factors are included, the formula can be written as it has been presented in IMO MEPC.1/Circ.681:

$$EEDI = \frac{\left(\prod_{j=1}^{M} f_j\right)\left(\sum_{i=1}^{nME} P_{ME(i)} \cdot C_{FME(i)} \cdot SFC_{ME(i)}\right) + \left(P_{AE} \cdot C_{FAE} \cdot SFC_{AE}*\right) + \left(\left(\prod_{j=1}^{M} f_j \cdot \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{neff} f_{eff(i)} \cdot P_{AEeff(i)}\right) C_{FAE} \cdot SFC_{AE}\right) - \left(\sum_{i=1}^{neff} f_{eff(i)} \cdot P_{eff(i)} \cdot C_{FME} \cdot SFC_{ME}\right)}{f_i \cdot Capacity \cdot V_{ref} \cdot f_w}$$

The EEDI formula, which may appear very complex at first look, is actually a rather simple representation of ship CO_2 efficiency as the separate the factors are put together. The unit of EEDI can also be derived from the formula:

$$[EEDI] = \frac{[gCO_2] / [h]}{[t] \cdot [nm] / [h]} = \frac{[gCO_2]}{[t] \cdot [nm]}$$

When grams of CO_2 per hour are divided by nautical miles per hour, the unit of hours is eliminated and the final unit of EEDI is gCO2/tnm.

5.2 Calculation principles

The EEDI calculation proceeds according to certain principles, which are described in detail in IMO MEPC.1/Circ.681 guidelines.

1. ***Capacity*** is measured in deadweight for cargo ships. The deadweight to be used in the calculation is according to the deepest operational draught (scantling draught) of the ship.

2. $\boldsymbol{P_{ME}}$ is calculated as 75% of installed total power, taking into consideration possible PTO generators and 75% of their load.

3. $\boldsymbol{V_{ref}}$ is the speed which is consistent with ***Capacity*** and $\boldsymbol{P_{ME}}$ as defined above. This means that the condition for which EEDI is calculated is: speed at scantling draught at 75% of main engine power taking into account possible PTO's.

4. ***SFC*** of main- and auxiliary engines is to be taken from EIAPP certificate NOx technical file. The value to be used is the measured and uncorrected specific

fuel consumption of the parent engine at 75% MCR for main engines and at 50% for auxiliary engines.

5. C_F factors for carbon conversion are defined based on fuel type from tables in the calculation guidelines.

6. P_{AE} means the actual required auxiliary engine power that is required to be supplied for normal sea load. Value for P_{AE} is calculated directly based on main engine power as 2,5…5% of installed MCR power. If the value obtained with this calculation considerably differs from the actual sea load, the auxiliary power should be separately calculated.

7. Elements *for* P_{PTI}, P_{eff} *and* P_{AEeff} are calculated for the EEDI condition (see definition of V_{ref}) if such technology exists.

8. Factors f_i, f_j *and* f_w are calculated based on separately given calculation guidelines when necessary.

From calculation accuracy point of view the most essential thing is to have all of the values consistent with each other. The challenge for calculating index values for existing ships is that speed for scantling draught and 75% engine power is not usually identified. Also, the SFC values, as defined by NOx technical file, are not currently public documents from engine makers.

5.3 Interpretation of EEDI value

EEDI value simply expresses the CO_2 efficiency of a ship at one design point.

This is the simplest way to regulate design efficiency since definition of regulatory baselines would be more or less impossible for more detailed emission calculation for real operation.

Therefore, the index values do not represent the actual transportation CO_2 efficiency of the ship since the operation profile and capacity utilization is not taken into account in the calculation.

Similarly, different types of ships should not be directly compared against each other since the index represents only one point of the total operation profile.

A good example is comparison of general cargo ships and RoRo ships. If index values and baseline curves of general cargo and RoRo ships are set against each other, it seems that RoRo transportation is not as efficient as transporting cargo with general cargo ships. Fist conclusion is that speed of RoRo ships is higher compared to general cargo and also ship lightweight/deadweight ratio is different. However, for RoRo ships there is usually cargo moving in both directions for all voyages where as for general cargo ships it is more difficult to obtain cargo for all voyages as the traffic can be more spot trading. This would actually mean that in many cases the actual transportation efficiency, measured in gCO_2/tnm, could be lot worse for general cargo ships than for a RoRo ship even though in index point of view the situation is opposite.

5.4 Possibilities to affect on EEDI value

In the following some of the most essential ways of affecting on EEDI value have been discussed. Sensitivity of EEDI value has been examined through an example in section 7.

5.4.1 Degrees of freedom for EEDI optimization

Before examining the sensitivity of EEDI it needs to be understood which of the factors are such design criteria that can not be affected. Excluding these parameters from the scope of EEDI optimization will finally show the potential for EEDI optimization that can be made by the designer.

Capacity: Since ship is always designed for certain transportation task, capacity of the ship could be considered as a fixed parameter which can not be affected unless the whole concept is redesigned.

V_{ref}, P_{ME}: Speed and main engine power are connected to each other. Speed/power relation is actually one way of measuring efficiency of the ship. If ship is designed for certain speed, the required engine power will be determined then by that speed and other related design criteria. From designer point of view, the speed is usually given as design criteria, and the possibilities to affect on power depend on designer's skills and degrees of freedom for hydrodynamic optimization.

SFC: Specific fuel consumption depends mainly on selection of machinery. Two stroke and four stroke engines have different specific fuel consumption and the gap depends on size of individual engines. These alternatives also differ slightly from propulsion train efficiency point of view. When the engine type is selected, there are only small possibilities to affect the actual SFC to be used on the calculation.

C_F: Fuel selection is one of the first decisions made by the shipowner regarding power plant. Sometimes HFO is the only practical alternative, but in certain areas and for certain ship types LNG is becoming a true alternative. Fuel selection between regular bunker fuel and LNG will heavily affect on specific CO_2 emissions. However, in a global scale considering all ship types, the practical possibilities for using LNG are still today quite limited.

P_{AE}: Auxiliary power could be affected to some extent by means of optimization of auxiliary systems. However, since the basic approach in EEDI calculation for cargo ships is to derive P_{AE} directly as certain percentage of P_{ME}, there are practically no chances to affect on this value independently.

P_{eff}, P_{AEeff}: Introduction of innovative technologies can be considered as an issue which can be affected by the designer.

f_i, f_j, f_w: The correction factors should not be parameters for EEDI optimization since their purpose is to normalize speed, power and capacity requirements or limitations set by the special design criteria.

The conclusion from above is that the main parameters which a ship designer can affect without considerable changes in the initial design criteria are: speed/power performance and introduction of innovative technologies. Additionally there are issues such as use of PTO and/or PTI which affect on the EEDI value and can be configured by the designer. The rest of the EEDI formula parameters are actually design criteria or alternatively the possibility to affect on them is very small.

5.4.2 Optimization of speed/power

Possibilities and potentials for optimizing ship's speed/power performance have been discussed in sections 7 and 9 of this report. Shortly said, the potential depends very much on the starting point. In some cases a significant improvement is possible by means of design optimization. However, in many cases the starting point is already quite good and thus the potential is rather limited. There are also certain practical limits for hydrodynamic optimization.

The current definition of speed and power in the EEDI formula is not quite favorable for design optimization.

Main engine power is taken in EEDI according to 75% of total installed power. If propulsion optimization is made without reducing the size of the main engine, the benefit of reduced shaft power at certain speed is translated to change of speed at the 75% MCR power.

Speed and power are interconnected to third exponent. The benefit in EEDI point of view in cases where optimization does not allow smaller main engine, is only cubic root of the power reduction. The situation is illustrated in following figure.

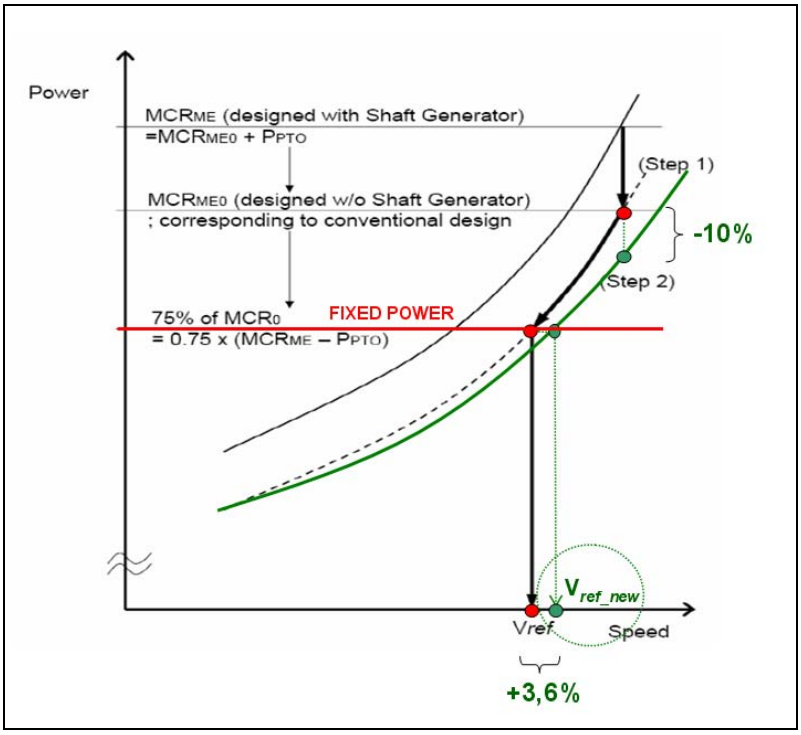


Figure 11 – Implication of propulsion optimization if size of main engine is not changed

In the above figure the green curve represents the optimized propulsion curve which is about 10% lower than the initial dotted curve. Since in calculation point of view the power is fixed and optimization is translated to increase of speed at that power, 10% reduced shaft power would mean about 3,6% increase in speed. This would mean the same 3,6% improvement in the EEDI value.

5.4.3 Introduction of innovative technologies

Several different innovative technologies have been discussed in sections 7 and 9 of this report. Short conclusion is that there certainly is a very interesting potential for savings in application of wind power, waste heat recovery solutions or other novel systems. Remarkable saving potentials are claimed also for many other new technologies. However, the downside today usually is lack of practical experience, and finally also rather high investment costs.

5.4.4 Reduction of design speed

As it has been mentioned earlier, design speed is usually a criteria which is given to the designer as a requirement. Selection of the design speed influences heavily the required engine power and thereby also the EEDI value.

Following figure shows an example of EEDI sensitivity for changes in selected design speed. For simplification reasons it has been assumed that the installed main engine power would follow directly the propulsion power requirement, which is actually not the case since there are certain steps (cylinder size) between each engine. Speed at related power requirement has been altered between 10 and 20,5 knots.

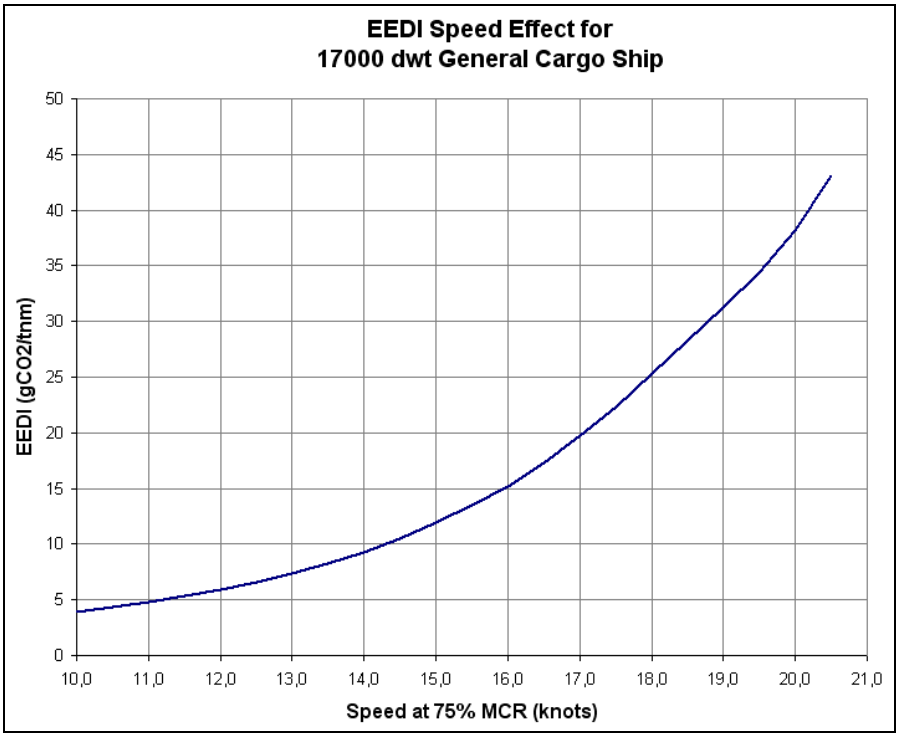


Figure 12 – EEDI sensitivity for speed

The above figure clearly illustrates the sensitivity of the index for selected design speed. The index value for 11 knots is 5 and if the speed is increased with 3kn, the index is nearly doubled. For higher speeds the curve is even steeper. Difference in EEDI value between 19,5 and 20,5 knot ship is about 20%.

The conclusion of above is that ships with higher design speeds have a very challenging starting point for EEDI and the only practical solution for matching with the baseline requirement could be reduction of design speed.

5.4.5 Loopholes in the current calculation method

The current calculation guidelines include some loopholes which can be used to manipulate the EEDI value of a ship without reducing the actual CO_2 emissions. Following ways of cheating in EEDI should be avoided by developing the formula and calculation instructions.

1. Power take out from main engine

According to the current calculation guidelines 75% of the installed PTO capacity can be subtracted from the main engine power. This obviously also reduces the operation speed at the same time, but since speed and power are connected to third exponent, the loss in speed is only cubic of the reduced power in relation to the total power. This calculation principle means that from EEDI point of view it is also beneficial to install a PTO, and the bigger the better. To avoid wrong kind of optimization and installation of oversized PTO's which can never be used, it should be further defined in the calculation guidelines that only the sea load of PTO generators could be deducted from ME power.

2. Switching power from main engine to auxiliary engines

As it was mentioned previously, PTO always gives benefit in EEDI point of view and the bigger the PTO, the bigger the benefit.

It would be possible to install a large PTO/PTI for an engine and get a rather considerable benefit in EEDI calculation by defining that the device shall be used as a PTO under normal seagoing. It could be further claimed in the design and classification phase that the PTI feature is only used in emergencies, for example as a "take me home" device.

However, it would be possible to use the same device as a booster motor to achieve higher speeds, which obviously would also mean higher emissions for the ship. The reserve power production would be "hidden" to higher installed auxiliary engine power which is not currently addressed in the index as such.

Similarly the same principle could be used for example for detaching engine driven pumps and using electric motor driven pumps to get a lower SFC value.

3. Manipulation of capacity

For RoPax and passenger ships the capacity is defined in gross tonnes. In order to obtain better index value, it would be possible to construct large empty volumes onboard the ship and by this mean increase the capacity factor. The good thing is that baseline requirement is tightening also as the capacity of the ship is bigger. In

some cases however there could be a clear benefit of artificially increasing the volume.

For smallest ships it could be actually easier to move horizontally on the baseline graph rather than vertically to match with the baseline requirement. This could also in some cases lead to artificial manipulation of ship's capacity. This could be the case for the smallest ships were the baseline curve is extremely steep. There the manipulation would actually work on other direction. Even a small reduction in capacity would give benefit in required (not obtained) index value. This could lead to minimization of fuel tanks to get an easier EEDI requirement.

5.5 One possible way forward with EEDI calculation for short sea shipping

As it has been mentioned earlier, the current EEDI approach is not fair for short sea shipping where the ships are in many cases operating according to schedules and other special criteria. EEDI could be further developed for these ships by taking into consideration the actual operation profile, and compare each ship only against similar ships, maybe even on that same service.

The same basic approach for calculation could be used. This would mean that CO_2 emissions would be calculated per transported cargo over a nautical mile. The difference would be that operation profile of the ship would be taken into consideration by calculating the EEDI value for different speeds. The final EEDI value would be the weighted average of these sub index values. Weighting of different speed points could be made according to how many hours per year the ship is spending on that speed. The calculation could also include port time and related emissions as well as emissions from oil fired boilers. Following example demonstrates the basic principle:

Table 12 – EEDI based on operation profile

Speed	10kn	15kn	18kn	20kn
EEDI	5	12	25	38
Share of time, %	10%	20%	50%	10%
Final EEDI calculation	0,1·5 +0,2·12 + 0,5·25 + 0,1·38			
Final EEDI	19,2			

The above calculation would allow ships to have power margin and would be more representative for the total actual CO_2 emission. The challenge is definition of regulatory framework.

One alternative could be to establish a standard operation profile for each ship type and calculate index according to that. This would actually be analogous with EU private car CO_2 emission testing. Private cars are not directly evaluated depending on their maximum power but the performance at certain profile. The cars are tested in a standard test profile, including certain amount of city- and highway driving and emissions are calculated according to that profile.

Another alternative is not to have a fixed baseline for a ship type but to always conduct a case-by-case calculation against other ships on similar service. This would mean more local type of regulation rather than global regulation of all ships of certain type.

6. EVALUATION OF THE CURRENT BASELINE CALCULATION METHOD

6.1 Basic principle of current baseline definition method

The basic principle is of the current baseline method as defined in IMO GHG WG 2/2/7 is explained in following.

Calculation of EEDI baselines in IMO GHG WG 2/2/7:

1) Data of all vessels built from January 1998 to December 2007 is taken from Lloyds Register Fairplay database. Ship data is divided into following categories:

   a. Dry bulk carriers
   b. Tankers
   c. Gas carriers
   d. Container ships
   e. General cargo ships
   f. Ro-ro cargo ships

2) Average index values are calculated for the data by applying following formula:

$$Average\ Index\ Value = 3.13 \cdot \frac{190 \cdot \sum_{i=1}^{NME} P_{MEi} + 210 \cdot P_{AE}}{Capacity \cdot V_{ref}}$$

3) The average index values are used as basis of calculating an exponential regression line for each of the ship categories. The regression line expresses the baseline value, which can then be calculated by using the following formula:

$$Baseline\ value = a \cdot Capacity^{-c}$$

   Factors (a) and (c) are constants derived from the regression line.

   Outliers which are more than two standard deviations from the regression line are removed, and a new regression line is calculated in order to remove special ships and erroneous data from the calculation.

4) Finally, using the mentioned information and definitions, assumptions, and calculations, the following results for baseline curves are obtained:

Ship type	a	Capacity	c	Number of samples	Excluded	R^2
Dry bulk carriers	1354.0	DWT	0.5117	2365	59	0.93
Tankers	1950.7	DWT	0.5337	3116	59	0.97
Gas carriers	1252.6	DWT	0.4597	416	11	0.93
Container ships	139.38	DWT	0.2166	2189	87	0.66
General cargo ships	290.28	DWT	0.3300	1824	90	0.63
Ro-ro cargo ships	19788	DWT	0.7137	402	27	0.80

6.2 Challenges in the current methodology

The most obvious challenges in the current baseline calculation method are discussed in the following.

a) Categorization of ships

Maybe the most difficult part of baseline definition is fair categorization of ships. The initial categorization as described in IMO GHG WG 2/2/7 divides ships in six different categories. The latest calculation guidelines in MEPC.1/Circ.681 have further grouped ships into ten categories. As it has been concluded for many of the examined ship types, even these ten categories of ships still include several clearly identifiable subtypes of ships, for which the current categorization is not fair.

b) Reliability of data in LRFP database

Reliability of data in LRFP database has not been verified. When calculating EEDI values for conventional as well as RoRo and RoPax ships, it was clearly noticed that there is a lot of erroneous data. The most obvious sources of error can be excluded with the current methodology of removing the ships with difference higher than two standard deviations from the regression line. However, it is very likely that this will not eliminate all ships with erroneous values. More sophisticated statistical methods for excluding the ships which are not belonging to the category could be developed by addressing power/capacity and speed/power ratios.

c) Consistency of power, capacity and speed

According to calculation guidelines of EEDI power should be taken as 75% of installed total main engine power deducting shaft generators and speed should be taken at this power at scantling draught. The current method of calculating average index value takes into consideration 75% of engine power but speed and capacity are directly extracted from the database. Shaft generators are not addressed at all. Based on the few examined examples where accurate data was available, the database speed values can be either at 100% MCR or 75/85% of MCR and usually without shaft generators. Sometimes speed can indicate trial speed. Also when looking at deadweight, it seems that it can be either at scanting draught or at design draught. For example general practice for bulk carriers is that capacity is reported according to scantling draught and speed is taken at smaller design draught without shaft generators.

Considering definition of baselines, the inconsistency of power, capacity and speed in the database potentially leads to too low “Average Index Values” and thus makes the requirement quite tight for certain types of ships.

d) Different size classes are affecting on each other

Baseline is currently calculated for data which contains data for the whole size range of ships within each category. This means practically that the ships bigger or smaller than the examined size category affect on baseline value, which could make the requirement too easy or too tight in some cases. It should be further studied whether the baseline could be defined separately for the different size classes such as Panamax, Suezmax, and Capesize cargo ships.

6.3 Conclusions on baselines

Regarding application of EEDI to a regulatory framework, the baseline definition will be equally important as the index calculation method itself.

Calculation of fair and reliable baselines with the current database method is very difficult due to previously mentioned challenges. Reliable and accurate EEDI values can only be calculated by parties and organizations having the access to the detailed, and typically confidential, ship information. Even though the final decision on the baseline levels will most likely be mainly political, it should still be verified by the industry that the final level of baselines is realistic for all different types and sizes of ships. The verification should be made with accurate and reliable ship information once the basic EEDI calculation method is agreed.

Too tight baseline could in worst case reduce installed power of ships too much and compromise safety, or make certain types of ships impossible to build. Too easy baseline would not on the other hand lead to any significant CO_2 saving.

Attention should also be paid on careful categorization of ships. Further categorization is reasonable only to certain extent and potentially for certain special ships there is need to develop correction factors to make them comparable with other ships and baselines if they are to be included in the scope of the index.

It also needs to be accepted that EEDI is not most suitable way to regulate efficiency of certain types of ships. Possibly the best way forward with this kind of ships is to further develop the index calculation concept and define the baselines later on when there are more experiences.

7. CASE EXAMPLE OF AFFECTING ON EEDI VALUE

7.1 Case Ship: 11350 dwt RoRo

Sensitivity of EEDI has been exemplified through set of calculations for a case RoRo ship. For demonstration purposes, an existing 11350 dwt RoRo design has been used as an example.

Conceptual design of the case ship has been made around ten years ago. A Far-Eastern shipyard has utilized the basic concept as a standard RoRo design and has built several series of practically identical ships for number of different shipowners.

Principal particulars of The Case Ship:

Ship type:	RoRo volume carrier
Capacity:	11350 dwt
Lane meters:	3455 m
Main engines:	2 x 9450 kW at 100% MCR
Speed:	20,0 kn at 75% MCR
PTO:	2 x 1200 kW
Fuel:	HFO
Ice class:	FS 1A
NB Cost:	~30 M€

7.2 Energy balance for the Case Ship

Energy balance is a calculation demonstrating the vessel's fuel consumption during normal operation and shows the energy consumption shares of each consumer. The balance is the basis of work on all Deltamarin newbuilding design and engineering projects for ensuring energy efficiency of the ship.

Energy balance for the case ship has been calculated based on available design documentation as well as on one possible operation profile in northern Europe, which is based on weekly scheduled rotation at Baltic Sea. In this expected operation profile annual hours are divided as follows: 20%=Port, 2%=Man, 3%=Sailing@17,5kn, 39%Sailing@18,2kn, 36%Sailing@18,7kn. Calculated annual fuel consumption and shares of main consumers are illustrated in Figure 13.

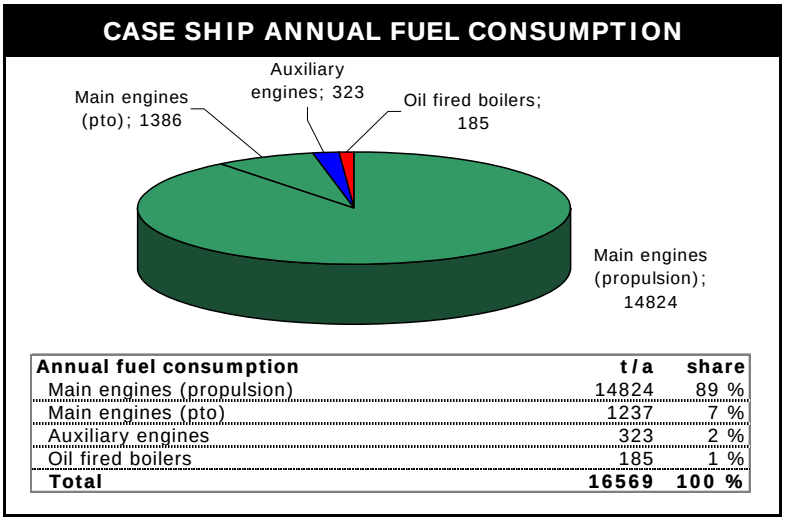
According to energy balance calculation, the annual fuel consumption and emissions would be about:

Fuel consumption	-	16 600 t/a
CO_2 emissions	-	51 600 t/a

In the expected operation profile the ship would be able to perform approximately following transportation task:

Cargo · Distance	-	993 512 293 t·nm

Above figure assumes 70% average dwt utilization and 51 weeks operation per year.



Annual fuel consumption	t/a	share
Main engines (propulsion)	14824	89 %
Main engines (pto)	1237	7 %
Auxiliary engines	323	2 %
Oil fired boilers	185	1 %
Total	**16569**	**100 %**

Figure 13 – Case Ship annual fuel consumption according to energy balance

Based on energy balance and related assumptions for operation profile, the actual transportation efficiency calculated with the basic EEDI philosophy would be:

CO_2 efficiency = CO_2 emissions / (Cargo Transported · Distance)
= 51600 tCO_2 / 993512293 t·nm
= 51,9 gCO_2/ t·nm

7.3 EEDI calculation for the Case Ship

For calculation of EEDI for the Case Ship, exact and ship specific model test data has been used and the calculation has been made according to the latest calculation guidelines as described in IMO MEPC.1/Circ.68. Ice-class correction factors have not yet been defined for RoRo volume carriers and therefore correction factors of "general cargo ship" have been used to take into account 1A Ice class. Also, baseline for RoRo volume carriers is not available and thus the used baseline is general RoRo ship baseline as defined in IMO GHG-WG 2/2/7.

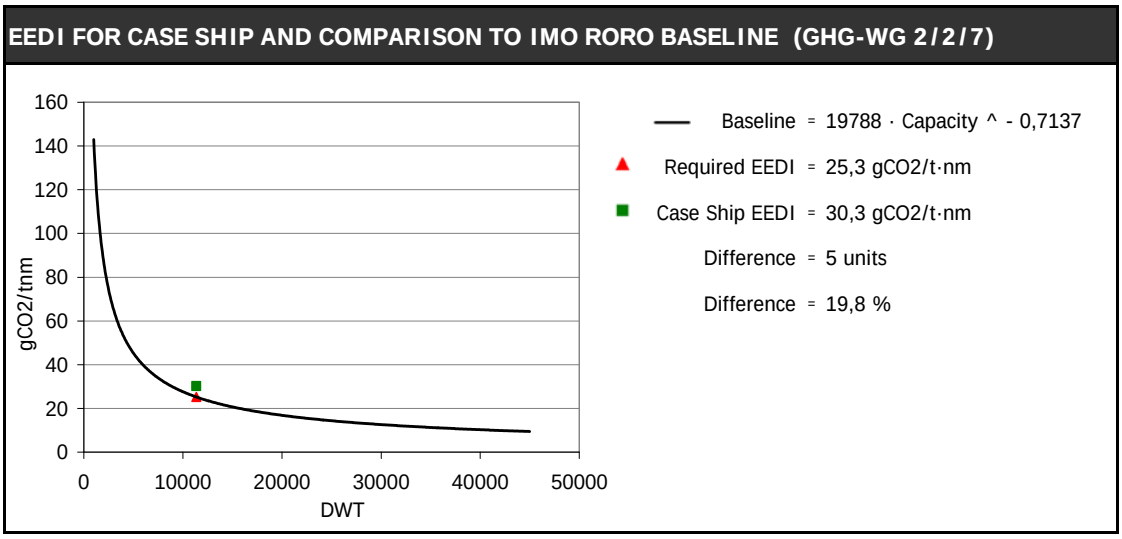


Figure 14 – Case ship EEDI and RoRo baseline

Calculated EEDI for the Case ship is **30,3 gCO_2/tnm**.

According to the current RoRo baseline, the requirement for 11350 dwt ship is 25,3 gCO_2/tnm thus the Case Ship is 5 units (~20%) above the baseline.

Visually it seems that EEDI of the ship is quite close to the baseline. However actual EEDI of the case ship would need to be improved by 5 units (or 20%) to match with the requirement.

The calculated EEDI (30,3 gCO_2/tnm) does not correspond to the actual CO_2 transportation efficiency (51,9 gCO_2/tnm) which is calculated from the real operation profile.

This is primarily due to fact that in real life 100% of dwt can not be constantly utilized for transportation. Also, there are currently some inconsistencies in EEDI calculation method which benefit the case vessel in index point of view. For instance, shaft generators of this ship are dimensioned to supply power for thrusters during manoeuvring. However, according to the current calculation guidelines of EEDI, PTO size can be taken out from ME power as 75% of installed motor power, even though this figure would be much higher than the actual load of shaft generators at sea. There are also certain things which are not addressed by EEDI but decrease the real transportation CO_2 efficiency. Consumption of auxiliary engines at port and fuel consumption of oil fired boilers are two examples.

7.4 Reduction of Case Ship EEDI value

In the following, ten different methods for improving performance and thus EEDI value of the Case Ship have been tested. The first two improvements have actually been proven in model tests when Deltamarin carried out hull- and propulsion optimization for the Case Ship. The last eight improvements are theoretical and the indicated benefit is based only on a desk study. Investment costs are very rough and the purpose is only to demonstrate the magnitude of additional cost due to improvement. The amount of saved fuel and CO_2 is calculated based on energy balance of the vessel taken into account its expected operation profile.

7.4.1 Hull hydrodynamic optimization

Generally speaking ships designed in Europe are quite good in hull performance point of view. However, optimization methods and knowledge are constantly developing and ten year old ships typically have potential for improvement when state of the art methods and knowledge is utilized. For the Case Ship, 5% reduction in propulsion power at design speed was achieved by redesigning the bulbous bow and fine-tuning critical parts of hull lines. Since main engine power is not changed, the 5% benefit in propulsion power is translated to 1,7 percent (0,35kn) higher speed at 75% MCR engine power. The associated cost is due to required optimisation work, tank testing of the new hull as well as required modifications to steel drawings.

Cost:	0,1 M€
Fuel saving:	740 t/a (-4.5%)
CO_2 saving:	2300 t/a (-4.5%)

EEDI benefit:	-5% in propulsion power → 0,35 kn higher speed
EEDI reduction:	30,3 → 29,7 = -0,6 units (-2%)

7.4.2 Propeller and rudder optimization

Propulsion optimization for the vessel included also optimization of propellers and rudders. In the case vessel optimally designed propellers in combination with efficiency rudders resulted in 5% saving in propulsion power at design speed. The implications in EEDI point of view are the same as in previous case. Since main engine power is not changed, the 5% benefit in propulsion power is translated to 1,7 percent (0,35kn) higher speed at 75% MCR engine power.

Cost:	0,25 M€
Fuel saving:	740 t/a (-4,5%)
CO_2 saving:	2300 t/a (-4,5%)

EEDI benefit:	-5% in propulsion power → 0,35 kn higher speed
EEDI reduction:	30,3 → 29,7 = -0,6 units (-2%)

7.4.3 Contra rotating propellers

Instead of having two shaftlines and regular CP propellers, the possibility to use single shaftline and contra rotating (CRP) propellers was examined. The arrangement would also affect on power plant as the CRP concept requires hybrid (mechanic-electric) power production configuration, which is not currently included in EEDI calculation guidelines. The gained benefit in propulsion power could be approximately 10% at design speed. For EEDI calculation purposes it has been simplified that the total installed power would not change and thus the benefit in power would be converted to about 0.7 knots higher operation speed at the same 75% MCR power.

Cost:	2,5 M€
Fuel saving:	1480 t/a (-9%)
CO_2 saving:	4600 t/a (-9%)
EEDI benefit:	10% in reduced propulsion power → 3,5% higher speed
EEDI reduction:	30,3 → 29,4 = -0,9 units (-3%)

7.4.4 Light weight reduction

Significance of light weight reduction was tested by assuming 10% light weight reduction potential with aid of aluminium and composite structures. The reduction in light weight would be converted to 9% increase in deadweight of the ship and in EEDI calculation speed and power would be the same as in the base case. From index point of view the trouble with this kind of optimization is that as the EEDI is improved by increased capacity, also the IMO baseline is tightening. In this case benefit in EEDI was 2,5 units, but as the baseline requirement is changing by -1,6 units, the net benefit in index is only 0,9 units.

Cost:	5,0 M€
Fuel saving:	- t/a
CO_2 saving:	- t/a
Benefit:	10% lower light weight → 9% higher deadweight
EEDI reduction:	30,3 → 27,8 = -2,5 units (-8,3%) but baseline requirement changing 25,3 → 23,7 = -1,6 units hence net EEDI benefit = 1,6 - 2,5 units = -0,9 units

7.4.5 Waste heat recovery system

Benefit of installing a waste heat steam generator and power turbine generator connected to power take in motor on propeller shaft was tested. Theoretically about 5...7,5% of main engine power could be recovered from the exhaust gases and transmitted to propeller shaft with aid of the system. This would increase ship speed by about 0,5 knots at 75% MCR. Alternatively P_{eff} factor in EEDI formula could be used to deduct recovered power from ME power. The latter option gives higher benefit in EEDI value. Interpretation of the formula with respect to use of the P_{eff} factor is not very clearly advised in the current calculation guidelines. The philosophy used within this case calculation has been to keep the speed at 20,0 knots and deduct the 7% of recovered power from 75% MCR.

Cost: 3,5 M€
Fuel saving: 1100 t/a (-6,5%)
CO_2 saving: 3400 t/a (-6,5%)

EEDI benefit: 7,5% reduced ME power through P_{eff} factor
EEDI reduction: 30,3 → 28,3 = -2 units (-7%)

7.4.6 Wind power

Sails could be in theory feasible on a RoRo ship in certain routes where the operation conditions are favourable. Accurate calculation of benefit would require detailed investigation of implications on ship stability, main dimensions, light weight, and other related matters.

For the purposes of this example, 5% reduced propulsion power has been estimated. Similarly as in the previous case this could be utilized in EEDI calculation as additional speed or alternatively taken into account through the P_{eff} factor. Also here deducting the power from main engine gives higher benefit in index point of view.

Cost: 2,0 M€
Fuel saving: 700 t/a (-4%)
CO_2 saving: 2200 t/a (-4%)

EEDI benefit: 5% reduced ME power through P_{eff} factor
EEDI reduction: 30,3 → 28,7 = -1,6 units (-5%)

7.4.7 LNG fuel

Liquefied natural gas (LNG) could be used as ship's fuel instead of HFO if it is available at ship's operation area. There would be several consequences to ship arrangement and machinery configuration due to use of dual fuel engines and LNG fuel system.

First of all LNG tanks require approximately two times more volume compared to HFO tanks. Certain amount of lane meters would need to be sacrificed from the lower cargo hold to accommodate LNG fuel tanks. This would affect on cargo carrying capacity of the vessel, but however not on deadweight of the vessel which is measure of capacity in EEDI formula.

From CO_2 emission point of view LNG is better fuel than HFO. Heat value of LNG is about 50 MJ/kg while for HFO the value is around 40MJ/kg. When efficiency difference of dual fuel engines is taken into account, the specific fuel consumption of dual fuel engines, measured in g/kWh, is about 10% lower in gaseous fuel mode compared to similar size medium speed four stroke HFO engine. As the carbon conversion factor for LNG is 2,75 instead of 3,1144 for HFO, each kilogram of fuel burned in dual fuel engine would also emit about 12% less CO_2 than in HFO fuelled engine. Combining the advantages in specific fuel consumption and carbon conversion would give a total benefit of about -20% in carbon emissions to LNG fuelled ship.

However, since cylinder power of dual fuel engine is slightly smaller than that of similar size heavy fuel oil engine. The power plant installed size would in reality be

slightly different if gas burning engines are selected. For simplification purposes this is however not taken into account in this case comparison.

LNG tanks are the most expensive part of the system and thus the added cost of application depends on size of the tanks. For this example tank capacity allowing regional operation in northern Europe has been used.

Cost:	4,0 M€
Fuel saving:	-
CO_2 saving:	10500 t/a (-21%)
EEDI benefit:	22% lower specific CO_2 emissions
EEDI reduction:	30,3 → 24,0 = -6,3 units (-21%)

7.4.8 Solar Power

The Case Ship has about 600m^2 free deck space on top of ship's deckhouse for solar panels. Electric power production of solar panels onboard the Case Ship could be about 60kW in bright sunlight and favorable sun position. In EEDI calculation the benefit would be calculated through the P_{AEeff} factor.

Cost:	0,25 M€
Fuel saving:	30 t/a (-0%)
CO_2 saving:	90 t/a (-0%)
EEDI benefit:	60kW reduced through P_{AEeff} factor
EEDI reduction:	30,3 → 30,3 = < 0,1 units (<0,3%)

7.4.9 Reduction of main engine power by 1 cylinder / engine

One possible way to decrease EEDI value of the ship is to install smaller main engines and have smaller design speed for the ship. Installing 2x8L engines instead of 2x9L engines would reduce installed main engine power by 2100 kW and design speed by 0,8 knots. Reduced design speed would affect on ship sailing schedules in certain routes. However, the operation profile considered in this example case would not be affected in normal weather conditions.

Cost:	-1,0 M€ (saving)
Fuel saving:	0
CO_2 saving:	0
EEDI benefit:	11% lower P_{ME}
EEDI reduction:	30,3 → 27,7 = -2,6 units (-9%)

7.4.10 Reduction of main engine power by 2 cylinders / engine

Consequences of installing two cylinder smaller main engines were also examined. For the Case Ship this would mean 4200kW (22%) smaller installed main engine power and consequently about 1,5 knots smaller design speed, which would already affect on sailing schedule and operation profile of the ship. Therefore it needs to be perceived that the indicated fuel saving is based on alternative operation profile where

port time is reduced in order to make it possible for the ship to reduce sailing speed at sea and thus keep the weekly schedule. This was made by setting the maximum schedule average speed of the ship to 18,0 knots and by reducing port time by 3 hours / week.

Cost: -2,0 M€ (saving)
Fuel saving: -910 t/a (-5,5%)
CO_2 saving: -2800 t/a (-5,5%)

EEDI benefit: 22% lower P_{ME}
EEDI reduction: 30,3 → 24,9 = -5,4 units (-18%)

7.5 Summary and conclusions

Following table summarizes the results of tests on EEDI sensitivity.

Table 13 – Summary of EEDI improvements

Tested means for reducing EEDI value	**Cost** [M€]	**Fuel saving** [t/a]	**CO2 saving** [t/a]	**EEDI benefit** [units]
1. Hull hydrodynamic optimization	0,1	740	2300	-0,6
2. Propeller and rudder optimization	0,25	740	2300	-0,6
3. Contra rotating propellers	2,5	1480	4600	-0,9
4. Light weight reduction	5,0	-	-	-0,9
5. Waste heat recovery system	3,5	1100	3400	-2
6. Wind power	2,5	700	2200	-1,6
7. LNG fuel	4,0	-	10400	-6,3
8. Solar power	0,25	30	90	<0,1
9. Reduction of ME power by 1 cyl /engine	-1,0	-	-	-2,6
10. Reduction of ME power by 2 cyl's /engine	-2,0	910	2800	-5,4

First of all it can be concluded that benefit in EEDI improvement and actual fuel saving on certain route do not necessarily correlate. Some of the improvements bring along considerable fuel savings when real operation profile is considered, but the impact on EEDI is rather small. Some of the improvements on the other hand reduce EEDI value without affecting on the actual carbon emission.

Optimizing the ship by traditional naval architectural and hydrodynamic optimization could give considerable savings in fuel consumption. Unfortunately these improvements suffer in EEDI point of view from the power definition methodology and thus the EEDI benefit is rather limited because optimization potential exceeding cylinder size of main engine is not very likely.

Technological improvements seem to have potential but problem in most cases seems to be the relatively high first cost. Most of the technological improvements presented here are rather complex and therefore the exact saving and cost, considering connections to other ship systems is difficult to estimate accurately.

Amongst the technological improvements LNG fuel shows very exiting potential both in EEDI as well as actual CO_2 reduction point of view. LNG would be excellent solution also in SO_x and NO_x point of view if it would be widely available for bunkering ships.

However, the most obvious and cost-effective way to affect on EEDI value is to reduce installed main engine power and thus reduce design speed (or –margins) of the ship. Reducing main engine size would bring along savings in cost of ship machinery and would not require installation complex and sometimes even risky new technologies. Implication on EEDI value is easy to estimate already on conceptual phase and there would be no risk of failing with baseline requirement on later phase.

Based on this example it can be finally concluded that EEDI would primarily mean power limit for new ships. This will equalize design speeds of ships down to a certain level depending on type and size of ship.

8. CONCLUSIONS ON APPLICABILITY OF EEDI

The primary objective of EEDI is to reduce carbon dioxide emissions from shipping by improving energy efficiency of newbuildings. The basic philosophy is to calculate transportation CO_2 efficiency index for ships and force the future newbuildings to be more effective than average in the past by applying regulatory baselines. The initial goal has been to develop a universal EEDI formula, applicable for all different types of ships and set a regulatory framework with aid of ship-type specific baselines.

The current EEDI formula is fairly simple and the calculation can be applied for majority of ships. Some of the formula parameters require further refinement in order to make the calculation fair. There are also some loopholes in the current calculation guidelines, through which EEDI of a ship can be manipulated without affecting on the actual emissions. However, these issues can be solved by further developing the formula and calculation guidelines.

Regarding applicability of the index It is essential to identify the ship types where EEDI represents comparable measure of efficiency, and moreover, to recognize the consequences of establishing limitations for index value of those ships.

First of all, categorization of ships needs to be done in a way that the design criteria of ships within each category are uniform. In other words, ships within a category need to be directly comparable with each other. This would mean that requirements on design speed, main dimensions, powering and other essential issues are decided on a similar basis. Some of the currently defined ship types are suitable for EEDI as such and some of them require further categorization or simply exclusion from the scope of indexation.

Secondly, the baselines need to be carefully considered. Examples shown in this study indicate that the absolute index value is difficult to affect without considerable reduction of installed main engine power. The basic conclusion is that EEDI would set power and thus a speed limit for new ships. It should be ensured that this limitation will not compromise safety for any type or size of ship.

Thirdly, the consequences of applying EEDI need to be addressed separately for each type and size of ships based on their trading schemes. Based on the brief analysis carried out within this study it seems that limitation of engine power could be feasible, with certain reservations, for oceangoing cargo ships. This would mean oceangoing ships of following types: tankers, bulkers, container ships and RoRo vehicle carriers. Also LNG and LPG carriers could be included to the scope of EEDI as separate ship types.

The current EEDI philosophy is not feasible for small ships, special ships, passenger ships and short sea shipping in general. This is because there are considerable differences in ship design criteria, which come out from the special tasks or from traffic schemes these ships are designed to operate at. Limiting power or speed of this kind of vessels could lead to wrong kind of sub-optimization of larger transportation systems and would make building of certain types of ships impossible.

This means that further development of the indexation methodology is needed for short sea shipping, including; general cargo ships, RoRo weight and volume carriers, RoPax ships, passenger ships, special vessels as well as small ships in general.

For many of these ships it could be more be more appropriate to calculate EEDI index according to the actual operation profile and to compare the index value locally with old ships on that same service.

The main conclusions on applicability of the current EEDI by ship type have been collected in Table 14. The ship types show the current categorization according to IMO MEPC.1/Circ.681.

Table 14 – Conclusions on applicability of current EEDI for different ship types

Ship type	Conclusion about EEDI	Notes
.1 Passenger ships	Requires further development	Not analysed within this study but the problems are obviously similar as for RoPax ships.
.2 Dry Cargo Carriers	Suitable for oceangoing bulkers > 50000dwt	Baseline definition for handymax, panamax etc. size classes?
.3 Gas Tankers	Suitable, but LNG and LPG ships need to be separated	LNG carrier baseline definition to take into account use of cargo as fuel
.4 Tankers	Suitable for oceangoing tankers > 50000 dwt	Baseline definition for Panamax, Suezmax, Aframax, Capesize? Exclusion of special tankers?
.5 Containerships	Suitable for oceangoing containerships > 25000 dwt	How will the transportation chain be affected by speed reduction?
.6 RoRo vehicle carriers	Suitable for oceangoing PCC's and PCTC's	Sea keeping and safe navigation on rough seas need to be ensured.
.7 RoRo volume carriers	Requires further development	Ships with diverse design criteria and mainly in scheduled traffic.
.8 RoRo weight carriers	Requires further development	Ships with diverse design criteria and mainly in scheduled traffic.
.9 General cargo ships	Suitable for oceangoing general cargo ships > 50000 dwt.	Design criteria of small general cargo ships very diverse. Needs further categorization.
.10 RoPax ships	Requires further development	Each ship with different design criteria since they are designed to certain route. Capacity definition difficult.

9. POTENTIAL FOR CO_2 REDUCTION

9.1 Conventional ships

Cargo ships are typically built in long series and customization of designs for different owners is usually rather limited. Especially during the past ten years when shipbuilding has been booming, the focus could have been more in standardizing the designs and minimizing investment cost and construction lead time.

Therefore, it would be easy to assume that there is a lot of optimization potential in the existing cargo vessels. Obviously this also is the case when it comes to the most standard and cheapest vessels, like standardized bulk carriers.

However, the potential for improvement depends always very much on starting point and unfortunately there is very little accurate and comparable data available for evaluating the overall efficiency situation for all kinds of ships.

Ship design is always a trade off between building costs and operational costs. If fuel economy is important, either due to higher fuel price or emission considerations, the fuel consumption can be reduced by either improving the design or by introducing new technology.

The most obvious way to reduce the EEDI index is to reduce installed main engine power and thus also reduce design speed of the ship. Propulsion power is typically proportional to speed in third power. A reduction of 10% in design speed should reduce the EEDI value by approximately 20% if also a smaller main engine is selected. This is the case in all ship type and all ship sizes. Reducing machinery power will also reduce the overall cost of the vessel, which makes speed reduction the most attractive way to affect on EEDI value.

From ship design point of view there are many ways how EEDI can be affected. Hydrodynamic optimization methods are constantly developing and experience has shown that about 0,5-1% improvement can be made each year by applying state of the are optimization tools and knowledge.

There are also many of technological innovations entering the market which are claimed to have very positive effects on ship's fuel consumption. Basically, the possibility for applying these novel technologies exists but the challenge today still is lack of experience and relatively high investment cost.

In general, for evaluating of the cost/benefit, more detailed calculations have to be made for specific design cases, taking into consideration both the overall building costs of the ship and the actual operation profile. For standard cargo vessels, especially small ones, the added cost of applying novel technologies is often unreasonably big compared to the total price of the vessel.

Potential for efficiency improvement by means of design optimization has been demonstrated through a bulk carrier example in section 9.3.

9.2 RoRo and RoPax ships

The relative performance of RoRo and RoPax vessels is usually rather good. Further very significant improvement of a good design by optimizing design details is not very likely. Certain potential always exists due to the constant development of optimization methods, but this potential is assumingly less than for standard cargo ships.

Also for RoRo and RoPax ships, the most obvious way of reducing EEDI value is to reduce installed main engine power. However, as it has been demonstrated earlier, this may not in every case reduce the actual emissions if the ship is in scheduled traffic. Reducing speed and power is also problematic for few other reasons.

One of the most interesting possibilities for CO_2 reduction for short sea shipping is the application of LNG fuel. Use of natural gas would reduce specific carbon emissions by about 20%. LNG is interesting alternative especially for RoRo and RoPax vessels since many of these ships are in regional traffic and LNG bunkering should be easier to organize than for globally operating cargo vessels. In technical point of view the main disadvantage is bigger volume needed for the LNG tanks. In economical point of view the additional investment needed for LNG system should be paid back in a rather short time, however depending on what will be price of LNG when it is available for ship bunkering.

Some of the technological innovations are more attractive for RoRo and RoPax ships than for standard cargo ships. This is since power levels are higher and therefore also the saving potential measured in absolute fuel tonnes is higher. Investment cost is not always linearly depending on the size of the equipment and therefore the pay back times tend to be shorter if the installation size is big. In some cases however the diversity of operation profile could be problematic.

Many of RoRo and RoPax ships are prototype vessels and there are more degrees of freedom for engineering. Also, especially for RoPax ferries, the additional cost of utilizing the novel energy saving technologies is smaller compared to the overall building cost of the ship.

Also for RoRo and RoPax ships evaluation of the cost-benefit need always to be based on specific design cases, taking into consideration the overall building costs of the ship and the actual operation profile.

9.3 Example of energy efficient bulk carrier design

Deltamarin has recently developed a family of standard bulk carrier designs. The goal has been to maximize payload and at the same time minimize fuel consumption of the ships. Following table summarizes the key characteristics of the ships.

Table 15 – Deltamarin standard bulk carrier key characteristics

	B.Delta37	**B.Delta64**
Length o.a.	179.99 m	199.99 m
Breadth mld	30.00 m	32.26 m
Design draught	9.5 m	11.30 m
DWT at design draft	35,000 t	51,600 t
Scantling draught	10.5 m	13.25 m
DWT at scantling draft	40,000 t	63,700 t
Service speed	14 kn	14.5 kn
Daily fuel consumption at service speed, incl. 15% sea margin	18.0 t	25.5 t

The ships have 10...15% higher payload capacity than any other design available today with the same main dimensions. At the same time, fuel consumption of the ships is 10%...45% lower than on any other bulk carrier design with same main dimensions.

The performance has been achieved by careful optimization of: hull geometry, hull details, propeller and rudder as well as power production efficiency. Low building cost has been one of the key design elements and thus ships have been designed for simple standard structure and geometry without any tricks. Also the ship machinery and all related auxiliary systems have been designed to be simple and robust, but also very effective and adaptive to the actual operation conditions.

B.Delta bulk carriers are also the only modern single screw full bodied ships which meet with IMO course stability requirements.

Efficiency of B.Delta37 and B.Delta64 are compared against three other standard bulk carrier designs with similar main dimensions in the following tables.

Table 16 – B.Delta37 and three competing designs

	Scantling DWT / Daft	Daily ME FOC	Design DWT / Draft	Service Speed	LOA / Beam / Depth (meters)	Cargo Volume
B.Delta37	**40,000 t / 10.5 m**	**18 t**	**35,000 t / 9.5 m**	**14.0 kn**	**180 / 30 / 15**	**50,000 m^3**
C1 - "Best" Competitor	37,300 t / 10.55 m	22.6 t	35,000 t / 10.0 m	14.0 kn	180 / 29.8 / 15	47,000 m^3
C2 - "Avg." Competitor	35,000 t / 10.15 m	25,2 t	35,000 t / 10.15	14.0 kn	180 / 30 / 14.7	47,500 m^3
C3 - "Worst" Competitor	34,770 t / 9.0 m	27,2 t	30,000 t / 9.0 m	14.0 kn	180 / 30 / 14.7	47,000 m^3

Table 17 – B.Delta64 and three competing designs

	Scantling DWT / Daft	Daily ME FOC	Design DWT / Draft	Service Speed	LOA / Beam / Depth (meters)	Cargo Volume
B.Delta64	**63,700 t / 13.25 m**	**26.8 t**	**51,600 t / 11.30 m**	**14.5 kn**	**199.99 / 32.26 / 18.6**	**77,000 m^3**
C1 - "Best" Competitor	60,700 t / 12.80 m	28.8 t	50,600 t / 11.20 m	14.5 kn	199.98 / 32.26 / 18.33	76,800 m^3
C2 - "Avg." Competitor	61,000 t / 13.00	29,6 t	51,000 t / 11.30 m	14.5 kn	199.99 / 32.26 / 18.6	77,500 m^3
C3 - "Worst" Competitor	58,600 t / 13.00	34,7	46,500 t / 11.00	14.5 kn	197.00 / 32.26 / 18.00	74,000 m^3

Based on the above comparisons it can be seen that B.Delta bulk carriers have 10…45% smaller main engine daily fuel oil consumption than the competing designs of same size. At the same time, comparing with the other designs, the payload carrying capability of B.Delta is higher with same main dimensions.

The following table shows EEDI for B.Delta designs. Accurate values have been used for calculation of index, except of SFC for engines, which is taken as SFC_{ISO} + 5% margin. For the competing concepts it is not possible to calculate EEDI value since all the parameters needed for calculating accurate EEDI are not available.

Table 18 – EEDI for B.Delta designs

	EEDI (gCO2/tnm)	IMO baseline	Difference to baseline	Difference in %
B.Delta37 (40 000 dwt)	**4,59**	5,98	-1,52 units	-23%
B.Delta64 (67 300 dwt)	**3,80**	4,71	-1,0 units	-20%

The calculation shows that B.Delta concepts are about 20% more effective than the current baseline requirement. The difference in EEDI performance would be even higher if B.Delta designs were compared against ships with similar main dimensions, but smaller capacity, as in the previous tables.

Figure 15 shows EEDI values of B.Delta ships compared to the current IMO baseline.

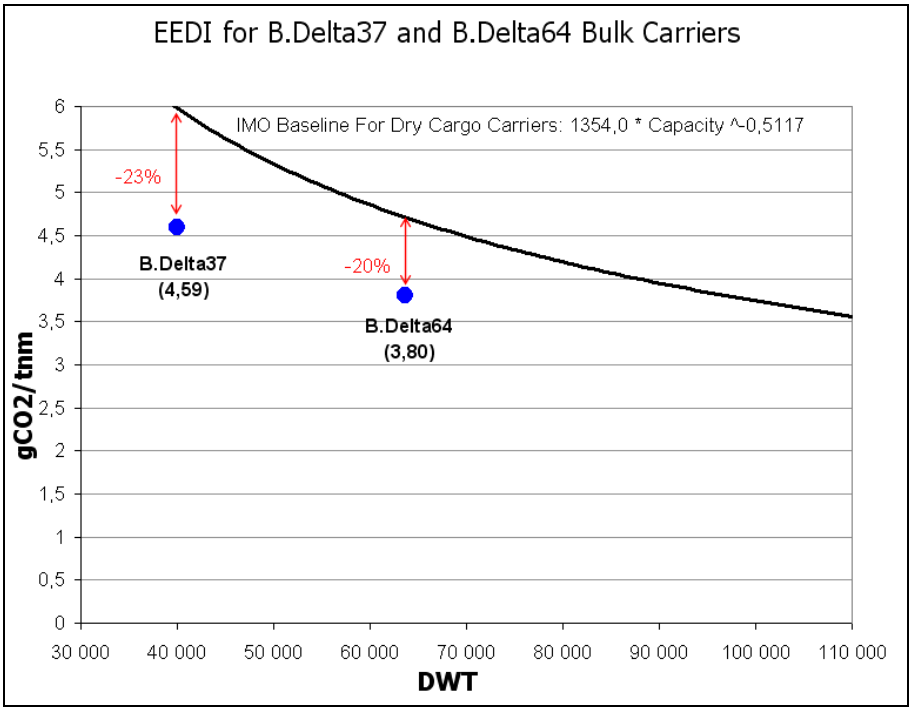


Figure 15 – EEDI of B.Delta ships compared to IMO baseline

Based on this example it can be concluded that, at least for the most standard and simple ships there is a clear performance improvement potential available by means of design optimization.

The identification of the actual potential in terms of % or gCO_2/tnm is difficult to estimate accurately since there is not enough detailed information available for different designs. If the current IMO baselines and ships of similar capacity are used as benchmark level, the previous example demonstrated about 20% improvement potential.

If ships of similar main dimensions are compared, the efficiency improvement was according to the previous tables about 10…45% calculated from the daily fuel consumption. Additionally, if cargo capacity of ships with similar main dimensions is considered, the improvement was up to 55% if efficiency is calculated as fuel consumption per carried cargo tonne per day.

However, the potential for improvement depends always very much on starting point and comparisons need to be made case-by-case for different ships taking also into consideration building costs.

10. ENERGY EFFICIENCY AS PART OF SHIP DESIGN AND ENGINEERING PROCESS

Energy- and environmental efficiency is today one of the key competence factors for ship operators and therefore these aspects also have to be one of the core elements in ship design process.

Ship design and optimization is a complex task where many different parameters need to be taken into consideration. In the beginning of the design process certain capacities and main dimensions are selected for the ship and the concept will be developed, through several project phases, for a detailed contract specification based on which the ship will be finally built.

Energy efficiency development has to be a merged part of the process. Energy efficiency is not only introduction of certain calculation, index or technology. Experience has shown that in order to ensure best results, development of energy efficiency needs to be a constant process within the newbuilding project, starting from definition of key performance indicators and finally ending with commissioning of onboard performance management system and training of onboard crew at ship delivery. The most important thing is that the process is constant and consistent in a way that development is always built on work carried out earlier in the design process.

Deltamarin utilizes energy efficiency development process, described shortly in following, in all newbuilding projects. The process has been applied in various extent for number of newbuilding projects and the experiences have been very positive.

1. Definition key performance indicators and targets

The first step on energy efficiency development has to be definition of key performance indicators for ship efficiency. EEDI or EEOI could be suitable indicators, but typically shipowners have also their own performance indicators which they prefer to use for measuring efficiency of ships. First definition of the target level for each performance indicator can be made with aid of energy balance calculation and benchmark with existing vessels, and updated later during the design process when more accurate information is available.

2. Introduction of energy balance

Energy balance is a calculation demonstrating the vessel's overall fuel consumption during normal operation, including the consumption shares of each main consumer group. Energy balance should be one of the first calculations made for a ship, and it has to be constantly developed and further specified during the project. The balance can be used as basis of all energy efficiency related development during the whole newbuilding project. Ship efficiency and the status of defined key performance indicators can be identified from the calculation and use as basis of decisions.

3. Machinery and propulsion study

When the ship concept is being outlined, machinery- and propulsion related issues need to be addressed systematically since selection of machinery and propulsion configuration are one of the most important issues affecting on energy efficiency of the ship. Best solution is to conduct a comprehensive study for the most feasible machinery- and propulsion configurations, including also different fuel alternatives, in an early phase of the project. It is very essential that all issues related to operational efficiency, emissions, maintenance, safety, building cost and also consequences to the ship concept itself are evaluated. Energy balance and key performance indicators provide good benchmarks for the purposes of this study.

4. Optimization of the most energy consuming systems

Once the machinery- and propulsion configuration has been decided, the most energy consuming systems can be unambiguously identified through the energy balance. It is important that the most energy consuming systems are addressed before ship contract is made, since after the ship contract it is usually rather difficult to affect on the basic configuration of systems. This includes hydrodynamic optimization as well as optimization of other ship systems. Today there are various optimization tools available, also for optimization of machinery- and ship auxiliary systems.

5. Development of ship specification

The outcome of energy efficiency development work has to be incorporated into the final contract specification of the ship. One of the most essential issues to be included in the specification are the key performance indicators, required performance levels, and verification procedures during sea trials. Also, all of the findings of the machinery and system optimization studies need to be included as specification text for different systems. It is also important that the final onboard energy management system and related automation and instrumentation are specified before the ship contract. A good specification will also ensure that the shipbuilder is committed to the energy efficiency development by requiring the shipyard and shipowner to establish an energy efficiency team directly after the ship contract.

6. Energy efficiency team

In order to ensure that the energy efficient principles are applied in the further ship design, an energy efficiency team should be formed directly after the ship contract. This group should consist of members from shipyard, shipowner and ship designer.

The basis of the work is energy efficiency related work carried out before ship contract and the team shall be responsible for the final development of efficiency including following:

Final hydrodynamic optimization; hull form and propulsion arrangement development and model testing will be continued until all parties: shipyard, ship owner, owners consultant and model basin agree that there is no further possibilities to improve the hull form design or agreed time limit is reached.

Final system optimization; the team shall ensure that all essential systems are optimized according to guidelines given in ship specification. A simulation program can be used as basis of further development and system energy models during basic design period of the ship. The developed simulation models can be used for benchmarking purposes for the onboard energy monitoring and management system.

Supplier selection; suppliers for the energy-sensitive systems shall not be selected based on first cost only. Further examination and comparison between different manufacturers and their profitability shall be executed by the team before selecting the final system configuration and supplier for the key energy consuming systems.

7. Development of energy efficiency operation manual for the ship

Ship delivery documentation should include a separate guidebook or manual for energy efficient operation of ship and her systems. The document could be written in form of ship energy efficiency management plan (SEEMP) and the system specific instructions and best practices could be appendixes of that documentation.

8. Commissioning of onboard energy management system

Each ship should be fitted with a system which allows real-time monitoring of energy efficiency. The system should be described in contract specification and could be used for verification of efficiency already during the sea trials. The extent of the system needs to be decided case-by-case depending ship's operation and shipowners preferences. State of the art systems can include real-time decision support for operators for ensuring best efficiency, combined with fleet energy management functions for the shipowner.

9. Crew training

The ship will be finally at hands of its crew and therefore it is extremely important that the operative personnel are aware of energy efficiency related matters in order to be able to operate the ship optimally. Experience has shown that crew training should take place before ship delivery and ship designers and builders should take responsibility of organizing the training since they have the best knowledge of design features for that specific ship. Developed system efficiency models and the onboard energy management system can be utilized for training purposes.

10. Continuous follow-up and improvement

A new ship always usually has a certain "learning curve", since it takes a while until all the systems are adjusted optimally for operational conditions and also it takes a while for the crew to learn how to run the ship optimally. This process can be considerably accelerated with aid of energy management system and related training. However, for optimal operation it is necessary that the energy consumption is constantly monitored against set goals and target performance. Comprehensive analysis on the data and a regular onboard energy audit are good ways of ensuring operational efficiency. Finally, the best approach could be to establish a standardized process for energy management procedures.

APPENDICES

(1) EEDI for Tankers
(2) EEDI for Bulkers
(3) EEDI for Container Ships
(4) EEDI for General Cargo Ships
(5) EEDI for Gas Carriers
(6) EEDI for RoRo Vehicle Carriers
(7) EEDI for RoRo Weight Carriers
(8) EEDI for RoRo Volume Carriers
(9) EEDI RoPax ships
(10) Basis of EEDI calculations