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Improved Formulation of the Energy Efficiency Design Index of Ships

Diploma Thesis
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…When the fog so thick would cover us,
We'd hear the cries of the lighthouses
And the ships unseen we'd hear,
Wailing as they passed and drifted away…

Nikos Kavvadias, Letter to the Poet Caesar Emmanuel

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1.Introduction

Human activities in the past 150 years generating greenhouse gas emissions have deteriorated atmospheric conditions at an extent never known to human history before. Among all greenhouse gasses, CO2 emissions are the principal pollutant responsible for global warming. Transportation activities generate CO2 emissions, resulting from the combustion of petroleum-based products in internal combustion engines. Shipping industry, by fully participating in the transportation sector, had contributed in 2007, to an estimated percentage of 2,7% of greenhouse gas emissions to the atmosphere*. [1]* With the increasing demands in the shipping industry, such a percentage is expected to rise. Therefore, the shipping community has undertaken initiatives to reduce greenhouse gas emissions in a responsible manner. Evidently, in order to address the issue efficiently, a variety of measures need to be taken into consideration.

It has become clear that, nowadays, even from the conception of a new design, one should not only consider cost-effectiveness in the traditional sense, but also energy efficiency. The latter does reflect respect for the environment and the society as a whole, but it is also linked to a strong economic incentive. Given the fact that the demand for sea transportation is continually growing, in the next decades the CO2 emissions by ships are expected to rise significantly. We are thus in critical time for adopting a new perspective regarding energy efficiency.

The main effective measures to reduce shipping emissions could be implemented both during the design and the operation stage. New concepts with improved hull and superstructure designs and state of the art propulsion systems are supposed to lead to more energy efficient ships. Improved fuels with lower carbon concentration and the use of renewable energy sources are other promising measures towards efficiency. Another measure that could ameliorate operational efficiency would be sailing at a lower speed. Since speed and power are related with a third power function, the corresponding fuel consumption would be significantly reduced. However, a speed reduction in a fast growing and demanding global market could complicate the economic aspect of shipping.

The International Maritime Organization (IMO) has taken the initiative to address air pollution by proposing several resolutions concerning energy efficiency of ships and by introducing the Energy Efficiency Design Index (EEDI) in MARPOL's Annex VI. This index has received both appreciation and criticism, but it is one of the first global steps to calculate CO2 emissions and to create an environmentally friendlier conscience among the shipping community.

However, the issue is still not settled and a lot of questions remain to be answered. Non-traditional ship categories seem to have been neglected and the EEDI value is not comparable between different ship types. In order to calculate energy efficiency though, it is required to have an instrument in our hands enabling us to make comparisons between different ship categories and different transportation methods. In such a way, we could have a clearer idea of which transportation method is more beneficial to society and less detrimental to the environment.

During this study, we have attempted to modify the energy efficiency design index in order to better reflect the anticipated operation for a ship at the design stage and to take better account of the benefit to society incurred by a ship's transport service In more detail, in the following will be discussed the introduction of a new energy efficiency formula based on different operational profiles of ships. Moreover, the benefit to society will be accounted through a newly conceived utility function, which could be used for comparisons across the different ship types. Last but not least, there will be an attempt to consider the energy efficiency in a lifecycle approach, from the first journey and for a period of 20 years.

2. Background

One of the mandatory measures to increase energy efficiency and reduce CO2 emissions from international shipping proposed by the IMO, perhaps the most controversial of all up until this day, is the implementation of the Energy Efficiency Design Index. Although Ships represent the most Carbon Efficient method of transport, with a CO2 emission contribution of only 2,7% of total transport, the Marine Environmental Protection Committee (MEPC) has developed the EEDI, as a method to calculate the CO2 emissions of a ship in relation to its value for society. [2]

EEDI formula:

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

For every ship new building the index value will be calculated and then compared to the required EEDI value. If the attained EEDI is below the baseline then the ship passes the index. The reference lines or baselines refer to average EEDI curves, statistically calculated and based on data from existing ships.

The EEDI formula was adopted at MEPC 62 and entered into force since 1 January 2013*.* The EEDI verification includes two stages: pre-verification and final verification. Pre-verification is based on model tank testing results whereas the final verification is based on commissioning trial results. The final EEDI Technical File is expected to include all the data required for the EEDI calculations. However, the current formula has received a lot of criticism from the scientific and shipbuilding community, particularly because it does not seem to address all ship types as effectively as supposed.

The necessity to implement a measure that could estimate, even from the design stage, the energy efficiency and the utility that the ship and its services can provide to society, is widely acknowledged. The critical question that rises at this point though is if this specific method is the best way to address the problem, or the impact that this method creates on ship design would only complicate things and negatively affect the global market.

The different phases in scheme for reduction of required EEDI for different ship types can be seen in the Table 1 below:

Table1: Phases in scheme for reduction of required EEDI for different ship types

Ship Type	Size (DWT)	Phase 0 1 Jan 2013–31 Dec 2014	Phase 1 1 Jan 2015 –31 Dec 2019	Phase 2 1 Jan 2020–31 Dec 2024	Phase 3 1 Jan 2025–and onwards
Bulk Carrier	≥20000	0	10	20	30
	10,000-20,000	n/a	0-10*	0-20*	0-30*
Gas tanker	≥10000	0	10	20	30
	2,000 – 10,000	n/a	0-10*	0-20*	0-30*
Tanker	≥20000	0	10	20	30
	4,000 – 20,000	n/a	0-10*	0-20*	0-30*
Container ship	≥15000	0	10	20	30
	10,000–15,000	n/a	0-10*	0-20*	0-30*
General Cargo ships	≥15000	0	10	15	30
	3,000 – 15,000	n/a	0-10*	0-15*	0-30*
Refrigerated cargo carrier	≥5000	0	10	15	30
	3,000 – 5,000	n/a	0-10*	0-15*	0-30*
Combination carrier	≥20000	0	10	20	30
	4,000 – 20,000	n/a	0-10*	0-20*	0-30*

*Reduction factors should be linearly interpolated between the two values dependent upon vessel size. The lower value of the reduction factor is to be applied to the smaller ship size.

3. Main Objective and Stages of Work

The objective of this study is to rationalize the current EEDI formula of ship design by considering possible alternative methods of calculation of energy efficiency. This project aims to analyze the methodology behind the index and explore the potential of introducing new methods of estimating transport work and utility besides the ones proposed by the responsible IMO Committee.

Towards achieving this, in the current work will be addressed the following topics:

- The calculation procedure and the influence of the various correction factors.
- An example calculation for a typical cargo vessel (bulk carrier) in order to identify weak points that need to be addressed during the development of the revised index.
- Consideration of ship types that seem to be problematic in the implementation of the EEDI index. In particular, consideration of the methodology proposed by Sweden concerning the inclusion of the Ro-Ro Cargo and Ro-Ro Passenger ship types into the IMO energy efficiency regulatory framework. [3]
- Application of the above calculation methodology on existing Ro-Ro passenger vessels.
- Critical review of the index and concerns about the future impact of the index on ship design.
- Inclusion of the service profile of ships into the efficiency formula.
- Application to existing ships.
- Introduction of the Baltic Dry Index in the concept of utility for bulk carriers and calculation.

- Discussion on the potential changes of the formula for other ship types and the necessity of an index suitable for comparing the energy efficiency of different ship types and transportation means available in general.

Even though the debate about the formula in principle seems to be concluded and only minor changes are anticipated in the future, the energy efficiency issue from a life cycle perspective is still open and needs to be considered.

In order to address the above topics we have followed the relevant resolutions published by IMO's Marine Environmental Protection Committee. [2], [3], [4]

4. Typical EEDI Calculation

4.1. Description of the formula

The Energy Efficiency Design Index calculates the amount of CO_2 (g) emitted, which is considered to be the environmental cost, over the social benefit represented in the formula by the capacity times the ship's speed. For merchant ships capacity is defined as deadweight and for ships carrying passengers as gross tons. To calculate the amount of exhausted carbon dioxide we have to multiply engine power by its specific fuel consumption (SFC) and a conversion factor (CF) from fuel to CO_2. It becomes evident therefore that by definition the EEDI directly depends on installed engine power, deadweight and speed of the ship.

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

The terms and factors of the above formula as defined in MEPC.1/Circ.681are listed below [2] :

- CF: is a non-dimensional conversion factor between fuel consumption measured in g and CO_2 emission also measured in g based on carbon content. The subscripts MEi and AEi refer to the main and auxiliary engine(s) respectively. CF corresponds to the fuel used when determining SFC listed in the applicable EIAPP Certificate. The value of CF is as follows in Table 2:

Table 2: CF values for different fuel types

Type of fuel	Reference	Carbon content	C_F (t-CO_2/t-Fuel)
1. Diesel/Gas Oil	ISO 8217 Grades DMX through DMC	0.875	3.206000
2. Light Fuel Oil (LFO)	ISO 8217 Grades RMA through RMD	0.86	3.151040
3. Heavy Fuel Oil (HFO)	ISO 8217 Grades RME through RMK	0.85	3.114400
4. Liquified Petroleum Gas (LPG)	Propane Butane	0.819 0.827	3.000000 3.030000
5. Liquified Natural Gas (LNG)		0.75	2.750000

- Vref :is the ship speed, measured in nautical miles per hour (knot), on deep water in the maximum design load condition (Capacity) at the shaft power of the engine(s) and assuming the weather is calm with no wind and no waves. The maximum design load condition shall be defined by the deepest draught with its associated trim, at which the ship is allowed to operate. This condition is obtained from the stability booklet approved by the Administration.

- Capacity:

  - ✓ For dry cargo carriers, tankers, gas tankers, containerships, ro-ro cargo and general cargo ships, deadweight should be used as *Capacity*.

  - ✓ For passenger ships and ro-ro passenger ships, gross tonnage should be used as *Capacity*.

  - ✓ For containerships, the capacity parameter should be established at 65% of the deadweight.

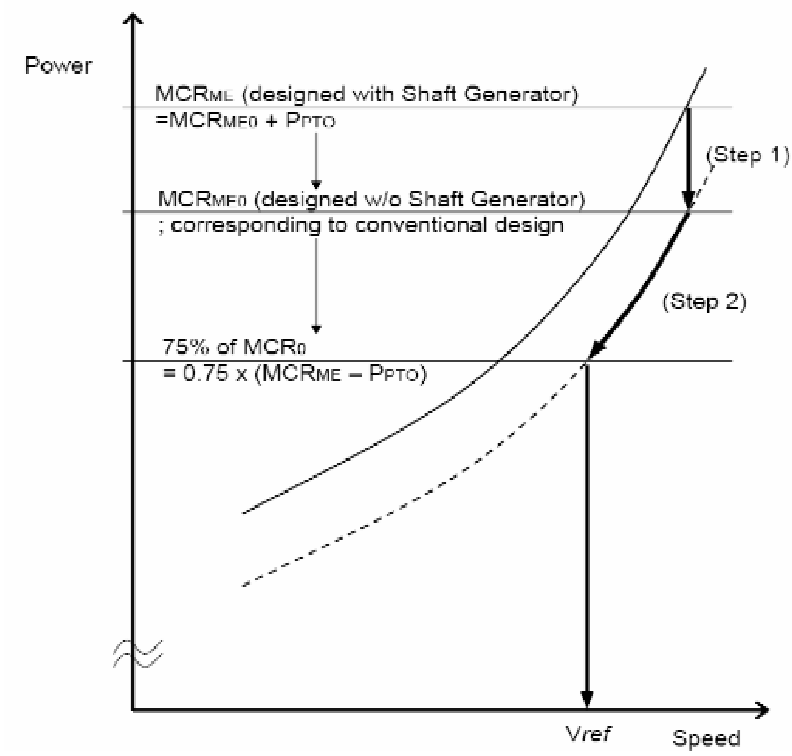
- Deadweight: means the difference in tones between the displacement of a ship in water of relative density of 1,025 kg/m3 at the deepest operational draught and the lightweight of the ship.

- $P_{ME(i)}$: is 75% of the rated installed power (MCR) for each main engine (*i*) after having deducted any installed shaft generator(s):

$$P_{ME(i)} = 0.75 \times (MCR_{MEi} - P_{PTOi})$$

The determination of $P_{ME(i)}$ is described in figure below, as it was given in MEPC1./Circ.681. [2]

Figure 1: Calculation of P_{ME}



- $P_{PTO(i)}$: is 75% output of each shaft generator installed divided by the relevant efficiency of that shaft generator.
- $P_{PTI(i)}$: is 75% of the rated power consumption of each shaft motor divided by the weighted averaged efficiency of the generator(s).
- $P_{eff(i)}$: is 75% of the main engine power reduction due to innovative mechanical energy efficient technology.
- $P_{AEeff\ (i)}$: is the auxiliary power reduction due to innovative electrical energy efficient technology measured at $P_{ME(i)}$.
    - ➢ For cargo ships with a main engine power of 10000 kW or above, P_{AE} is defined as:

$$P_{AE} = (0.025 \times \sum MCR_{ME}) + 250$$

- For cargo ships with a main engine power below 10000 kW, P_{AE} is defined as:

$$P_{AE} = 0.05 \times \sum MCR_{ME}$$

- *SFC*: is the certified specific fuel consumption, measured in g/kWh, of the engines. The subscripts $_{ME(i)}$ and $_{AE(i)}$ refer to the main and auxiliary engine(s), respectively.

- f_j :is a correction factor to account for ship specific design elements. The f_j for ice-classed ships is determined by the standard f_j in Table 3.

Table 3: f_j correction factor values depending on ice class

Ship type	f_j	Limits depending on the ice class			
		IC	IB	IA	IA Super
Tanker	$\frac{0.516 L_{pp}^{1.87}}{\sum_{i=1}^{nME} P_{iME}}$	$\begin{cases} max\ 1.0 \\ min\ 0.72 Lpp^{0.06} \end{cases}$	$\begin{cases} max\ 1.0 \\ min\ 0.61 Lpp^{0.08} \end{cases}$	$\begin{cases} max\ 1.0 \\ min\ 0.50 Lpp^{0.10} \end{cases}$	$\begin{cases} max\ 1.0 \\ min\ 0.40 Lpp^{0.12} \end{cases}$
Dry cargo carrier	$\frac{2.150 L_{pp}^{1.58}}{\sum_{i=1}^{nME} P_{iME}}$	$\begin{cases} max\ 1.0 \\ min\ 0.89 Lpp^{0.02} \end{cases}$	$\begin{cases} max\ 1.0 \\ min\ 0.78 Lpp^{0.04} \end{cases}$	$\begin{cases} max\ 1.0 \\ min\ 0.68 Lpp^{0.06} \end{cases}$	$\begin{cases} max\ 1.0 \\ min\ 0.58 Lpp^{0.08} \end{cases}$
General cargo ship	$\frac{0.0450 \cdot L_{pp}^{2.37}}{\sum_{i=1}^{nME} P_{iME}}$	$\begin{cases} max\ 1.0 \\ min\ 0.85 Lpp^{0.03} \end{cases}$	$\begin{cases} max\ 1.0 \\ min\ 0.70 Lpp^{0.06} \end{cases}$	$\begin{cases} max\ 1.0 \\ min\ 0.54 Lpp^{0.10} \end{cases}$	$\begin{cases} max\ 1.0 \\ min\ 0.39 Lpp^{0.15} \end{cases}$

- f_w : is a non-dimensional coefficient indicating the decrease of speed in representative sea conditions of wave height, wave frequency and wind speed (e.g., Beaufort Scale 6). According to MEPC.1/Circ.796 [5] the wind resistance coefficient in the formula of added resistance due to wind should be calculated by a formula with considerable accuracy, which has been confirmed by model tests in a wind tunnel.

- $f_{eff(i)}$: is the availability factor of each innovative energy efficiency technology. For instance, $f_{eff(i)}$ for waste energy recovery system is one 1.

- f_i: is the capacity factor for any technical/regulatory limitation on capacity, and can be assumed one (1.0) if no necessity of the factor is granted. f_i for ice-classed ships is determined by the standard f_i in Table 4.

Table 4: f_i factor values depending on the ice class

Ship type	f_i	Limits depending on the ice class: IC	IB	IA	IA Super
Tanker	$\frac{0.00115 L_{PP}^{3.36}}{capacity}$	$\begin{cases} max\,1.31 L_{PP}^{-0.05} \\ min\,1.0 \end{cases}$	$\begin{cases} max\,1.54 L_{PP}^{-0.07} \\ min\,1.0 \end{cases}$	$\begin{cases} max\,1.80 L_{PP}^{-0.09} \\ min\,1.0 \end{cases}$	$\begin{cases} max\,2.10 L_{PP}^{-0.11} \\ min\,1.0 \end{cases}$
Dry cargo carrier	$\frac{0{,}000665 \cdot L_{PP}^{3.44}}{capacity}$	$\begin{cases} max\,1.31 L_{PP}^{-0.05} \\ min\,1.0 \end{cases}$	$\begin{cases} max\,1.54 L_{PP}^{-0.07} \\ min\,1.0 \end{cases}$	$\begin{cases} max\,1.80 L_{PP}^{-0.09} \\ min\,1.0 \end{cases}$	$\begin{cases} max\,2.10 L_{PP}^{-0.11} \\ min\,1.0 \end{cases}$
General cargo ship	$\frac{0{,}000676 \cdot L_{PP}^{3.44}}{capacity}$	1.0	$\begin{cases} max\,1.08 \\ min\,1.0 \end{cases}$	$\begin{cases} max\,1.12 \\ min\,1.0 \end{cases}$	$\begin{cases} max\,1.25 \\ min\,1.0 \end{cases}$
Containership	$\frac{0.1749 \cdot L_{PP}^{2.29}}{capacity}$	1.0	$\begin{cases} max\,1.25 L_{PP}^{-0.04} \\ min\,1.0 \end{cases}$	$\begin{cases} max\,1.60 L_{PP}^{-0.08} \\ min\,1.0 \end{cases}$	$\begin{cases} max\,2.10 L_{PP}^{-0.12} \\ min\,1.0 \end{cases}$
Gas tanker	$\frac{0.1749 \cdot L_{PP}^{2.33}}{capacity}$	$\begin{cases} max\,1.25 L_{PP}^{-0.04} \\ min\,1.0 \end{cases}$	$\begin{cases} max\,1.60 L_{PP}^{-0.08} \\ min\,1.0 \end{cases}$	$\begin{cases} max\,2.10 L_{PP}^{-0.12} \\ min\,1.0 \end{cases}$	1.0

According to MEPC 64/INF.22, the conversion factor CF and the specific fuel consumption, SFC, are determined from the results recorded in the parent engine Technical File as defined in paragraph 1.3.15 of the NOx Technical Code 2008. [6]

4.2. Example calculation of the EEDI value of an existing vessel

In order to understand fully the calculation procedure and the contribution of each factor to the attained value, we followed the IMO guidelines for an existing vessel. In particular, we chose a bulk carrier with the following general particulars:

Bulk 1

Gross tonnage: 28,693 GRT

Length overall: 189.90 m

Length between perpendiculars: 180.00 m

Breadth moulded: 32.20 m

Design draught: 11.12 m

Scantling draught: 12.17 m

Propulsion type: MAN B&W 6S50MC

Vref: 14.16 kt. This is the speed at 75% of the MCR and at the draught corresponding to the DWT figure.

The particular ship does not have shaft generators or shaft motors so the calculation of Power Take Out term PTO(i) and Power Take In term PTI(i) was omitted.

The next step was the calculation of the emissions of the main engines. The power at MCR is equal to 8,580 kW, so the power at 75% MCR deducting shaft generators $P_{ME(1)}$ would be 6,435 kW. The fuel type used for NO_X certification is Heavy Fuel Oil, so the non-dimensional conversion factor $C_{FME(1)}$ is equal to 3.11440. The Specific fuel consumption of main engine $SFC_{FME(1)}$ is 175.1 g/kWh. As a result, the amount of CO_2 emitted from the main engine comes up to 3,509,208 g CO_2/h.

For the calculation of the emissions from the auxiliary engines we made the following calculations. The required auxiliary engine power P_{AE} is 429 kW. The specific fuel consumption of the auxiliary engine SPC_{AE} is equal to 199 g/kWh. The CO_2 emissions from the auxiliary engines come up to 256,879 g CO_2/h.

Given the fact that there are no innovative technologies installed on board, there is no main engine and auxiliary engine power reduction due to innovation.

The ice class of the specific ship is IA type and the calculated fj value concerning specific design elements for dry cargo carrier is 0.9168 and the corresponding minimum limit depending on ice class is 15.3346, whereas the calculated f_i value concerning technical/regulatory limitation in capacity is 1.1280 with a maximum limit depending on ice class of the same value.

The next step is the calculation of the denominator. The ship's capacity, in this case the deadweight, is 50,259 t and the attained speed 14.16 knots. The factor f_w is considered to be equal to 1 and the factor f_i is equal to 1.1280 as calculated in the previous step. The formula denominator takes the value of 802,740.32 t-nm/h.

The numerator term, the total CO_2 emissions come up to 4,224,164.51gCO_2/h. Finally, the Energy Efficiency Design Index for Bulk 1 is 5.26 gCO_2/t-nm.

The calculated EEDI for a ship will be called the attained EEDI. This attained EEDI must less than the reference EEDI or reference line. This reference line becomes stringent at different phases.

The Reference line values shall be calculated as follows:

$$\text{Reference line value} = a \times b^{-c}$$

Where a, b and c are the parameters given in Table 5 below.

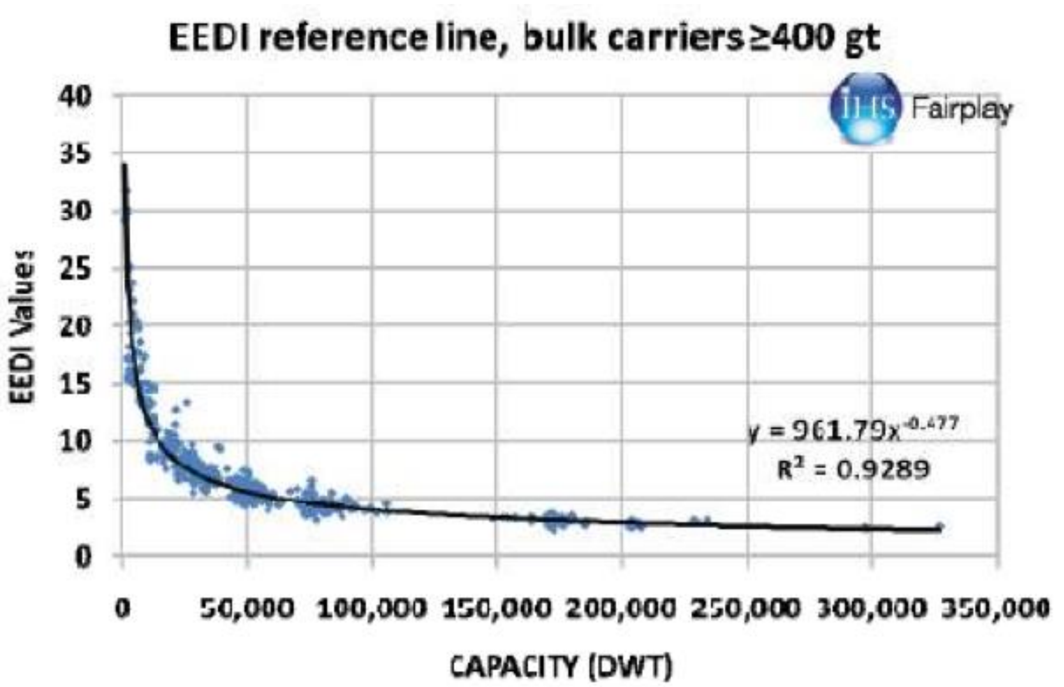
Table 5: Reference line values.

Ship type defined in regulation	a	b	c
2.25 Bulk carrier	961.79	DWT of the ship	0.477
2.26 Gas tanker	1120.00	DWT of the ship	0.456
2.27 Tanker	1218.80	DWT of the ship	0.488
2.28 Container ship	174.22	DWT of the ship	0.201
2.29 General cargo ship	107.48	DWT of the ship	0.216
2.30 Refrigerated cargo carrier	227.01	DWT of the ship	0.244
2.31 Combination carrier	1219.00	DWT of the ship	0.488

* If the design of a ship allows it to fall into more than one of the above ship type definitions, the required EEDI for the ship shall be the most stringent (the lowest) required EEDI.

The reference line for bulk carriers as it was published in MEPC 62/6/4 [7] can be seen in the Figure 1 below.

Figure 1: Reference line for bulk carrier, from MEPC 62/6/4 document



According to MEPC65/22 Annex 14 page 4 [8], the equation for calculating the estimated index value for each ship (excluding containerships and ro-ro cargo ships (vehicle carrier) is as follows:

Estimated Index Value= $3.1144 * \frac{190 * SP_{ME} + 215 * P_{AE}}{Capacity * Vref}$ = 7.5377> EEDIattained

In addition, the EEDI attained value is below the EEDI required value as it is seen in Figure 1 and as a result the Bulk 1 index passes the requirements.

EEDI *attained* < EEDI *required*

From the above calculation, one can easily make the following observations. First of all, the ship does not always travel in full load condition, but in various loading conditions and also in ballast condition. In all these conditions the engine still emits CO2. As a result, even without producing transport work, the ship is polluting the environment. These journeys are not taken into account in the calculation procedure. Furthermore, the ship, for example a bulk carrier, does not always operate at the same draught so the calculated value of the index may not give an objective assessment of the ship's environmental performance. Another point requiring consideration would be the benefit to society reflected by the capacity term. In the case of a bulk carrier for instance, the denominator is calculated using deadweight as a parameter. Obviously, payload seems to be a better alternative to determine the benefit to society. However, the type of cargo of a bulk carrier could vary between journeys (coal, grain, etc.). These cargos have a different value from a societal perspective. Therefore, it is necessary to form the denominator of the formula in such a manner that the benefit to society could be best reflected.

4.3. Problems in including Ro-Ro Cargo and Ro-Ro passenger ships

After the introduction of the formula, it has been widely acknowledged that the methodology in the regulation complicates the definition of a required EEDI for the ro-ro ship sector and therefore they have been excluded from the first phase of the implementation. In addition, it was proven to be difficult to develop an EEDI reference line that could fairly represent the ship types engaged in short sea shipping in general. Certain passenger ships are designed to carry only a few passengers and much cargo, resulting in a high deadweight, while other passenger ships are designed to meet the needs of many passengers on board resulting in large ships with small deadweight demands. Due to the particular geometrical constrains and the nature of the service they provide, it has become clear that a different approach is necessary concerning ro-ro ship types.

As a result, in MEPC 64/4 [3], Sweden in cooperation with CESA came up with a specific proposal for the inclusion of the ro-ro cargo and ro-ro passenger ship types into the IMO energy efficiency regulatory framework. According to this proposal, two non-dimensional correction factors have been introduced in the formula. Initially, a ship specific design correction factor, fj, has been proposed so that the diversity in design conditions can be considered given the fact that the data for these ship types given in the HIS Fairplay Database is limited.

Moreover, there has been introduced a capacity correction factor, fc, for ro-ro passenger ships of DWT/GT-ratio less than fleet average. The purpose of this correction factor is to take into consideration the fact that ro-ro passenger ships are combination carriers and therefore the definition of transport work requires attention.

Specifically, the methodology as it was presented in MEPC 64/4, is described below:

- *Capacity:* For bulk carriers, tankers, gas tankers, ro-ro cargo ships, ro-ro passenger ships, general cargo ships, refrigerated cargo carrier and combination carriers, deadweight should be used as Capacity.

- f_j: For ro-ro cargo and ro-ro passenger ships f_{jRoRo} is calculated as follows:

$$f_{jRoRo} = \frac{1}{Fn_L^{a} * (\frac{Lpp}{Bs})^{b} * (\frac{Bs}{ds})^{g} * (\frac{Lpp}{\nabla^{1/3}})^{d}}$$

where the Froude's number is defined as:

$$Fn_L = \frac{0.5144 * Vref}{\sqrt{Lpp \times g}}$$

and the exponents α, β, γ, δ are defined in Table 6

Table 6: definition of α, β, γ, δ exponents:

Ship Type	α	β	γ	δ
Ro-Ro Cargo Ship	2.00	0.50	0.75	1.00
Ro-Ro Passenger Ship	2.50	1.00	0.50	0.75

- For ro-ro passenger ships having a DWT/GT- ratio less than 0.25, the following cubic capacity correction factor, f_{cRoPax} should apply:

- $f_{cRoPax} = \left(\frac{(\frac{DWT}{GT})}{0.25}\right)^{-0.8}$

  Where DWT is the Capacity and GT is the gross tonnage in accordance with the International Convention of Tonnage Measurement of Ships [9]

- Summer load line draught, ds, is the vertical distance, in metres, from the moulded baseline at mid-length to the waterline corresponding to the summer freeboard draught to be assigned to the ship.

- Breadth, Bs, is the greatest moulded breadth of the ship, in metres, at or below the load line draught, ds.

- Volumetric displacement, ∇ , in cubic metres, (m^3), is the volume of the moulded displacement of the ship, excluding appendages, in a ship with a meta shell, and is the volume of displacement to the outer surface of the hull in a ship with a shell of any other material, both taken at the summer load line draught, ds, as stated in the approved stability booklet/loading manual.

- *Estimated Index Value:*

  - For ro-ro cargo ships the estimated index value of each individual ship is calculated as follows:

Estimated Index Value= $\dfrac{f_{jRoRo} * 3.1144 * (190 * SP_{ME} + 215 * P_{AE})}{Cap * Vref}$

  - For ro-ro passenger ships the estimated index value for each individual ship is calculated as follows:

Estimated Index Value= $\dfrac{f_{jRoRo} * 3.1144 * (190 * SP_{MEi} + 215 * P_{AE})}{f_{cRoPax} * Cap * Vref}$

- Calculation of reference line: The parameters for determination of reference values for the different ship types are listed in Table 7 below as it was presented in MEPC 64/4 Annex 1 [3].

Table 7: definition of parameters used for determination of reference values

Ship Type defined in Regulation 2	**a**	**b**	**c**

2.25 Bulk Carrier	961.79	DWT of the ship	0.477
2.26 Gas Carrier	1120.00	DWT of the ship	0.456
2.27 Tanker	1218.80	DWT of the ship	0.488
2.28 Container Ship	174.22	DWT of the ship	0.201
2.29 General Cargo Ship	107.48	DWT of the ship	0.216
2.30 Refrigerated Cargo Carrier	227.01	DWT of the ship	0.244
2.31 Combination Carrier	1219.00	DWT of the ship	0.488
2.34 Ro-Ro Cargo Ship	1280.00	DWT of the ship	0.497
2.35 Ro-Ro Passenger Ship	1362.29	DWT of the ship	0.433

For ro-ro passenger ships, parameters “a” and “c” are determined from a regression analysis undertaken by plotting the calculated estimated index values against corrected deadweight, DWT’, for ships to which the capacity correction factor, fcRoPax, applies and against 100 per cent deadweight (100% DWT) for ships to which the capacity correction factor does not apply. With the inclusion of Froude’s number in the formula we end up with a calculation method where the speed and power are neglected.

$$EEDI = \frac{SP*CF*SFC}{DWT*V*V^2}*\frac{\dfrac{L*g}{0.5144^2}}{\dfrac{Lpp}{Bs}^b*\dfrac{Bs}{ds}^g*\dfrac{Lpp}{\square^{1/3}}^d}$$

Therefore, a major concern of this method is the fact that the increase of the propulsion and speed is not reflected with an increase in the EEDI value, which is the main goal of EEDI implementation.

4.4. EEDI example calculation of existing Ro-Ro passenger ships

In order to fully understand the calculation procedure proposed by Sweden [3], concerning the inclusion of the Ro-Ro cargo and Ro-Ro passenger ships in the index and the problems of the formula during it's application, we followed the given guidelines in the EEDI calculation of two Ro-Ro passenger ships. Particularly, the two ships used in the application are currently in service. The main particulars of these two vessels are listed below:

Ro-Ro 1:

Year delivered: 2000

Length: 176m

Beam: 25,7m

Draft: 6,45m

Gross Tonnage: 29415 GRT

Deadweight: 4500 t

Vref: 23,4 knots

Propulsion Type: 8L 58/64 MAN B&W

Fuel: IFO 380

Ro-Ro 2:

Year delivered: 2011

Length: 145m

Beam: 22m

Draft: 5,5m

Gross Tonnage: 18498 GRT

Deadweight: 2775 t

Vref: 25.5 knots

Propulsion Type: 16 V32/40 MAN

Fuel: HFO

Following the guidelines presented in MEPC 64/4, we calculated the terms f_{cRoPax} , f_{jRoRo} and EEDI value for these two cases.

For Ro-Ro 1:

fjRoRo= 0.37199

fcRoPax=1.48128

EEDI= 44.57

For Ro-Ro 2:

fjRoRo= 0.2487

fcRoPax=1.5047

EEDI= 33.22

The above EEDI values, as calculated for Ro-Ro 1 and Ro-Ro 2 cannot be compared to EEDI values of other ship types. Moreover, the current limitations concerning reference lines deprive us of comparing EEDI values even between ships belonging to the same segment.

4.5. EEDI Implementation Concerns

By simply examining the EEDI formula, one can easily understand that the major methods to reduce the value of the index are the following:

- Alternative and innovative technologies and fuels
- Deadweight increase
- Speed reduction

The options we have basically are limited to two: innovation in technology and fuels and speed reduction. Speed reduction appears to be the simplest way to reduce EEDI. However, the encouragement for very large and slow moving vessels does not seem to reflect the commercial reality and the needs of the market. With the adequate technology to go faster and 'greener' at the same time, how can slower ships compete with other methods of transport and prove to be more beneficial to society? For instance, as far as Ro-Ro passenger and Ro-Ro cargo ships are concerned, frequency and time consistency are supposed to be a fundamental factor for the level of the service quality they provide to society. The same can be applied to other ship types, such as containerships or tankers, to name but a few.

As far as innovative and/or advanced technologies and fuels are concerned, there are some other considerations we should take into account. Some of the existing technologies that could be used for the reduction of the index, could be for example:

- Waste Heat Recovery
- Optimized Hull Form
- Propeller-Rudder integration
- Variable speed drives

Apart from existing technologies, some of the new technologies that we are encouraged to use are:

- Hull Improvements including air lubrication etc.
- Fuel cells
- Alternative fuels
- Renewable energies such as wind and solar

Particularly, the implementation of some of the above technologies or their combination, promises a CO2 potential reduction of up to 40%, percentage that could vary a lot depending on the ship. However, for the calculation and verification of the EEDI when such measures have been implemented, MEPC 64/4/39 submitted by Greece [10] raises some interesting issues. The principal concern is the possibility that a technology introduced could contribute to a good calculation of the attained index value but has a minor or negative impact when the ship is operating in actual sea conditions. More specifically, the resolution questions the effectiveness and the accuracy when evaluating technologies installed on board such as photovoltaic systems, wind propulsion and air lubrication systems. Given the fact that their performance cannot be accurately evaluated at sea trials only, one can easily conclude that the EEDI reduction percentage proves to be nothing but an assumption, at some cases very different from the value when operating under actual conditions.

Another rather controversial issue has proved to be the calculation of the EEDI, and more precisely the data used. The publicly available IMO reference lines are ship-type-specific and they are based on ship size. They are derived to define the status of existing ships and refer to statistically average EEDI curves based on existing ships' data. However, the IHS Fairplay Database has limitations in relation to very small and very large vessels, thus excluding them from the regulation. Such limitations exist also for the Ro-Ro segment.

Moreover, in the calculation process we observed that auxiliary power is assumed to be merely a fraction of the available power. In the case of cruise and passenger ships though, we use a significantly high percentage in the generation of electricity mainly due to their hotel element in their load profile. It is evident thus that in this type of ships, one can effectively reduce fuel and power consumption from their hotel arrangements. But such a reduction could never be reflected in the index in its current form. As a result, there is no incentive given to ship operators for such a reduction.

As mentioned above, the EEDI leads to a significant reduction in the installable main engine power, in other words has introduced a speed limit, giving to existing ships a competitive advantage over the new designs. [11] For some ship types this will result in underpowered ships resulting in manoeuverability concerns during adverse weather. In MEPC 62/5/19 resolution there is a proposal for minimum propulsion to ensure safe manoeuvring in adverse conditions. [12] However, given the short timeframe ship designers have in their disposal, installing a smaller engine to an existing design rather than designing better hull lines from the start, seems to be the easy solution.

On the other hand, recent studies have shown that in the past 30 years the block coefficient of bulk carriers and tankers has increased and the length displacement ratio has decreased. These dimensional changes resulted in higher propulsion demands for the specific ship types, leading in higher EEDI values. Therefore, it becomes clear that naval architects should adopt a new approach towards ship design so as to meet the EEDI future requirements. [13]

The above discussion refers only to some issues that have been raised with the implementation of EEDI. It becomes clear that the unique approach of the Index towards different ship types with different services to society does not reflect in the best way the commercial reality. At the same time, the definition of the 'benefit to society' factor could be highly debatable. On the other hand, the calculation of an index that could enable the comparison between different ship types and even different transportation methods, as far as CO_2 emissions are concerned, could be more than useful.

5. Introduction of Operational Profiles into the Calculation

In the existing formula only one situation is being examined: the ship is operating at full capacity and with a speed corresponding to the maximum design load condition. In reality, such a scenario reflects only one percentage of the ship's operational performance. During its lifetime, a vessel is supposed to travel in ballast condition as well as partially loaded. In these cases there are CO2 emissions with a small to none benefit to society. Of course, to different ship types correspond different operational profiles. The inclusion of such a calculation to the index could give the incentive to operators to minimize the percentage of travelling that is less beneficial to society.

In order to have a more accurate image of the profile of a ships life, we examined the case of three bulk carriers. We calculated the EEDI value for each ship with the existing formula and then we inserted the additional data to the formula so that we could compare the results. The principal idea is that in the denominator, the capacity term appears as the total of the three main conditions: ballast condition, partially loaded (3/4 of full load), fully loaded. For the speed term we assumed that the speed would be the same for the full load and the ¾ full load conditions but for the ballast condition slightly higher.

The application was made for three ships. Their main particulars are given in Table 8 below:

Table 8: Vessels' Main Particulars

Vessel	Flag	Built	LOA	Beam	Summer Draft	GRT	NRT	DWT
Bulk4	Greek	2002	224.9	32.26	14.12	39,973	25,437	75,000
Bulk3	Greek	2011	193.07	32.26	13.019	31,901	19,014	58,000
Bulk2	Greek	2006	189.99	32.26	12.60	31,091	17,993	54,000

The above vessels operate 40% of their time fully loaded, 30% partially loaded and 30% in ballast condition. For three different speeds, high speed, med speed and eco speed we have the corresponding fuel consumptions. We calculated the index value for all three different speeds. Their speeds and fuel consumptions can be seen in Table 9 below:

Table 9: Vessels fuel consumption and speed

FULL LOAD CONDITION:

BULK2 54,000 DWT

	SPEED	IFO ME	IFO GE	TOTAL
HIGH SPD	14	32.2	2	34.2
MED SPD	13	27	2	29
ECO SPD	11.5	20	2	22

BULK3 58,000 DWT

	SPEED	IFO ME	IFO AE	TOTAL
HIGH SPD 1	14.5	32.5	2	34.5
HIGH SPD 2	14	30.5	2	32.5
MED SPD	13	25	2	27
ECO SPD	11.5	20.5	2	22.5

BULK4 75,000 DWT PANAMAX

	SPEED	IFO ME	IFO AE	TOTAL
HIGH SPD	14	33	2	35
MED SPD	13	29.5	2	31.5
ECO SPD	11.5	23	2	25

BALLAST CONDITION

BULK2 54,000 DWT

	SPEED	IFO ME	IFO AE	TOTAL
HIGH SPD	14.5	30	2	32
MED SPD	13.5	25.5	2	27.5
ECO SPD	12.5	22.5	2	24.5

BULK3 58,000 DWT

	SPEED	IFO ME	IFO AE	TOTAL
HIGH SPD 1	14.5	29	2	31
HIGH SPD 2	14	25.5	2	27.5
MED SPD	13.5	22.5	2	24.5
ECO SPD	12.5	19	2	21

BULK4 75,000 DWT PANAMAX

	SPEED	IFO ME	IFO AE	TOTAL
HIGH SPD	14.5	32	2	34
MED SPD	13	25.5	2	27.5
ECO SPD	12.5	23.5	2	25.5

* IFO stands for Intermediate Fuel Oil, ME for main engine and AE for auxiliary engine.

5.1. Calculation of the Index for the three vessels

The form of the denominator was changed in the following way:

- Capacity term:(0.4*DWT+0.3*0.75*DWT)
- Speed term: (0.7*SPD1+0.3*SPD2) where:
    - SPD1: refers to the full load and partial load condition.
    - SPD2: refers to the ballast condition and is assumed to be slightly higher.

As far as the numerator is concerned the CO2 emissions were found by calculating the emissions contributed by the three different loading conditions. Due to lack of information, for the intermediate condition (the partially loaded condition), we made the assumption that the fuel consumption would be between the other two conditions and closer to the fully loaded condition.

For the three different speeds, we have three different EEDI values.

BULK 2:

High SPD		
Nominator	4358396.7	gCO2/h
Denominator	477562.5	t*nm/h
EEDI	9.126	
Med SPD		
Nominator	3718799.7	gCO2/h
Denominator	443812.5	t*nm/h
EEDI	8.379	
Eco SPD		
Nominator	3040043.7	gCO2/h
Denominator	398250	t*nm/h
EEDI	7.634	

*Current EEDI Value = **5.905 gCO2/t*nm***

BULK 4:

High SPD		
Numerator	4521559.2	gCO2/h
Denominator	663281.25	t*nm/h
EEDI	6.817	
Med SPD		
Numerator	3927647.7	gCO2/h
Denominator	609375	t*nm/h
EEDI	6.445	
Eco SPD		
Numerator	3296535.15	gCO2/h
Denominator	553125	t*nm/h
EEDI	5.959	
High SPD 2		
Numerator	3997481.25	gCO2/h
Denominator	553125	507500
EEDI	7.877	

*Current EEDI Value= **4.351 gCO2/t*nm***

BULK 3

High SPD1		
Numerator	4338817.2	gCO2/h
Denominator	525625	t*nm/h
EEDI	8.255	

Med SPD		
Numerator	3406833	gCO2/h
Denominator	476687.5	t*nm/h
EEDI	7.147	

Eco SPD		
Numerator	2870354.7	gCO2/h
Denominator	427750	t*nm/h
EEDI	6.710	

Current EEDI Value= ***5.2244 gCO2/t*nm***

As it was expected, the index value is higher in all three cases (high speed, med speed and eco speed) in relation to the value of the existing formula. Moreover, we understand that if the ship operates with eco speed the index value can be significantly reduced. Therefore, the eco speed is recommended.

5.2. Impact of different operational profiles on the index

The above calculations were made with given the fact that the ship operates 40% fully loaded, 30% partially loaded (3/4 of full load) and 30% in ballast condition. It would be interesting to examine how the index is affected as we change the contribution of each of the above conditions to the ship's performance.

More specifically, we examined the scenarios of the vessel being fully loaded for 40-80% of the time (0.4,0.5,…0.8) and in ballast condition for 20-50% of the time (0.2,0.25…0.5). The partially loaded condition received the remaining values.

Table 10: Case scenario

CASE SENARIOS		
Full Load %	Ballast %	3/4 Full Load %
0.4	0.2	0.4
0.4	0.25	0.35
0.4	0.3	0.3
0.4	0.35	0.25
0.4	0.4	0.2
0.4	0.45	0.15
0.4	0.5	0.1
0.5	0.2	0.3
0.5	0.25	0.25
0.5	0.3	0.2
0.5	0.35	0.15
0.5	0.4	0.1
0.5	0.45	0.05
0.5	0.5	0
0.6	0.2	0.2
0.6	0.25	0.15
0.6	0.3	0.1
0.6	0.35	0.05
0.6	0.4	0
0.7	0.2	0.1
0.7	0.25	0.05
0.7	0.3	0
0.8	0.2	0

Results:

Table 11: Case scenarios EEDI results for high speed (gCO2/t*nm)

CASE SCENARIOS			HIGH SPEED		
FULL LOAD (%)	BALLAST (%)	3/4FULL LOAD (%)	BULK2	BULK4	BULK3
0.4	0.2	0.4	8.219	6.122	7.432
0.4	0.25	0.35	8.647	6.450	7.820
0.4	0.3	0.3	9.126	6.817	8.255
0.4	0.35	0.25	9.667	7.231	8.744
0.4	0.4	0.2	10.282	7.701	9.301
0.4	0.45	0.15	10.986	8.241	9.939
0.4	0.5	0.1	11.803	8.866	10.678
0.5	0.2	0.3	7.947	5.915	7.191
0.5	0.25	0.25	8.345	6.219	7.552
0.5	0.3	0.2	8.788	6.559	7.954
0.5	0.35	0.15	9.286	6.940	8.405
0.5	0.4	0.1	9.849	7.371	8.916
0.5	0.45	0.05	10.491	7.862	9.497
0.5	0.5	0	11.229	8.427	10.166
0.6	0.2	0.2	7.694	5.721	6.966
0.6	0.25	0.15	8.064	6.004	7.302
0.6	0.3	0.1	8.476	6.319	7.675
0.6	0.35	0.05	8.936	6.672	8.093
0.6	0.4	0	9.453	7.068	8.562
0.7	0.2	0.1	7.457	5.539	6.755
0.7	0.25	0.05	7.802	5.804	7.069
0.7	0.3	0	8.185	6.097	7.417
0.8	0.2	0	7.235	5.369	6.558

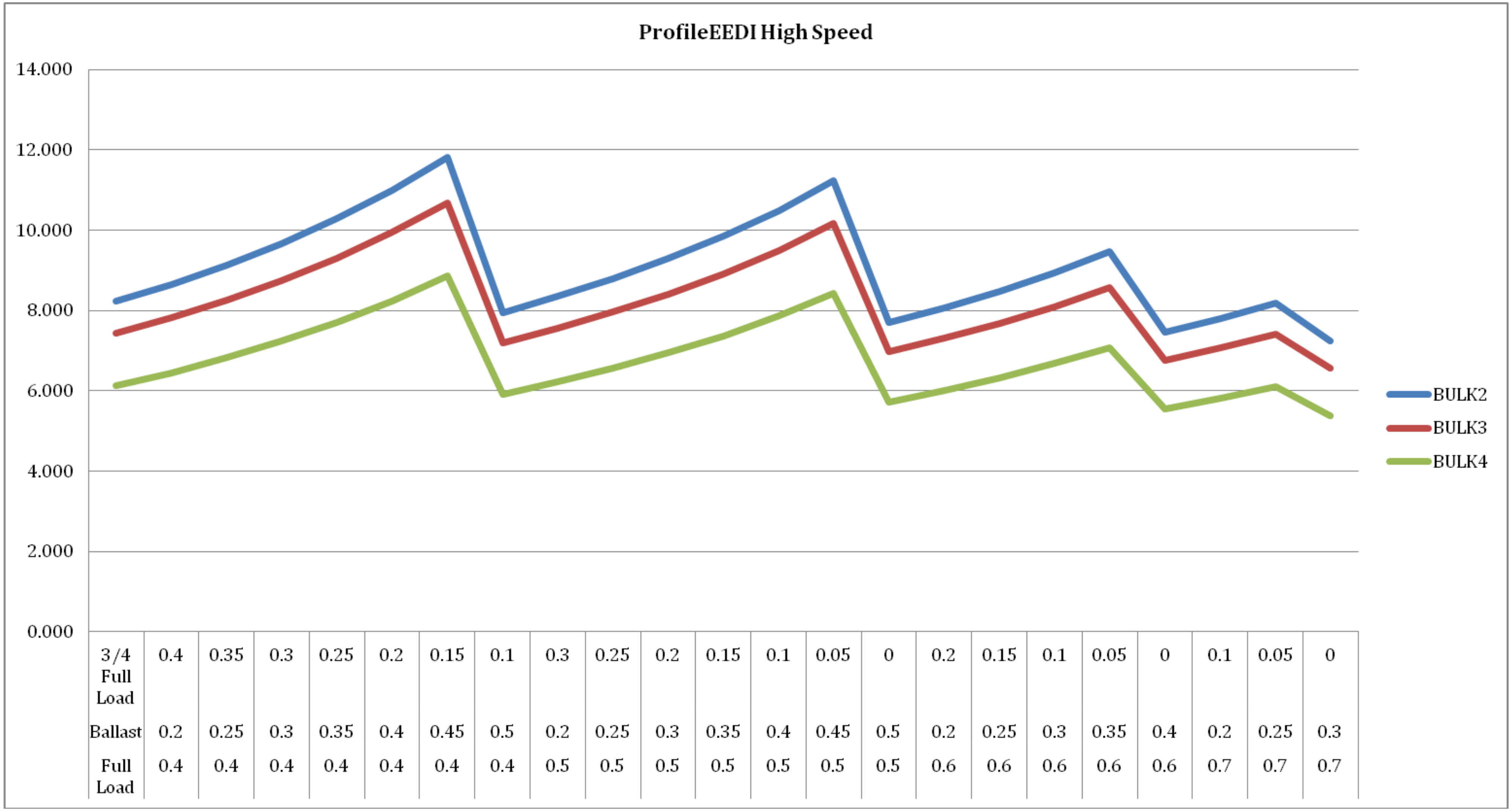


Chart 1: EEDI Case scenarios for High Speed

Table 12: Case scenarios EEDI results for med speed (gCO2/t*nm)

CASE SCENARIOS			MED SPEED		
FULL LOAD (%)	BALLAST (%)	3/4FULL LOAD (%)	BULK2	BULK4	BULK3
0.4	0.2	0.4	7.544	5.780	6.555
0.4	0.25	0.35	7.938	6.073	6.913
0.4	0.3	0.3	8.379	6.403	7.314
0.4	0.35	0.25	8.877	6.774	7.766
0.4	0.4	0.2	9.442	7.195	8.280
0.4	0.45	0.15	10.091	7.679	8.868
0.4	0.5	0.1	10.842	8.238	9.550
0.5	0.2	0.3	7.289	5.584	6.341
0.5	0.25	0.25	7.655	5.857	6.674
0.5	0.3	0.2	8.063	6.160	7.046
0.5	0.35	0.15	8.521	6.502	7.463
0.5	0.4	0.1	9.038	6.887	7.935
0.5	0.45	0.05	9.629	7.326	8.472
0.5	0.5	0	10.307	7.832	9.090
0.6	0.2	0.2	7.051	5.401	6.141
0.6	0.25	0.15	7.391	5.655	6.452
0.6	0.3	0.1	7.769	5.936	6.798
0.6	0.35	0.05	8.192	6.251	7.184
0.6	0.4	0	8.668	6.605	7.619
0.7	0.2	0.1	6.828	5.231	5.954
0.7	0.25	0.05	7.146	5.467	6.245
0.7	0.3	0	7.497	5.728	6.568
0.8	0.2	0	6.620	5.071	5.779

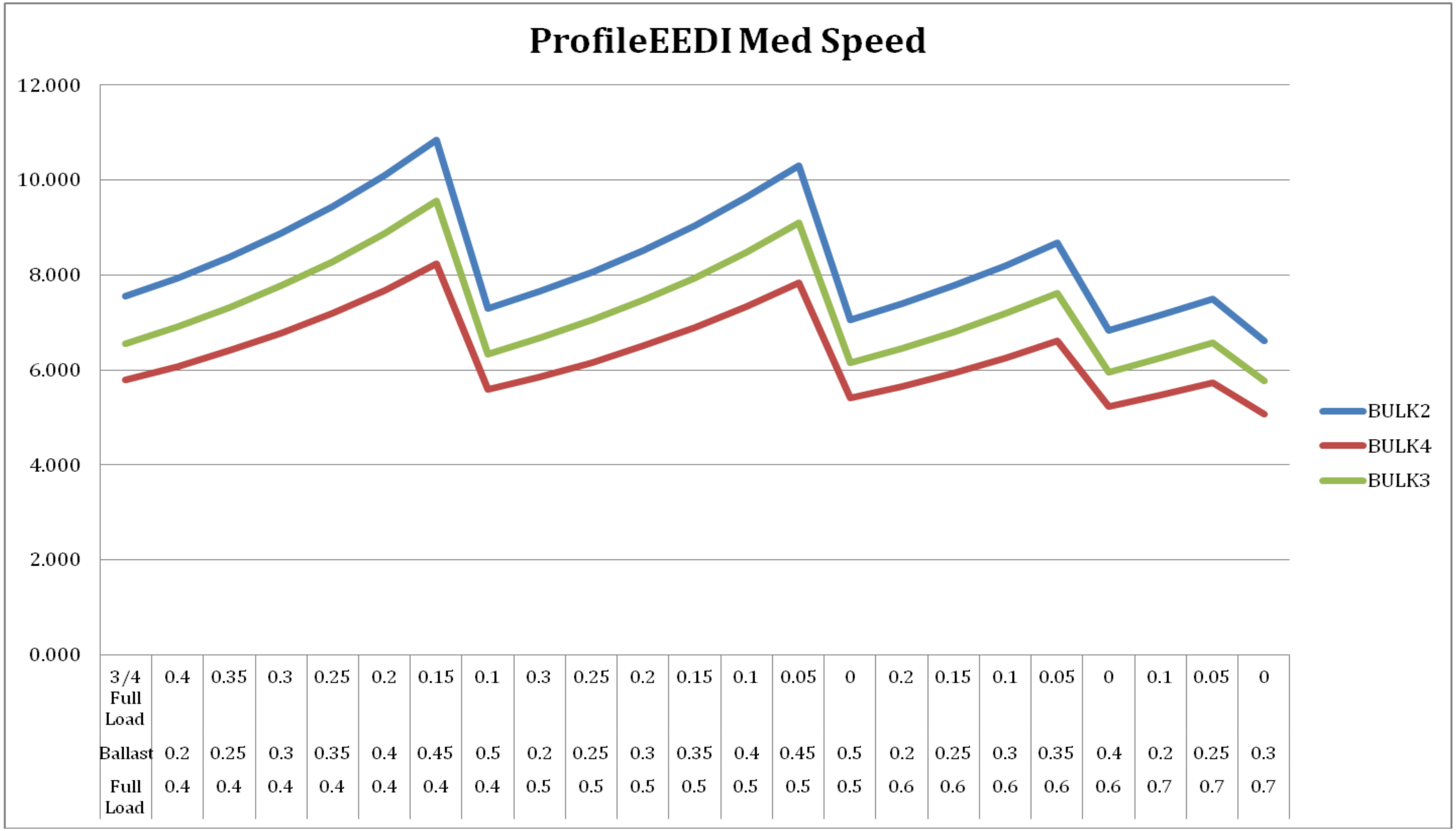


Chart 2: EEDI Case scenarios for Med Speed

CASE SCENARIOS			ECO SPEED		
FULL LOAD (%)	**BALLAST (%)**	**3/4FULL LOAD (%)**	**BULK2**	**BULK4**	**BULK3**
0.4	0.2	0.4	6.853	5.102	6.078
0.4	0.25	0.35	7.221	5.414	6.376
0.4	0.3	0.3	7.634	5.764	6.710
0.4	0.35	0.25	8.099	6.159	7.088
0.4	0.4	0.2	8.627	6.609	7.517
0.4	0.45	0.15	9.234	7.124	8.009
0.4	0.5	0.1	9.936	7.720	8.580
0.5	0.2	0.3	6.566	4.919	5.874
0.5	0.25	0.25	6.905	5.210	6.150
0.5	0.3	0.2	7.283	5.535	6.458
0.5	0.35	0.15	7.708	5.900	6.804
0.5	0.4	0.1	8.189	6.312	7.196
0.5	0.45	0.05	8.737	6.783	7.643
0.5	0.5	0	9.367	7.324	8.158
0.6	0.2	0.2	6.297	4.749	5.683
0.6	0.25	0.15	6.611	5.020	5.940
0.6	0.3	0.1	6.959	5.323	6.225
0.6	0.35	0.05	7.348	5.661	6.544
0.6	0.4	0	7.787	6.041	6.903
0.7	0.2	0.1	6.046	4.589	5.505
0.7	0.25	0.05	6.336	4.844	5.743
0.7	0.3	0	6.658	5.125	6.008
0.8	0.2	0	5.811	4.439	5.338

Table 13: Case scenarios EEDI results for eco speed (gCO2/t*nm)

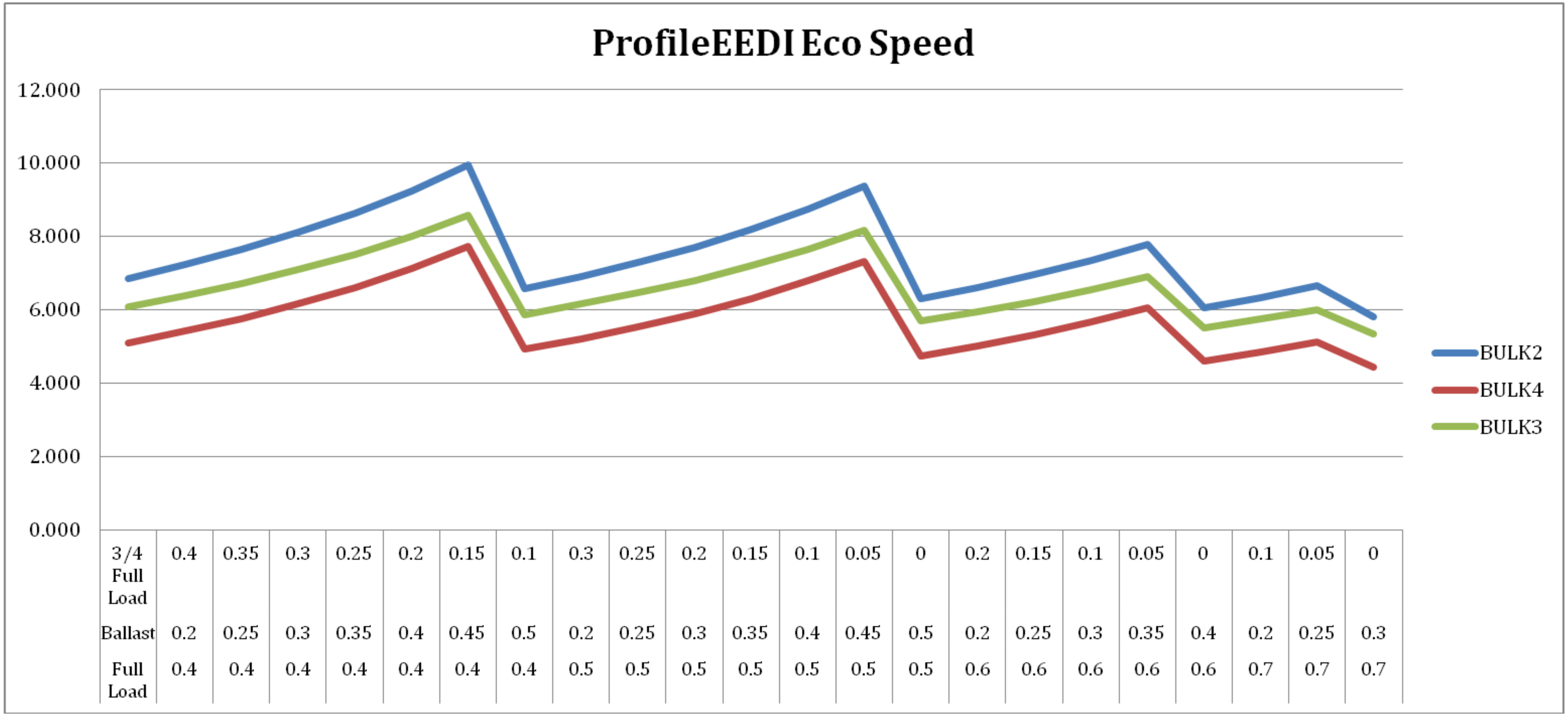


Chart 3: EEDI Case scenarios for Eco Speed

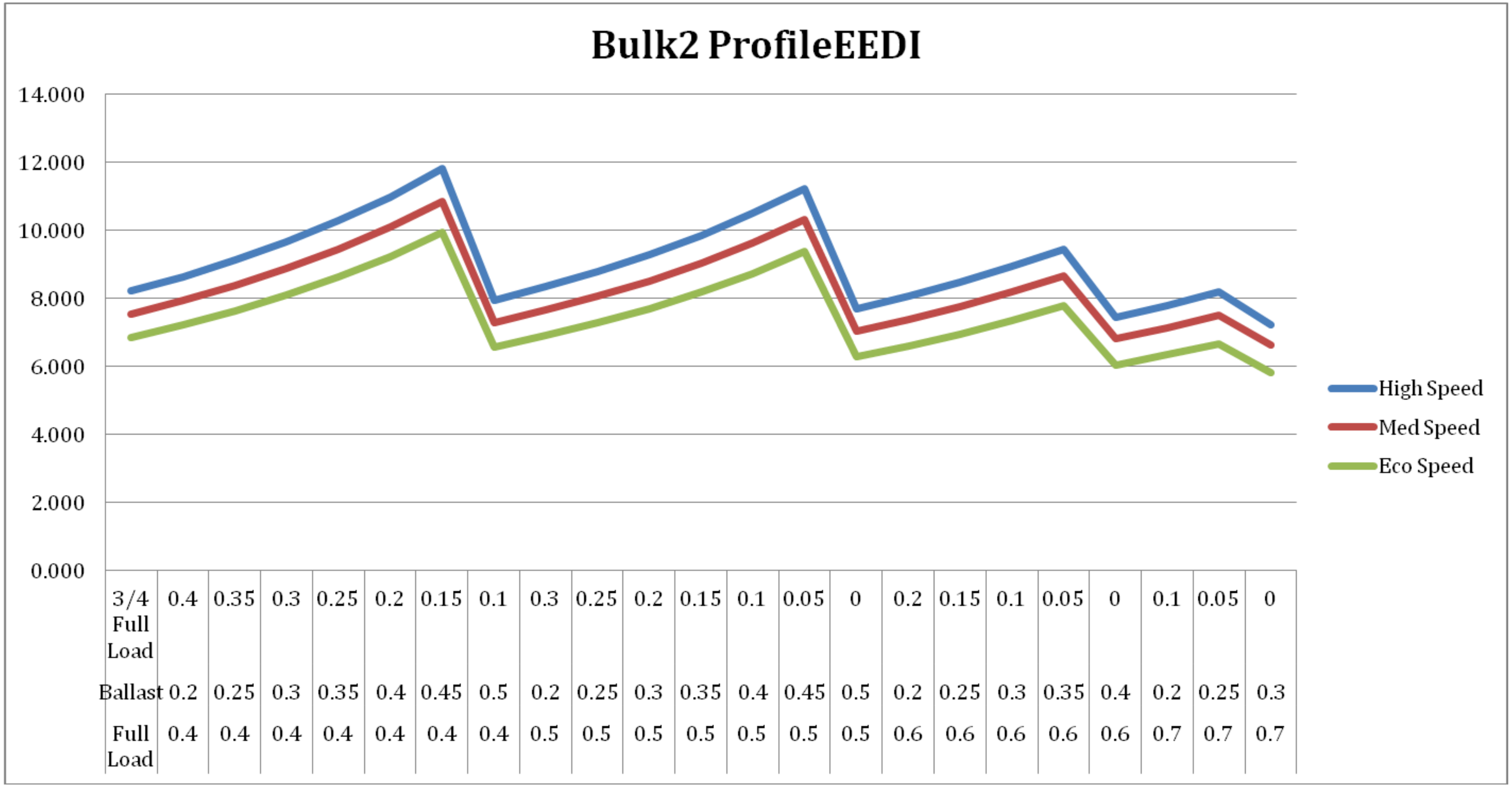


Chart 4: Bulk2 EEDI values for different speeds

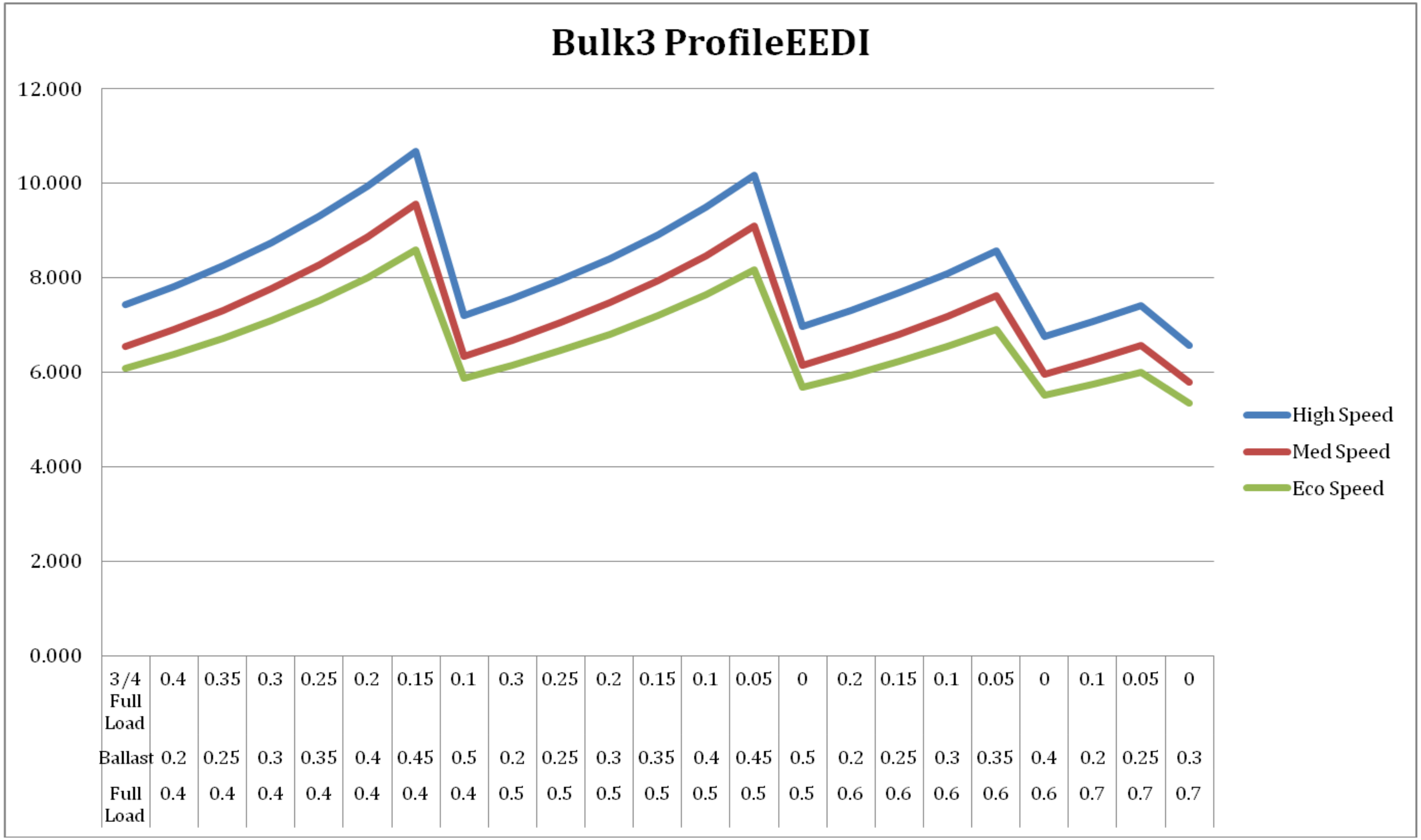


Chart 5: Bulk3 EEDI values for different speeds

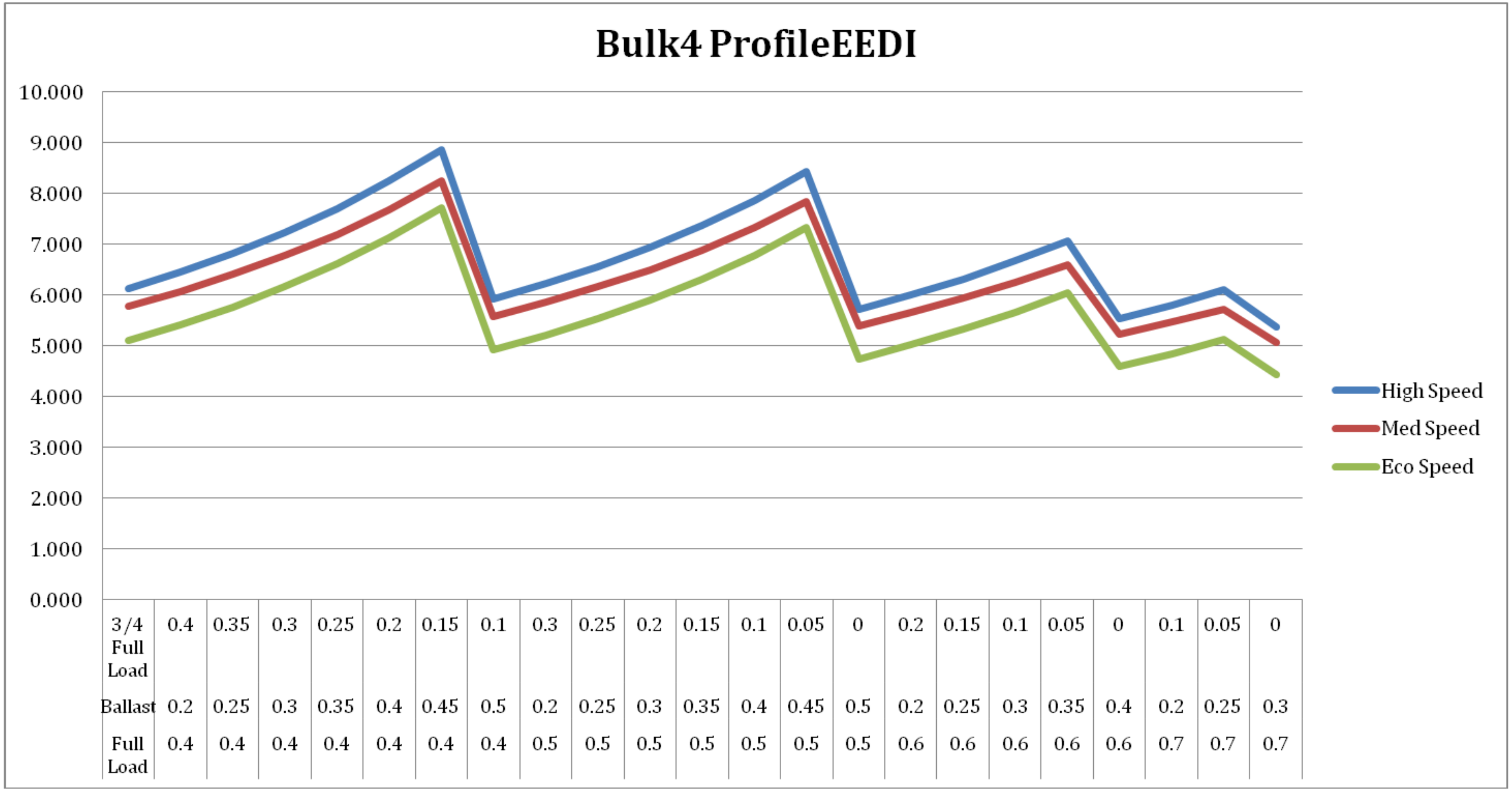


Chart 6: Bulk4 EEDI values for different speeds

The above diagrams lead us to several conclusions. To begin with, we easily understand that the larger ship, in terms of Capacity, has the lowest EEDI value whereas the smaller one (Bulk 2) results in a much higher EEDI calculation. Such a conclusion was expected, since the index encourages larger ships, the capacity of which provides a bigger service to society per journey. Moreover, again as expected, the best EEDI performance corresponds to Eco speed.

As far as the engagement of the different case scenarios is concerned, we observe that some operational profiles lead to significantly high indexes whereas others result in much smaller values. The highest picks correspond to a scenario where the ballast condition corresponds with 50% to the overall performance. More precisely, the highest pick observed for all three ships corresponds to a scenario of 50% full load condition and 50% ballast condition. The lowest EEDI values represent the scenarios where the ballast condition has the smallest participation possible, that of 20%. Specifically, the lowest EEDI value is accomplished with a scenario of 80% full load condition, 20% ballast condition and 0% partially loaded. Such a result, gives the incentive to operators to make a better time management in order to travel fully loaded for most of their time and travel at ballast condition only when extremely necessary. Therefore, the benefit to society for the ship's services proves to be significantly higher.

An interesting tool also would be the introduction of several indifference curves to the matter. For example, for a particular vessel being fully loaded for a specific percentage of its time at sea, how could we achieve the same EEDI values by changing the speed? How the contribution of the other loading conditions combined would affect the final speed so that the EEDI value does not change?

In the case of two of the above vessels, we chose three EEDI values and a specific percentage of the fully loading condition to examine the resulting speed and the contribution of the other loading conditions. The speed change however has an impact on the fuel consumption and as a result the fuel consumption should be calculated in accordance with the ship's speed. For the calculation of the fuel consumption we used the principle of the propeller law and more specifically, for low-speed ships like bulk carriers the following relationship for estimation at the normal ship speed range [14]:

$P=C*V^{3.5}$

Due to lack of information, we assumed that the necessary power for the movement of the vessel would be proportional to the fuel consumption.[15] The above calculation led us to the following diagrams:

Case 1: Bulk4 high speed, fully loaded 50%

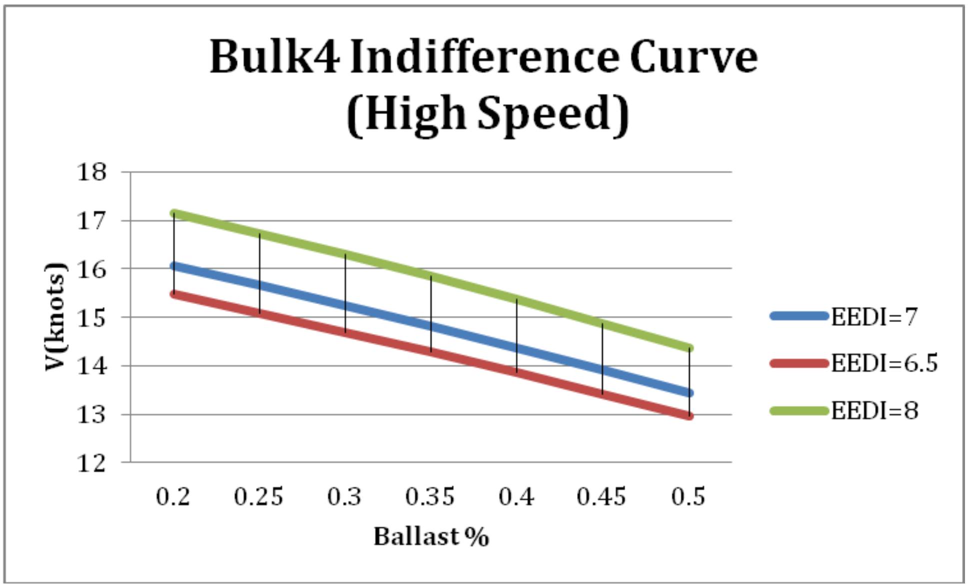


Chart 7: Bulk4 Indifference Curve

Case 2: Bulk2 med speed, fully loaded 70%

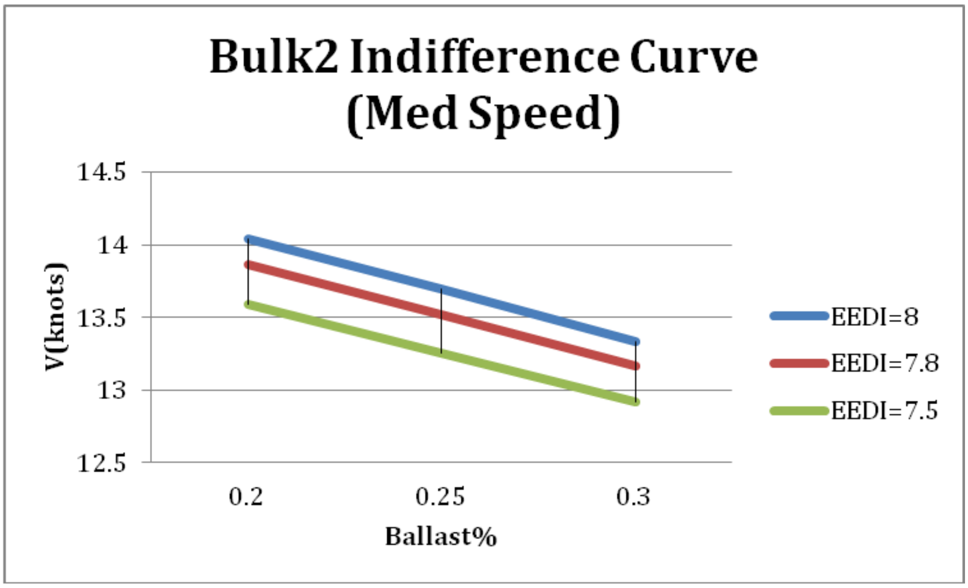


Chart 8: Bulk2 Indifference Curve

For the above cases the ballast percentage was calculated between 20% and 50% and the partially loaded condition received the remaining values. From what we can observe from the above diagrams, we can achieve the same EEDI value by operating the ship with a speed difference of almost 2 knots în the first case. In the second case we can have the same EEDI results with a speed difference of almost 0.5 knot. The higher the percentage of the ballast condition contribution, the more reduced would be the final speed value. Such a result underlines once again that with a minimum contribution of the ballast condition in the operational profile we can achieve higher speed with the same EEDI value. Therefore, in order to increase the benefit to society, it is preferable to minimize the ship's journeys in the ballast condition.

Another important factor we should consider at this point would be trim. With changes in the trim of a vessel, the overall resistance of the vessel would be affected. On the other hand, the vessel needs adequate thrust to overcome the overall resistance to the movement. The shaft power that in the end results being the efective power, in other words the necessary thrust to move the vessel at the desirable speed, originally comes from the fuel conversion into break power. As a result, the power we need to overcome the total resistance is considered to be the shaft power. With the main contributors in the overall resistance being the frictional resistance, the wave resistance and the wind resistance, one can easily understand that the only controlable resistance component is the frictional resistance that is affected by the ship's speed, trim and desplacement.

However, when operating the vessel we may have a trim that results in higher ressistance leading to an increase in the fuel consumption, so that the shaft power can achieve the vessel's motion. Unpredictabe trim conditions at sea can highly affect the vessel's fuel consumption. With the increase of fuel consumption also comes the increase of CO_2 emissions resulting in a higher EEDI value. Therefore, trim optimization is a measure that not only would be cost effective for the ship owners, reducing the total fuel cost, but it would also contribute to more enery effective and environmentally friendly ships. [16]

Such a research, seems to have a great economic and environmental interest and could affect significantly the EEDI calculation proceedure. However, in this thesis we do not have at our disposal the adequate data to permit us examine the calculation of EEDI by taking into consideration the impact of trim. We sincerely hope that such an examination would be accomplished in the future.

5.3. Introduction of Operational Profiles for the EEDI Calculation of Ro-Ro Passenger Ship

The above procedure was also executed in the case of the Ro-Ro passenger ship Ro-Ro 2. More specifically, in this case we used the assumption that the vessel is travelling in three conditions (full load, ¾ full load and ½ full load) with a contribution of full load condition 40% of the time, ¾ full load condition 30% of the time and ½ load condition 30 % of the time as well. The speed used for the calculation is the reference speed of the ship, 25.5 knots. The capacity term participating in the calculation of the denominator of EEDI can be seen below:

Capacity term: (0.4*DWT+0.3*0.75*DWT+0.3*0.5*DWT)

Denominator: fcRoPax*Capacity*Vref=1.5047*2150.625*25.5

EEDI=42.86

In this case scenario, the EEDI value was equal to 42.86, a much higher value related to the one calculated by the existing method. Such a result was expected, since when the vessel is partially loaded cannot reach the same level of transport work.

5.4. Impact of different operational profiles of Ro-Ro passenger on the index value

The above calculations were made with given the fact that the ship operates 40% fully loaded, 30% partially loaded (3/4 of full load) and 30% at 1/2 of full load. In order to examine how the index is affected, we changed the contribution of each of the above conditions to the ship’s performance.

More specifically, we examined the scenarios of the vessel being fully loaded for 20-70% of the time (0.2,0.3,0.4…0.7) and in partially loaded condition at 3/4 of full load for 20-60% of the time (0.2,0.3…0.6). The partially loaded condition at 1/2 of full load received the remaining values.

Table 14: Case scenarios

Case scenarios		
Full Load	**3/4 Full Load**	**1/2 Full Load**
0.2	0.2	0.6
0.2	0.3	0.5
0.2	0.4	0.4
0.2	0.5	0.3
0.2	0.6	0.2
0.3	0.2	0.5
0.3	0.3	0.4
0.3	0.4	0.3
0.3	0.5	0.2
0.3	0.6	0.1
0.4	0.2	0.4
0.4	0.3	0.3
0.4	0.4	0.2
0.4	0.5	0.1
0.4	0.6	0
0.5	0.2	0.3
0.5	0.3	0.2
0.5	0.4	0.1
0.5	0.5	0
0.6	0.2	0.2
0.6	0.3	0.1
0.6	0.4	0
0.7	0.2	0.1
0.7	0.3	0

Table 15: Case scenarios results

Full load condition	3/4 full load	1/2 full load	EEDI at reference Speed
0.2	0.2	0.6	51.899
0.2	0.3	0.5	50.326
0.2	0.4	0.4	48.846
0.2	0.5	0.3	47.450
0.2	0.6	0.2	46.132
0.3	0.2	0.5	48.138
0.3	0.3	0.4	46.782
0.3	0.4	0.3	45.500
0.3	0.5	0.2	44.287
0.3	0.6	0.1	43.136
0.4	0.2	0.4	44.885
0.4	0.3	0.3	43.704
0.4	0.4	0.2	42.583
0.4	0.5	0.1	41.519
0.4	0.6	0	40.506
0.5	0.2	0.3	42.044
0.5	0.3	0.2	41.006
0.5	0.4	0.1	40.018
0.5	0.5	0	39.077
0.6	0.2	0.2	39.542
0.6	0.3	0.1	38.622
0.6	0.4	0	37.744
0.7	0.2	0.1	37.320
0.7	0.3	0	36.500

For the above results, we assumed that the ship is travelling with the same speed in all conditions. We realize that the lowest EEDI value (36.5) is achieved with the ship fully loaded for 70% of the time, ¾ loaded for the 30% of the time and ½ loaded for 0% of the time. Such a result reflects fully the EEDI concept, giving the incentive to the ships to be travelling fully loaded and thus reach the highest transport work possible. Whereas, the highest EEDI value (51.899) is achieved with the ship being fully loaded for 20% of the time, ¾ loaded 20% of the time and ½ loaded 60% of the time. In the following diagram we can observe that the picks correspond to the scenarios where the partially loaded conditions have a relatively high participation role in the operation of the ship, whereas the lowest values correspond to the cases where the ship is fully loaded for most of the time. From the same perspective, we can understand that a ship travelling partially loaded for the most of its time at sea, cannot be beneficial to both the ship owner and the society. From the above results, it becomes clear that the inclusion of the different possible operational profiles of the ship in the index at the design stage can prove to be a more realistic approach to the problem, giving the incentive to ship operators to operate their ships in a more eco-friendly manner.

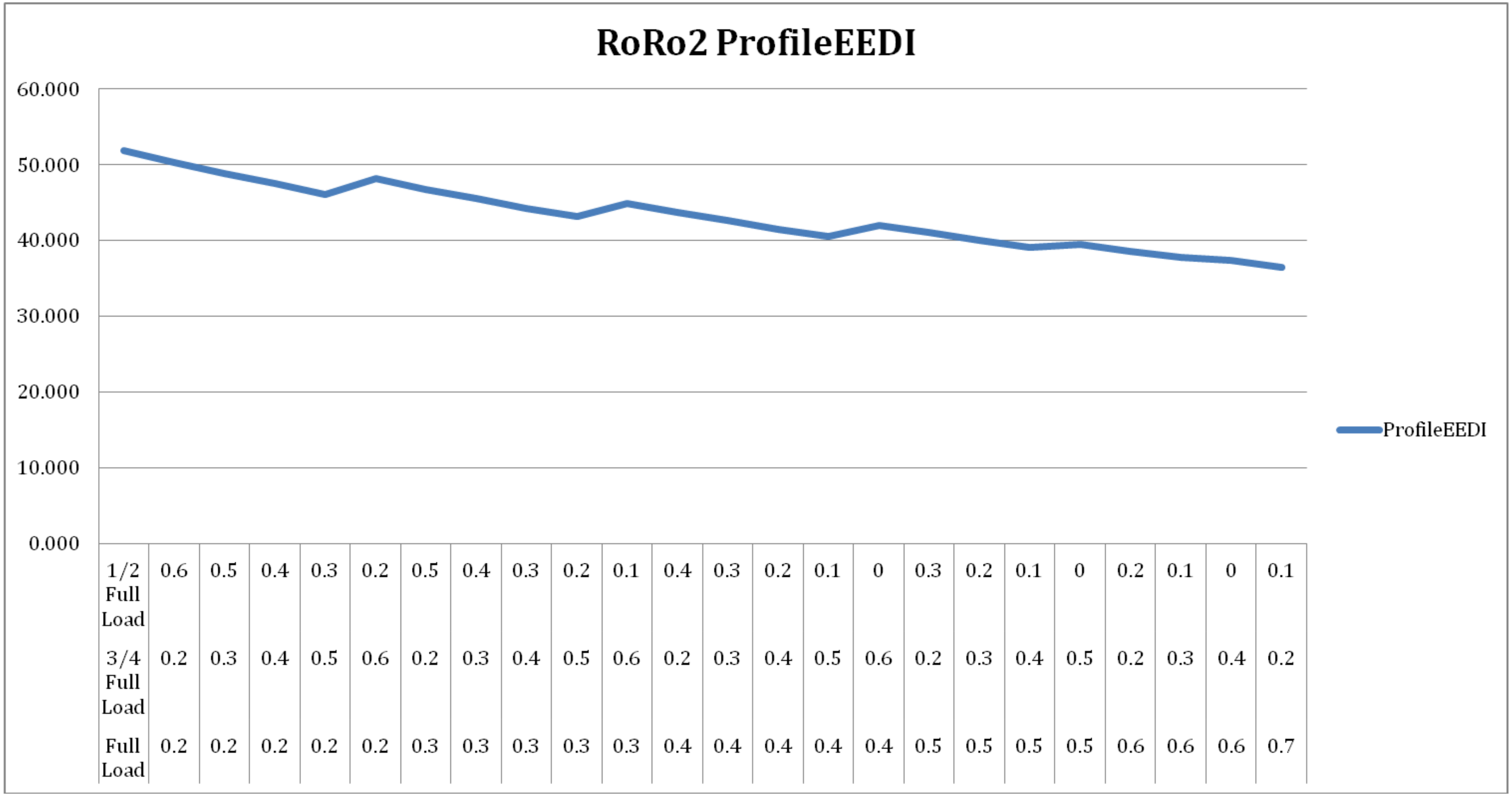


Chart 9: Ro-Ro 2 EEDI case scenarios

6. Consideration of the “Transport Work” Term of the Index

A rather highly debatable issue is the one of the definition of transport work, in other terms, the benefit to society. In principle, the EEDI is supposed to express the environmental impact from the shipping activity versus the benefit to society. In the calculation procedure, the benefit to society is defined as the cargo transported (loosely represented by the deadweight) multiplied with the speed at which it is being transported. However, many seem to disagree with the above definition underlining the fact that the denominator, in its current form, cannot be compared between different ship types or different transportation methods. With this in mind, we easily understand that in order to establish the competitiveness of a transportation method or company and the corresponding utility of a service provided, we need a term that quantifies the preference of society. In other words, the index used should reflect the reality of the market.

In the economic world, the measurement of the utility of a service is more of a subjective quantity. In reality, the measurement of the utility of a product or a service comes to reply to the question: ‘How much is it worth to me to be able to buy a product or service at a particular price?’ According to Joan Robinson:

“Utility is the quality in commodities that makes individuals want to buy them, and the fact that individuals want to buy commodities shows that they have utility" [17]

However utility and value are two different concepts that should not be confused. In her definition of value, Joan Robinson states the following:

“It does not mean market prices, which vary from time to time under the influence of casual accidents; nor is it just an historical average of actual prices. Indeed it is not simply a price; it is something which will explain how prices come to be what they are.” [17]

However, the willingness of the society to pay for a service can be reflected on the price of the service, if we consider the law of demand and supply that sets in motion the world market. Even though we cannot define the value of a service merely by its price, we can use it as an instrument to depict its necessity to society. With that being said, in this current study, the inclusion of an indicator of the price that the people are willing to pay for transportation of goods by sea, is considered necessary so as to describe transport in a more sufficient sense. Since the equilibrium between demand and supply changes rapidly, the price on its own would be a rather unstable instrument. Therefore, it is believed that the use of an indicator reflecting people's willingness to pay would prove to be more appropriate.

6.1. Inclusion of the Baltic Dry Index in the calculation of EEDI for bulk carriers

In our attempt to reflect in the final index value the utility that society attributes to the service provided by the operation of the ship, the inclusion of the Baltic Dry Index (BDI) seemed to be a first possible approach to the matter as far as bulk carriers are concerned. By being an assessment of the price of moving the major raw materials by sea, BDI measures the demand for shipping capacity versus the supply of dry bulk carriers. Indirectly, it measures the demand of the market for the raw materials being transferred by sea. In this way, BDI index becomes an instrument indicating future market activity. The Baltic Dry Index is a value resulting from the submission of current freight cost corresponding to a number of representative routes calculated in USD per day.

In order to include the BDI in our calculations we used information published by the Clarksons database. [18] In the following diagrams we can see how the BDI value ranges through the years.

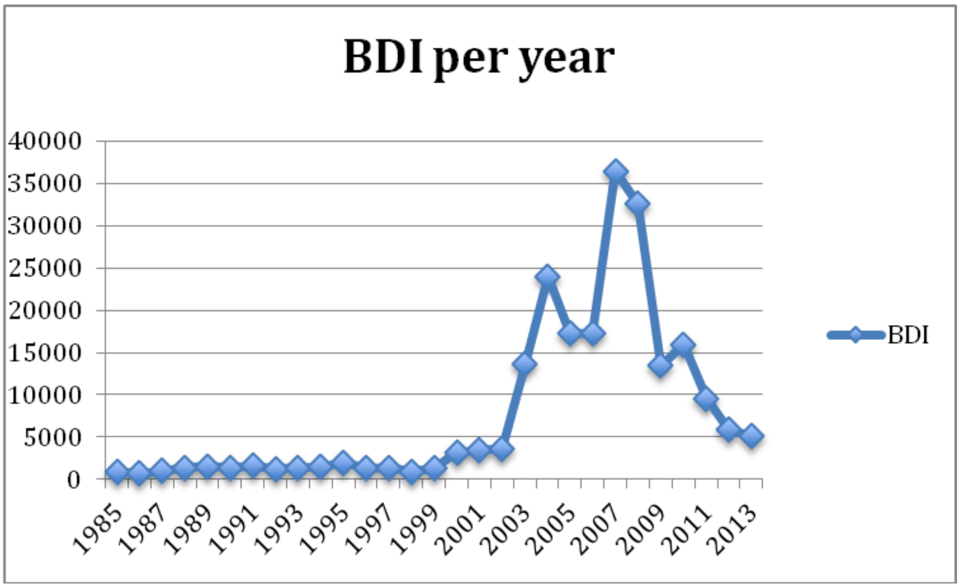


Chart 10: BDI value per year

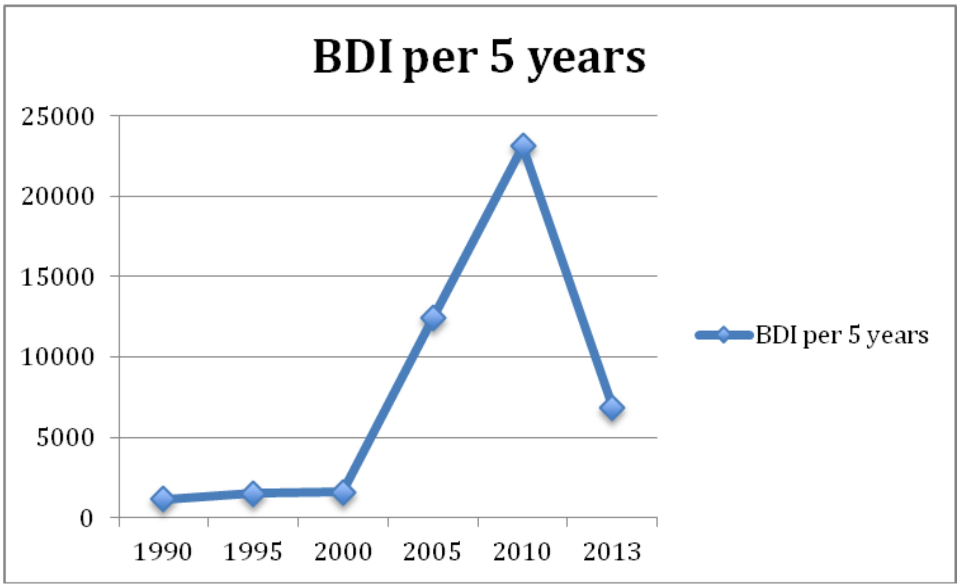


Chart 11: BDI value per five years

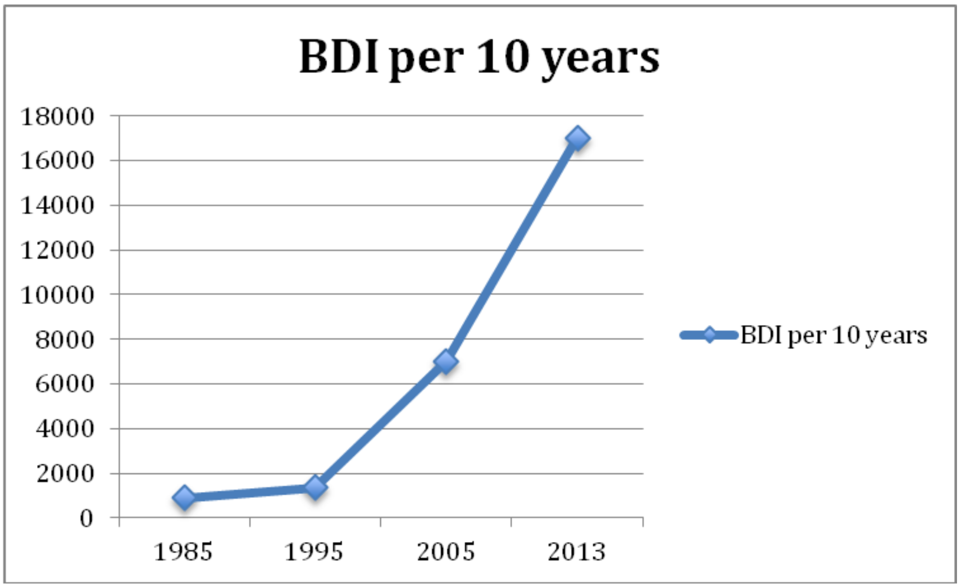


Chart 12: BDI value per ten years

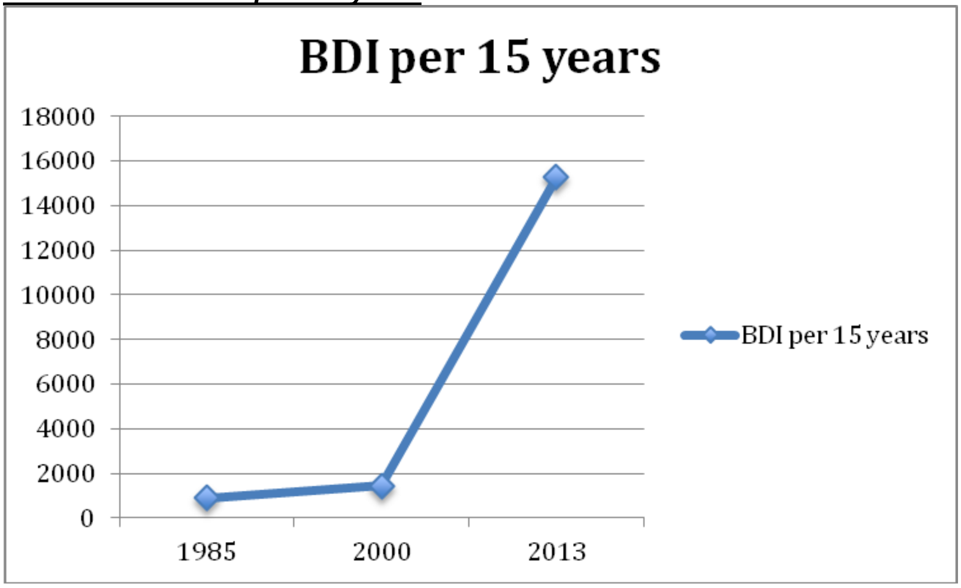


Chart 13: BDI value per fifteen years

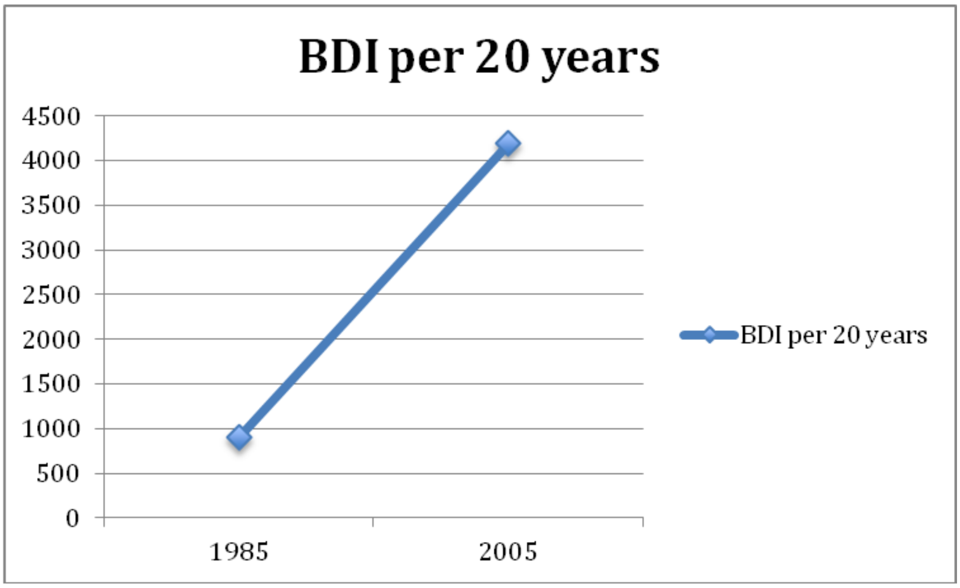


Chart 14: BDI value per twenty years

From the above diagrams we can understand that the value of the index had a rather large variation in a period of 20 years. [18] Such a conclusion is not surprising if we consider that the Baltic Dry Index corresponds to the laws of the overall market. The particular instability however does not facilitate the prediction of a BDI value for the future thus making it difficult for us to include it in the EEDI calculation. With this in mind, we used as an indicator the index's logarithm with values shown in the following diagram:

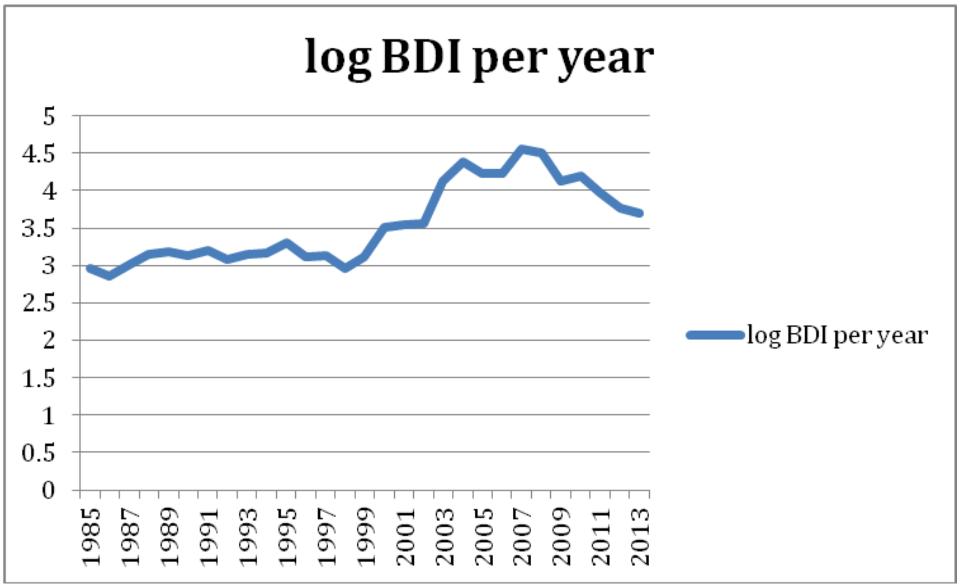


Chart 15: BDI's logarithm per year

Since 1985 until present, the average BDI logarithm is equal to 3.55. For the calculation of EEDI we included in the denominator the different operational profiles multiplied with the average BDI logarithm. The above method led us to the following results as far as the bulk carriers Bulk2, Bulk3 and Bulk4 are concerned.

Table 16: Case scenario results for high speed

CASE SENARIOS			BDI HIGH SPEED		
FULL LOAD%	BALLAST%	3/4FULL LOAD%	BULK2	BULK4	BULK3
0.4	0.2	0.4	2.315	1.725	2.094
0.4	0.25	0.35	2.436	1.817	2.203
0.4	0.3	0.3	2.571	1.920	2.325
0.4	0.35	0.25	2.723	2.037	2.463
0.4	0.4	0.2	2.896	2.169	2.620
0.4	0.45	0.15	3.095	2.321	2.800
0.4	0.5	0.1	3.325	2.497	3.008
0.5	0.2	0.3	2.239	1.666	2.026
0.5	0.25	0.25	2.351	1.752	2.127
0.5	0.3	0.2	2.476	1.847	2.241
0.5	0.35	0.15	2.616	1.955	2.368
0.5	0.4	0.1	2.775	2.076	2.511
0.5	0.45	0.05	2.955	2.215	2.675
0.5	0.5	0	3.163	2.374	2.864
0.6	0.2	0.2	2.167	1.611	1.962
0.6	0.25	0.15	2.272	1.691	2.057
0.6	0.3	0.1	2.387	1.780	2.162
0.6	0.35	0.05	2.517	1.879	2.280
0.6	0.4	0	2.663	1.991	2.412
0.7	0.2	0.1	2.101	1.560	1.903
0.7	0.25	0.05	2.198	1.635	1.991
0.7	0.3	0	2.306	1.717	2.089
0.8	0.2	0	2.038	1.512	1.847

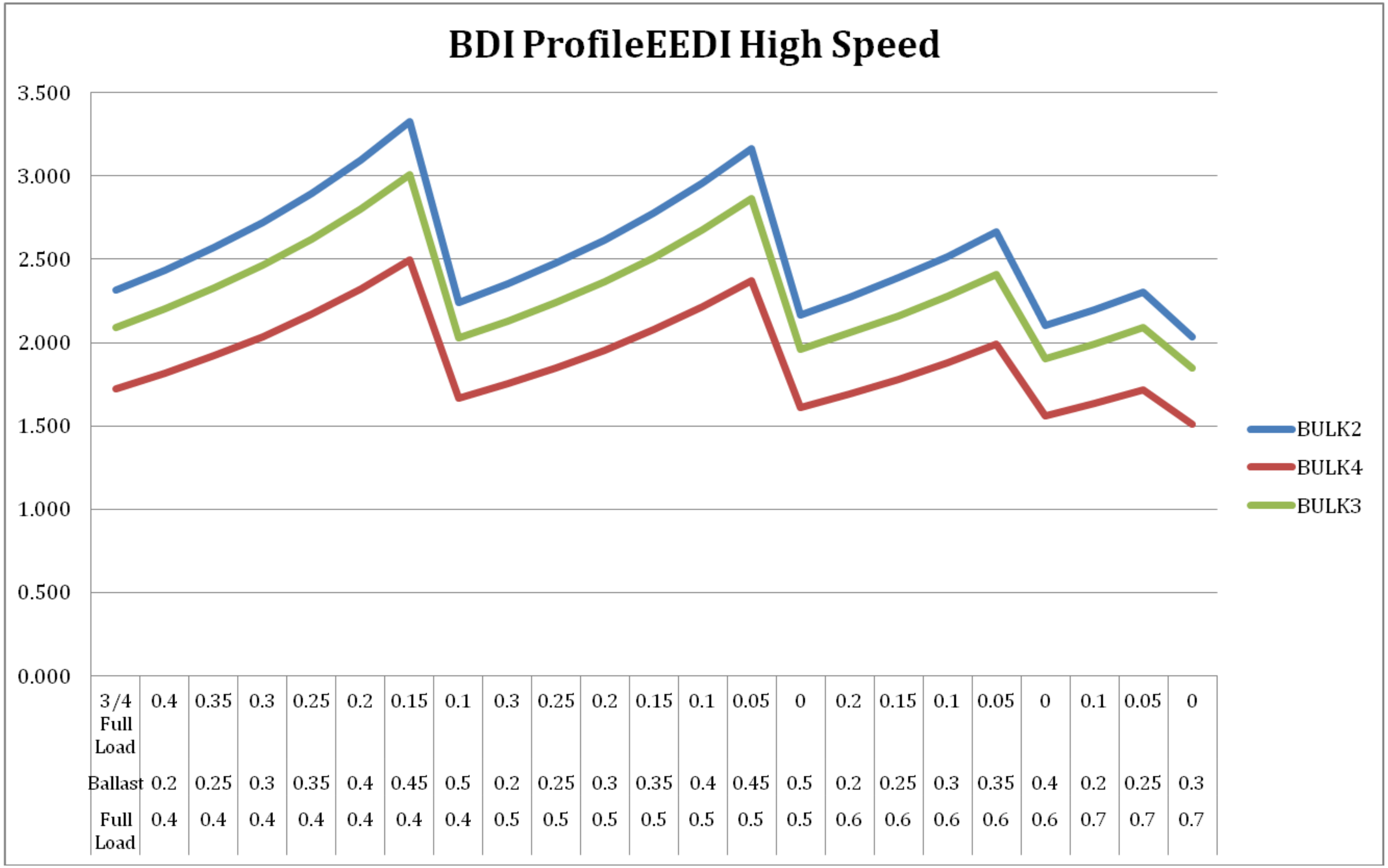


Chart 16: EEDI High Speed case scenarios with BDI inclusion

Table 17: Case scenario results for medium speed

CASE SENARIOS			BDI MED SPEED		
FULL LOAD%	**BALLAST%**	**3/4FULL LOAD%**	**BULK2**	**BULK4**	**BULK3**
0.4	0.2	0.4	2.125	1.628	1.846
0.4	0.25	0.35	2.236	1.711	1.947
0.4	0.3	0.3	2.360	1.804	2.060
0.4	0.35	0.25	2.501	1.908	2.188
0.4	0.4	0.2	2.660	2.027	2.332
0.4	0.45	0.15	2.843	2.163	2.498
0.4	0.5	0.1	3.054	2.321	2.690
0.5	0.2	0.3	2.053	1.573	1.786
0.5	0.25	0.25	2.156	1.650	1.880
0.5	0.3	0.2	2.271	1.735	1.985
0.5	0.35	0.15	2.400	1.831	2.102
0.5	0.4	0.1	2.546	1.940	2.235
0.5	0.45	0.05	2.712	2.064	2.387
0.5	0.5	0	2.903	2.206	2.561
0.6	0.2	0.2	1.986	1.522	1.730
0.6	0.25	0.15	2.082	1.593	1.818
0.6	0.3	0.1	2.189	1.672	1.915
0.6	0.35	0.05	2.308	1.761	2.024
0.6	0.4	0	2.442	1.860	2.146
0.7	0.2	0.1	1.924	1.473	1.677
0.7	0.25	0.05	2.013	1.540	1.759
0.7	0.3	0	2.112	1.614	1.850
0.8	0.2	0	1.865	1.428	1.628

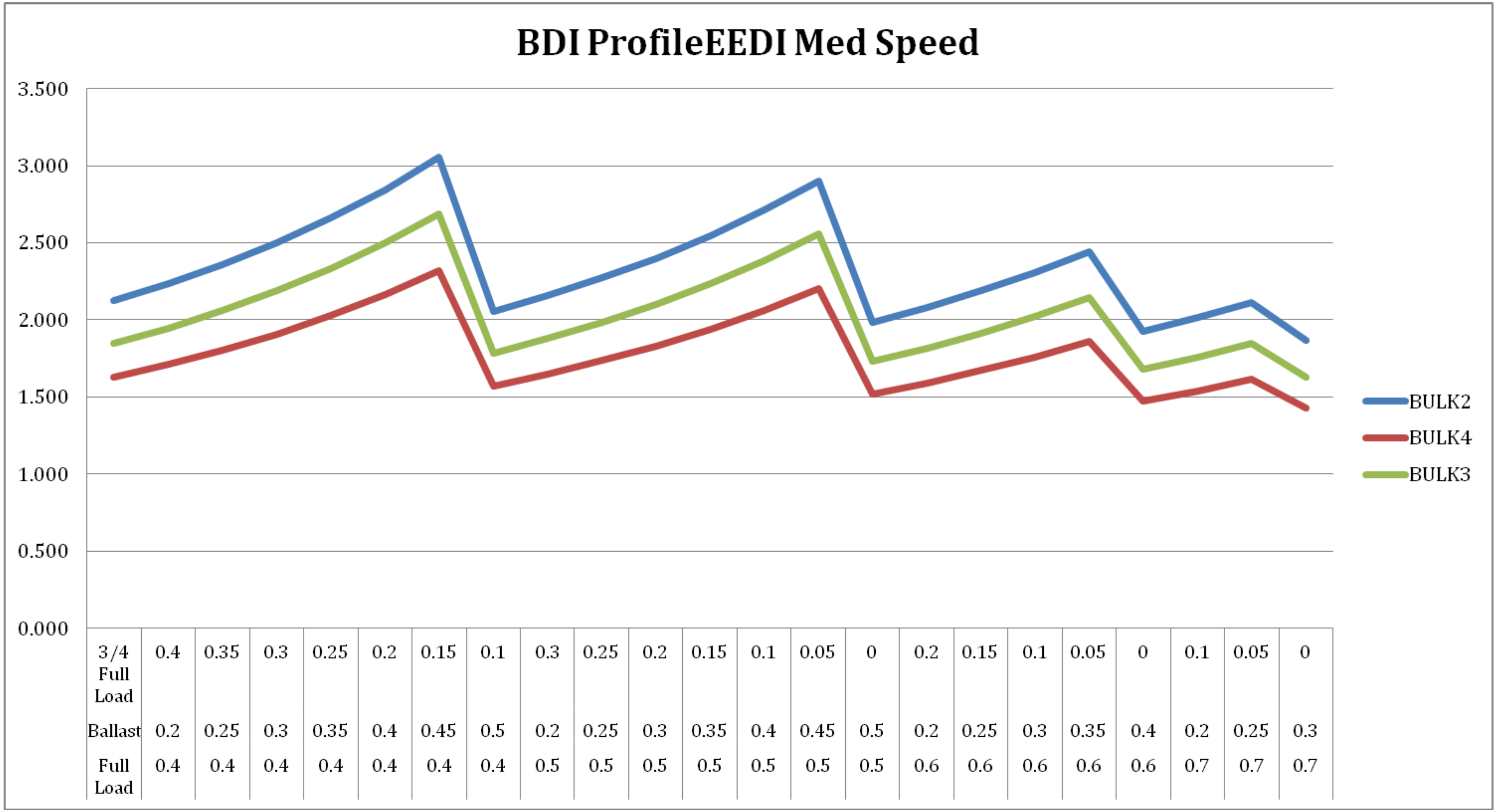


Chart 17: EEDI Med Speed case scenarios with BDI inclusion

Table 18: Case scenario results for eco speed

CASE SENARIOS			BDI ECO SPEED		
FULL LOAD%	**BALLAST%**	**3/4FULL LOAD%**	**BULK2**	**BULK4**	**BULK3**
0.4	0.2	0.4	1.930	1.437	1.712
0.4	0.25	0.35	2.034	1.525	1.796
0.4	0.3	0.3	2.150	1.624	1.890
0.4	0.35	0.25	2.281	1.735	1.996
0.4	0.4	0.2	2.430	1.862	2.117
0.4	0.45	0.15	2.601	2.007	2.256
0.4	0.5	0.1	2.799	2.175	2.417
0.5	0.2	0.3	1.849	1.386	1.655
0.5	0.25	0.25	1.945	1.468	1.732
0.5	0.3	0.2	2.052	1.559	1.819
0.5	0.35	0.15	2.171	1.662	1.917
0.5	0.4	0.1	2.307	1.778	2.027
0.5	0.45	0.05	2.461	1.911	2.153
0.5	0.5	0	2.639	2.063	2.298
0.6	0.2	0.2	1.774	1.338	1.601
0.6	0.25	0.15	1.862	1.414	1.673
0.6	0.3	0.1	1.960	1.499	1.753
0.6	0.35	0.05	2.070	1.595	1.843
0.6	0.4	0	2.193	1.702	1.944
0.7	0.2	0.1	1.703	1.293	1.551
0.7	0.25	0.05	1.785	1.364	1.618
0.7	0.3	0	1.875	1.444	1.692
0.8	0.2	0	1.637	1.251	1.504

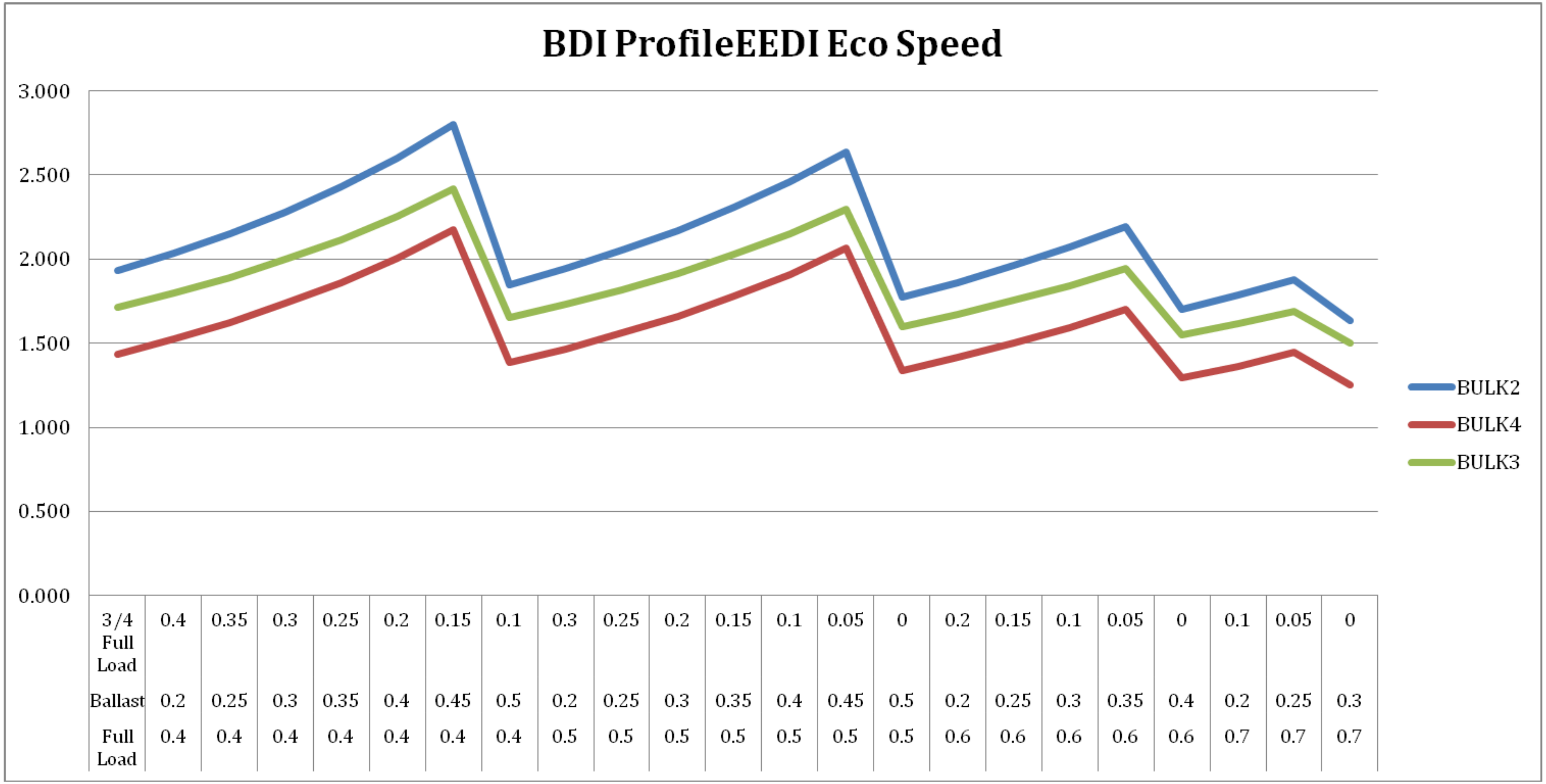


Chart 18: EEDI Eco Speed case scenarios with BDI inclusion.

7. EEDI Calculation: Considering a Lifecycle Approach

In our effort to minimize the negative impact on environment created by sea transportation, one should take into consideration the different operations of the ship throughout its lifetime. To begin with, in a realistic world we need a transportation system that would not only prove to be environmentally friendly but mostly cost-effective. Driven by the law of demand and supply, ship owners may decide at some point to change the operation of their ships, by changing the carried commodity. Moreover, CO2 emissions are being produced not only at sea, but also during shipbuilding, ship dismantling and loading and unloading operations at ports. In a lifetime of about 20 up to 25 years, we should consider all stages and operations before we arrive at any conclusions concerning economic and environmental sustainability.

In the previous section, we attempted to reflect the reality of the market in the index by including BDI logarithm in the calculation. However, such a measure on its own cannot give us an accurate perspective corresponding to the market's constant variations. By using it as a future indicator, we could ideally include in the calculation of the EEDI the assumed CO2 emissions for a period of 20 years of the ships operations versus the benefit to society. In this context, 'benefit to society' would be best described as the profit of the ship owner overall.

Since bulk commodities represent about three quarters of the total ton-miles performed in 2012, during this study we examined the performance of a bulk carrier from a lifecycle perspective, that meaning from the first journey until the last. The major five dry bulk commodities transferred by sea are *coal, iron ore, grain, bauxite/alumina* and *phosphate rock*. [19] In the case scenario of a Panamax of 75000 DWT, we will assume that in a period of 20 years it will carry different dry commodities covering different sea routes.

By examining the market of bulk carriers the past 20 years and the variation of their freight rates, we can easily observe in this ship segment too the impact of global economy. Recently, the deterioration of global economy has affected bulk market at such an extent that ship owners were forced to take drastic measures such as change of fuels, cancelation of new orders and ship scrapping plans so that overall costs would be reduced.

Another element deserving consideration is the variation in the equilibrium of demand and supply of the transferred commodities. Only by looking at the data of the main bulk commodities in the years 2012-2013, we can understand that despite of the deterioration of global economy, dry cargo trade volumes are growing impressively. More specifically, during this year coal shipments total volumes was increased 12.3%, steel production was increased by 1.2%, the total grain demand fell about 1.7%, bauxite and alumina total volumes fell by 5.3% in 2012 and phosphate rock shipments were increased by 3.4%. At this point, it is worth mentioning that the global bulk carrier fleet has an average age of 9.9 years, making it the youngest ship segment. [19]

However, one would be justified to support that the prices of the carried goods are responsible for shaping indirectly the freight rates of bulk carriers. By clarifying that in this study we are interested only in obtaining a clearer idea of the development of the market and not in forecasting accurately the market trends, we will attempt to include in the calculation the assumed profit of the ship owner comparing it to the 20 years ship's emissions.

For example, in the case of a Panamax of 75000 DWT we used the Clarxons database to calculate the average BDI for the past 20 years and we will use it as a predicting instrument to calculate the possible profit of the ship owner. Since 1985 until 2013, BDI average is $7617.1/day. For a period of 20 years (7300 days), we assume that 80% of the time the ship will be at sea and 20% of the time at ports. During the time that the ship is travelling, we assume again that 40% of the time it will be travelling fully loaded, 30% of the time in ballast condition and 30% of the time partially loaded (3/4 DWT). For our calculations we will use again bulk carrier Bulk4 (75000 DWT).

Table 20: Average BDI value.

YEAR	BDI
1985	901
1986	715
1987	1019
1988	1385
1989	1545
1990	1358
1991	1593
1992	1203
1993	1400
1994	1477
1995	1981
1996	1318
1997	1336
1998	906
1999	1296
2000	3188
2001	3450
2002	3682
2003	13584
2004	24038
2005	17293
2006	17254
2007	36449
2008	32582
2009	13433
2010	15923
2011	9587
2012	5906
2013	5094
AVERAGE	7617.1

Taking into consideration the above assumptions, the estimated profit for the ship owner would be 20796.2064 thousands of $. The calculations are made only for medium speed. The same procedure can be followed for all three speeds given. The nominator calculates the emissions for 20 years of the ship, taking into account that the ship produces CO2 emissions at an average rate of 31.5 tons/day at sea fully loaded, 30.8 tons/day partially loaded, 27.5 tons/day in ballast condition and has an assumed fuel consumption of 24 tons/day at port. The denominator multiplies the speed with the transferred deadweight and the total profit in thousands of $. The EEDI value is the logarithmic value of the fraction. The above calculations led us to an EEDI value of 1.892 log (grCO2/tn*nm*$thousands).

Obviously such a value cannot be compared to any other EEDI value since the calculation process is different. In the current formula we can include different percentages of the ship's operational profiles just like we did in chapter 5.

Table 21: Logarithmic EEDI calculation

CASE SENARIOS			**EEDI MED SPEED**
FULL LOAD%	**BALLAST%**	**3/4FULL LOAD%**	**BULK4**
0.4	0.2	0.4	1.890
0.4	0.25	0.35	1.891
0.4	0.3	0.3	1.892
0.4	0.35	0.25	1.893
0.4	0.4	0.2	1.894
0.4	0.45	0.15	1.895
0.4	0.5	0.1	1.896
0.5	0.2	0.3	1.804
0.5	0.25	0.25	1.804
0.5	0.3	0.2	1.805
0.5	0.35	0.15	1.805
0.5	0.4	0.1	1.806
0.5	0.45	0.05	1.806
0.5	0.5	0	1.807
0.6	0.2	0.2	1.732
0.6	0.25	0.15	1.732
0.6	0.3	0.1	1.732
0.6	0.35	0.05	1.732
0.6	0.4	0	1.732
0.7	0.2	0.1	1.671
0.7	0.25	0.05	1.670
0.7	0.3	0	1.670
0.8	0.2	0	1.617

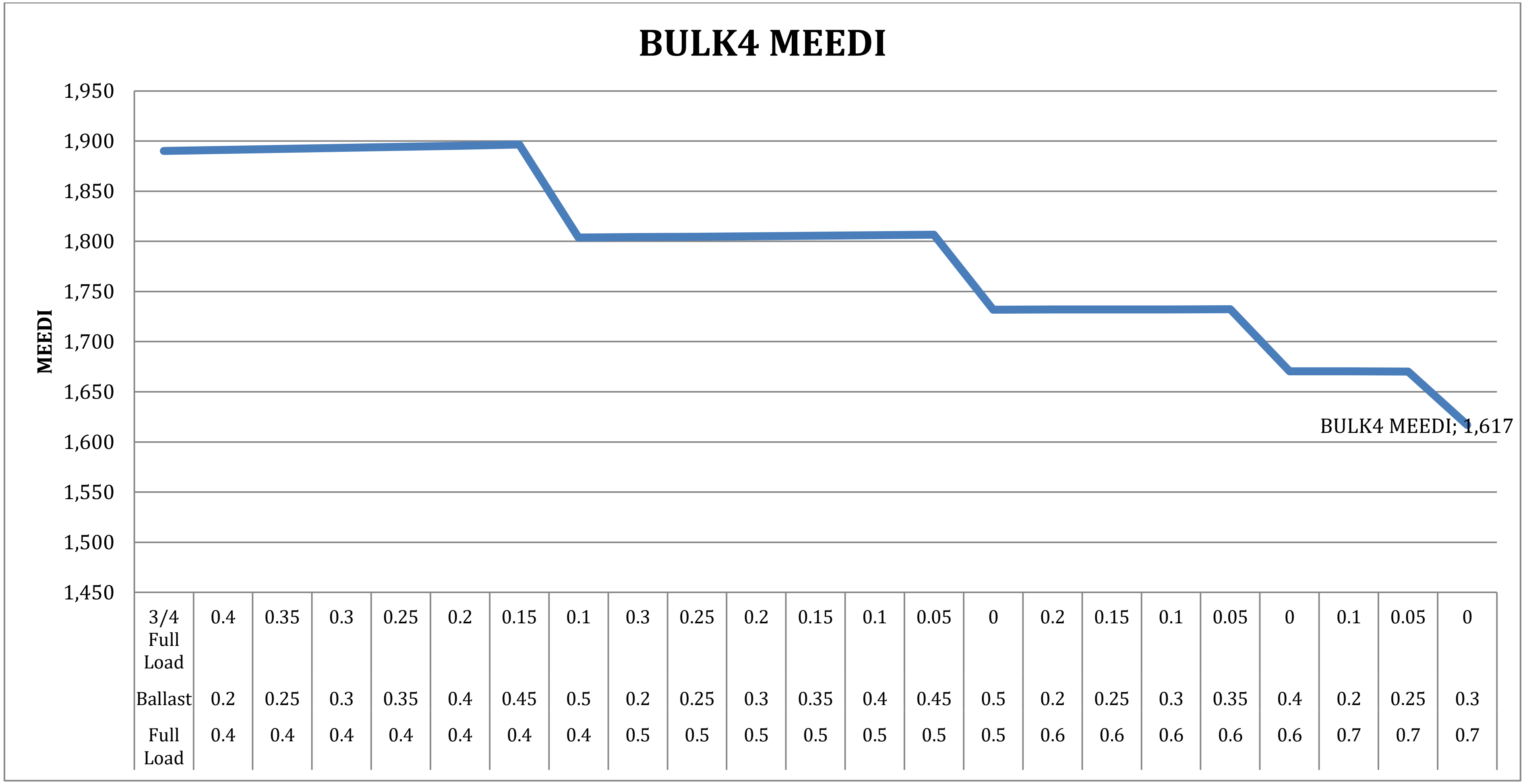


Chart 20: Eagle EEDI case scenario calculations; logarithmic value

8. Conclusions

In this study we approached the Energy Efficiency Design Index as a tool to reflect ship's energy efficiency in all possible loading conditions. By altering the numerator of the formula, we had the opportunity to contrast ship's emissions with the resulting benefit to society from a more realistic perspective. By including three different loading conditions in the EEDI formula and the percentage of their contribution, it became clear that by differentiating the operational profile of a vessel, we could achieve significantly different EEDI values. The best results were generated in a combination of 80% full load condition and 20% ballast condition operational profile.

The small contribution of the ballast condition in the above result gives the incentive to ship operators to minimize as far as possible the journeys in ballast condition, raising in such a way the final benefit to society. Another conclusion was that by sailing at a slightly lower speed, the "eco" speed, we could achieve a significantly lower EEDI value. With the inclusion of the indifference curves, it became clear that we could reach the same EEDI value and sail at a higher speed, by simply reducing the percentage of journeys at ballast condition and increasing the percentage of journeys at full load condition. Of course this is not completely in the hands of the ship operators as the availability of cargos is outside their control.

As far as the Ro-Ro sector is concerned, the above method led as to a similar conclusion. By reducing the contribution of the partially loaded condition in the operational profile, we can have "greener" and more beneficial ships to society with that being reflected in the final EEDI value.

During this study, the transport work term contributing to the denominator of the formula was also discussed. The definition of the benefit to society of a service should include in some way the utility of this service, in other terms people's willingness to pay for the specific service. In our calculation we used as a utility index, the logarithm of the Baltic Dry Index for bulk carriers. However, a comparison between different ship types could not be achieved by this method and the market's constant variations complicate future predictions.

Finally, we used the average BDI value of the past 20 years as a predicting tool to calculate ship owner's profit and we included this profit in the denominator. Again in this new formula we calculated ship's emission in all three loading conditions by using different case scenarios, but we also take into consideration the emissions when the ship is at ports. The resulting value appears as a logarithmic value and it calculates emissions in relation with ship's speed, capacity and profit to its owner for a period of 20 years. Such an approach gives as a more global image of the ship's damaging footprint to the environment.

This study gave us the opportunity to understand that there are many factors one should consider before calculating efficiency. Even the terms "efficiency" and "benefit to society" are still open for discussion. In order to calculate accurately the ship's emissions and their impact to society, we should not neglect the emissions created during the construction and the dismantling of the ship. It would be more than interesting to address the issue from a lifecycle perspective. Moreover, a study concerning how trim optimization can affect energy efficiency and fuel consumption reduction could change our opinion about ship operation. Another interesting study would be to calculate how all the new installations and innovative technologies promising to reduce EEDI can affect the final value. It is undeniable that in the field of efficiency a lot of work remains to be done and a lot of questions remain to be answered. We cannot but wait and welcome new studies and suggestions.

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