CHALMERS

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

Impact of EEDI on Ship Design and Hydrodynamics

A Study of the Energy Efficiency Design Index and Other Related Emission Control Indexes

Master of Science Thesis

S. M. RASHIDUL HASAN

Department of Shipping and Marine Technology
Division of Sustainable Ship Propulsion
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden, 2011
Report No. X-11/272

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Abstract

Around 90% of global trade is carried by sea[1] due to the reason that it is the most economical and fuel efficient mode of cargo transportation. The total trade volume is increasing throughout the last century for the same reason. On the other hand according to the Green House Gas study by IMO, International Maritime Organization in 2000, ships engaged in international trade in 1996 contributed about 1.8% of the total world's CO_2 emissions which is approximated as 2.7% in 2007[2]. At the present trend, this percentage could go two or three times higher from the present by 2050[3].

In order to control this CO_2 emission from shipping, IMO has developed the first ever global CO_2 reduction index in the world, known as 'EEDI', Energy Efficiency Design Index. The basic formulation of EEDI is based on the ratio of total CO_2 emission per tonne.mile. As CO_2 depends upon fuel consumption and fuel consumption depends upon the total power requirements, eventually this EEDI formulation has certain impact on ship design parameters and hydrodynamics.

At this point SSPA Sweden AB[4] wanted to have an in depth knowledge about the background of EEDI, other indexes (except EEDI) for reducing CO_2 emission developed by other organizations, formulations of different indexes and working method, impact of EEDI on ship design and the hydrodynamics. In order to find the impact on ship design and hydrodynamics, parametric analyses of ship is accomplished for different ship types such as Bulk Carrier, Tanker, Container vessel etc. A simple tool has been developed to calculate resistance and power with Holtrop & Mennen, 1982 method. Using the tool the main engine power is predicted after calculating the resistance and finally EEDI is calculated with the current IMO formulation.

Finally, the results are presented as the effect on EEDI and hydrodynamics by changing ship design parameters such as Length, Beam, Draft, Prismatic Coefficient, Block Coefficient and suggestions have been made in order to achieve the required EEDI. An effort was also made to analyse the criticism against the present EEDI formulation, guideline and reference line, as it is quite a heavy debate now, whether this implementation will really reduce the CO_2 emission or not.

Keywords: International Maritime Organization, Marine Environment Protection Committee, Energy Efficiency Design Index, Green House Gas, MARPOL, Reference EEDI, Attained EEDI, United Nations Framework Convention on Climate Change, Kyoto Protocol.

Preface

This thesis is a part of the requirements for the master's degree at Chalmers University of Technology, Gothenburg, and has been carried out at SSPA Sweden AB, under the supervision of SSPA and the Division of Division of Sustainable Ship Propulsion, Department of Shipping and Marine Technology, Chalmers University of Technology.

I would like to acknowledge and thank my examiner and supervisor, Associate Professor Rickard Bensow at the Department of Shipping and Marine Technology, Administrative supervisor at SSPA Björn Allenström and my tutor at SSPA Roger Karlson for their effort, support, suggestion and guidance.

I also would like to give special thanks to Jan Bergholtz for his cordial and kind effort and time, Mikael Johansson and Adam Larsson from Det Norske Veritas for their support and PHD student from Shipping and Marine Technology department, Hannes Johnson.

Special thanks to my friends at the department and home, my family members. I always got mental support throughout the thesis project.

And finally, thanks to the All mighty, to help me for everything.

Gothenburg, November, 2011
S.M. Rashidul Hasan

Contents

1 Introduction

1.1 Background

Within shipping a number of indexes are being discussed, developed and promoted to improve the environmental performance of sea transport. The one closest to an application is the ‘EEDI, Energy Efficiency Design Index’. Marine Environment Protection Committee (MEPC) under IMO has developed the EEDI for all new ships which will enter into force from January, 2013[5], to create stronger incentives for further improvements in ships’ fuel consumption. The purposes of IMO’s EEDI are:

- To achieve a minimum energy efficiency level for new ships;
- To stimulate continued technical development of all the components influencing the fuel efficiency of a ship;
- To separate the technical and design based measures from the operational and commercial measures; and
- To enable a comparison of the energy efficiency of individual ships to similar ships of the same size which could have undertaken the same transport work (moved the same cargo).

Simply described the EEDI is calculating the emissions of a vessel under design condition (installed power, trial speed etc.) divided with the transport work done under the same condition as per the equations below (first the basic idea, then the “complete” equation):

$$EEDI = \frac{CO_2 Emission}{Transport\ work}$$

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

The formulation depends upon several factors and coefficients. IMO is also discussing an operational index, EEOI, based on actual CO_2 emissions and the actual transport work done. The EEOI can therefore be influenced by changes in the operation of ships, whereas the EEDI is only linked to the design features of the vessel.

There are also other regional, national and local indexes proposed. In Sweden a Clean Shipping Index, CSI, is in the process of being implemented. Some large buyers of transports are also developing their own indexes. Also, the European Union (EU) has their own regulations against pollution from ship and there are some region known as Emission Control Area (ECA), where ships also have to maintain some specific rules. Following the IMO regulations, EU or ECA controls the emission and pollution from ship in specific region.

1.2. Objective with the investigation

In recent days, Energy Efficiency Design Index became an important topic in the maritime industry, after being adopted as mandatory in the 62nd MEPC meeting on July, 2011.It was decided on that meeting that, all new ships from the 1st of January, 2013 have to fulfil the minimum criteria of the EEDI. For most ship owners, shipping and ship design companies, it becomes interesting and scary in some way. Most of the questions for them are like:

- Is EEDI going to break the present trend of efficient ship design?
- What are the possible modifications of ship design needed to achieve the required EEDI?
- Hydrodynamically efficient ship and EEDI efficient ship, will they follow the same branch or two different branches; that is, whether EEDI formulation contradicts with hydrodynamics of ship or not.

There are some criticisms against EEDI such as

- EEDI formulation contradicts with basic Naval Architectural formula or hydrodynamics of ship.
- EEDI forbids building bigger ships.
- Target of CO_2 reduction will not be achieved.

The objective of this project is to investigate on behalf of SSPA Sweden AB, the development of different environmental indexes with focus on the EEDI. The work aims to answer the following questions, concentrating on the last one:

- Where do IMO, EU and others stand regarding development and implementation of different indexes?
- What is the likely formulation of indexes?
- When will they be implemented, and for what part of the shipping fleet?
- How will the implication affect vessel design and operation? There has been criticism that these indexes will, in different ways, hamper the development of efficient ships, and that they could also affect safety negatively. In the case of EEDI, for instance, the sole coupling to design parameters for full speed and cargo penalizes arrangements for additional redundancy on board (extra power installed for redundancy is included in the index).
- What is the impact on hydrodynamic issues?

1.3. Methodology

In order to understand the impact of EEDI on ship design parameters and hydrodynamics, a tool is developed to calculate the effective power and propulsion power of ship and then the EEDI. In this tool, it is possible to make parametric analyses for all types of ships that cover the current EEDI formulations and requirements by IMO. For resistance and propulsion calculations, Holtrop and Mennen method, 'An approximate power prediction method'[6] with the correction by Holtrop in 1984[7]is used. The accuracy of this method was tested with two model test data (one Panamax Product Tanker and one Ropax Vessel) as supplied by SSPA and average and maximum error found as 2% and 4%. At this design stage, it can be accepted as correct.

2. Development of different environmental indexes and emission control measures by IMO, EU and others.

2.1. Present Status of IMO

IMO has been working on emission control from shipping as a mandate to the Kyoto Protocol[5]. In the 62nd MEPC meeting, mandatory measures to reduce emissions of greenhouse gases (GHGs) from international shipping were adopted by parties to MARPOL Annex VI, which is the first every mandatory global greenhouse gas reduction regime for an international industry sector.

New ships (building contract as from 1st of January 2013 and the delivery of which is on or after 1 July 2015.) will have to meet a required Energy Efficiency Design Index (EEDI). In addition, all ships, new and existing, are required to keep on board a ship-specific Ship Energy Efficiency Management Plan (SEEMP) which may form part of the ship's Safety Management System (SMS). The SEEMP shall be developed taking into account guidelines developed by IMO. The regulations apply to all ships of 400 gross tonnages and above and are expected to enter into force on 1 January 2013.

A new provision allows Administrations to delay the enforcement of these amendments by up to 4 years. This means that ships built under the flag of such Administrations would not be bound to have EEDI certification (i.e. International Energy Efficiency Certificate) if their building contract is dated before 1 January 2017. Each Administration giving such waivers needs to inform the IMO. Parties to MARPOL Annex VI have agreed to allow ships with such waivers to call to their ports.

IMO, through the MEPC has agreed on a work plan to continue the work on energy efficiency measures for ships, to include the development of the EEDI framework for ship types and sizes, and propulsion systems, not covered by the current EEDI requirements and the development of EEDI and SEEMP-related guidelines.

The Regulation has a set of initial values for the required EEDI which are individualized for each ship type through a reference line. The reference line of each ship type will also give the value of the required EEDI for each ship’s size. Finally, the Regulation includes a step–by-step phase-in scheme for reduction of the required EEDI values as described in table 1.

The Regulation requires assessment that the installed propulsion power shall not be less than the propulsion power needed to maintain the manoeuvrability of the ship under adverse conditions as defined in the guidelines to be developed by IMO.

The Regulation also provides that, at the beginning of Phase 1 of the phase-in, the IMO shall review the status of technological developments and, if proven necessary, adjust the time periods and reduction rates set out for Phases 2 and 3.

Table1. Phase 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.

With regard to tankers, the Regulation applies to tankers of 4,000 dwt and above. The Regulation will not apply to ships which have diesel-electric propulsion, turbine propulsion or hybrid propulsion systems until such time as the method of calculation of the attained EEDI for each of these categories of ships is established in the guidelines for the method of calculation of the attained EEDI for new ships, and the EEDI reference lines for these categories of ships have been established.

As reported, it was agreed to hold another MEPC Working Group inter sessional meeting to finalize all the associated guidelines for these new amendments to MARPOL Annex VI which are:

- Draft Guidelines on the method of calculation of the Energy Efficiency Design Index (EEDI) for new ships;
- Draft Guidelines for the development of a Ship Energy Efficiency Management Plan (SEEMP);
- Draft Guidelines on Survey and Certification of the EEDI;
- Draft interim Guidelines for determining minimum propulsion power and speed to enable safe manoeuvring in adverse weather conditions;

- Identify the necessity of other Guidelines or supporting documents for technical and operational measures;
- Consider EEDI for larger size sectors of tankers and bulk carriers (the background is that the current reference lines seem to be unfairly low as compared to the calculated EEDIs for all existing large bulk carriers and VLCCs);
- Consider improvement of Guidelines on Ships Energy Efficiency Operational Indicator (EEOI)

2.2. European Union Activities

The EU, European Union is actively working, along with other developed countries to pursue the reductions in emissions from international maritime transport, as an obligation to the Kyoto protocol. The EU has a target to reduce CO_2 emissions by at least 20% by 2020 until a global and comprehensive post-2012 agreement is concluded[8].

In various fora around the globe, The EC, European Commission has stressed that[9], 'shipping as a global business, should, if possible, be regulated on a global basis, but has also noted that the progress in IMO has been slow.' Later, The Commission has supported the proposal from IMO Secretary General to accelerate the organization's work on GHG emissions as much as possible.

This decision and commitment to accelerate the organization's work has been discussed in the third recital of DIRECTIVE 2009/29/EC[10] amending Directive 2003/87/EC, it has been decided to improve and extend the greenhouse gas emission allowance trading scheme of the Community. This decision has the prospect of potential future regional action if no solution can be achieved at IMO.

The Commission established a working group on shipping in 2011, composed of the Member States and of all interested stakeholders, under the framework of the European Climate Change Program. The major job of this working group is to assess the feasibility of an EU regional market based instrument.

The Commission has a Strategy to reduce atmospheric emissions from seagoing ships and the thematic Strategy on Air Pollution underline the importance of reduction of emissions of sulphur dioxide (SO_2), nitrogen oxide (NO_x) and particulate matter (PM) from ships for the improvement of health and environment. The aim of the strategy is to reduce premature deaths significantly caused by air pollution by 2020 whilst simultaneously resolving environmental impacts such as acidification and eutrophication and associated losses in biodiversity.

In the Directive 1999/32/EC[11] (amended by Directive 2005/33/EC) the maximum sulphur content of gas oils and heavy fuel oil in land-based applications as well as marine fuels was established. It serves as the EU legal instrument to incorporate the sculpture provisions of the MARPOL Annex VI. Also, there are some additional fuel specific requirements on the directive that, for ships calling at EU ports, obligations related to the use of fuels covered by the Directive, and the placing on the market of certain fuels (e.g. marine gas oils). The Directive does not contain provisions to regulate ship emissions of NO_x or PM.

Before 21st December, 2009, there was no recommendation in the EC on the safe implementation of the use of low sulphur fuel. On that day, the EC had adopted a recommendation about the use of low sulphur fuel by ships at berth in EU ports.

On December 2010, the Commission had decided the criteria for LNG carriers as an alternative to use low sulphur marine fuels. In the amendment 2005/33/EC[11], the parallel requirements in the EU to those in MARPOL Annex VI is set with respect to the sulphur content of marine fuels. It was also introduced that a 0.1% maximum sulphur requirement for fuels used by ships at berth in EU ports from January 2010. Well, this directive is currently under review and it is expected that, the review would be align with the directive 2008 MARPOL Amendment.

EU wanted in the 62nd MEPC meeting at IMO to retain the provision in Singapore's draft resolution reiterating the right under international law for port states to deny entry to non EEDI- compliant ships thus putting pressure on shipbuilders to order EEDI-compliant ships despite the fact of the waiver. This right of denial of port entry had been a central element in the resolution of the double-hulled issue at the IMO a decade earlier. The EU had unilaterally banned single-hulled ships from entering EU ports following the loss of the single-hulled oil tanker Erika off the Brittany coast in 1999. The IMO's subsequent proposal for a phase-out of these ships to give developing countries time to adjust was supported by the EU but subject to an important reiteration of the proviso in the Law of the Sea preserving the right of EU states to deny entry of ships (in this case single-hulled tankers) to EU ports irrespective of the IMO regulation. In the case of the EEDI, developed countries were offering support for an implementation waiver while also reserving their rights under international law re denial of entry. The issue was debated back and forth with developing countries finally securing a commitment to delete the denial of port entry paragraph without any corresponding concessions on the length of the waiver. Although this concession does not alter port state rights under international law, developed states seemed to have been out manoeuvred. If EU ports were to deny entry to non-EEDI ships this would have a major bearing on owners' decisions when agreeing new ship designs. But intentions remain unclear. Failure to shorten the waiver period is a major shortcoming and weakens the effectiveness of the IMO's decision.

2.2.1 European Maritime Safety Agency Role

EMSA[12] is a **decentralized agency,** set up by the EU since 1975, to carry out technical tasks on behalf of the EC and the member states. This agency has been providing technical assistance to the Commission on the greenhouse gas related matters since 2008. EMSA has been particularly involved in the work relating to the Energy Efficiency Design Index (EEDI). In their technical studies, the implications and potential problems associated with the implementation of the EEDI have been commissioned.

EMSA is trying to deliver their knowledge to the member states and industry representatives by organizing series of workshops regarding technical issues related to the development and implementation of the design index, the operational indicator (EEOI) and the latest developments at IMO more generally.

Use and development of alternative fuel is very important from the greenhouse gas reduction point. In order to foster the development of the alternative fuel, EMSA organized two workshops with the main industry stakeholders to identify the best alternatives and innovative ideas and the base of the development of the LNG fuelled ships.

A part of task that EMSA has done is to prepare the Commission decision on an equivalency methodology to allow LNG tankers to burn boil off gas when at berth instead of using 0.1% sulphur fuel. The Commission decision was taken in December 2010.

EMSA has also provided a technical report analysing the studies made on the implication by new sulphur requirements, 0.1% in SECA by 1 January 2015, that will have implication for the traffic within the SECA-areas and in addition listing the alternatives to reach the limits introduced by the 2008 MARPOL amendments was issued in 2010.

2.3. Environmental indexes as described by different organizations and authorities other than IMO

Along with IMO, different other organizations, authorities have their own emission control indexes and methods. Several classification societies, port authorities, research institutions have been working on this to make an environment friendly ship. This section will describe some of those emission control methods. Description of the indexes has been adjusted for this report from the original documents.

2.3.1 Continuous Marine Diesel Engine Emissions Monitoring - MariNOx™[13]

This monitoring system has been developed by the company named 'Martek Marine', a United Kingdom based company. As declared by them, this is the first ever classification society approved on board NO_x, SO_x, and CO_2 emissions monitoring system. (Approved by the Lloyd's Register of England and Det Norske Veritas of Norway).

The latest software is equipped with IMO's current EEDI formula and this has further enhanced the accuracy of emissions level recording and trend analysis. It also complies with MARPOL Annex VI regulation 13 for NO_x reduction, ISO14001 for environmental performance management system, emissions trading system, classification society environmental notations.

$MariNO_x$ Evolution can be configured to integrate opacity sensor input, measuring the density of engine smoke, directly into its control software. It is designed to be future proof against future regulations, as claimed by Martek Marine.

2.3.2 The Ulstein Ship Emission Index[14]

The Ulstein Ship Emission Index assists the ship owner dealing with challenges like environmental impact of emissions, political and industrial problems, increased new building and operational cost by advising on issues such as:

- The emission foot print.
- The calculated emission index.
- The CO_2 benchmark level score.

The purpose of the index is to quantify the differences between designs and sailing vessels. Defined as emissions per work performed over a certain time period (day, week or year) factors considered in this model are, energy consumption, production profile (load balance), ship particulars, ship system arrangement and operational profile.

This index does not prescribe any method to reduce the emission rather provides a way of measuring and comparing the emissions being generated from different vessel design solutions.

A CO_2 benchmark level score is used based on regression analysis that will be able to compare ships of the same type but with different sizes, ship system arrangements and operational profiles.

The mission foot print is the amount of CO_2, NO_x, and SO_x per unit work or time, presented as kg/unit work or tonnes/year. The calculated emission index will result in the following form,

- External emission costs: (euro or dollar in millions)/year
- Emission cost index: (euro or dollar)/unit work
- Emission per year: tonne-equivalents/year
- Index: Kg-equivalents/unit work.

The vessel subjected to the emission indexation, is compared among peers of similar vessels by giving a level score for 1-7 and compared to an average value which is 4. Level score higher than 4 means that emission performance of current is better that the sample average.

The index will be available at a point where it is still possible to improve the design. 80 % of the emissions are determined by design configurations. Improvements and measures must be reflected in the index. Standardizing the methodology is critical to be able to compare similar ships. Can be used for all ship types, but it is not the intention to compare ships with different functionality. The benchmark line does not need to be accurate, but representative.

2.3.3 Life Cycle Approach to shipbuilding and ship operation[15]

It comprises a global approach to evaluate and reduce the environmental impact of a vessel or marine equipment. A simple, but decisive design criterion has been developed for the selection of environmental alternatives depending on the ship energy efficiency index.

This is software named ‘SSD’, developed by EVEA (environmental consultant) in association with shipbuilders and subcontractors who supplied numerous data on their technologies. This holistic approach does not provide the designers shipyards and supplier with quantitative guidelines on technology selection, rather, this SSD tools offer the designer the opportunity to assess the environmental benefits of a technical solution for one sub system on a specific ship design without going detailed life cycle analysis of the whole ship.

Measurement in the SSD software considers the impact and flow indicators where the impact indicators are

- Global warming- IPCC 2007 (CO_2 equivalent)
- Eutrophication (PO_4 equivalent)
- Atmospheric acidification (SO_2 equivalent)
- Ozone layer depletion (CFC11 equivalent)
- Human toxicity
- Fresh water aquatic eco toxicity
- Marine aquatic eco toxicity
- Terrestrial eco toxicity
- Respiratory effects
- Abiotic depletion (Antimony, Sb equivalent),
  The flow indicators are
- Water (m^3)
- Energy consumption (MJ eq.)
- Bulk waste production (kg)
- Hazardous waste production (kg).

For each indicator, the total environmental impact I of the ship through her life cycle is described as:
I = M+n.E
Where, M is the environmental impact induced by construction and scraping phases, while E is the impact due to ship operation and maintenance during one year and n is the number of operational year.

It is possible to compare two different technologies on same ship as following:
Let's compare two technologies on one given ship with an average displacement 'Δ', a yearly environmental impact 'E' during operation and 'α' the part of energy consumption due to propulsion in the total energy consumption of the ship, including hotel load and maintenance. The first technology has a weight W1 and an environmental impact I1 over its life cycle, while the second technology has a weight W2 and an environmental impact I2. Then the second technology is more interesting than the first one from an environmental point of view over the n years of operation if:

$$\frac{I_2 - I_1}{n} < \frac{2}{3} * \frac{\alpha * E}{\Delta}(W_1 - W_2)$$

The selection of a technology can be established on a ship's environmental design criterion called C_E based on the yearly environmental impact on propulsion per unit ship's weight:
$C_E = \frac{2}{3}\frac{\alpha * E}{\Delta}$, this criterion can be used for evaluating green technology.

The additional equipment to reduce the environmental impact usually represents a light ship weight increase, i.e;

$$I_2 - I_1 < 0 \; and \; W_1 - W_2 < 0$$

Advanced green equipments are of interest for a given ship profile, if $\frac{I_2 - I_1}{n(W_2 - W_1)} > C_E$ which means that larger the environmental design criterion C_E, the more difficult it will be to find relevant green technologies.

When the lighter material is used, it will induce additional pollution during its manufacturing phase and end of life, i.e.:

$I_2 - I_1 > 0 \; and \; W_1 - W_2 > 0$

Thus, advanced light materials are of interest for a given ship profile if:

$$\frac{I_2 - I_1}{n(W_2 - W_1)} < C_E$$

This means that larger the environmental design criterion C_E, the more interesting it will be to consider light construction material with high mechanical performances.

This index criterion or methodology can be applied to improve a given design due to green technologies. It cannot be applied to compare ships with different operational profiles or sizes.

2.3.4 Environmental Ship Index (ESI)[16]

Fifty-five of the world's key ports have committed themselves to reduce their greenhouse gas emission (GHG) while continuing their role as transport and economic centres. One of the projects within the World Ports Climate Initiative (WPCI) is the development of an Environmental Ship Index (ESI), which will identify seagoing ships that are beyond the current standards in reducing air emissions.

This index has been characterized as a voluntary system, helping environmental performance of maritime shipping. ESI will give points for the performance of ships compared to the current international legislation (mainly IMO). It can be applied to all ships for comparison.

The overall ESI formula is built up of different parts for NO_x, SO_x, and CO_2. It is considered that an average environmental damage from NO_x from ship is assumed to be twice the damage from SO_x. The overall ESI ranges from 0 for a ship that meets the environmental performance regulations in force to 100 for a ship that emits no SO_x and NO_x and reports or monitors its energy efficiency. By comparing the actual performance of a ship with a baseline set, the ESI points can be defined. These baselines are based on the IMO regulations in force.

The index gives a relative higher weight on emissions at berth as these have a larger environmental and health impact. The formula for the index is:

$$ESI_{overall} = \frac{1}{3.1}(2 * ESI_{NOx} + ESI_{SOx} + RR_{CO2})$$

Where, ESI_{NOx} is the environmental ship index for NO_x.
ESI_{SOx} is the environmental ship index for SO_x.
RR_{CO2} is the reward for reporting on ship energy efficiency based on the EEOI or a SEEMP.
The ESI_{NOx} and ESI_{SOx} both range from 0 to 100. The weight of ESI_{NOx} is twice the weight of ESI_{SOx}. For energy efficiency reporting (RR_{CO2}), the additional score is 10 points. The total amount of points to be scored is 310.

ESI_{NOx} is defined as

$$ESI_{NOx} = \frac{100}{\sum_{i=1}^{n} P_i} * \sum_{i=1}^{n} \frac{(NO_{X\,limit\,value} - NO_{X\,rating}) * P_i}{NO_{X\,limit\,value}}$$

Where,
P_i is the rated power of engine i,
NO_x rating is the certificated NO_x emissions of engine i, in g/kWh,
$NO_{xlimitvalue}$ is the maximum allowable NO_x emissions for an engine with the speed of engine i,
n number of engines.

A ship that does not have an Engine International Air Pollution Prevention (EIAPP) certificate onboard, cannot obtain points for ESI_{NOx}.
ESI_{SOx} is defined as
ESI_{SOx} =a%*30+b%*35+c%*35
Where, a = the relative reduction of the average sulphur content of fuel used on the high seas,
b = the relative reduction of the average sulphur content of fuel used in the ECA'S (Emission Control Areas),
c = the relative reduction of the average sulphur content of fuel used at berth, and
ESI_{SOx} can be established after inspection of the bunker fuel delivery notes of a ship over the past year,
RR_{CO2}: CO_2 emissions are not reflected in the index directly. However, the ESI gives points to ships that report on energy efficiency with 10 points.

Baseline for ESI calculations are shown in table 2 and Figure1 gives the IMO Annex VI NO_x emission limits for current future Tiers. From table 3, the required data to calculate the index is described.

Table 2: The baseline of ESI is in line with the above presented IMO sulphur limits

Date	Sulphur Limit in Fuel (% m/m)		
	High Sea	SO_x ECA	Berth
2005	4.5%	1.5%	1.5%
July 2010		1.0%	0.1%
2012	3.5%		
2015		0.1%	
2020*	0.5%		

*alternative date is 2025, to be decided by a review in 2018

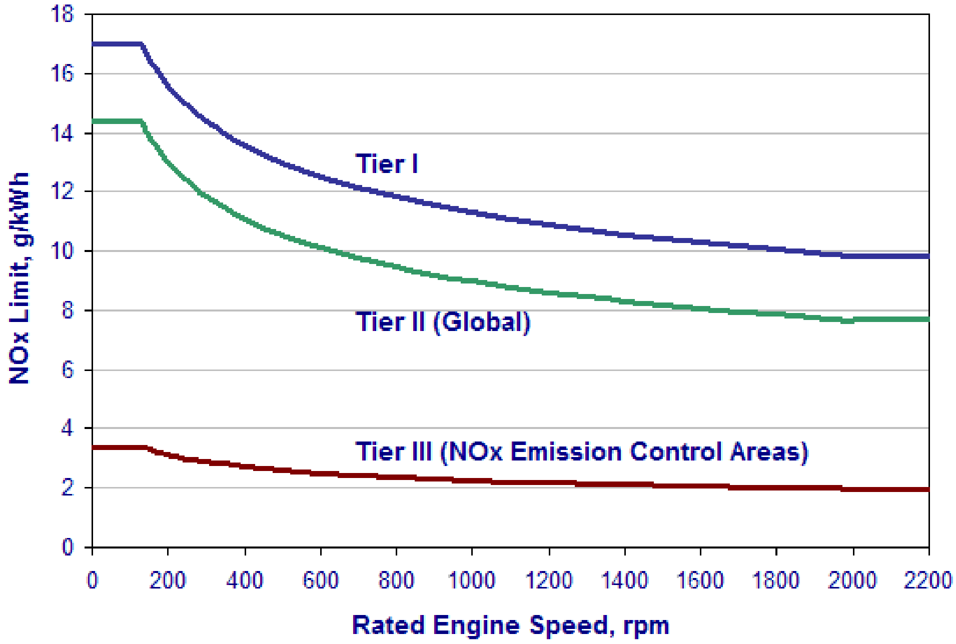

Figure1: IMO Annex VI NO_x emission limits for current future Tiers

Table 3: Required data for ESI calculation

Required data for ESI calculation			
	ESI NO_x	ESI SO_x	RR CO_2
Document	EIAPP certificate	Bunker delivery notes over 1 year	EEOI reporting or ship energy efficiency management plan
Data needed	Rated Power (kW) and rated engine (rpm) main engine	Average fuel sulphur content per bunkering per kind of fuel	Submission of EEOI reporting or ship energy efficiency management plan
	Rated power (kW) and rated speed (rpm) auxiliary engines	Amount of fuel, per kind of fuel, bunkered per delivery (ton)	
	Actual NOx emission value (g/kWh)		

To calculate the ESI_{NOx}, the IMO limit value for a particular engine needs to be compared with the engine's actual certified value. This information is documented in the engine International Air Pollution Prevention (EIAPP) certificate. This certificate has been issued since 2000 for all engines that meet the IMO Tier I standard. Ships that do not have these certificates available cannot apply for ESI_{NOx}.

2.3.5 The BSR (Business for Social Responsibility) Index[17]

The BSR index has been developed in order to enable companies who have goods transported by containers at sea to calculate the CO_2 emission related to the transportation of their cargo. These companies know how many containers they have sent on a specific route via a known shipping company, but not necessarily by which ship. The BSR index is intended as an index for the emissions and transport work done by all ships operated by any given company on any given route. The index expresses CO_2 emissions in g/TEU-km. The ship owner calculates the BSR index for his route and sends it to interested customers who calculate the emission related to their activity. Monitoring the performance of individual ships has never been an objective with the BSR index.
The BSR index differs from the IMO index on these points

- The index has been developed for container ships only.
- The index is calculated assuming the ship is fully loaded at all times.
- Fuel consumption used to cool containers is not included in the figure.
- The index is calculated for a group of ships on the same route.

2.3.6 The INTERTANKO (Tanker Ship Organization) index[17]

The INTERTANKO index has been developed in parallel with the IMO index with the same principal objective. Both indexes are defined as CO_2 emitted divided by transport work. The difference between the IMO index and the INTERTANKO index is the definition of transport work. According to the INTERTANKO transport work is defined as,

Transport work = Cargo mass * (distance sailed with cargo + 0*distance sailed in ballast). The distance sailed in ballast included in the calculation of CO_2 emission, so that total emission is taken into consideration in a total voyage.

Distance sailed in ballast is not included in the IMO definition of transport work, hence according to the IMO definition: Transport work = Cargo mass * distance sailed with cargo.

2.3.7 Clean Ship Index (CSI) [18]

This index has been developed by the Clean Shipping Project, Gothenburg, Sweden. It takes into account the major part of environmental effects, such as emission to air and water, use of chemicals, antifouling etc. This is a holistic approach to classify ships, where overall environmental effects are considered.

The index is focused on the vessels' operational impact on the environment and scoring is obtained in five different areas: SO_x, NO_x, Particulate Matters (PM), and CO_2 emissions, Chemicals, Water and waste control.

The scoring system is divided into 5 areas with a maximum total score of 150p, each areas having 30p maximum. This scoring system allows comparing, how good a vessel is performing for any specific criteria. The weighting together of all score gives a hint of the overall performance. Every area has several criteria and points. If the criteria are fulfilled, the ship will get the point.

CSI project recommends to define three levels of environmental performance in the colours of red (low performance), yellow (medium performance), and green (good performance).Detailed scoring system is developed (Table 4).

Table 4: Scoring system of CSI

	Carriers	Vessels
Green	≥90% vessels reported. The carrier verified.	The vessel verified. Total score =50%, and =30% in all five fields, scoring in all subgroups under chemical and waste & water.
	≥40% weighted total score	
Yellow	≥ 20% vessels reported	
	≥ 10% weighted total score	Total score =20%
Red	<20% vessels reported or.	
	<10% weighted total score	

2.3.8 KoFC's Green Ship Program[19]

Korea Finance Corporation, KoFC has announced the green ship finance plan that incentives including a form of lower interest rates on loans will be provided to the ship owners who obtain the vessels designed to reduce emissions. In order to qualify for these financial incentives, the vessels must be built using technologies to reduce air pollutants (e.g. NO_x, SO_x, etc), CO_2, or GHG.

This is available for the Korean ship owners under the government's policy which will provide Korean ship owners for ship financing of a costlier green ship construction than other normal ship at a prime rate.

In order to take the advantage an applicant should first get certification on a green ship. The green ship is a ship equipped with devices helping to reduce of greenhouse gas emissions including NO_x, SO_x, CO_2 and other air pollutants. The green ship should be certified by DNV Korea recognized by the Korean government as a public certification organization before the applicant files the green ship program with KoFC.

2.3.9 Green award[20]

The Green Award procedure is carried out by the Bureau Green Award, the executive body of the independent non-profit Green Award Foundation. The certification procedure consists of an office audit and an audit of each individual ship applying for certification. Amongst many others, the assessment focuses on crew, operational, environmental and managerial elements.

Green Award certifies ships that are extra clean and extra safe. Ships with a Green Award certificate reap various financial and non-financial benefits. By rewarding high safety and environmental standards in shipping, Green Award makes above standard ship operation economically more attractive.

The main steps towards successful certification can be identified as,

- Application
- Document review
- Office audit
- Ship survey
- Verification
- Certification
- Publication

The most recent update of the Green Award requirements covers for example Monitoring of Ship Exhaust Emissions, MARPOL NO_x emission limits. Green Award develops and maintains the requirements in house and the Board of Experts keeps the requirements under review to ensure they keep pace with developments in the industry and regulatory worlds and retain their relevance. An example is the development of a 'blue label', an additional award that won't affect a "normal" Green Award certificate, but will be issued in addition to it to show the extra effort put in by ship owners and managers and to motivate the industry to comply. The Blue Label will be issued to ships when they obtained ranking scores meet particular exhaust emission requirements that go beyond international regulations.

The Green Award Foundation is active all over the world with the certification scheme for dry bulk carriers and oil tankers that go above and beyond the set standards in cleanliness and safety. All efforts are made to benefit the marine environment, including cleaner seas.

Efforts and benefits are also key issues for the ship owners. Admittedly, it is quite an effort to meet the stringent Green Award requirements. But once certified and proven to be more environmentally friendly, the ship owners reap various benefits like,

- Discount on port dues
- Charter preference
- Continuous improvement
- Lower costs
- Lower insurance premiums
- Acceptation by PSC / vetting inspections
- Quality more visible
- Better image
- Motivation and pride of crew
- Less incidents

2.3.10 Class notation by DNV[21]

The Environmental Class Notations **CLEAN** and **CLEAN DESIGN** are voluntary Class Notations, limiting the emissions of harmful pollutants, and limiting the probability and consequences of accidents.
CLEAN: MARPOL compliance with additional requirements.
CLEAN DESIGN: As for **CLEAN**, but with more stringent requirements, and in addition provisions for accident prevention and limitation.

The rules for Environmental Class are under constant development as legislation comes into force and new legislation is proposed. Vessels holding the Class Notation **CLEAN** or **CLEAN DESIGN** are in the forefront of the international legislative regime on environmental issues. This also means that as some requirements in the Rules for **CLEAN** and **CLEAN DESIGN** are becoming mandatory, the Rules must be developed by adopting new legislation not yet ratified.

- Vessels with CLEAN usually carry IMO NO_x-certificates or equivalent for the relevant engines, thereby fulfilling the requirements of the Rules.
- For CLEAN DESIGN the engines must emit about 30% less NO_x than specified by the IMO NOx-curve, and this is difficult to achieve by engine tuning alone without compromising engine efficiency.
- In order to prove that the vessel is operated in accordance with the Rules, operational procedures should make sure only fuel with sulphur content less than the specified maximum limit is ordered.
- The vessels must also be able to prove that they operate with low sulphur fuel in Sulphur Emission Control Areas (SECA) and ports.

2.3.11 RINA's Green Star and Green plus Notation[22]

Italian classification society RINA has further strengthened its commitment to environmentally friendly shipping by launching a new goal-based class notation, **GREEN PLUS**. The voluntary notation will be based on an environmental performance index which covers all aspects of the vessel's impact on the environment, including carbon emissions.

RINA's **GREEN STAR** notation has become a watchword for environmental excellence in shipping, anticipating the requirements of MARPOL and other relevant legislation, and placing owners and operators in an advantageous position. Now, with **GREEN PLUS**, RINA is taking the process one stage further by introducing a new class notation only to be granted to new vessels which make a significant investment in design solutions, on board equipment, and operational procedures which contribute to an improvement in environmental performance beyond the minimum levels required by regulation.

Design solutions and on board equipment include anything which reduces the risk of pollution, or which lowers fuel consumption and air emissions. Innovative engine design, alternative fuels, high-efficiency propellers, optimal hull design and bio-degradable oils all fall into these categories.

Operational procedures covered by a **GREEN PLUS** notation include those which ensure that design solutions and on board equipment are correctly used, voyage planning programmes resulting in reduced fuel consumption and emissions, or training courses designed to increase the environmental awareness of officers and crews.

RINA envisages that it will be possible to transfer existing ships from **GREEN STAR** to **GREEN PLUS** notation, assuming that the requirements relating to on board equipment, operational procedures and solutions can be satisfied.

2.3.12 Class regulations by Class NK[23]

Additional requirement other than MARPOL

- Reduction in NO_x emissions, 80% or below the bench level or the limit.
- The sulphur content of all fuel oils is not to be exceeding 0.1%.

2.3.13 Lloyd's register rules[24]

The rules for Environmental Protection, formulated using environmental risk assessment techniques are regularly updated using service experience and operational feedback to maintain them as the industry benchmark.

The Rules consist of two parts: the core requirements and optional module. The core requirements are,

Attain a level of environmental Performance in excess of international legislative requirements and cover:
- Oxides of nitrogen (NO_x) and sulphur (SO_x) emissions
- Refrigerants and fire-fighting agents
- Oil pollution prevention
- Garbage handling and disposal
- Sewage treatment
- Hull anti-fouling systems
- Ballast water.

Optional modules, with more stringent requirements, cover:

- Hull anti-fouling
- Ballast water management
- Grey water
- NO_x emissions
- Oily bilge water
- Protected oil tanks
- Refrigeration systems
- SO_x emissions
- Vapour emission control systems.

2.3.14 ABS Enviro and Enviro+ notation[25]

The ENVIRO notation identifies the level of compliance with international environmental protection requirements and integrates associated ABS requirements which influence environmental protection. For the ENVIRO+ notation, this Guide invokes compliance with more stringent criteria for environmental protection related to design characteristics, management and support systems, sea discharges, and air discharges.

ENVIRO Notation complies with the applicable requirements of Annexes I, II, IV, V, and VI to the International Convention for the Prevention of Pollution from Ships, MARPOL 73/78, as amended, is a prerequisite for receiving the class notation ENVIRO.

ENVIRO+ Notation complies with applicable requirements of the ENVIRO notation and Annexes I, II, IV, V, and VI to the International Convention for the Prevention of Pollution from Ships, MARPOL 73/78, as amended, is a prerequisite for receiving the class notation ENVIRO+.

2.3.15 ISO Standard[26]

The ISO 14000 family addresses various aspects of environmental management. The very first two standards, ISO 14001:2004 and ISO 14004:2004 deal with environmental management systems (EMS). ISO 14001:2004 provides the requirements for an EMS and ISO 14004:2004 gives general EMS guidelines.

The other standards and guidelines in the family address specific environmental aspects, including: labelling, performance evaluation, life cycle analysis, communication and auditing.

An EMS meeting the requirements of ISO 14001:2004 is a management tool enabling an organization of any size or type to:

- Identify and control the environmental impact of its activities, products or services, and to
- Improve its environmental performance continually, and to
- Implement a systematic approach to setting environmental objectives and targets, to achieving these and to demonstrating that they have been achieved.

ISO 14001:2004 does not specify levels of environmental performance. If it specified levels of environmental performance, they would have to be specific to each business activity and this would require a specific EMS standard for each business. That is not the intention.
ISO has many other standards dealing with specific environmental issues. The intention of ISO 14001:2004 is to provide a framework for a holistic, strategic approach to the organization's environmental policy, plans and actions.

ISO 14001:2004 gives the generic requirements for an environmental management system. The underlying philosophy is that whatever the organization's activity, the requirements of an effective EMS are the same.

This has the effect of establishing a common reference for communicating about environmental management issues between organizations and their customers, regulators, the public and other stakeholders.

Because ISO 14001:2004 does not lay down levels of environmental performance, the standard can be implemented by a wide variety of organizations, whatever their current level of environmental maturity. However, a commitment to compliance with applicable environmental legislation and regulations is required, along with a commitment to continual improvement – for which the EMS provides the framework.

2.3.16 Helsinki Commission[27]

The Helsinki Commission, or HELCOM, works to protect the marine environment of the Baltic Sea from all sources of pollution through intergovernmental co-operation between Denmark, Estonia, the European Community, Finland, Germany, Latvia, Lithuania, Poland, Russia and Sweden.

In pursuing this objective and vision the riparian countries have jointly pooled their efforts in HELCOM, which works as

- An environmental policy maker for the Baltic Sea area by developing common environmental objectives and actions;
- An environmental focal point providing information about the state of/trends in the marine environment, the efficiency of measures to protect it and common initiatives and positions which can form the basis for decision-making in other international fora;
- A body for developing, according to the specific needs of the Baltic Sea, recommendations of its own and recommendations supplementary to measures imposed by other international organizations;
- A supervisory body dedicated to ensuring that HELCOM environmental standards are fully implemented by all parties throughout the Baltic Sea and its catchment area; and
- A coordinating body, ascertaining multilateral response in case of major maritime incidents.

The principle responsibility is to restore the ecosystem of the Baltic Sea area and preserve its ecological balance the Contracting Parties shall individually or jointly take all appropriate legislative, administrative or other measures to prevent and eliminate pollution.

Preventive measures must be taken whenever there are reasonable grounds to believe that substances or energy directly or indirectly introduced into the marine environment might harm human health, living resources or marine ecosystems, or damage amenities or interfere with other legitimate uses of the sea.

Best Environmental Practices and Best Available Technologies will be

- Promoted by the Contracting Parties to prevent the pollution of the Baltic Sea. Additional measures shall be taken if the consequent reductions of inputs do not lead to acceptable results.
- The "polluter pays" principle should serve as the economic basis for the control of environmentally harmful activities, emphasizing the importance of responsibility by forcing polluters to pay for the true costs of their activities.

Emissions from both point sources and diffuse sources into water and the air should be measured and calculated in a scientifically appropriate manner by the Contracting Parties.

Implementing the Helsinki Convention should neither result in trans boundary pollution affecting regions outside the Baltic Sea area, nor involve increases or changes in waste disposal or other activities that could increase health risks. Any measures taken must not lead to unacceptable environmental strains on the atmosphere, soils, water bodies or groundwater.

2.3.17 Emission Control Area (ECA) Regulations[28]

IMO has defined the Emission Control Area, where more stringent rules and regulations are applicable for type of fuels and emission of ships. Two sets of emission and fuel requirements are defined by MARPOL Annex VI: (1) global requirements, and (2) more stringent requirements applicable to ships in Emission Control Areas (ECA). An Emission Control Area can be designated for SO_x and PM, or NO_x, or all three types of emissions from ships, subject to a proposal from a Party to Annex VI.
Existing Emission Control Areas include:

- Baltic Sea (SO_x, adopted: 1997 / entered into force: 2005)
- North Sea (SO_x, 2005/2006)
- North American ECA, including most of US and Canadian coast (NO_x & SO_x, 2010/2012).

NO_x Emission Standards are shown in table 5 and emission limits are set for diesel engines depending on the engine maximum operating speed (n, rpm), as shown in Table 5 and presented graphically in Figure 2. Tier I and Tier II limits are global, while the Tier III standards apply only in NO_x Emission Control Areas.

Table 5: NO_x standards in ECA and other

Tier	Date	NOx Limit, g/kWh		
		N<130	130 =n<2000	n =2000
Tier I	2000	17	45*n^-0.2	9.8
Tier II	2011	14.4	44*n^-0.23	7.7
Tier III	2016†	3.4	9*n^-0.2	1.96

† In NO_x Emission Control Areas (Tier III standards apply outside ECAs)

SO_x Emission Standards is included in the MARPOL Annex VI regulations include caps on sulphur content of fuel oil as a measure to control SO_x emissions and, indirectly, PM emissions (there are no explicit PM emission limits). Special fuel quality provisions exist for SO_x Emission Control Areas (SO_x ECA or SECA). The sulphur limits and implementation dates are listed in Table 2 and illustrated in Figure 2.

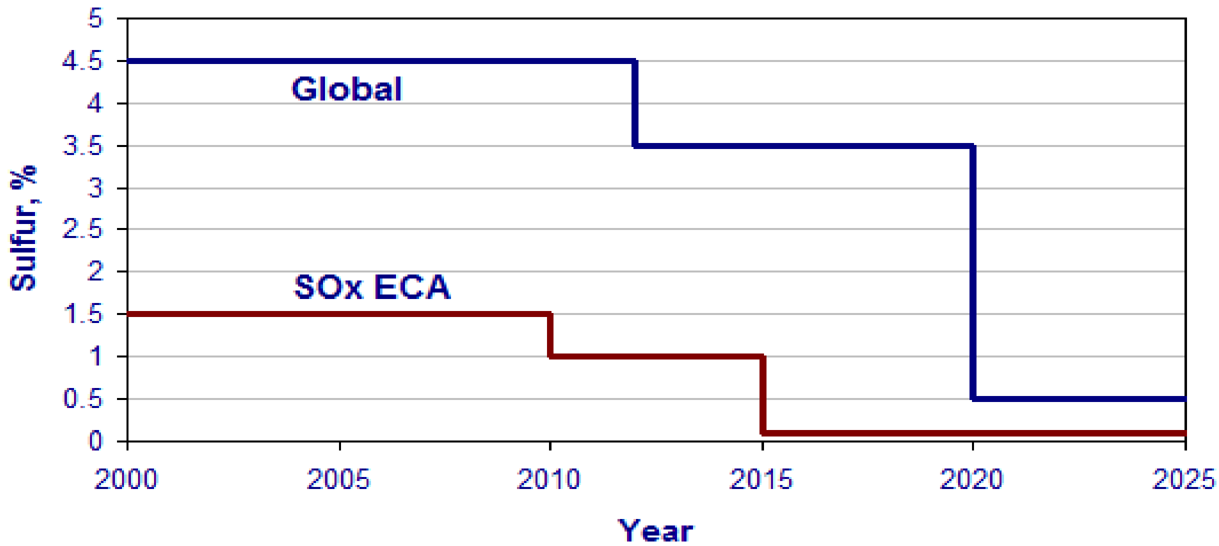

Figure2: IMO Annex VI SO_x emission limits for current and future.

2.3.18 Baltic Region Environmental Efficiency Index (BREEI)[29]

The Baltic Region Environmental Efficiency Index (BREEI) consists of three main groups, namely 'Potable water, Waste water and Garbage', 'Oil, Ballast and Special' and 'Air Emissions and fuel Consumption''.

For every main group, there are various sub groups. These subgroups are graded according to their special properties and the effect on the environment. The grading has their individual meaning, and cannot be compared between groups. BREEI is now at preliminary stage. Before getting ready, more development is needed.

In this index, the ships are divided into four types and graded separately. The four types are, Cargo (including all the ships carrying merchandise and no passenger), Cruise (including all the ships carrying only passengers with voyage time longer or equal to two hours), RoPax (including all the ships carrying both passengers and cargo in a voyage time longer or equal to two hours), Ferry (including all ships carrying passengers and possibly cargo, in voyages shorter than two hours.

The index grading starts from -3 to +5, according to the ship type and the impact on the environment. 'Minus points are awarded to the methods that are most harmful to the environment, whereas plus points are awarded to the methods that are most rational considering the ship operation and overall environmental efficiency'.

By summing up all the points for each subgroup, the score of each main group is obtained, and the total BREEI score is the summation of the main group score.

2.3.19 Right Ship Environmental Rating[30]

In 2011, some 2,400+ users worldwide used Right Ship's Ship Vetting Information System (SVIS©) as a risk assessment tool, as declared by the 'Right Ship', Australia. In February 2011, Right Ship added a new rating service – the environmental rating. The environmental rating has two components: an environmental risk star rating - based on analysis of data including pollution incidents, ISO14001, MARPOL deficiencies and affiliations with Right Ship partners including AUSMEPA, Green Award and class societies' environmental certification/programs, and a GHG emission rating.

The Right Ship GHG emission rating is based on calculation and comparative analysis of the EEDI. Data Sources for Right Ship Rating: EEDI is calculated from the ship data and performance. The data will be verified with the existing data in SVIS©, IHS Fair play (IHS) database, classification societies and owners data. With their existing risk rating, Right Ship will give feedback on any missing/additional/inconsistent information directly through the SVIS© portal or via there communication link.

Assumptions made in this rating are, where ship specific data are not available (e.g. specific fuel consumption), the values used in the Right Ship calculation of EEDI are based on the same assumptions used in the IMO GHG Study and/or detailed in IMO Circulars on calculation of the energy efficiency measure. Our approach also utilises the same data set recognised by IMO MEPC in their establishment of an EEDI "reference line" for new ships.

The categories of ship used for the derivation of comparative GHG ratings follow those in IMO document MEPC 61/WP.10.Greenhouse Gas Emissions Calculation: The EEDI value of a particular ship is calculated according to IMO's defined method and then for that ship, the overall average values for all ships of that type and to other ships of a similar size within this type is compared.

The 'A-G' rating reflects a comparison of vessels of similar size within a type. A-G rating is based on the EEDI (Size) rating as shown in table 6.

Table 6: Right ship EEDI rating

Rating	A	B	C	D	E	F	G
EEDI(Size) Rating	>2.0	>1.0	>0.5	>-0.5	>-1.0	>-2.0	<-2.0

This rating will almost always use different data set for each vessel's relative calculation; the EEDI figure produced will be comparable across all vessels in the database.

Calculating with statistical z-score method, the EEDI of individual ship is compared and reported in the Right ship environmental rating. A z-score is a standard measure of the variation of an individual value from the average and is calculated with the following formula:

Z-score=$\frac{y_i - y}{s}$, where

y_i is the ship ln EEDI value.
y is the average of the ln EEDI values for the type or size group.
s the standard deviation of the ln EEDI value distribution for the type or size group.

For the purpose of the Right Ship GHG rating, the negative z score is used; i.e. the sign, positive or negative, of the calculated z score is reversed. This is done because the z score calculation will give positive numbers for values above the average (i.e. high EEDI) and negative numbers for values below the average (i.e. low EEDI). Because low EEDI values represent better energy efficiency, assigning a positive value to the score is considered to better represent good performance.

The GHG Rating for the EEDI is achieved by the addition of two scores: the z score determined relative to the size class ("(Size) Rating"), added to the z score determined relative to the overall ship type ("(Type) Rating").
GHG Rating = (-z $\text{score}_{\text{Type}}$) + (-z $\text{score}_{\text{Size}}$)

The incorporation of the two components are considered due to the fact that, both the efficiency of the ship relative to other ships of the same type and similar size, and the efficiency within the type overall.

Calculated data is presented in a snapshot summary showing the actual values of the EEDI rating and a graphic indicating performance relative to the standardized average for the ship size and ship type.

2.4. Brief description of IMO indexes

As a mandate given to IMO under the Kyoto Protocol, IMO started working to have an emission control measure to hold the CO_2 increment from shipping industry. It has formed different working group to identify the total volume of CO_2 emission, the growth rate of shipping industry. These studies were important at that time to understand the present impact on the environment and prediction on future impact if IMO does not have any emission control measure.

The following sections will briefly describe the present status and background of several emission control indexes as developed by the IMO.

2.4.1. Background of index establishment

The Kyoto Protocol under the United Nations Framework Convention on Climate Change (UNFCC), it was decided that[31],

- The Parties included in Annex I shall pursue limitation or reduction of emissions of greenhouse gases not controlled by the Montreal Protocol from Aviation and Marine Bunker Fuels, working through the International Civil Aviation Organization (ICAO) and the International Maritime Organization (IMO).
- The Parties included in Annex I shall ensure that their aggregate anthropogenic carbon dioxide equivalent emissions of the greenhouse gases do not exceed their assigned amounts, with a view to reducing their overall emissions of such gases by at least 5% below 1990 levels in the commitment period 2008 to 2012.

Based on the Kyoto protocol, IMO has developed some policies and practices, as described in their resolusion[32]

Establishment of a GHG Emission Baseline

- Development of a Methodology to describe a GHG Emission Index
- Development of Guidelines of GHG Emission Indexing Scheme
- Evaluation of Technical, Operational and Market-Based Solutions
- Development a Work Plan with a Timetable
- Review on the continuing IMO Policies and Practices
- Co-operation with UNFCCC.

2.4.2 Development of Emission Index in IMO

IMO started working on the development of emission control index and during several meetings of MEPC, the progress was discussed and decisions were made. Finally on the 62nd MEPC session, new regulation was adopted which is the first ever global CO_2 emission control index in the industry level. The progress made in the MEPC meetings is described in brief in this section[33].

In July 2005, the MEPC at its 53rd session approved interim guidelines for voluntary ship CO_2 emission indexing for use in trials for the purposes of developing a simple system that could be used voluntarily by ship operators during a trial period.

MEPC is continuing their efforts addressing the phenomena of climate change and global warming and in the light of the mandate given to IMO in the Kyoto Protocol to reduce the greenhouse gas. On its 58th session in October 2008, an energy efficiency design index for new ships and an energy efficiency operational index an efficiency management plan, suitable for all ships and a voluntary code on best practice in energy efficiency ship operations are developed. The MEPC also agreed to discuss a market based measures in future sessions.

On the 59th MEPC meeting in July 2009, it was agreed to spread the following measures and intended to be used for trial purposes until the MEPC's 60th session in March 2010.

- Interim guideline on the method of calculation and voluntary verification of Energy Efficiency Design Index (EEDI), for new ships.
- Guidance on the development of a Ship Energy Efficiency Management Plan (SEEMP), as well as the guidelines for voluntary use of the Ship Energy Efficiency Operational Index (EEOI) for new and existing ships.

An in depth discussion was also made on the market based instrument and agreed a work plan for the development of it during the next sessions.

On March 2010 during the 60th MEPC meeting, the committee has agreed to establish an international work group to work on the EEDI, SEEMP and EEOI. Despite of being capable of preparing the draft text on mandatory requirements for EEDI and SEEMP, the committee understood that, it is required to finalize the issues concerning ship size, capacity, vessel speed reduction rate, target dates to implement in relation to the EEDI requirements.

For the concept of market based measures, the committee agreed to establish an expert group on the subject to undertake a feasibility study.

Further progress made on the 61st session and all three indexes and measures, namely technical (EEDI), operational (EEOI), and market based measures are in an applicable form. But the decision on how to proceed with these measures is still not fixed. However, the committee will take the decision to adopt these measures as mandatory under MARPOL Annex VI by the committee's next session.

The report from the expert group on suitable Market Based Measures (MBM) for international shipping has been submitted which had carried a feasibility study and impact assessment of several possible MBMs submitted by governments and observer organizations.

Under the terms of the amendment procedure set out in the MARPOL Convention, the proposed amendments will now be considered for adoption at the next session of the Organization's Marine Environment Protection Committee (MEPC), which meets in July 2011.

Once adopted, the regulations would represent the first ever mandatory efficiency standard for an international transport sector, paving the way for significant reductions in emissions from shipping into the foreseeable future.

It was the 62nd MEPC session in July 2011, when mandatory measures to reduce emissions of greenhouse gases (GHGs) from international shipping were adopted by Parties to MARPOL Annex VI represented in the MEPC.

The amendments to MARPOL Annex VI Regulations for the prevention of air pollution from ships, add a new chapter 4 to Annex VI on Regulations on energy efficiency for ships to make mandatory the Energy Efficiency Design Index (EEDI), for new ships, and the Ship Energy Efficiency Management Plan (SEEMP) for all ships. Other amendments to Annex VI add new definitions and the requirements for survey and certification, including the format for the International Energy Efficiency Certificate.

The regulations apply to all ships of 400 gross tonnage and above and are expected to enter into force on 1 January 2013.

2.4.3 Brief Description of Energy Efficiency Design Index (EEDI)

As mentioned in the section 1.1 the EEDI can be described[34] as

$$EEDI = \frac{CO2\ Emission}{Transport\ work}$$

$$= \frac{Power * Specific\ fuel\ consumption * CO_2 conversion\ factor}{Capacity * Speed}$$

$$= \frac{Emission\ from\ Main\ Engine + Emission\ from\ Auxiliary\ Engine + Emission\ for\ running\ shaft\ motor - Efficient\ Tech.\ Reduction}{Capacity * Reference\ Speed}$$

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

$$= \frac{kw*\frac{g_{fuel}}{kwh}*\frac{g_{CO2}}{g_{fuel}}}{Tonne*knotical\ mile/h}$$

$$= \frac{g_{CO2}}{Tonne*knotical\ mile}$$

The main EEDI equation contains different constants and coefficients. The definition and meaning of those should be understood clearly before being implemented.

C_F is a non-dimensional conversion factor between fuel consumption measured in g and CO_2 emission also measured in gram based on carbon content. The subscripts *MEi* and *AEi* refer to the main and auxiliary engine(s) respectively. C_F corresponds to the fuel used when determining SFC listed in the applicable EIAPP Certificate. The values of the conversion factors, C_F are given in table 7.

Table 7: C_F values for different types of fuel.

Type of fuel	**Reference**	**Carbon content**	***C_F*** **(t-CO2/t-Fuel)**
Diesel/Gas Oil	ISO 8217 Grades DMX through DMC	0.875	3.206
Light Fuel Oil (LFO)	ISO 8217 Grades RMA through RMD	0.86	3.15104
Heavy Fuel Oil (HFO)	ISO 8217 Grades RME through RMK	0.85	3.1144
Liquefied Petroleum Gas (LPG)	Propane Butane	0.819 0.827	3.0 3.03
Liquefied Natural Gas (LNG)		0.75	2.75

V_{ref} is the ship speed, measured in nautical miles per hour (knot), on deep water in the maximum design load condition (Capacity) (as defined in point number 3) at the shaft power of the engine(s) (as defined in the point number 5) and assuming the weather is calm with no wind and no waves. The maximum design load condition shall be defined by the scantling 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 is defined as

- 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 in accordance with the International Convention of Tonnage Measurement of Ships 1969, Annex I, regulation 3 should be used as Capacity.
- For containerships, the capacity parameter should be established at 70% of the deadweight.

Deadweight means the difference in tonnes between the displacement of a ship in water of relative density of 1.025 kg/m^3 at the deepest operational draught and the lightweight of the ship.

'P' is the power of the main and auxiliary engines, measured in kW. The subscripts ***ME*** and ***AE*** refer to the main and auxiliary engine(s), respectively. The summation on ***i*** is for all engines with the number of engines (***nME***). (See the diagram in the Appendix.)

$P_{ME(i)}$ 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 following figure 3 gives guidance for determination of $P_{ME(i)}$

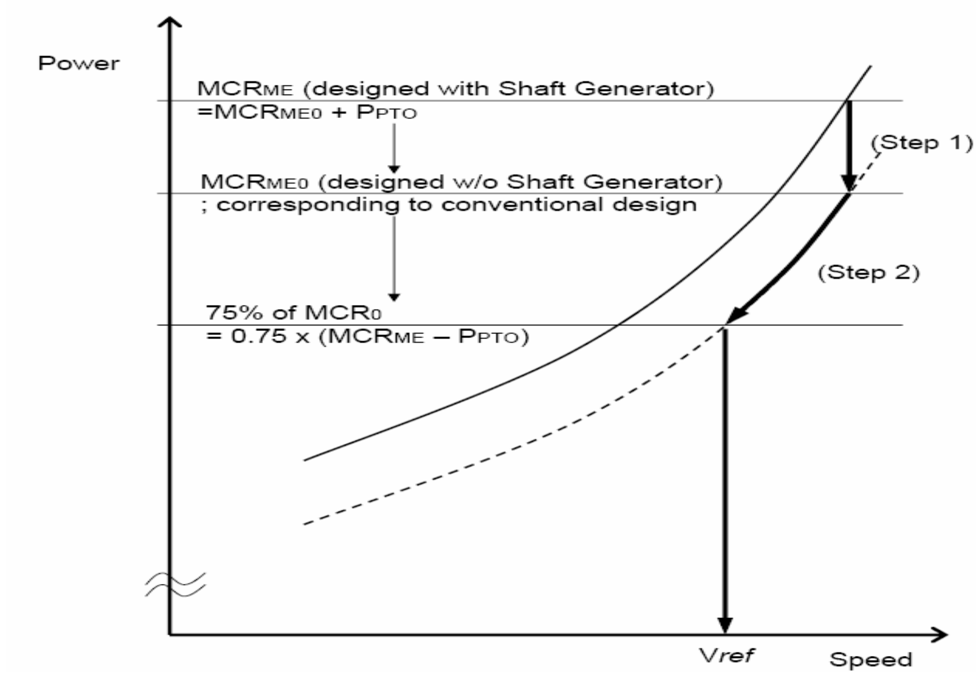

Figure 3: Calculation of P_{ME}, as described in IMO circular 681.

$P_{PTO(i)}$ 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).In case of combined *PTI/PTO*, the normal operational mode at sea will determine which of these to be used in the calculation.

$P_{eff(i)}$ is 75% of the main engine power reduction due to innovative mechanical energy efficient technology. Mechanical recovered waste energy directly coupled to shafts need not be measured.

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

$\boldsymbol{P_{AE}}$ is the required auxiliary engine power to supply normal maximum sea load including necessary power for propulsion machinery/systems and accommodation, e.g., main engine pumps, navigational systems and equipment and living on board, but excluding the power not for propulsion machinery/systems, e.g., thrusters, cargo pumps, cargo gear, ballast pumps, maintaining cargo, e.g., reefers and cargo hold fans, in the condition where the ship engaged in voyage at the speed ($\boldsymbol{V_{ref}}$) under the design loading condition of Capacity.

For cargo ships with a main engine power of 10000 kW or above, P_{AE} is defined as:
$P_{AE(MCRME>10000kW)} = (0.025 * \sum_{i=1}^{nME} MCR_{MEi}) + 250$
For cargo ships with a main engine power below 10000 kW P_{AE} is defined as:
$P_{AE(MCRME<10000kW)} = 0.05 * \sum_{i=1}^{nME} MCR_{MEi}$
For ship types where the P_{AE} value calculated by the above two equations is significantly different from the total power used at normal seagoing, e.g., in cases of passenger ships, the P_{AE} value should be estimated by the consumed electric power (excluding propulsion) in conditions when the ship is engaged in a voyage at reference speed ($\boldsymbol{V_{ref}}$) as given in the electric power table, divided by the weighted average efficiency of the generator(s).

$\boldsymbol{V_{ref}}$, ***Capacity*** and ***P*** should be consistent with each other.

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. For engines certified to the E2 or E3 duty cycles of the NO_x Technical Code 2008, the engine Specific Fuel Consumption ($\boldsymbol{SFC_{ME(i)}}$) is that recorded on the EIAPP Certificate(s) at the engine(s) 75% of MCR power or torque rating. For engines certified to the D2 or C1 duty cycles of the NO_x Technical Code 2008, the engine Specific Fuel Consumption ($\boldsymbol{SFC_{AE(i)}}$) is that recorded on the EIAPP Certificate(s) at the engine(s) 50% of MCR power or torque rating.

For ships where the $\boldsymbol{P_{AE}}$ value calculated by 2.5.6.1 and 2.5.6.2 is significantly different from the total power used at normal seagoing, e.g., conventional passenger ships, the Specific Fuel Consumption ($\boldsymbol{SFC_{AE}}$) of the auxiliary generators is that recorded in the EIAPP Certificate(s) for the engine(s) at 75% of $\boldsymbol{P_{AE}}$ MCR power of its torque rating. SFC_{AE} is the weighted average among $\boldsymbol{SFC_{AE(i)}}$ of the respective engines ***i***.

For those engines which do not have an EIAPP Certificate because its power is below 130 kW, the ***SFC*** specified by the manufacturer and endorsed by a competent authority should be used.

fj is a correction factor to account for ship specific design elements. For ice-classed ships are determined by the standard ***fj*** in Table 8.For other ship types, ***fj*** should be taken as1.0.

Table8. Correction factor for power ***f j*** for ice-classed ships

Ship type	fj	Limits depending on the ice class			
		IC	IB	IA	IA Super
Tanker	$\frac{0.516L_{PP}^{1.87}}{\sum_{i=1}^{nME} P_{iME}}$	{max 1.0 min $0.72L_{PP}^{0.06}$}	{max 1.0 min $0.61L_{PP}^{0.08}$}	{max 1.0 min $0.5L_{PP}^{0.1}$}	{max 1.0 min $0.4L_{PP}^{0.12}$}
Dry cargo carrier	$\frac{2.15L_{PP}^{1.58}}{\sum_{i=1}^{nME} P_{iME}}$	{max 1.0 min $0.89L_{PP}^{0.02}$}	{max 1.0 min $0.78L_{PP}^{0.04}$}	{max 1.0 min $0.68L_{PP}^{0.06}$}	{max 1.0 min $0.58L_{PP}^{0.08}$}
General cargo ship	$\frac{0.045L_{PP}^{2.37}}{\sum_{i=1}^{nME} P_{iME}}$	{max 1.0 min $0.85L_{PP}^{0.03}$}	{max 1.0 min $0.7L_{PP}^{0.06}$}	{max 1.0 min $0.54L_{PP}^{0.1}$}	{max 1.0 min $0.39L_{PP}^{0.15}$}

fw 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), and should be determined as follows:

It can be determined by conducting the ship-specific simulation of its performance at representative sea conditions. The simulation methodology should be prescribed in the guidelines developed by the organization and the method and outcome for an individual ship shall be verified by the administration or an organization recognized by the administration.

In case that the simulation is not conducted, f_w should be taken from the "Standard f_W"table/curve. A "Standard f_W"table/curve, which is to be contained in the guidelines, is given by ship type (the same ship as the "baseline" below), and expressed in a function of the parameter of Capacity (e.g., DWT). The "Standard f_W"table/curve is to be determined by conservative approach, i.e. based on data of actual speed reduction of as many existing ships as possible under representative sea conditions.

f_w should be taken as one (1.0) until the guidelines for the ship-specific simulation or f_W table/curve becomes available.

$f_{eff(i)}$ is the availability factor of each innovative energy efficiency technology. ***$f_{eff(i)}$*** for waste energy recovery system should be 1.

fi 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.

fi for ice-classed ships are determined by the standard f_i in Table 9. For other ship types, ***fi*** should be taken as 1.0.

Table9. Capacity correction factor *fi* for ice-classed ships

Ship type	*fi*	Limits depending on the ice class			
		IC	IB	IA	IA Super
Tanker	$\frac{0.00115L_{PP}^{3.36}}{capacity}$	max 1.31 $L_{PP}^{-0.05}$ min 1.0	max 1.54 $L_{PP}^{-0.07}$ min 1.0	max 1.8 $L_{PP}^{-0.09}$ min 1.0	max 2.1$L_{PP}^{-0.11}$ min 1.0
Dry cargo carrier	$\frac{0.000665L_{PP}^{3.44}}{capacity}$	max 1.31 $L_{PP}^{-0.05}$ min 1.0	max 1.54 $L_{PP}^{-0.07}$ min 1.0	max 1.8 $L_{PP}^{-0.09}$ min 1.0	max 2.1$L_{PP}^{-0.11}$ min 1.0
General cargo ship	$\frac{0.000676L_{PP}^{3.44}}{capacity}$	1.0	max 1.08 min 1.0	max 1.12 min 1.0	max 1.25 min 1.0
Container ship	$\frac{0.1749L_{PP}^{2.29}}{capacity}$	1.0	max 1.25 $L_{PP}^{-0.04}$ min 1.0	max 1.6 $L_{PP}^{-0.08}$ min 1.0	max 2.1$L_{PP}^{-0.12}$ min 1.0
Gas tanker	$\frac{0.1749L_{PP}^{2.33}}{capacity}$	max 1.31 $L_{PP}^{-0.04}$ min 1.0	max 1.6 $L_{PP}^{-0.08}$ min 1.0	max 2.1 $L_{PP}^{-0.12}$ min 1.0	1.0

Length between perpendiculars, L_{pp} means 96 % of the total length on a waterline at 85 % of the least moulded depth measured from the top of the keel, or the length from the foreside of the stem to the axis of the rudder stock on that waterline, if that were greater. In ships designed with a rake of keel the waterline on which this length is measured shall be parallel to the designed waterline. The length between perpendiculars (L_{pp}) shall be measured in meters.

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:
Reference line value = a $\times b^{-c}$
Where a, b and c are the parameters given in Table 10.

.

Table10. Parameters for determination of reference values for the different ship types

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 is based on the vessel database of Lloyd's Register Fair play, built in last 10 years and the basic concept of regression formula was proposed by Denmark.

Figure 4 gives a sample reference line for a bulk carrier.

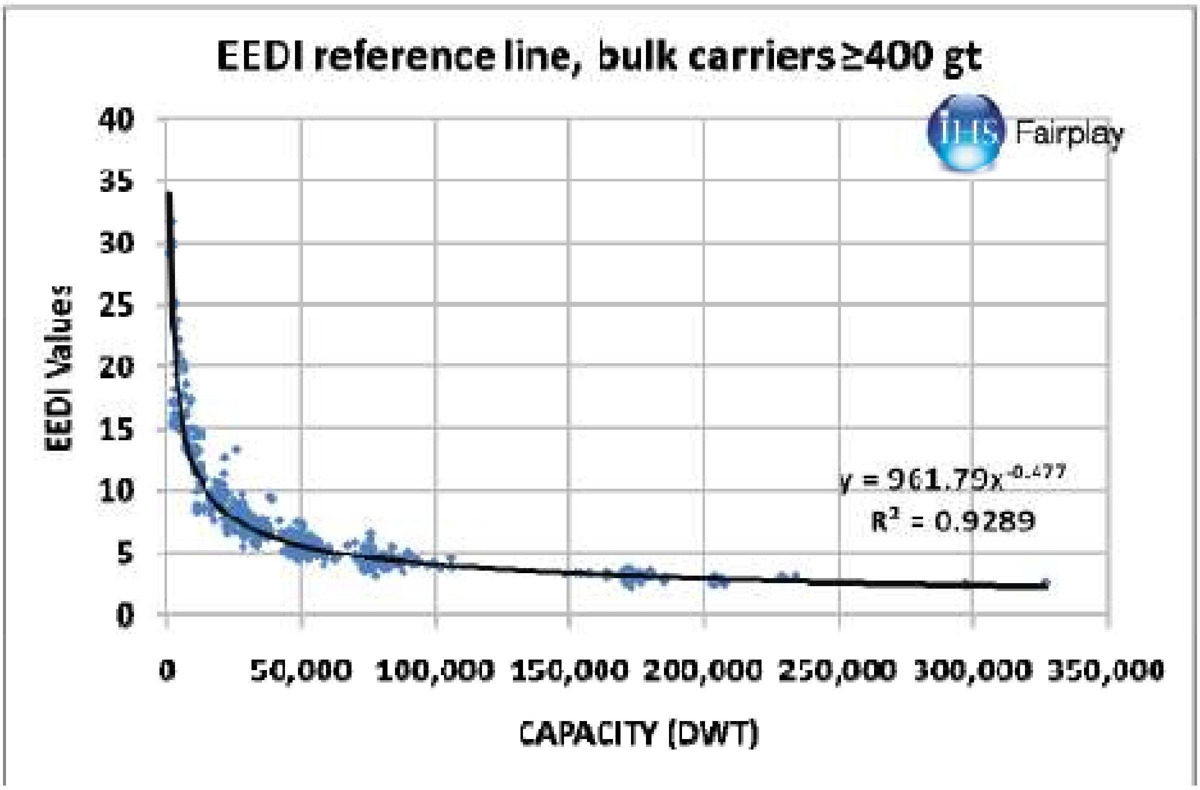

Figure 4: Reference line sample for bulk carrier, from MEPC 62/6/4 document.

The present EEDI rules will be more stringent in different phases. The phases and stringency level is described in table 11.

Table 11 Reduction factors (in percentage) for the EEDI relative to the EEDI Reference line

Ship Type	Size	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	20,000 DWT and above	0	10	20	30
	10,000 – 20,000 DWT	n/a	0-10*	0-20*	0-30*
Gas tanker	10,000 DWT and above	0	10	20	30
	2,000 – 10,000 DWT	n/a	0-10*	0-20*	0-30*
Tanker	20,000 DWT and above	0	10	20	30
	4,000 – 20,000 DWT	n/a	0-10*	0-20*	0-30*
Container ship	15,000 DWT and above	0	10	20	30
	10,000 – 15,000 DWT	n/a	0-10*	0-20*	0-30*
General Cargo ships	15,000 DWT and above	0	10	15	30
	3,000 – 15,000 DWT	n/a	0-10*	0-15*	0-30*
Refrigerated cargo carrier	5,000 DWT and above	0	10	15	30
	3,000 – 5,000 DWT	n/a	0-10*	0-15*	0-30*
Combination carrier	20,000 DWT and above	0	10	20	30
	4,000 – 20,000 DWT	n/a	0-10*	0-20*	0-30*

*Reduction factor to 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.
n/a means that no required EEDI applies.

2.4.4. Ship Energy Efficiency Management Plan (SEEMP)[35]

For the operational measure of efficiency, SEEMP has been developed for the shipping industry, so that they can operate their vessel in the most energy efficient way. The EEOI is considered to be the governing criteria of SEEMP. SEEMP can be considered as an approach of 'monitoring ship and fleet efficiency performance over time using EEOI as a monitoring tool and serves as a benchmark tool'. The basic expression for EEOI for a voyage is defined as,

$$\text{EEOI} = \frac{\sum_j (FC_j * C_{Fj})}{m_{cargo} * \text{D}}$$

Where average of the indicator for a period or for a number of voyages is obtained, the indicator is calculated as:

$$\text{Avg. EEOI} = \frac{\sum_i \sum_j (FC_{ij} * C_{Fj})}{\sum_i (m_{cargo,i} * D_i)}$$

j is the fuel type.
i is the voyage number;
F_{Cij} is the mass of consumed fuel j at voyage i;
C_{Fj} is the fuel mass to CO_2 mass conversion factor for fuel j;
m_{cargo} is cargo carried (tonnes) or work done (number of TEU or passengers) or gross tonnes for passenger ships; and
D is the distance in nautical miles corresponding to the cargo carried or work done.

2.4.5 Guidance on Best Practices for Fuel Efficient Operation of Ships

As described in the MEPC circular number 683[35], for best practice of a ship to be fuel efficient in her operation, the following tasks should be maintained.

- Improved voyage planning.
- The optimum route and improved efficiency can be achieved through the careful planning and execution of voyages. Thorough voyage planning needs time, but a number of different software tools are available for planning purposes
- Weather routing.
- Good early communication with the next port should be an aim in order to give maximum notice of berth availability and facilitate the use of optimum speed where port operational procedures support this approach.
- Optimized port operation could involve a change in procedures involving different handling arrangements in ports. Port authorities should be encouraged to maximize efficiency and minimize delay.
- Speed optimization can produce significant savings. However, optimum speed means the speed at which the fuel used per tonne mile is at a minimum level for that voyage. It does not mean minimum speed; in fact sailing at less than optimum speed will consume more fuel rather than less. Reference should be made to the engine manufacturer's power/consumption curve and the ship's propeller curve. Possible adverse consequences of slow speed operation may include increased vibration and shooting and these should be taken into account.
- Most ships are designed to carry a designated amount of cargo at a certain speed for certain fuel consumption. This implies the specification of set trim conditions. Loaded or unloaded, trim has a significant influence on the resistance of the ship through the water and optimizing trim can deliver significant fuel savings. For any given draft there is a trim condition that gives minimum resistance. In some ships, it is possible to assess optimum trim conditions for fuel efficiency continuously throughout the voyage. Design or safety factors may preclude full use of trim optimization.
- Ballast should be adjusted taking into consideration the requirements to meet optimum trim and steering conditions and optimum ballast conditions achieved through good cargo planning. Selection of the propeller is normally determined at the design and construction

stage of a ship's life but new developments in propeller design have made it possible for retrofitting of later designs to deliver greater fuel economy. Whilst it is certainly for consideration, the propeller is but one part of the propulsion train and a change of propeller in isolation may have no effect on efficiency and may even increase fuel consumption.

- Docking intervals should be integrated with ship operator's ongoing assessment of ship performance. Hull resistance can be optimized by new technology-coating systems, possibly in combination with cleaning intervals. Regular in-water inspection of the condition of the hull is recommended.
- Propeller cleaning and polishing or even appropriate coating may significantly increase fuel efficiency. The need for ships to maintain efficiency through in-water hull cleaning should be recognized and facilitated by port states.
- Marine diesel engines have a very high thermal efficiency (~50%). This excellent performance is only exceeded by fuel cell technology with an average thermal efficiency of 60%.
- Maintenance in accordance with manufacturers' instructions in the company's planned maintenance schedule will also maintain efficiency. The use of engine condition monitoring can be a useful tool to maintain high efficiency.
- Additional means to improve engine efficiency might include: Use of fuel additives; adjustment of cylinder lubrication oil consumption, valve improvements, torque analysis, and automated engine monitoring systems.
- Waste heat recovery is now a commercially available technology for some ships. It uses thermal heat losses from the exhaust gas for either electricity generation or additional propulsion with a shaft motor.

3. Impact on ship design and hydrodynamics of ship upon implementing the Energy Efficiency Design Index (EEDI)

It is very important to understand and know the impact of EEDI upon the design of ship and hydrodynamics. A designer must have clear conception about the individual and holistic impact of different ship design parameters and coefficient on EEDI and vice versa. Another aspect of this analysis is to investigate whether the present EEDI formulation contradicts the hydrodynamic rules or not.

This chapter will describe the methodology of the investigation, assumptions made and the calculated results.

3.1. Analysis Method

On the 62nd Marine Environment Protection Committee (MEPC) meeting, the EEDI has been adopted as mandatory for all new ships, coming into force from the January, 2013. It is very interesting to investigate the impact on ship design parameters if we consider EEDI.

For this purpose, a parametric analysis is made for Tanker vessels, Bulk carriers, Container vessels and Ro-Pax vessel. For these four types of vessels, ship speed, the water line length

(L_{wl}), Beam (B), Draft (T), L/B ratio, B/T ratio, Prismatic Coefficient (Cp) is varied to see the effect on EEDI.

In order to carry on this analysis an excel calculation sheet was made which calculates the effective power of the ship by the Holtrop-Mennen[6,7] method and EEDI (attained and reference) with current IMO adopted formulation.

The effective power with Holtrop-Mennen method was tested for existing vessel's model test data and the average error was found as 2%, while the maximum was 4%. At this stage, this error was considered acceptable.

To investigate the hydrodynamic impact, Effective power (Pe)/Displacement was plotted against each parameter. The idea is to observe, whether this curve follows the attained EEDI curve or not. As it is described in Section 2.4.3, EEDI is proportional to the power (kW)/dead weight (tonne) for constant specific fuel oil consumption (SFC), conversion factor between fuel consumption (C_F) and speed, $EEDI_{attained}$ curve should have the same trend line as the effective power (Pe)/Displacement has.

It should be noted that the change of EEDI has to be calculated by considering the dependency of all parameters together to have the actual change in EEDI. As the ship design parameters and coefficients are interlinked to one another it is important to investigate the total impact. For instance, increasing the length of the ship gives better results of EEDI. But that does not always mean that increasing the length will give better result as, this change will affect the L/B ratio, Beam, B/T ratio, draft and eventually hydrodynamic coefficients and hydrodynamics of ship. So, the best design parameters will be a combination of each individual parametric effect on EEDI.

3.2 Holtrop and Mennen method and the limitations

This is a very well-known approximate resistance and power prediction method for displacement and semi displacement vessels. However, not all types of ships are covered by this method. The approximate formulations are based on hydrodynamic theory with coefficients obtained from the regression analysis of the results of 334 ship model tests. This method works well for tankers, general cargo vessels, bulk carrier, container ship; fishing vessels tug boats and frigates with a certain boundary of prismatic coefficient, L/B and B/T. The limitations are shown in table 12. In order to have the most accurate results for the power prediction by this method; these limitations were maintained in the analysis process.

Table12: Limitation for Holtrop and Mennen's method.

Ship type	Max Froude no.	Cp		L/B		B/T	
		Min	Max	Min	Max	Min	max
Tankers, bulk carriers	0.24	0.73	0.85	5.1	7.1	2.4	3.2
Trawlers, tugs	0.38	0.55	0.65	3.9	6.3	2.1	3.0
Container ships, destroyers	0.45	0.55	0.67	6.0	9.5	3.0	4.0
Cargo liners	0.3	0.56	0.75	5.3	8.0	2.4	4.0
RoRo Ships, Car ferries	0.35	0.55	0.67	5.3	8.0	3.2	4.0

3.3 Analysis of EEDI for different types of vessel.

As the method described in Section 3.1, three types of vessels are analysed to investigate the impacts of EEDI on ship design parameters and coefficients. Bulk carrier, Container vessel and Oil tanker vessels are investigated as these three types are the most commercially used and transport the most cargos in sea.

3.3.1 Change of EEDI upon changing different individual ship parameters for Bulk Carriers, Container vessel and Oil Tanker

The following figures are developed from the calculations of EEDI for the change of various particulars of a bulk carrier, container and oil tanker. The target is to show the effect of different ship design particulars and coefficients on EEDI. For bulk carrier and oil tanker, all the design parameters were investigated at 12 and 18 knots and for container vessel 12 and 24 knots. The intention is to investigate the impact at low and high Froude number.

3.3.2 Assumptions made in the analysis

It is customary to say that, during the initial design of a vessel designer has to make some assumption to move into the next step. And, if the investigation is based on parametric analysis, where all the ship design parameters are varied against each other, proper assumptions are important. Following assumptions were made during the investigation,

- For bulk carrier, dead weight/Displacement = 0.85, Shaft Power required = Effective Power/0.75
- For container vessel, dead weight/Displacement = 0.75, Shaft Power required = Effective Power/0.75
- For tanker, dead weight/Displacement = 0.85, Shaft Power required = Effective Power/0.75

3.3.3 Change in Vessel speed (V)

Particulars considered for the analysis are as shown in the following table:

Ship type	V (knots)	Length (m)	Froude No.	Beam (m)	Draft (T)	L/B	B/T	Cp	Cb
Bulk Carrier	8-18	200	0.09-0.21	39.2	16.3	5.1	2.4	0.73	0.72
Container Vessel	10-39	200	0.11-0.45	33.3	11.1	6	3	0.6	0.57
Tanker	10-22	200	0.11-0.25	39.2	16.3	5.1	2.4	0.83	0.82

From the figure 5, 6, and 7 it can be said that

- The difference between $EEDI_{ref}$ and $EEDI_{attained}$ decreases with the increase of speed. It cuts the zero line after 14 knots for bulk carrier, 21 knots for the container vessel and 14 knots for tanker, indicating the maximum attainable speed.
- Effect of speed on $EEDI_{attained}$ is comparatively smaller at slow speed. After 30 knots for container vessel and 20 knots for tankers, it increases very rapidly.
- $EEDI_{attained}$ and Effective Power (Pe)/Displacement line has similar trend.
- It can be decided easily that low speed gives the better performance in terms of EEDI.

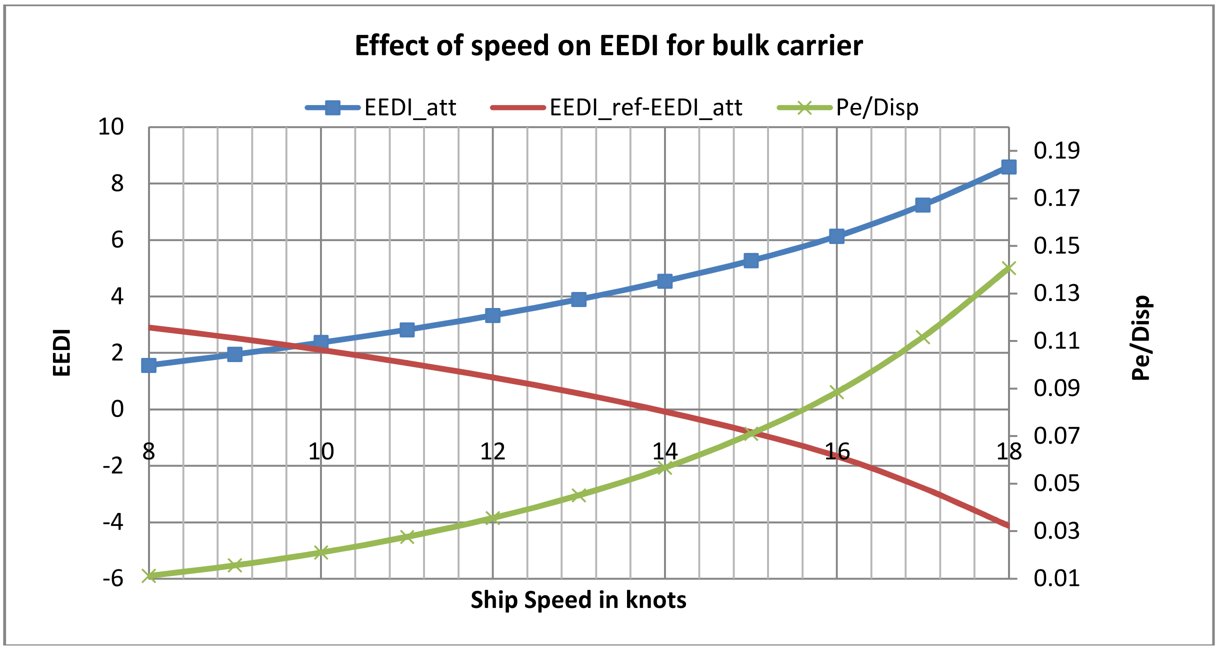

Figure 5: EEDI of bulk carrier at different Speed.

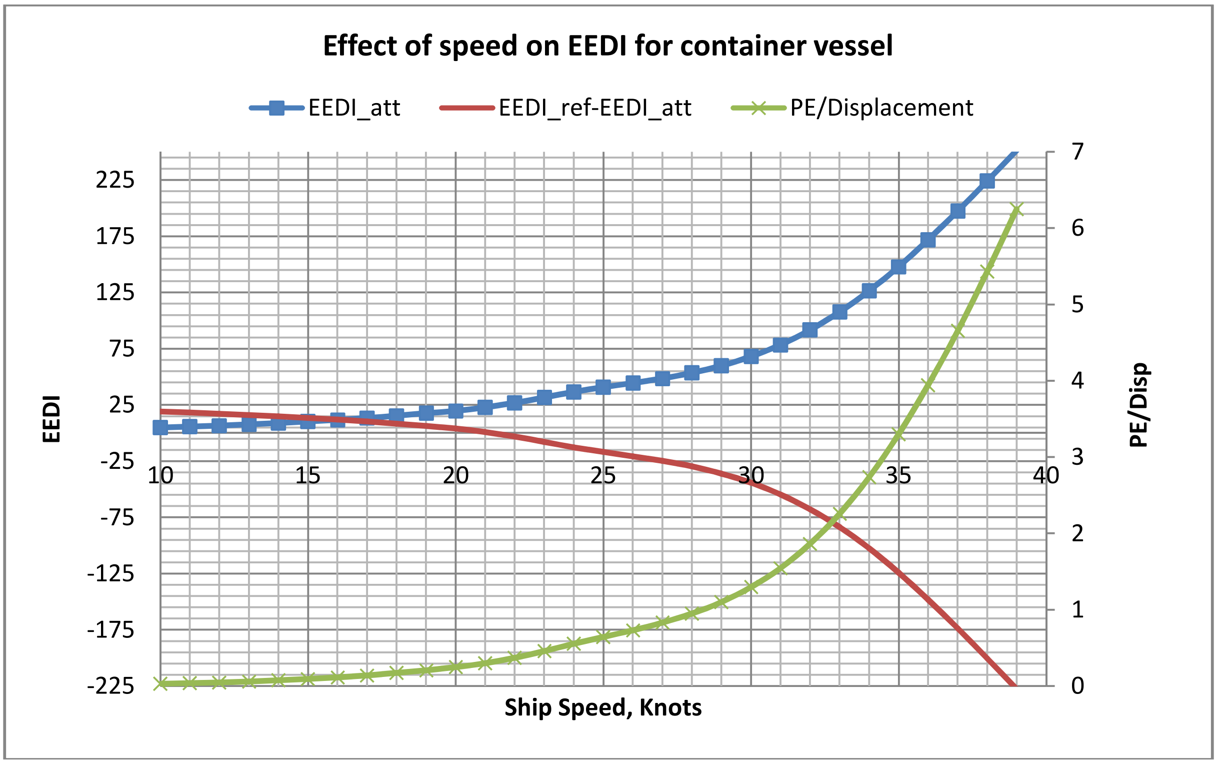

Figure 6: EEDI of Container vessel at different Speed.

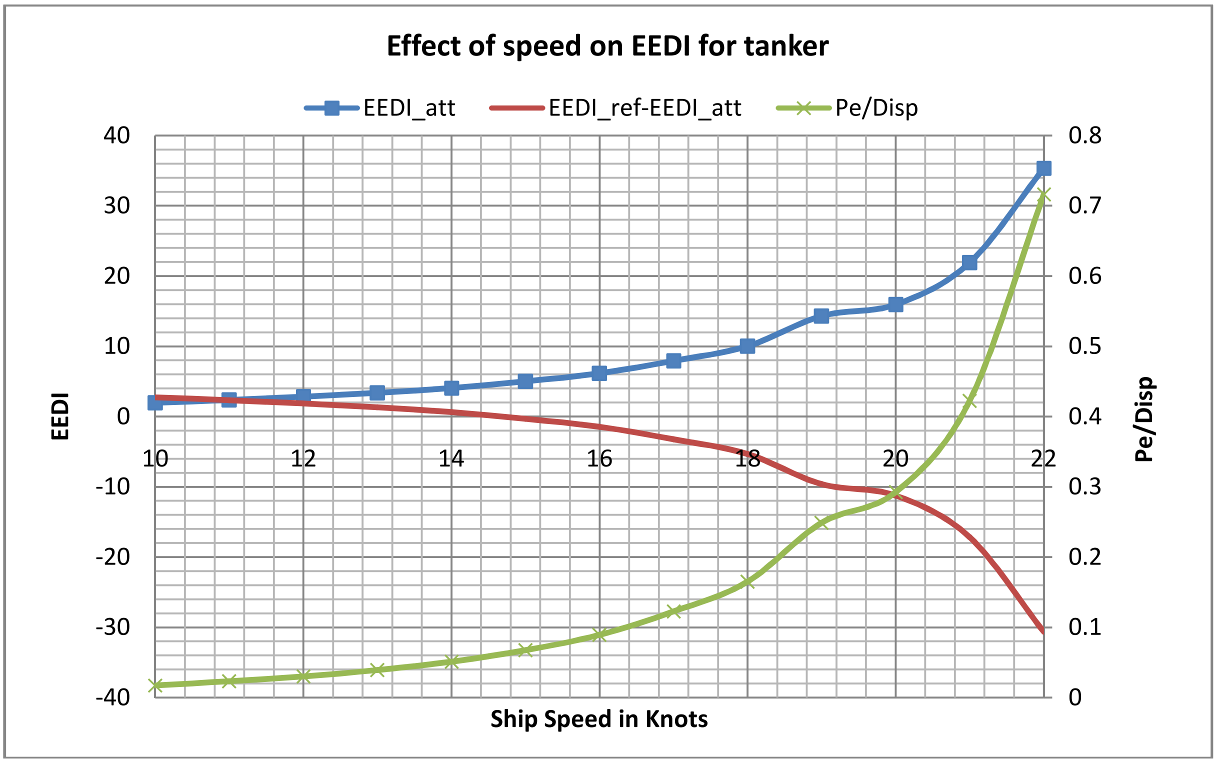

Figure 7: EEDI of a Tanker at different Speed

3.3.4 Change in Waterline Length of the ship (Lwl)

Particulars considered for the analysis are as shown in the following table:

Ship type	V (knots)	Length (m)	Froude No.	Beam (m)	Draft (T)	L/B	B/T	Cp	Cb
Bulk Carrier	12 & 18	100-390	0.1-0.2 & 0.15-0.29	19.6-76.5	8.17-31.9	5.1	2.4	0.73	0.72
Container Vessel	12 & 24	100-250	0.13-0.2 & 0.25-0.39	16.7-41.7	5.56-13.9	6	3	0.6	0.57
Tanker	12 & 18	150-270	0.12-0.16 & 0.18-0.24	29.4-52.9	11.42-20.55	5.1	2.57	0.83	0.82

From figure 8-13 it is obvious that

- The difference between $EEDI_{ref}$ and $EEDI_{attained}$ decreases with the increase of length at 12 knot speed, but increases with the increase of length at higher speeds. The reason behind it is the wave resistance that increases at high speed. So at higher speed, longer vessels are performing well.
- The effect of length on EEDI for small vessels (100-150 meters) is higher than large ones for bulk carriers and container vessel.
- $EEDI_{attained}$ and Effective Power (Pe)/Displacement line has similar trend.
- It can be decided easily that, at low speed it is better to have small vessels and vice versa.

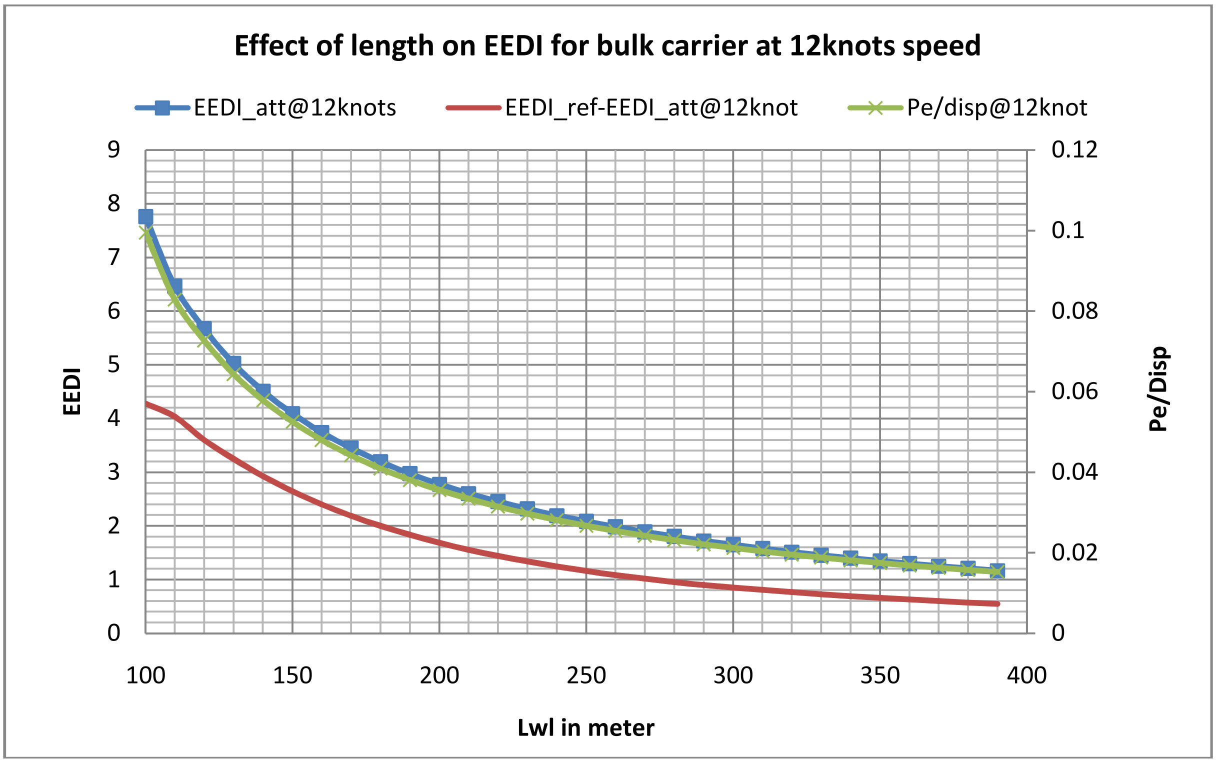

Figure 8: EEDI of bulk carrier at different ship length at 12knot Speed.

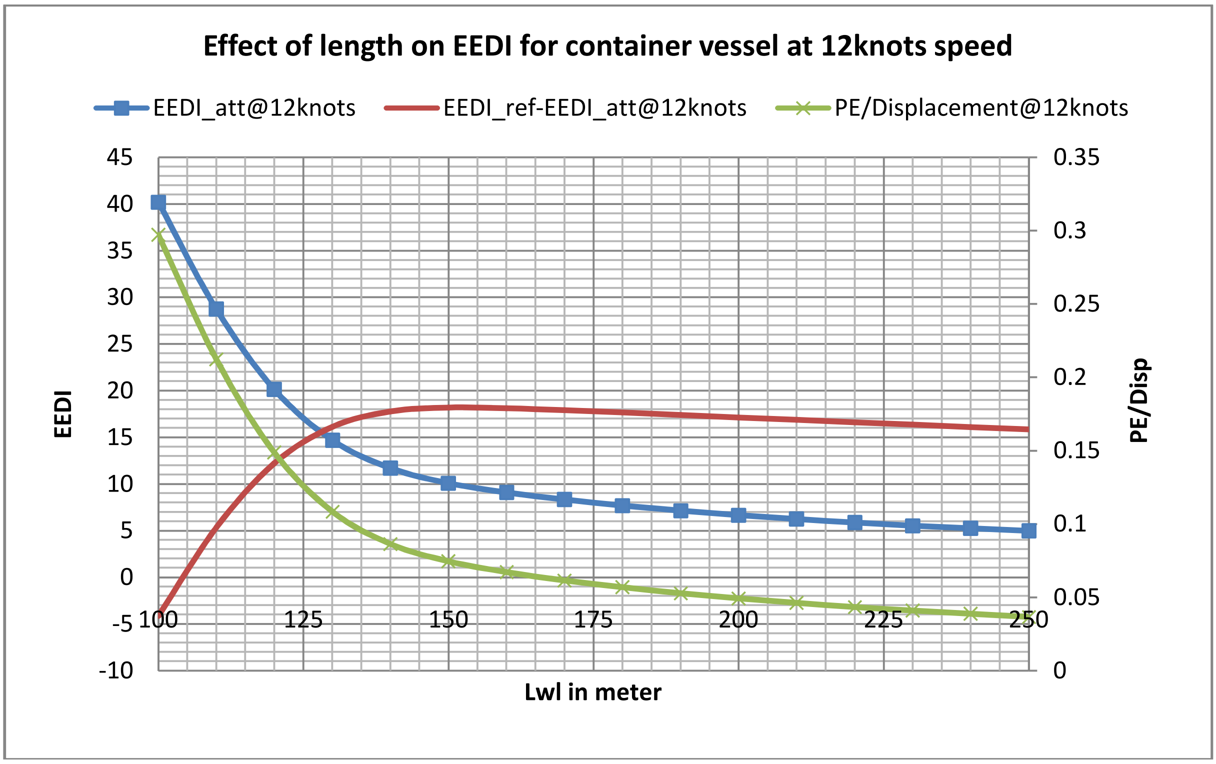

Figure 9: EEDI of container vessel at different ship length at 12knot Speed.

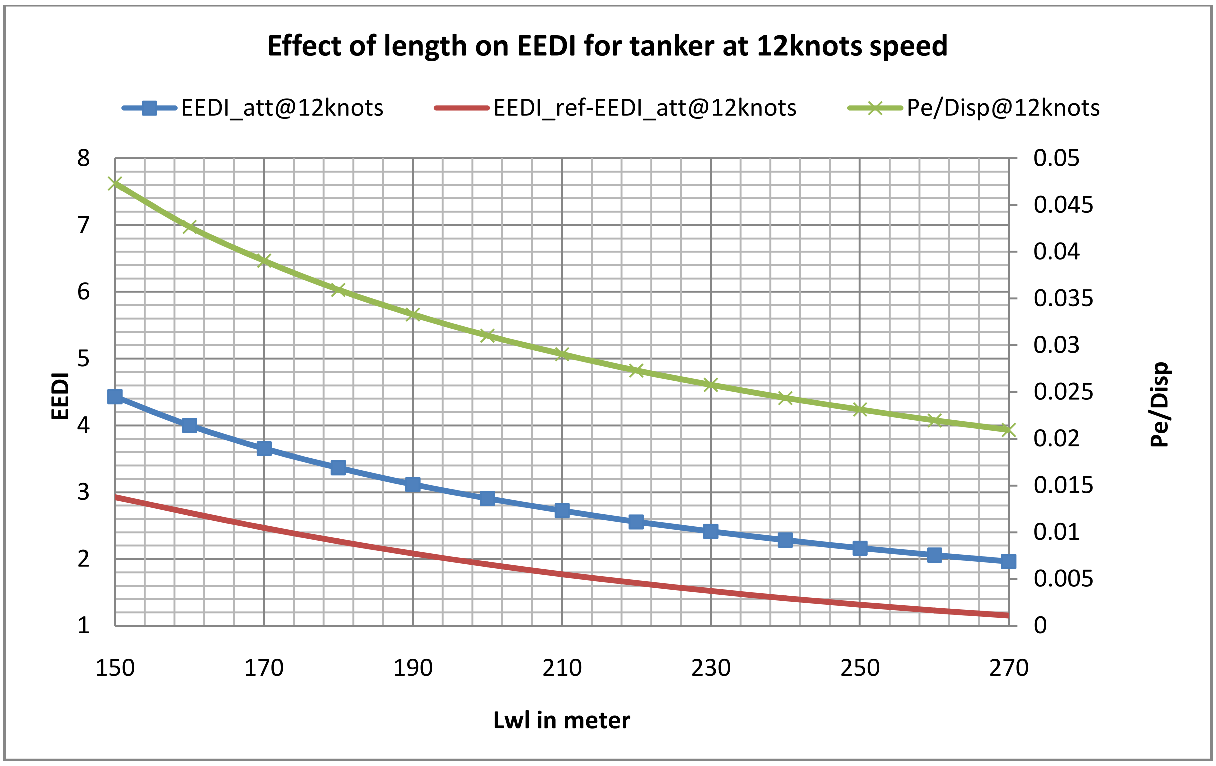

Figure 10: EEDI of Tanker at different ship length at 12knot Speed.

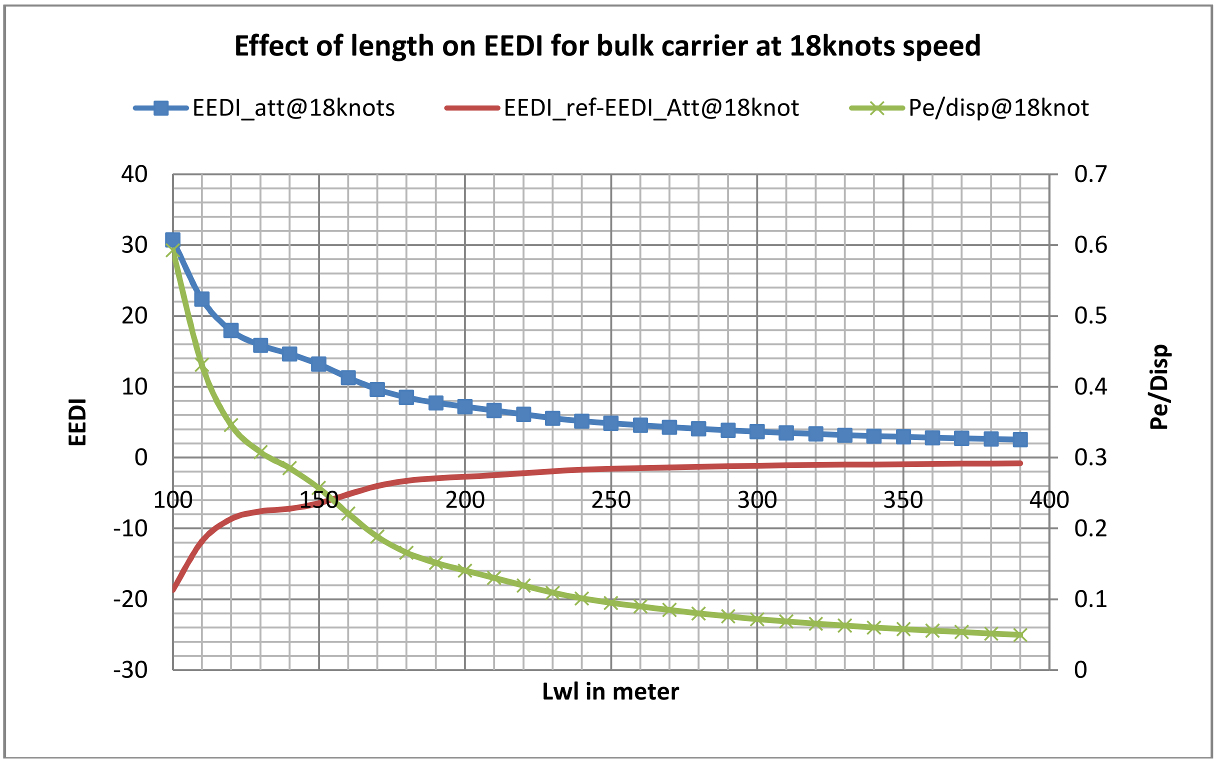

Figure 11: EEDI of bulk carrier at different ship length at 18knot Speed.

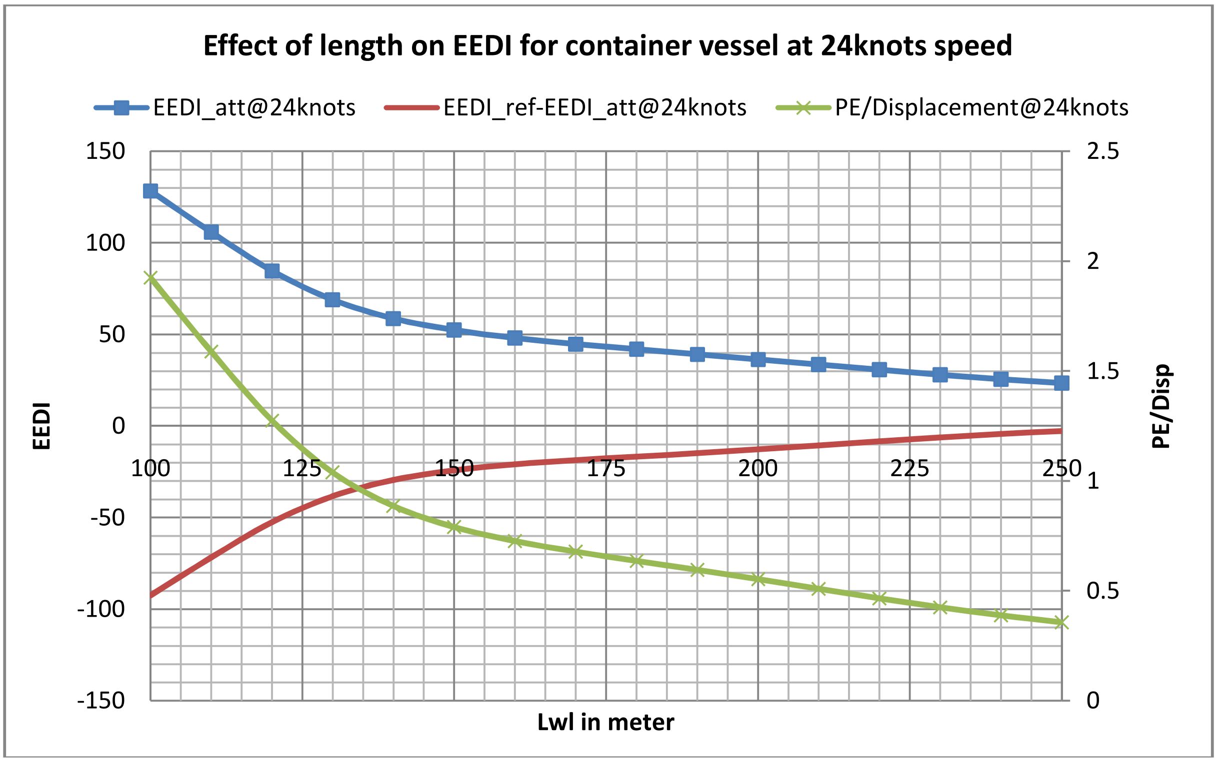

Figure 12: EEDI of container vessel at different ship length at 24knot Speed.

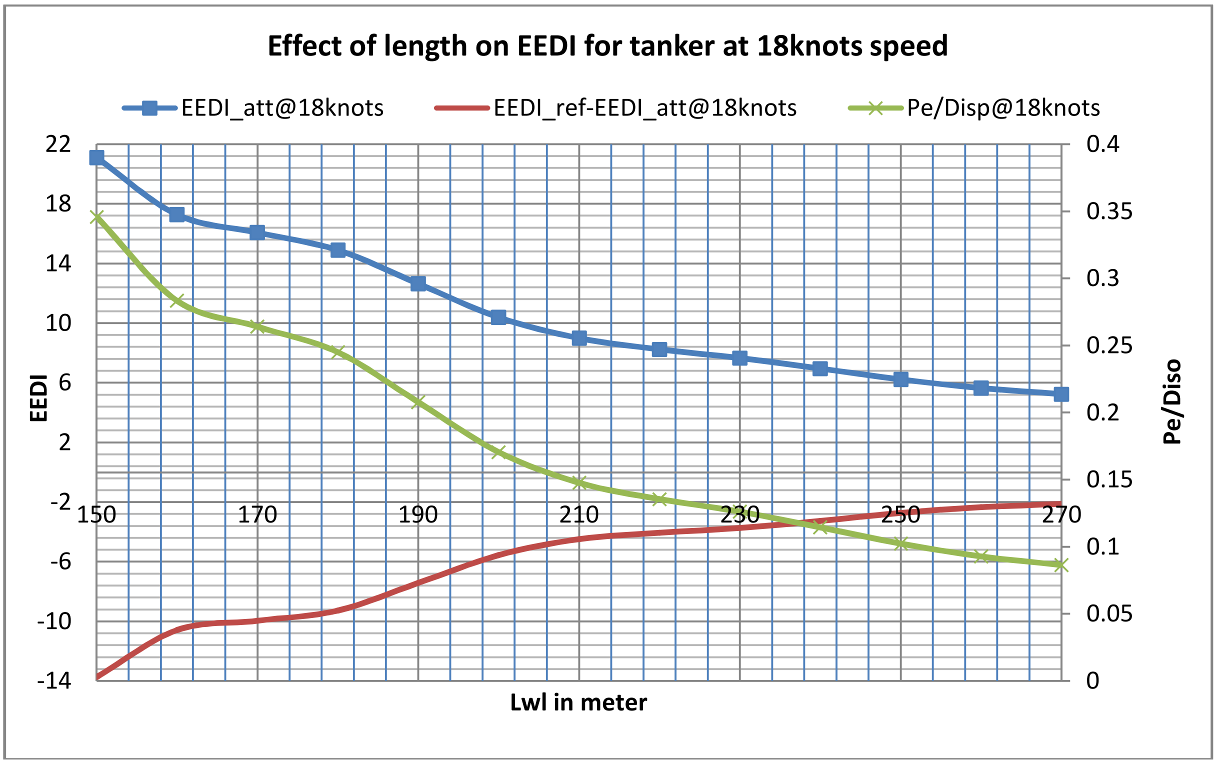

Figure 13: EEDI of Tanker at different ship length at 18 knot Speed.

3.3.5 Change in Beam of Ship (B)

Particulars considered for the analysis are as shown in the following table:

Ship type	V (knots)	Length (m)	Froude No.	Beam (m)	Draft (T)	L/B	B/T	Cp	Cb
Bulk Carrier	12 & 18	200	0.14 & 0.21	28.1-39.2	11.7-16.3	5.1-7.1	2.4	0.73	0.72
Container Vessel	12 & 24	200	0.14 & 0.28	22.2-33.3	7.41-11.1	6-9	3	0.6	0.57
Tanker	12 & 18	200	0.14 & 0.21	28-39.2	10.87-15.22	5.1-7.1	2.57	0.83	0.82

From the figure 14-19, it can be decided that

- The difference between $EEDI_{ref}$ and $EEDI_{attained}$ decreases with the increase of breadth at 12 knot speed, but increases with the increase breadth at higher speed (18 and 24 knots).
- $EEDI_{attained}$ and Effective Power (Pe)/Displacement line has similar trend.
- It can be decided easily that, low speed it is better to have small breadth and vice versa.

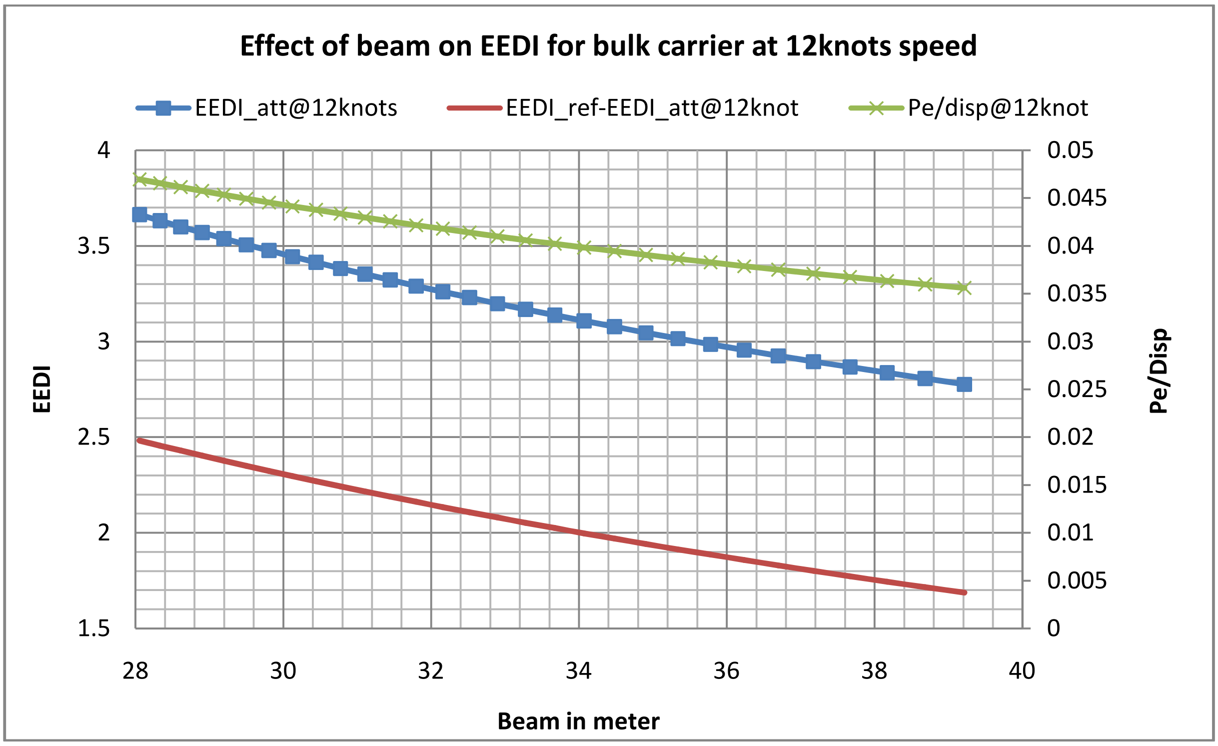

Figure 14: EEDI of bulk carrier at different ship breadth at 12knot Speed.

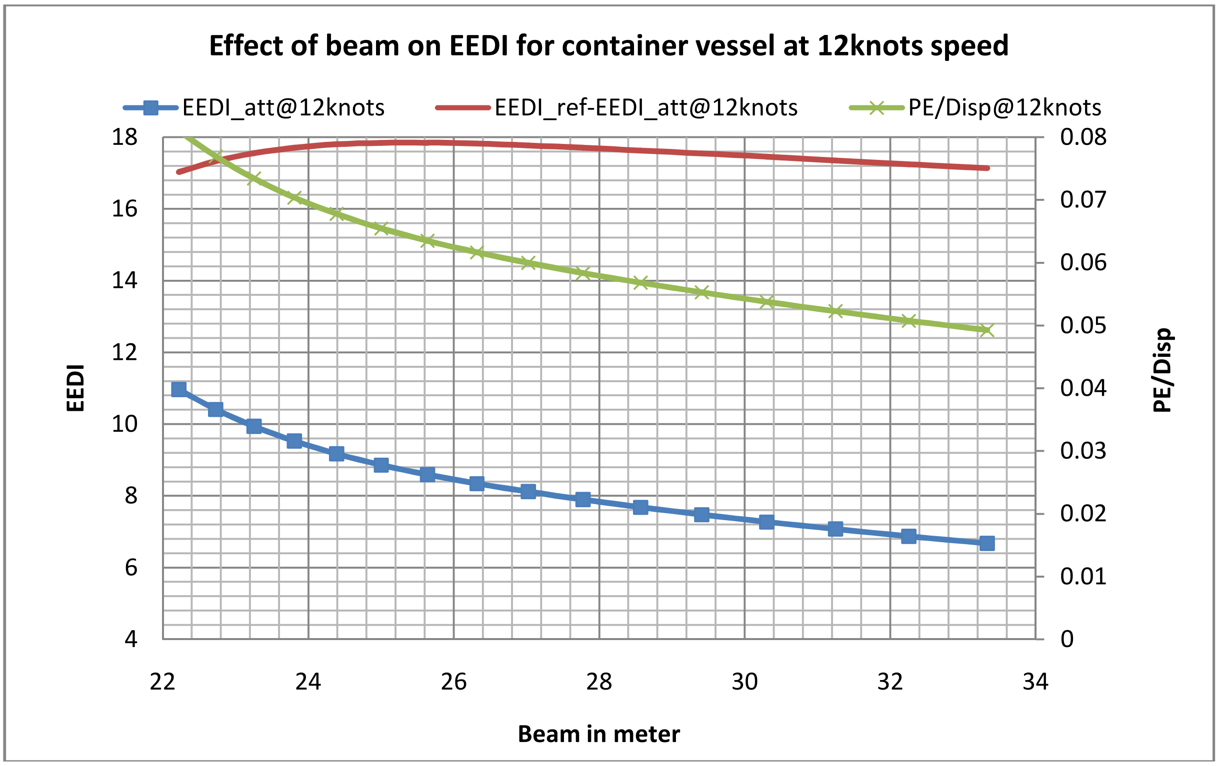

Figure 15: EEDI of container vessel at different ship breadth at 12knot Speed.

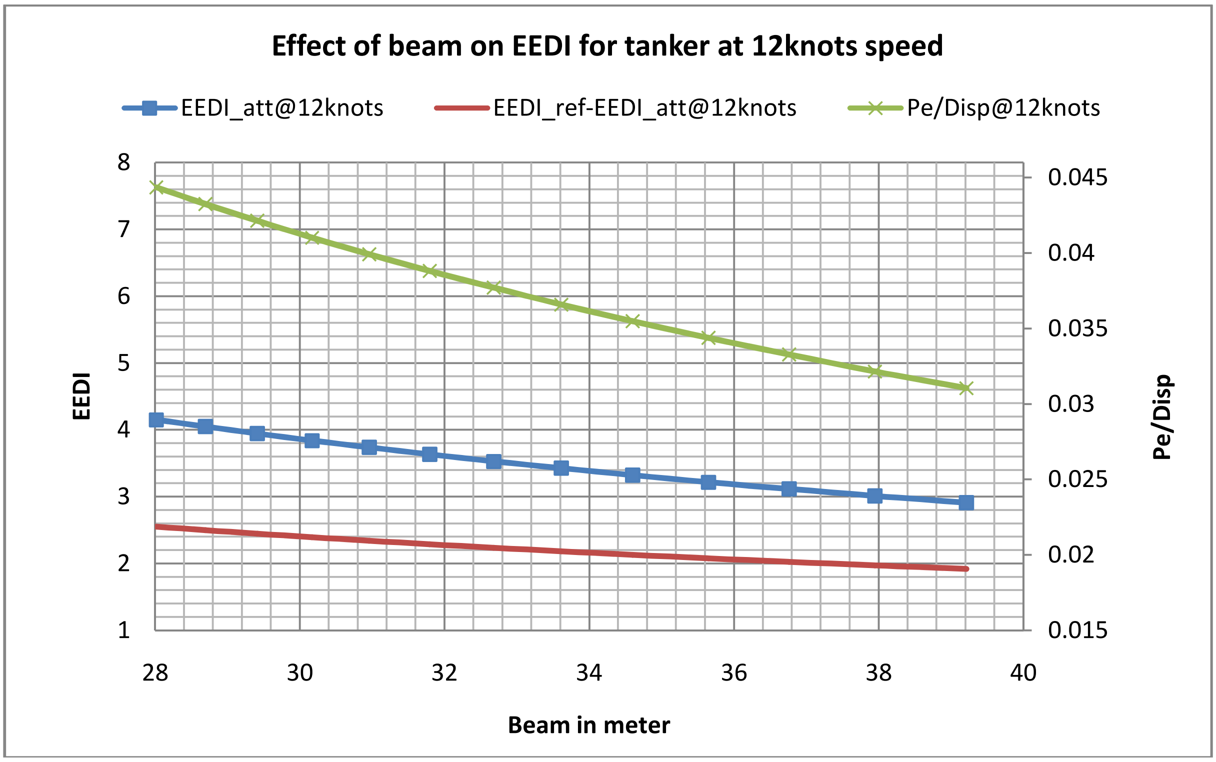

Figure 16: EEDI of Tanker at different ship breadth at 12knot Speed.

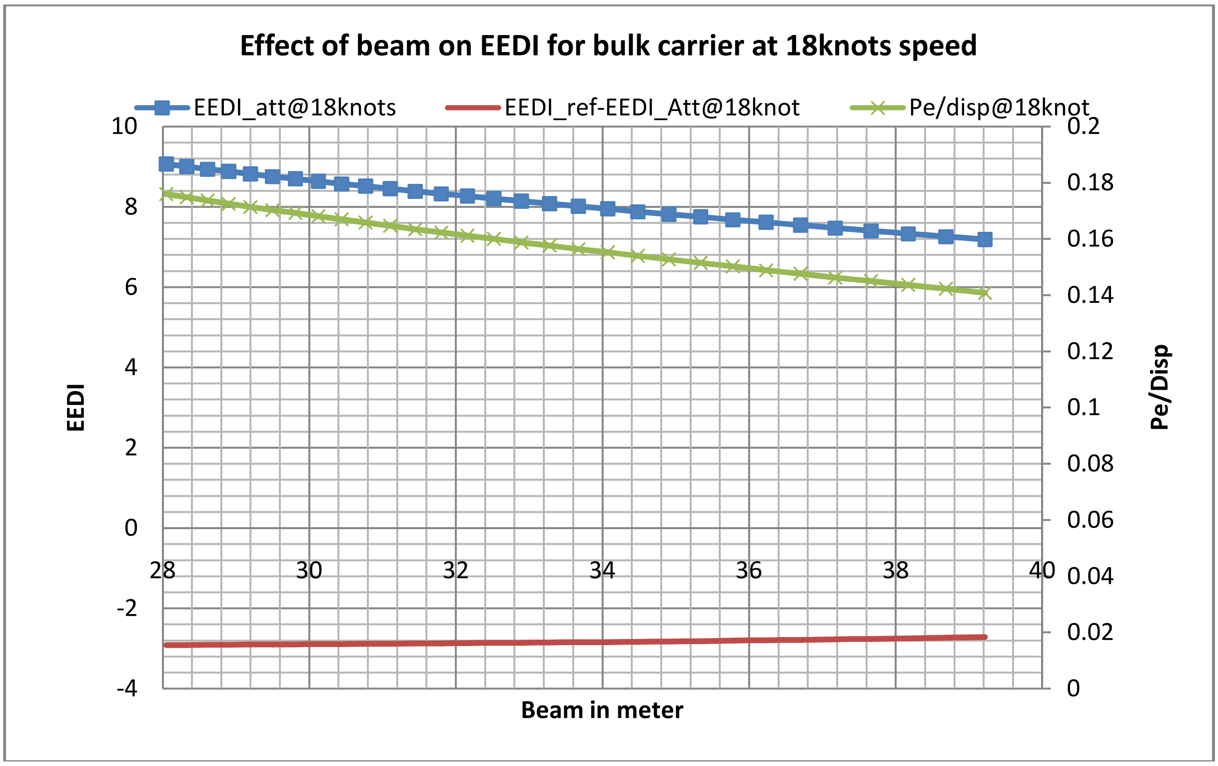

Figure 17: EEDI of Bulk carrier at different ship breadth at 18knot Speed.

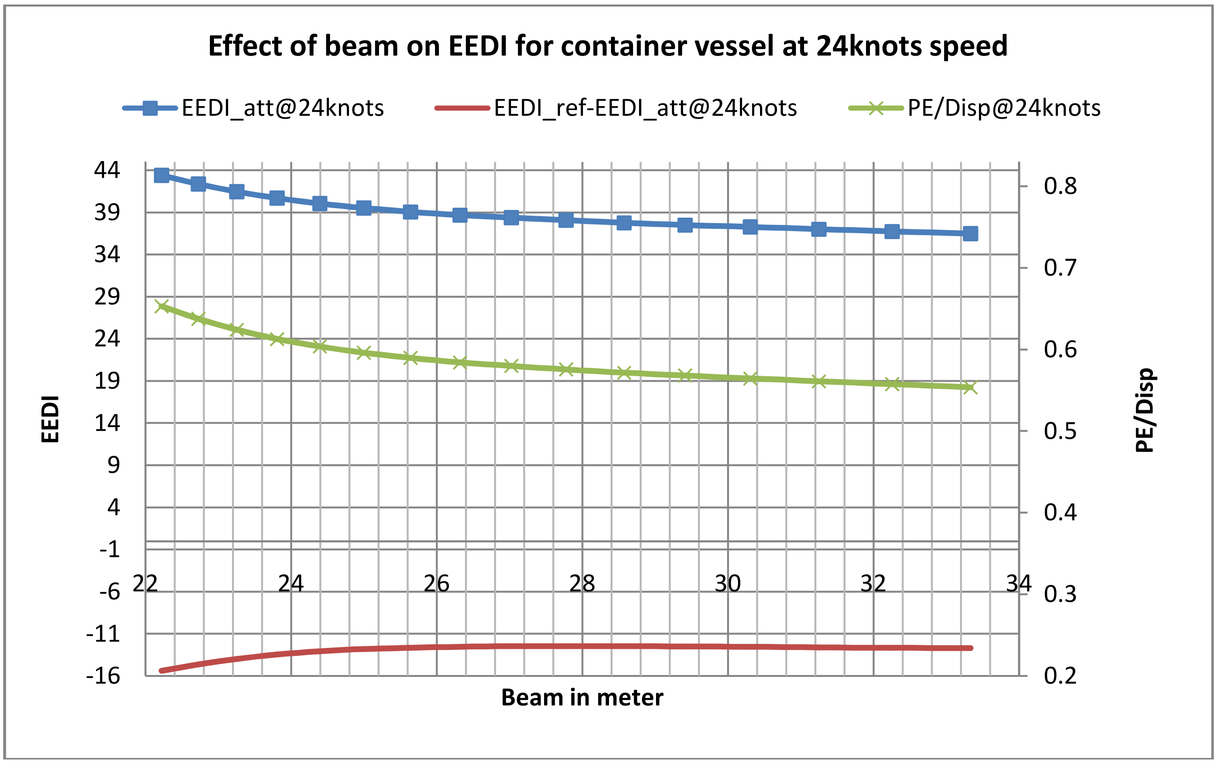

Figure 18: EEDI of container vessel at different ship breadth at 18knot Speed.

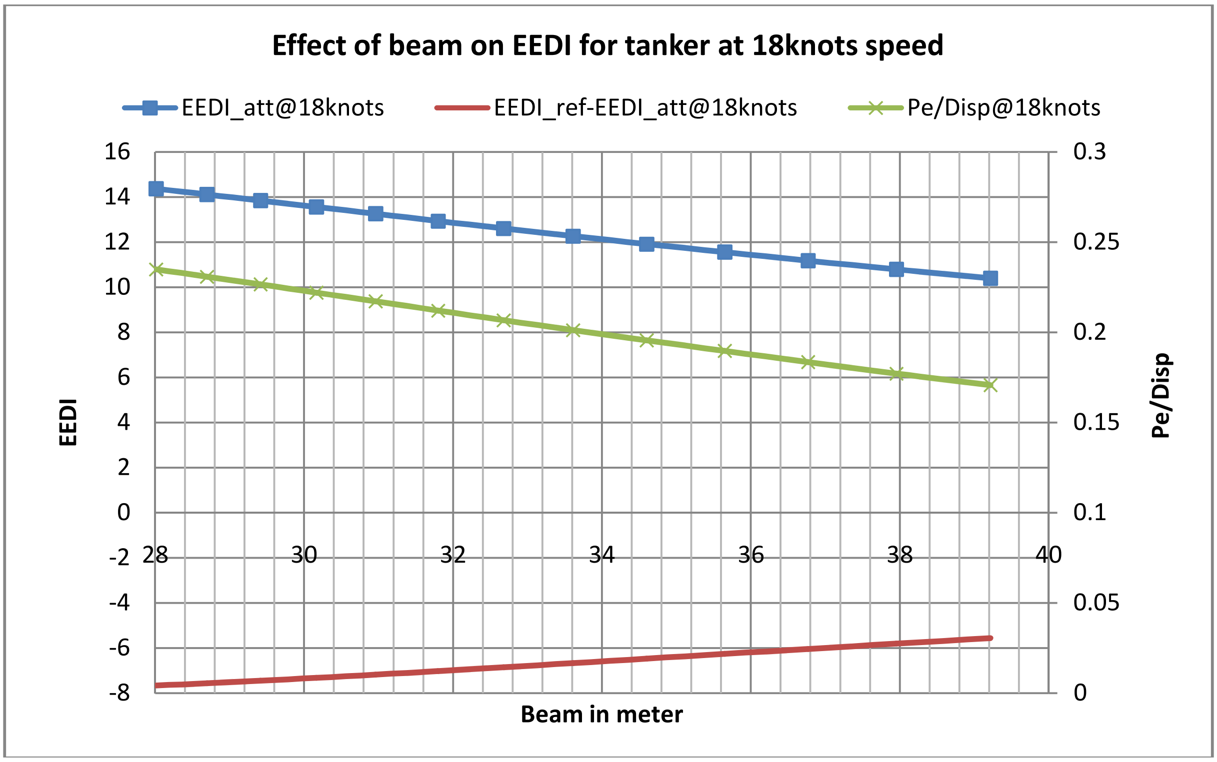

Figure 19: EEDI of Tanker at different ship breadth at 18knot Speed.

3.3.6 Change in draft of Ship (T)

Particulars considered for the analysis are as shown in the following table:

Ship type	V (knots)	Length (m)	Froude No.	Beam (m)	Draft (T)	L/B	B/T	Cp	Cb
Bulk Carrier	12 & 18	200	0.14 & 0.21	39.2	12-16.3	5.1	2.4-3.2	0.73	0.72
Container Vessel	12 & 24	200	0.14 & 0.28	33.3	8.23-11.1	6	3-4	0.6	0.57
Tanker	12 & 18	200	0.14 & 0.21	39.2	12.1-16.34	5.1	2.4-3.2	0.83	0.82

From the figure 20-25, it can be said that,

- The difference between $EEDI_{ref}$ and $EEDI_{attained}$ decreases with the increase of draft at 12 knot speed, but increases with the increase of draft at higher speed (12 and 24 knots).
- $EEDI_{attained}$ and Effective Power (Pe)/Displacement line has similar trend.
- It can be decided easily that, low speed it is better to have small draft and vice versa.

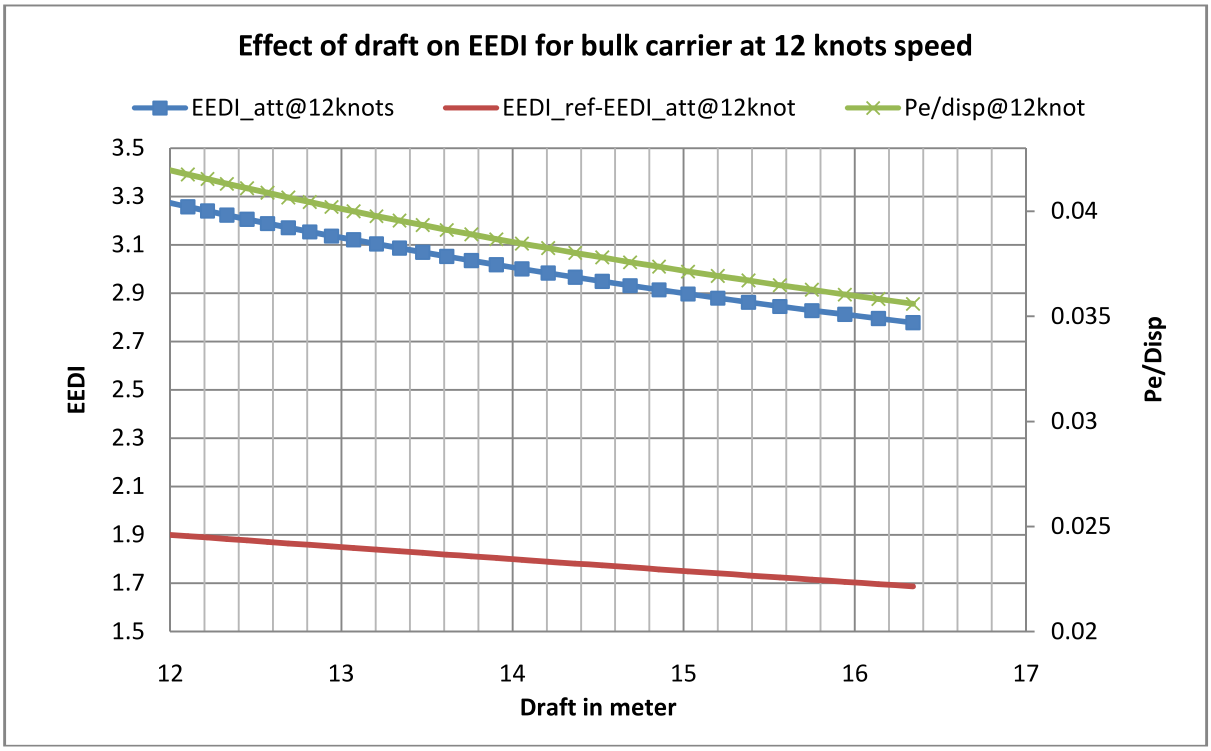

Figure 20: EEDI of Bulk carrier at different ship draft at 12 knot Speed.

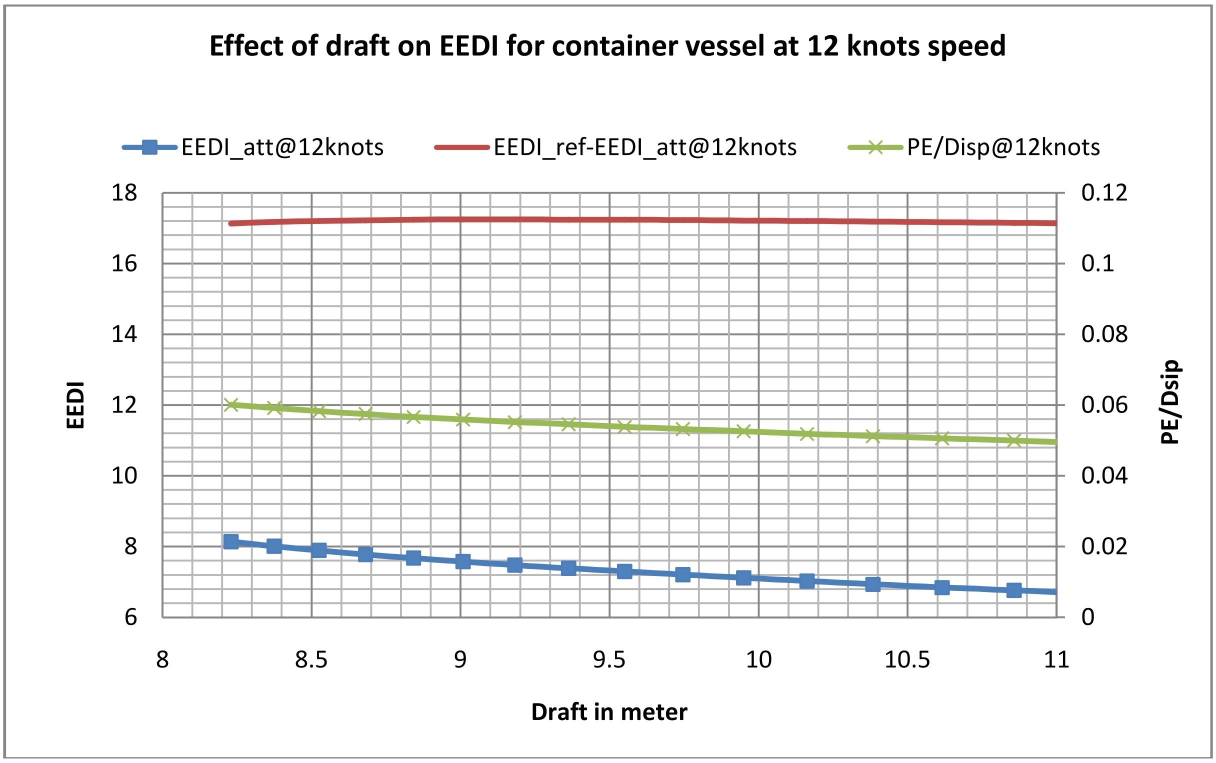

Figure 21: EEDI of container vessel at different ship draft at 12 knot Speed.

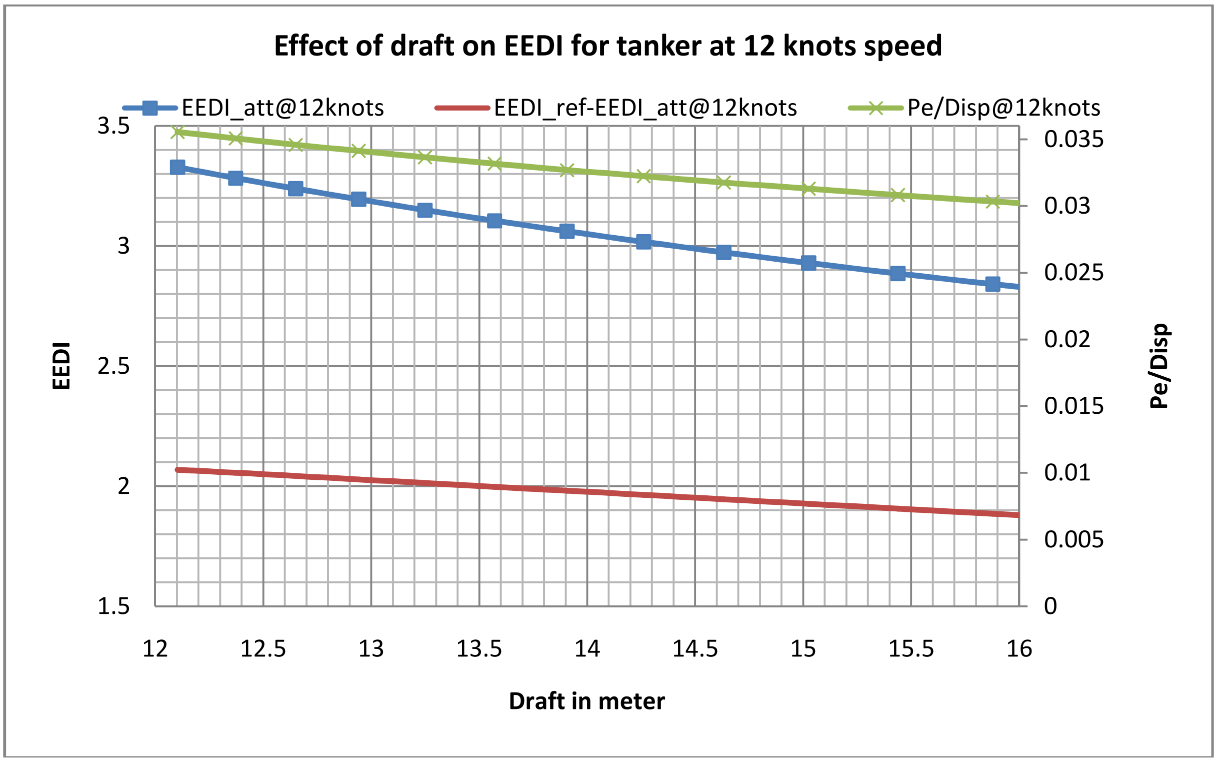

Figure 22: EEDI of Tanker at different ship draft at 12 knot Speed.

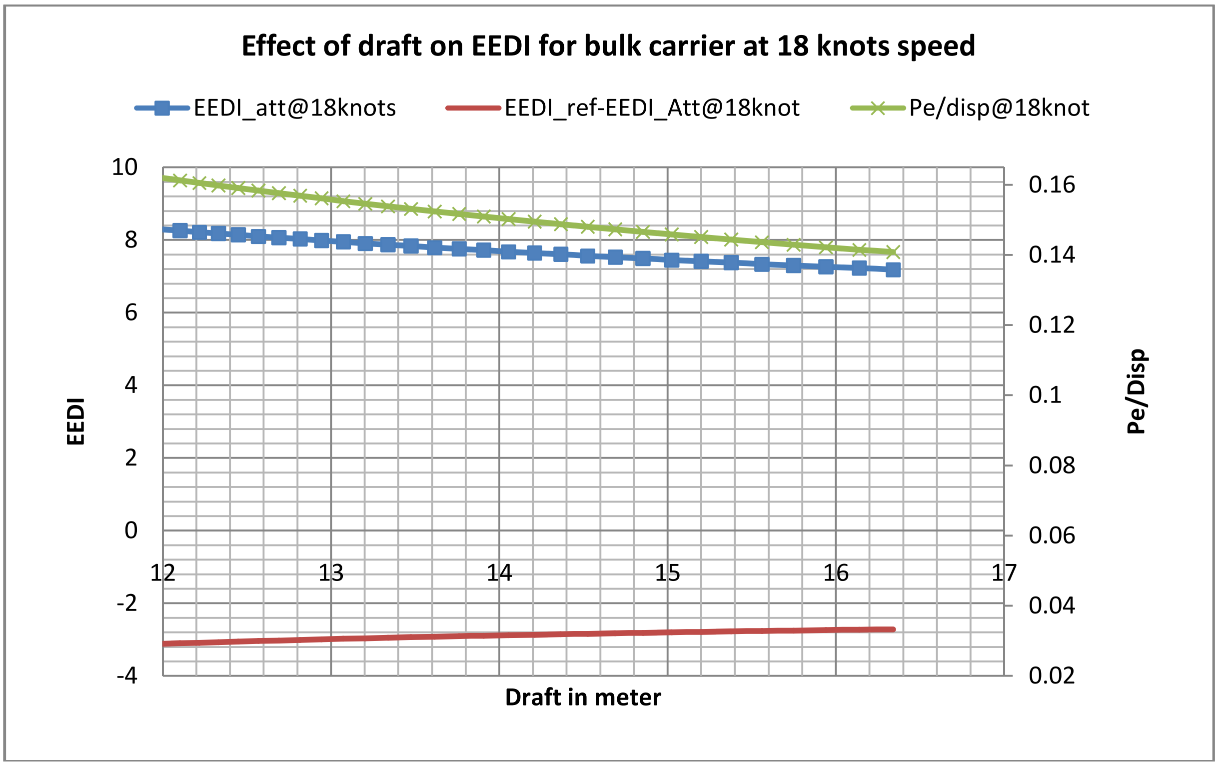

Figure 23: EEDI of Bulk carrier at different ship draft at 18 knot Speed.

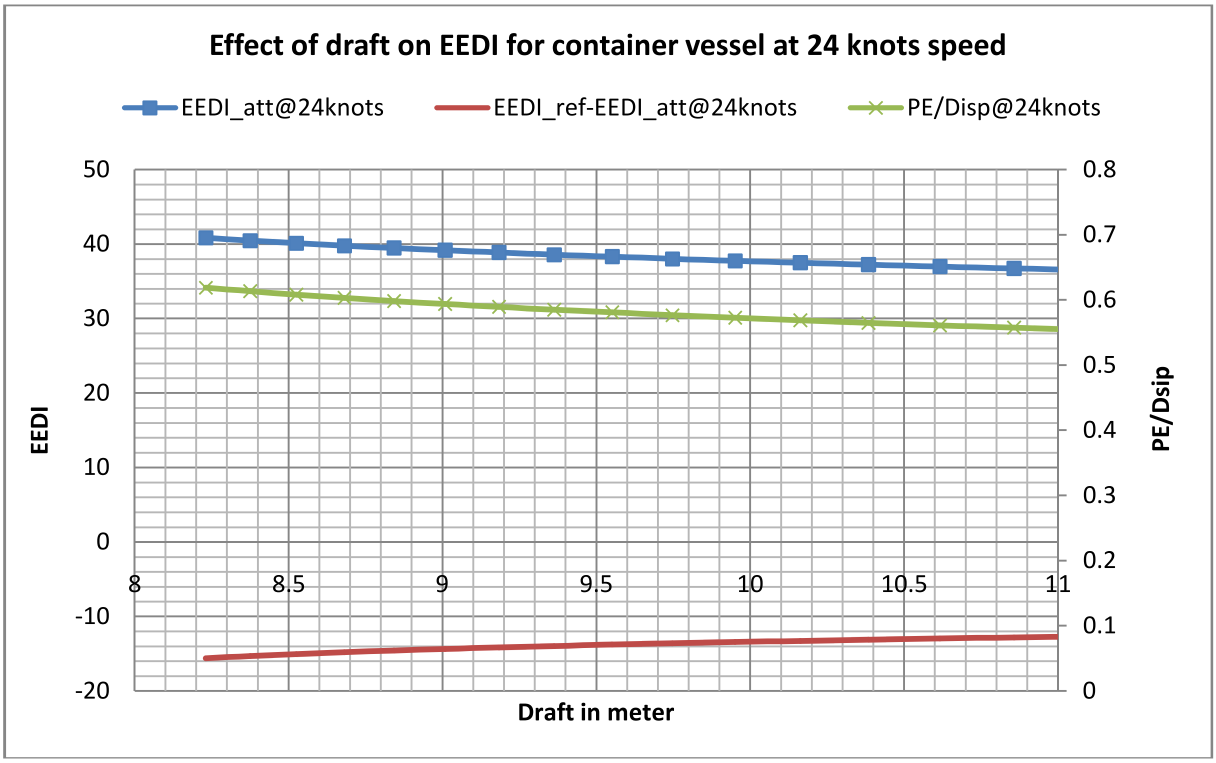

Figure 24: EEDI of container vessel at different ship draft at 18 knot Speed.

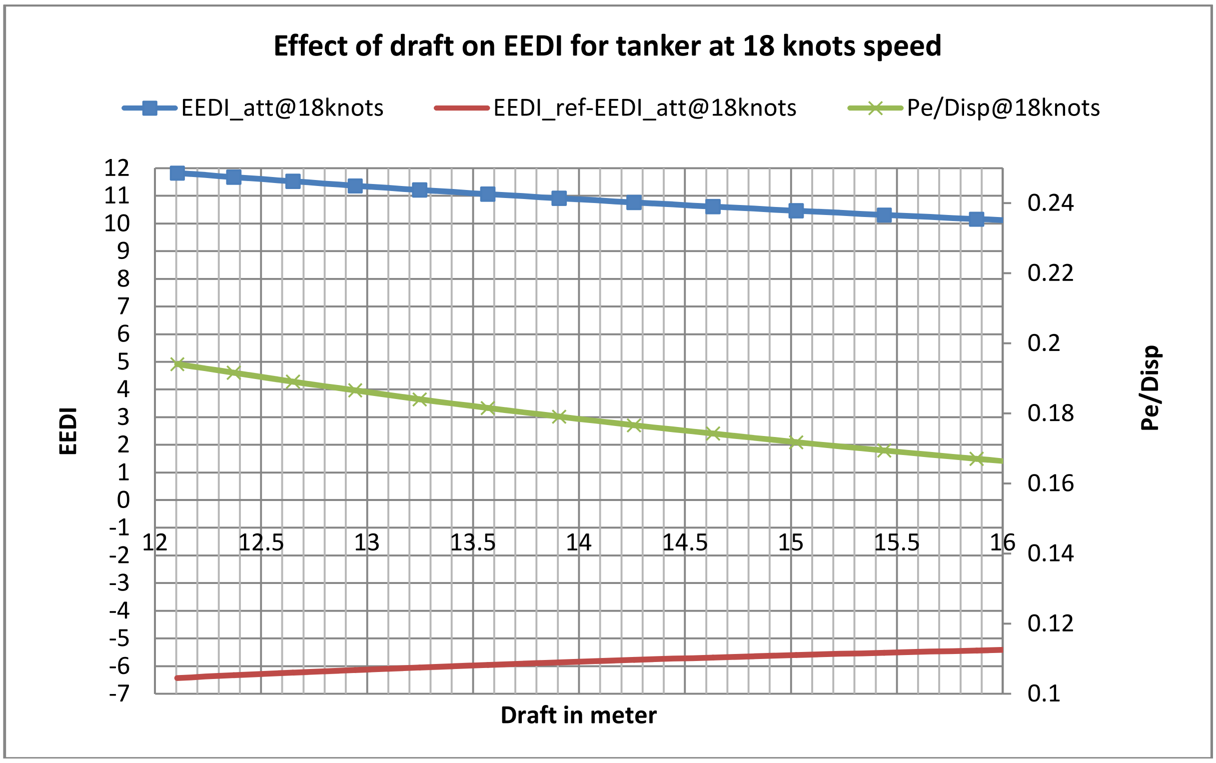

Figure 25: EEDI of Tanker at different ship draft at 18 knot Speed.

3.3.7 Change in L/B ratio

Particulars considered for the analysis are as shown in the following table:

Ship type	V (knots)	Length (m)	Froude No.	Beam (m)	Draft (T)	L/B	B/T	Cp	Cb
Bulk Carrier	12 & 18	200	0.14 & 0.21	28.1-39.2	11.7-16.3	5.1-7.1	2.4	0.73	0.72
Container Vessel	12 & 24	200	0.14 & 0.28	22.2-33.3	7.41-11.1	6-9	3	0.6	0.57
Tanker	12 & 18	200	0.14 & 0.21	28-39.2	11.67-16.34	5.1-7.1	2.4	0.83	0.82

Figure 26-31 can be described as follows,

- The difference between $EEDI_{ref}$ and $EEDI_{attained}$ increases with the increase of L/B at 12 knot speed, but decreases with the increase of L/B at higher speed (18 and 24knots).
- $EEDI_{attained}$ and Effective Power (Pe)/Displacement line has similar trend.
- It can be decided easily that, low speed it is better to have large L/B and vice versa.

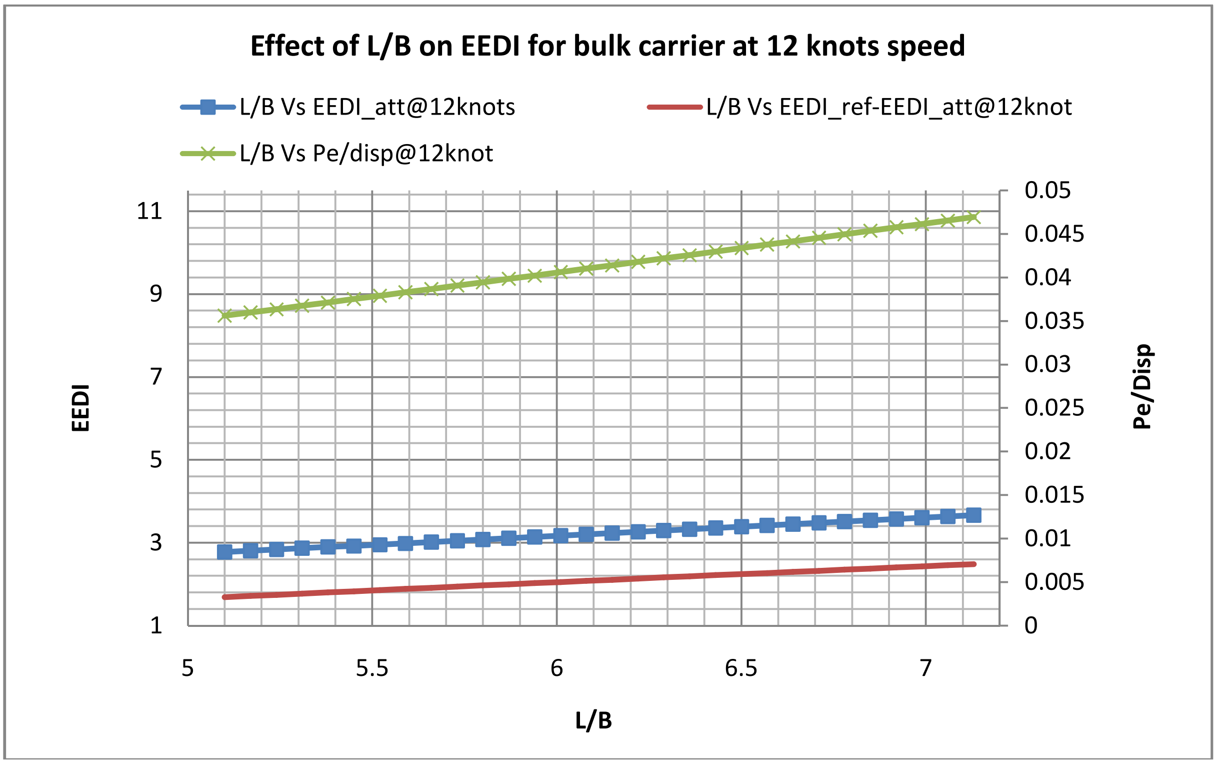

Figure 26: EEDI of Bulk carrier at different L/B ratio at 12 knot Speed.

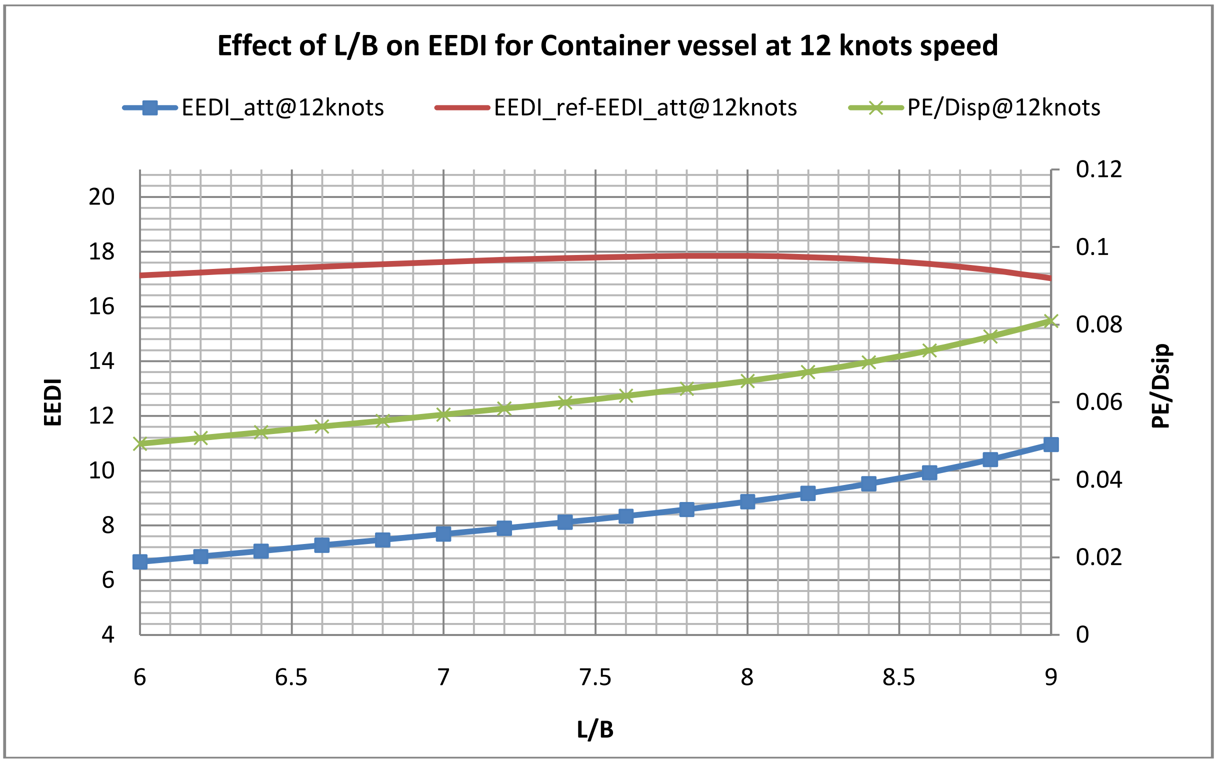

Figure 27: EEDI of container vessel at different L/B ratio at 12 knot Speed.

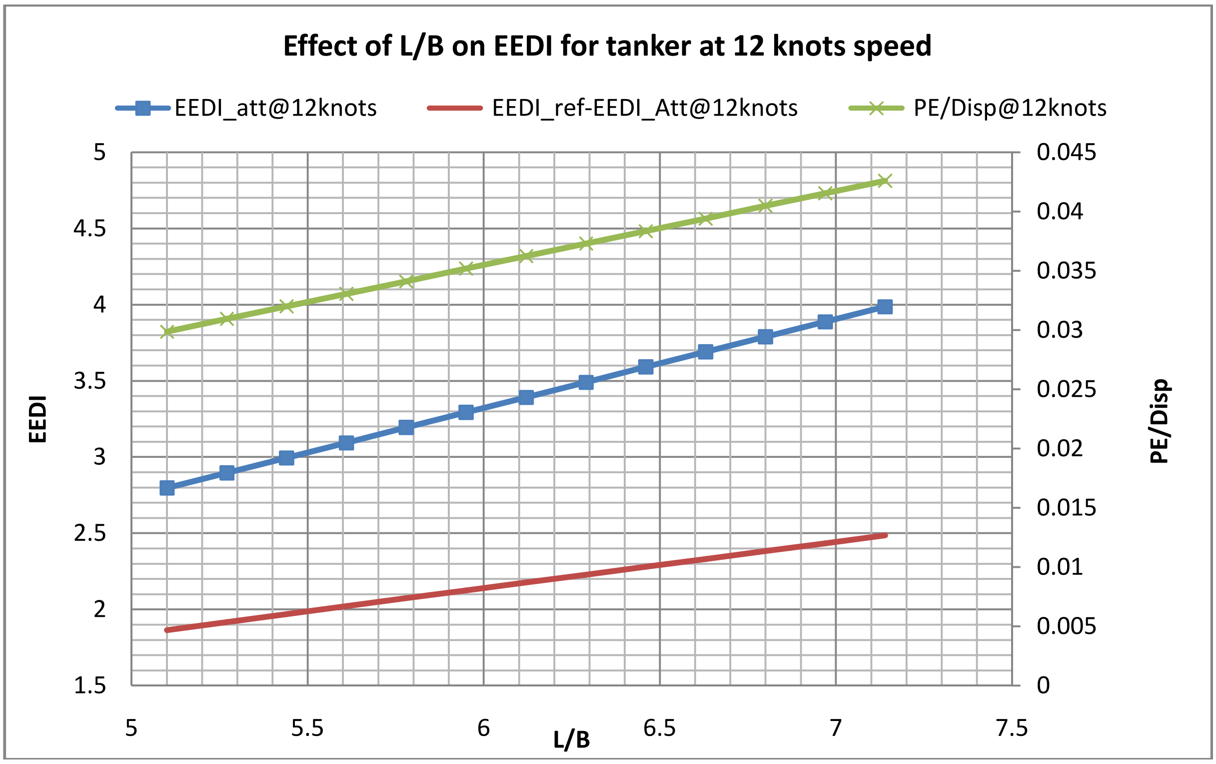

Figure 28: EEDI of Tanker at different L/B ratio at 12 knot Speed.

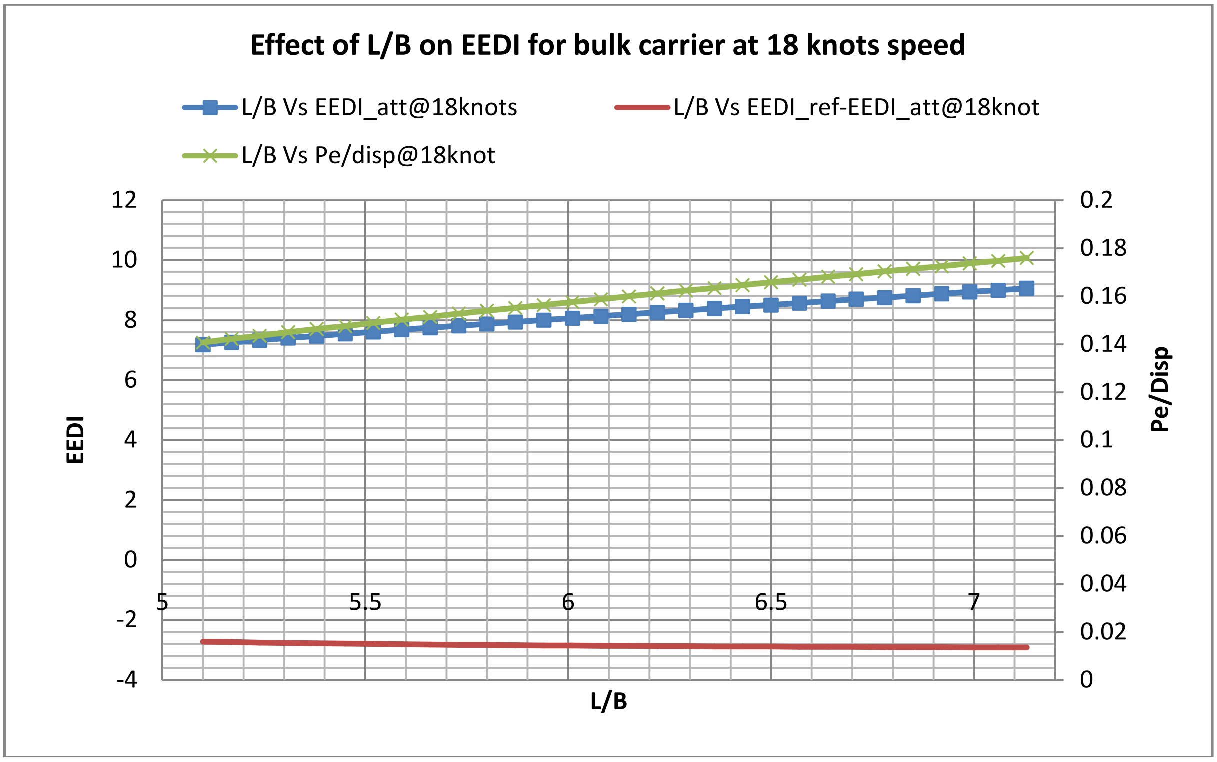

Figure 29: EEDI of Bulk carrier at different L/B ratio at 18 knot Speed.

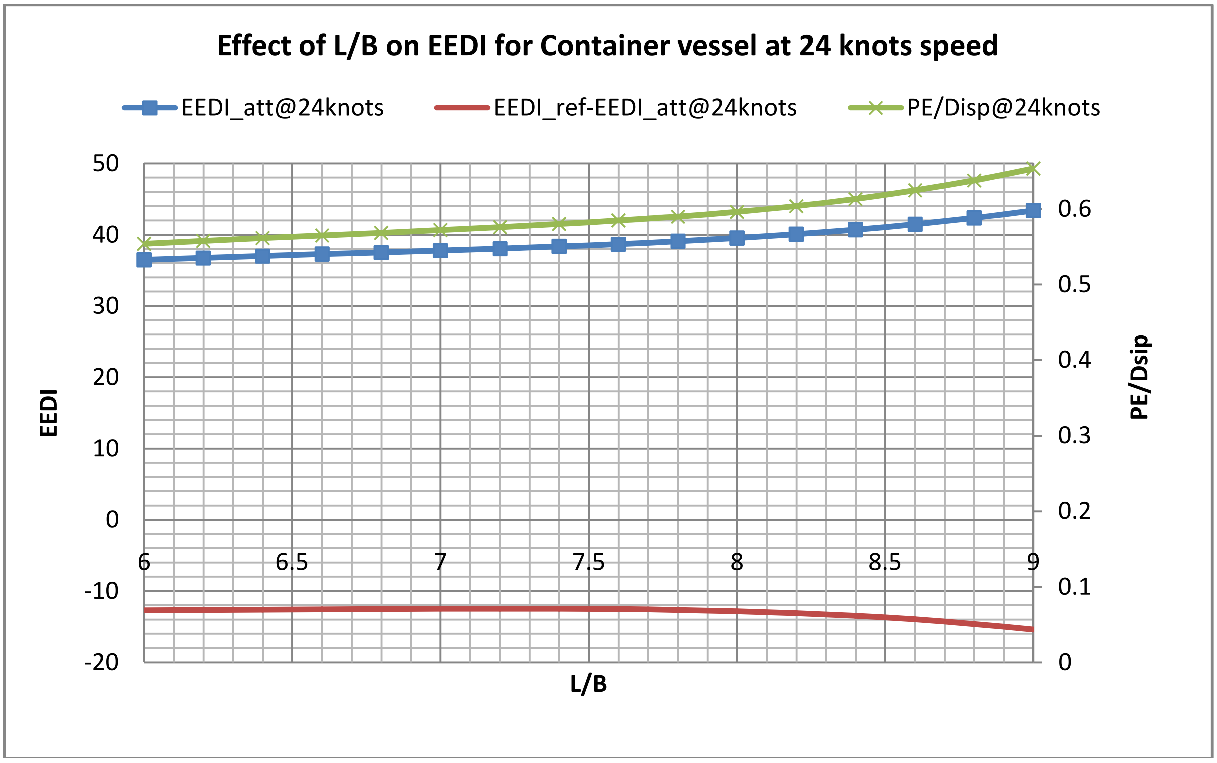

Figure 30: EEDI of container vessel at different L/B ratio at 18 knot Speed.

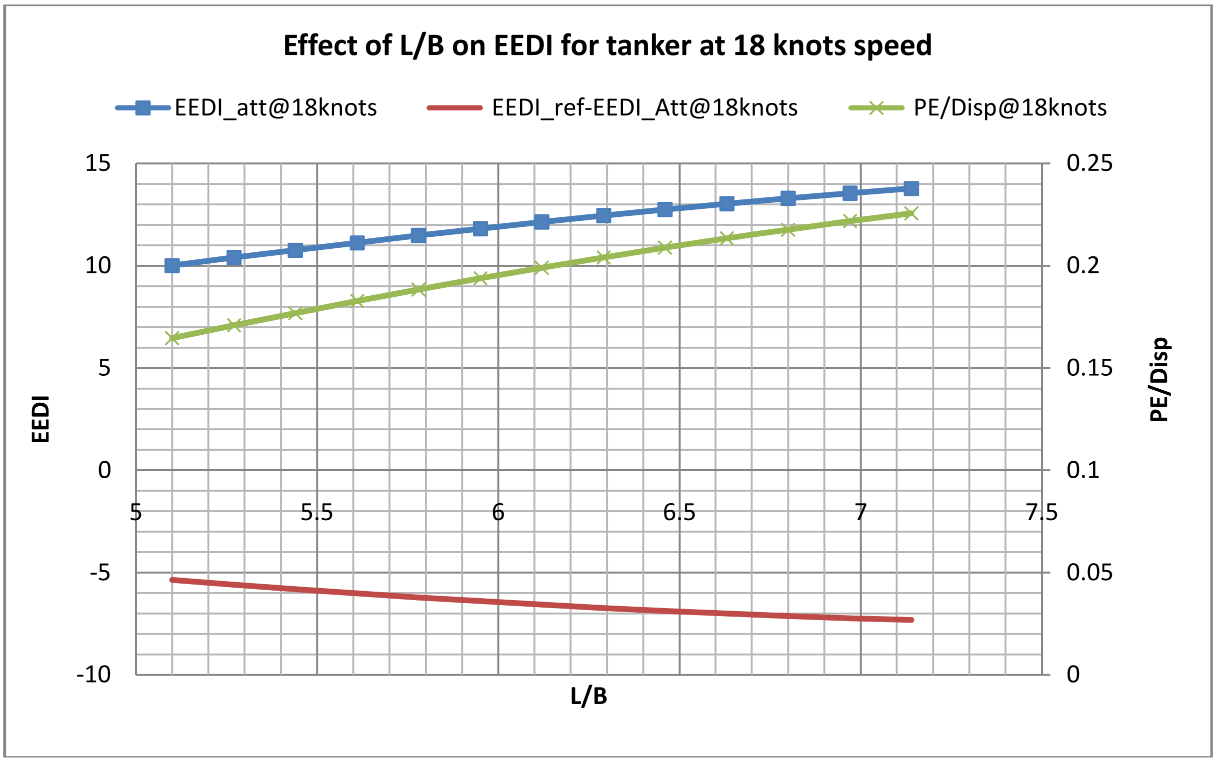

Figure 31: EEDI of Tanker at different L/B ratio at 18 knot Speed.

3.3.8 Change in B/T ratio

Particulars considered for the analysis are as shown in the following table:

Ship type	V (knots)	Length (m)	Froude No.	Beam (m)	Draft (T)	L/B	B/T	Cp	Cb
Bulk Carrier	12 & 18	200	0.14 & 0.21	39.2	12-16.3	5.1	2.4-3.2	0.73	0.72
Container Vessel	12 & 24	200	0.14 & 0.28	33.3	8.23-11.1	6	3-4	0.6	0.57
Tanker	12 & 18	200	0.14 & 0.21	39.2	12.1-16.34	5.1	2.4-3.2	0.83	0.82

Figure 32-37 describes the following facts

- The difference between $EEDI_{ref}$ and $EEDI_{attained}$ increases with the increase of B/T at 12 knot speed, but decreases with the increase of B/T ratio at higher speed (18 and 24 knots).
- $EEDI_{attained}$ and Effective Power (Pe)/Displacement line has similar trend.
- It can be decided easily that, low speed it is better to have large B/T and vice versa.

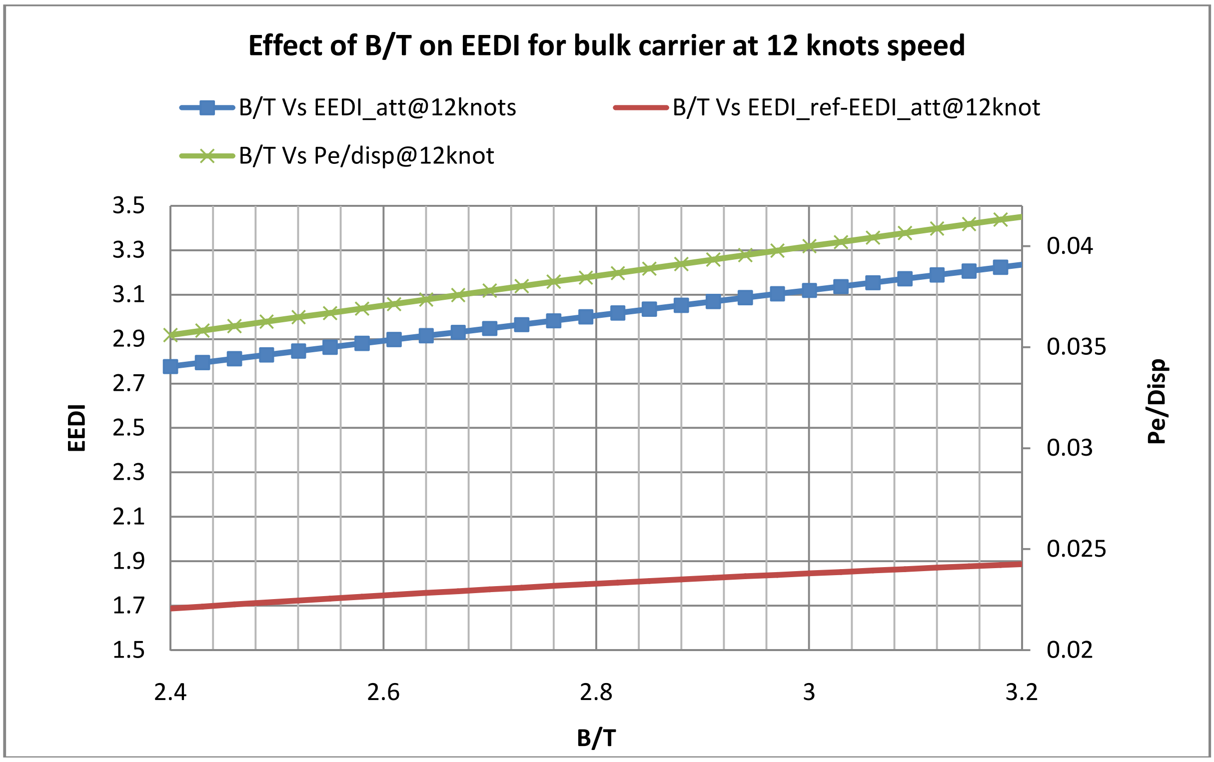

Figure 32: EEDI of Bulk carrier at different B/T ratio at 12 knot Speed.

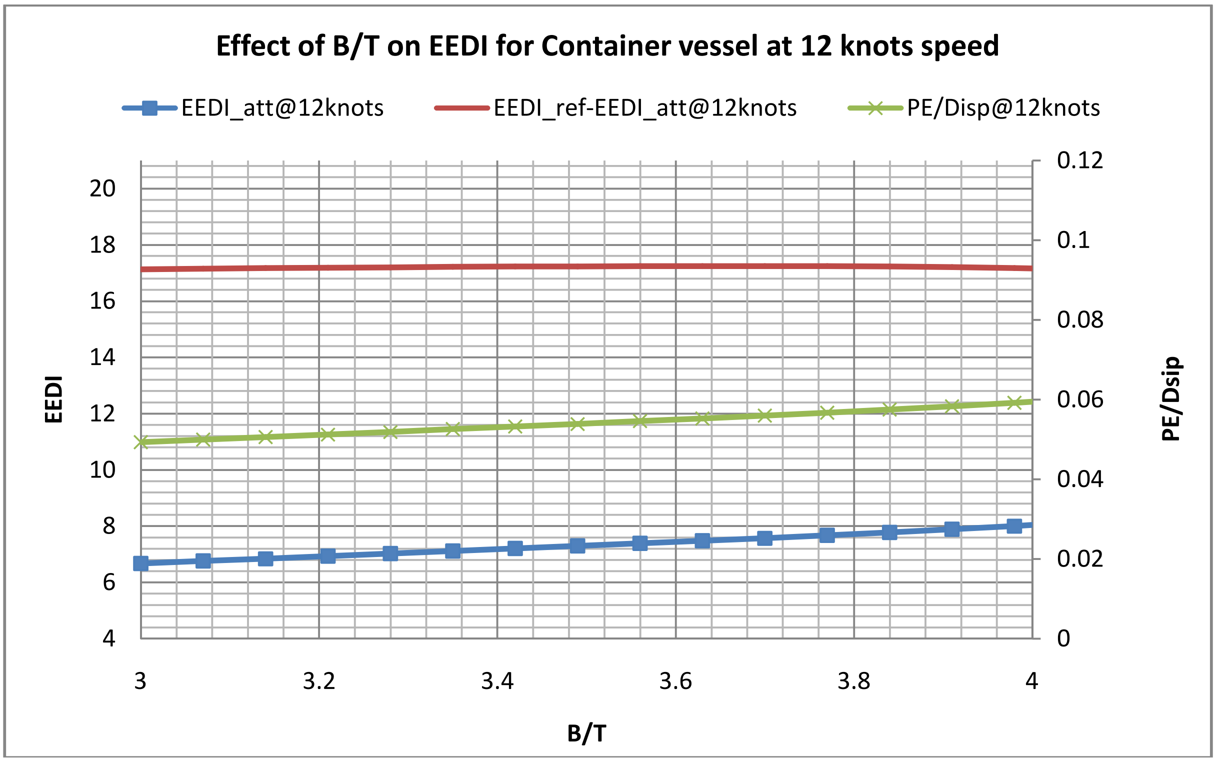

Figure 33: EEDI of container vessel at different B/T ratio at 12 knot Speed.

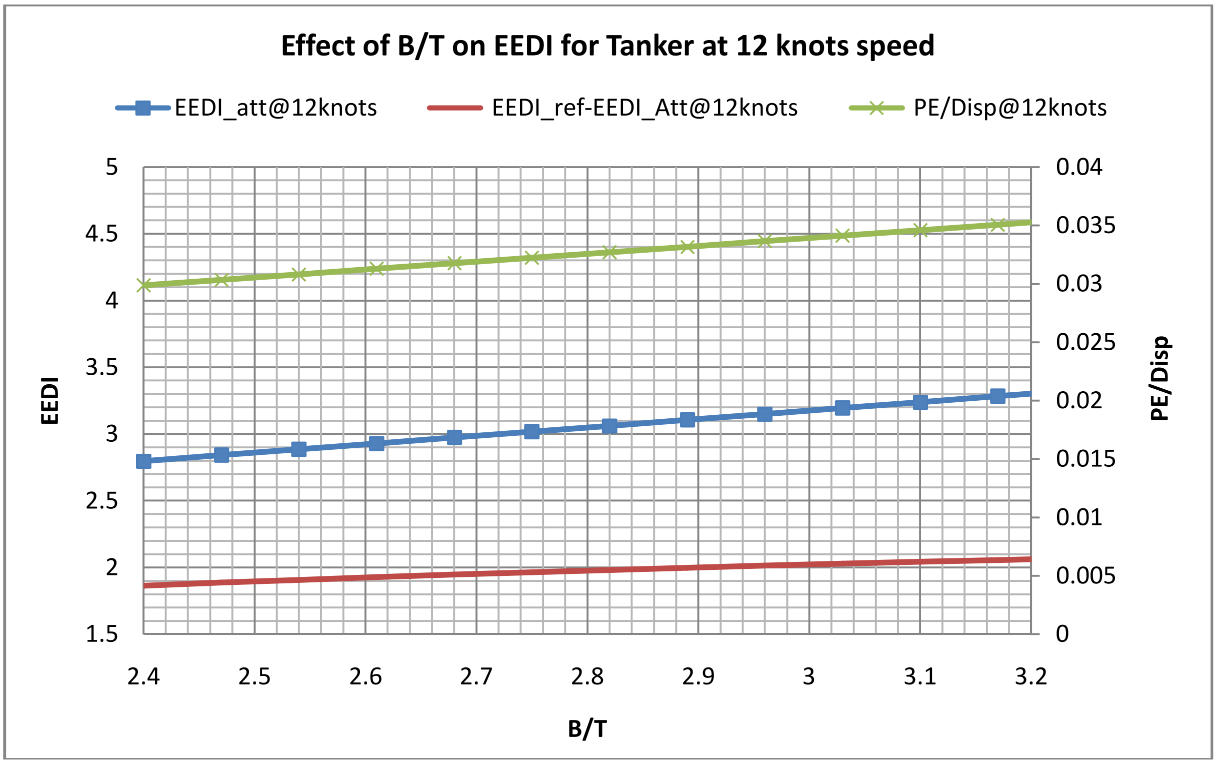

Figure 34: EEDI of Tanker at different B/T ratio at 12 knot Speed.

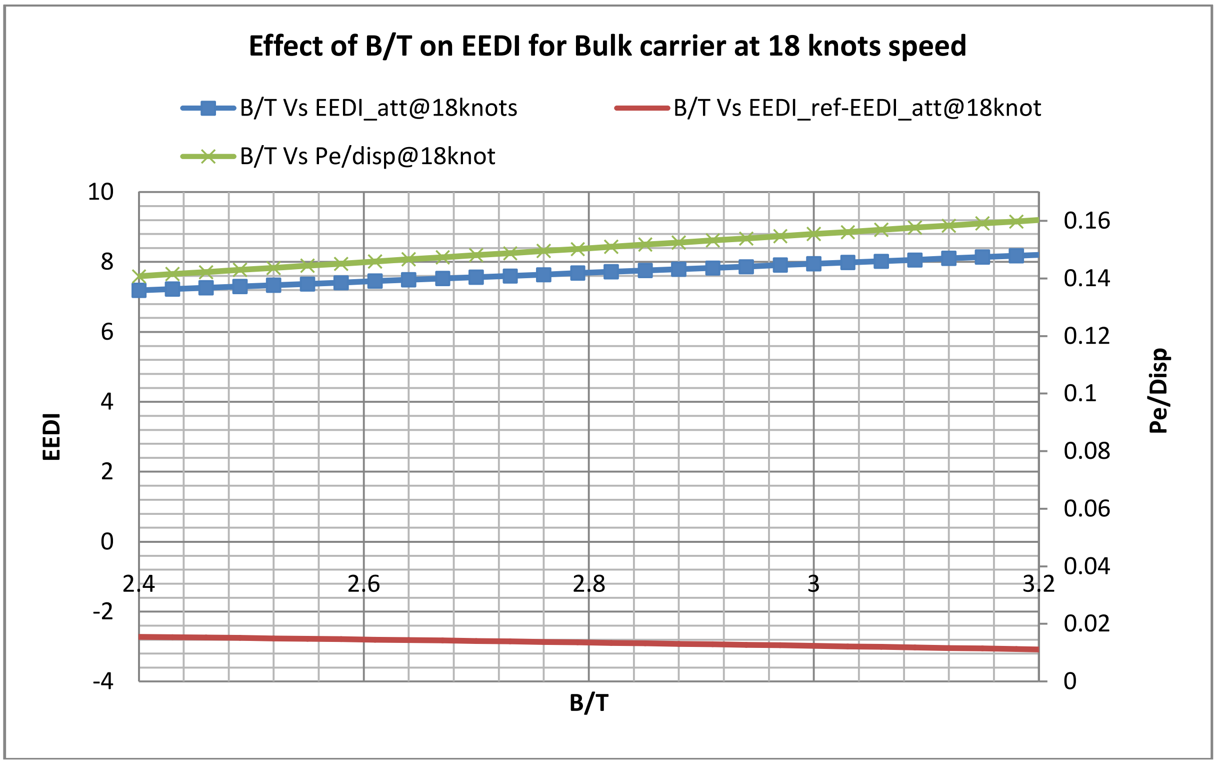

Figure 35: EEDI of Bulk carrier at different B/T ratio at 18 knot Speed.

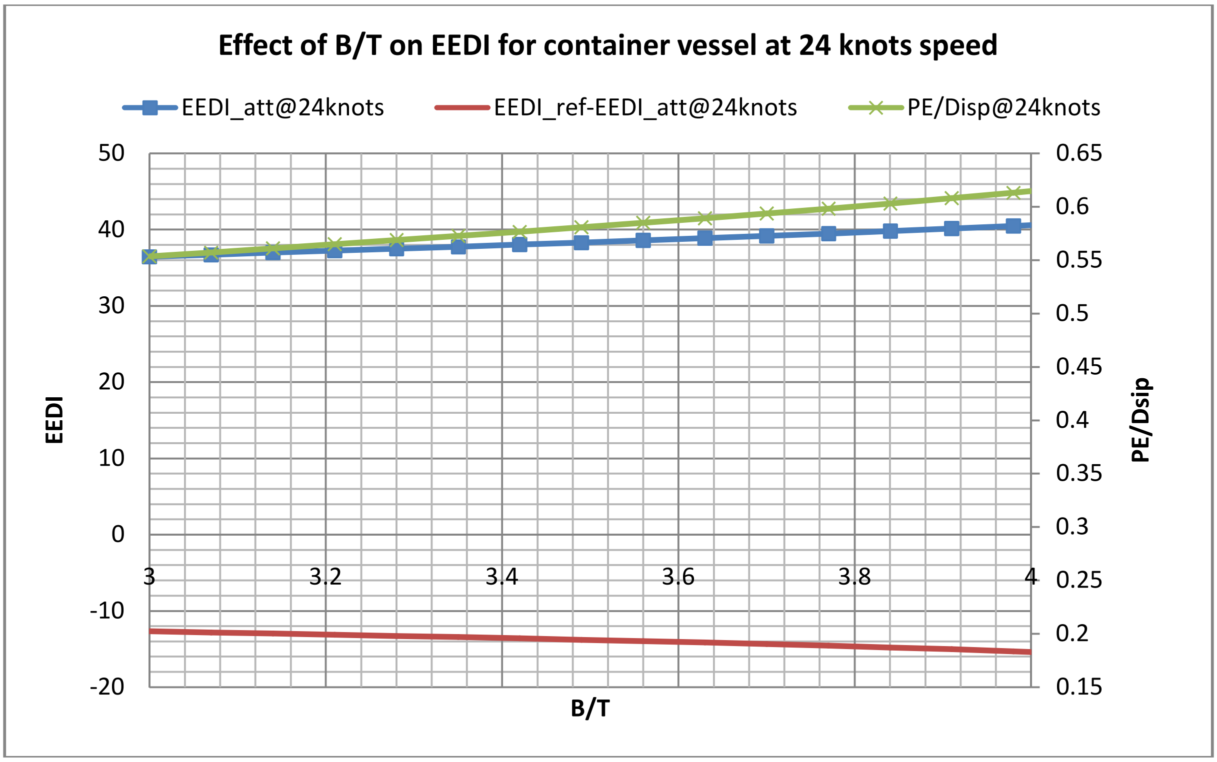

Figure 36: EEDI of container vessel at different B/T ratio at 24 knot Speed.

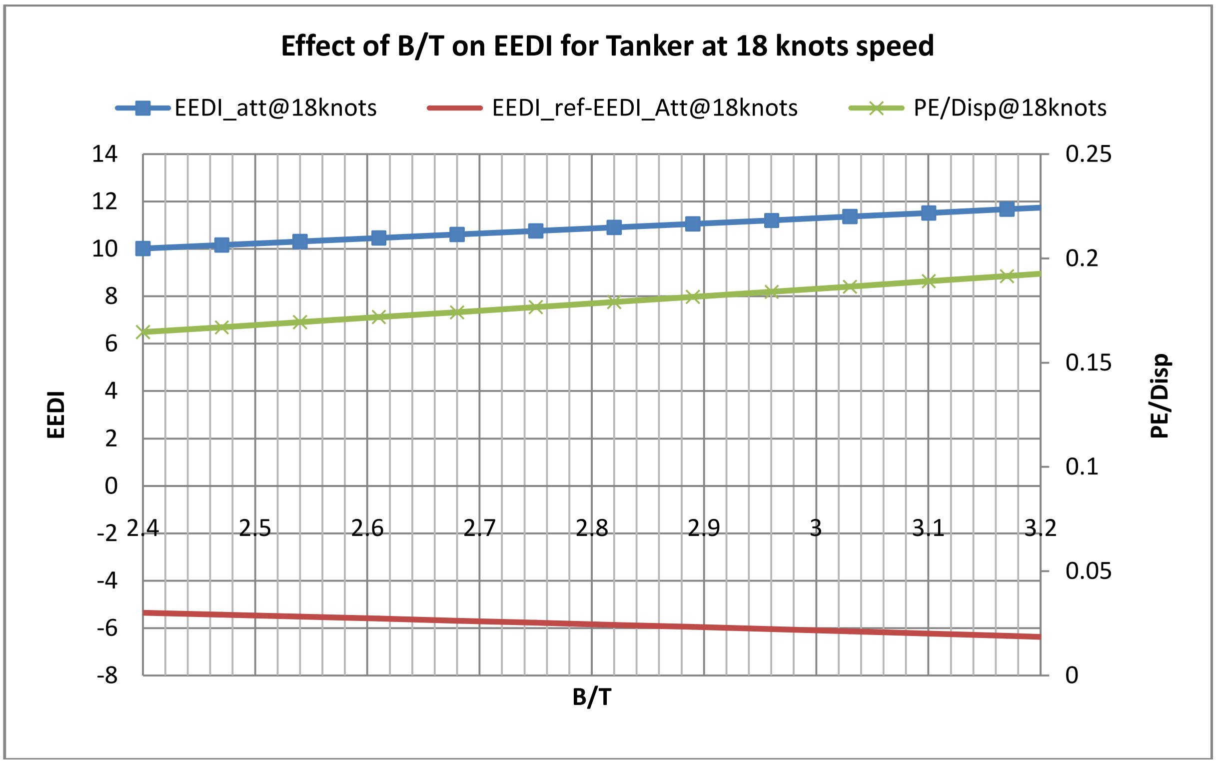

Figure 37: EEDI of tanker at different B/T ratio at 18 knot Speed.

3.3.9 Change in Prismatic Coefficient, Cp

Particulars considered for the analysis are as shown in the following table:

Ship type	V (knots)	Length (m)	Froude No.	Beam (m)	Draft (T)	L/B	B/T	Cp	Cb
Bulk Carrier	12 & 18	200	0.14 & 0.21	39.2	16.3	5.1	2.4	0.5-0.94	0.49-0.92
Container Vessel	12 & 24	200	0.14 & 0.28	33.3	11.1	6	3	0.55-0.7	0.52-0.67
Tanker	12 & 18	200	0.14 & 0.21	39.2	15.2	5.1	2.57	0.6-0.9	0.59-0.89

From figure 38-43, it can be understood that,

- No matter what the speed is, low prismatic coefficient is better for all three types of vessel.
- The difference between $EEDI_{ref}$ and $EEDI_{attained}$ decreases with the increase of prismatic coefficient and, from 0.5 to 0.85, this decrease is quite low, but after that, it drops suddenly.
- $EEDI_{attained}$ and Effective Power (Pe)/Displacement line has similar trend.
- Like length, breadth and draft, the trend of $EEDI_{ref}$ - $EEDI_{attained}$ does not alter at low and high speed.
- It can be decided easily that, at any speed it is better to have small prismatic coefficient.

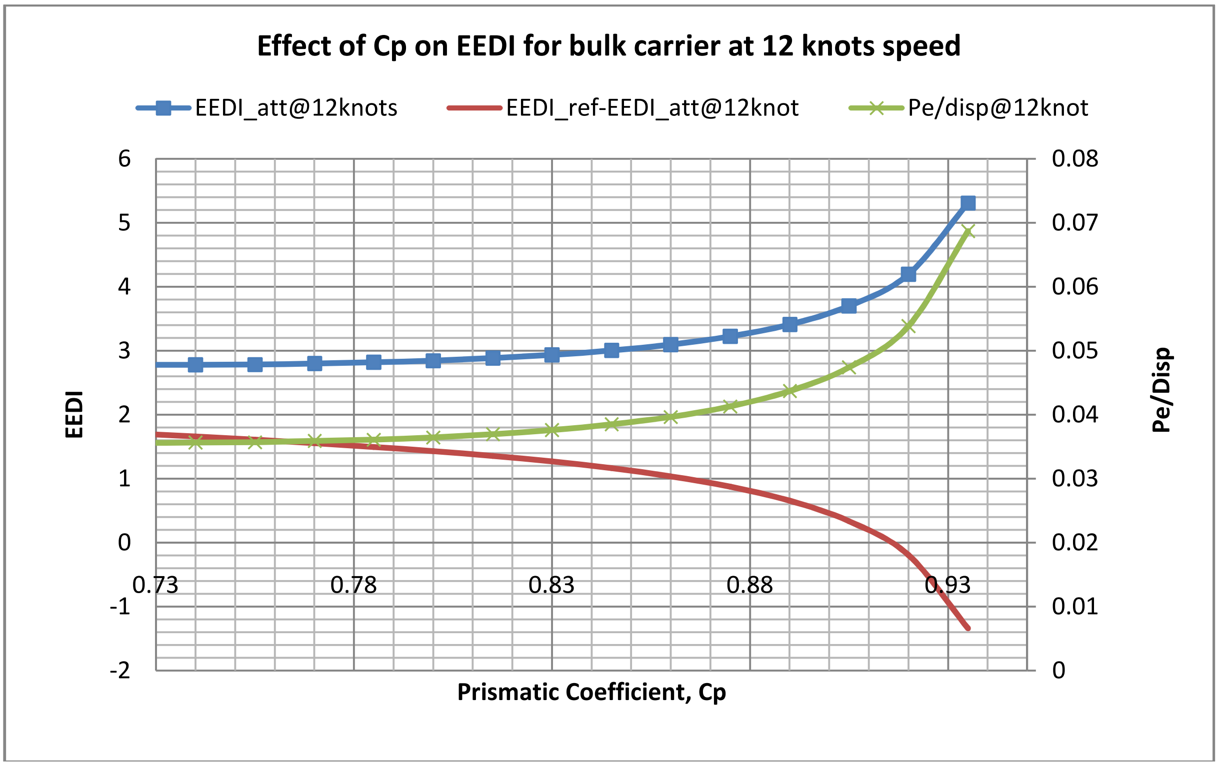

Figure 38: EEDI of Bulk carrier at different Prismatic coefficient at 12 knot Speed.

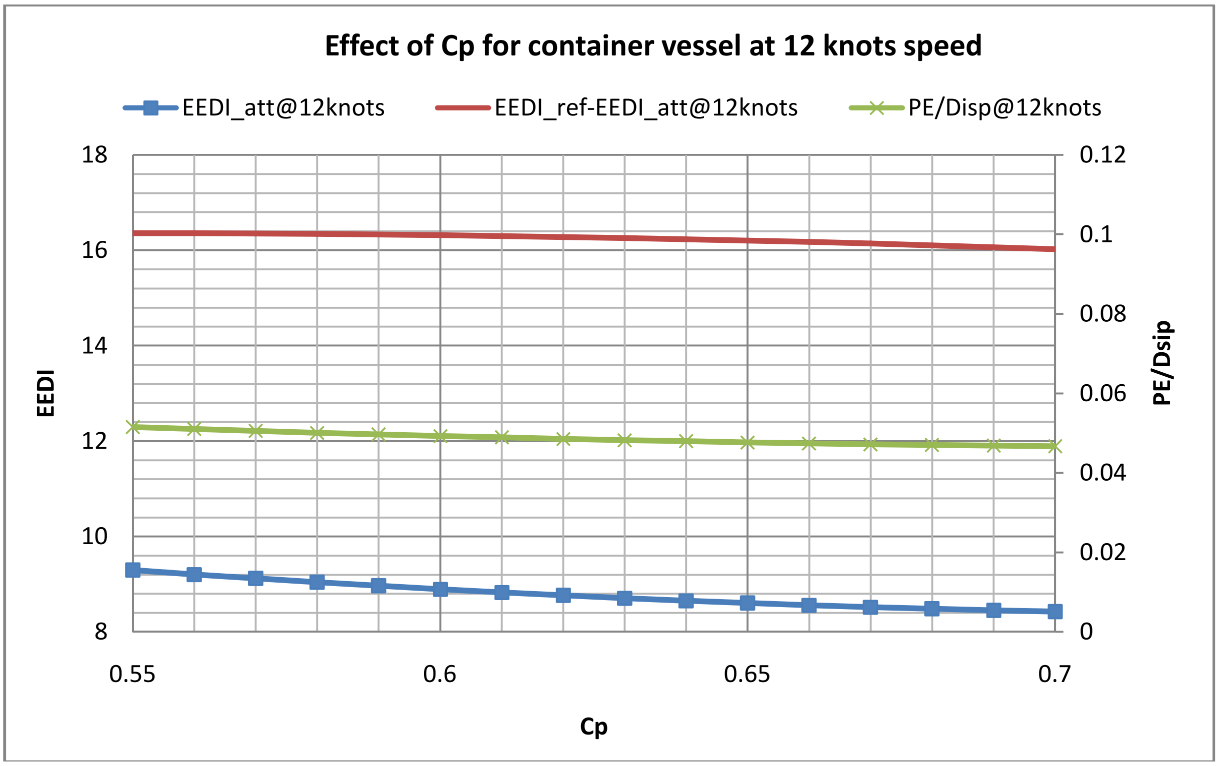

Figure 39: EEDI of Container vessel at different Prismatic coefficient at 12 knot Speed.

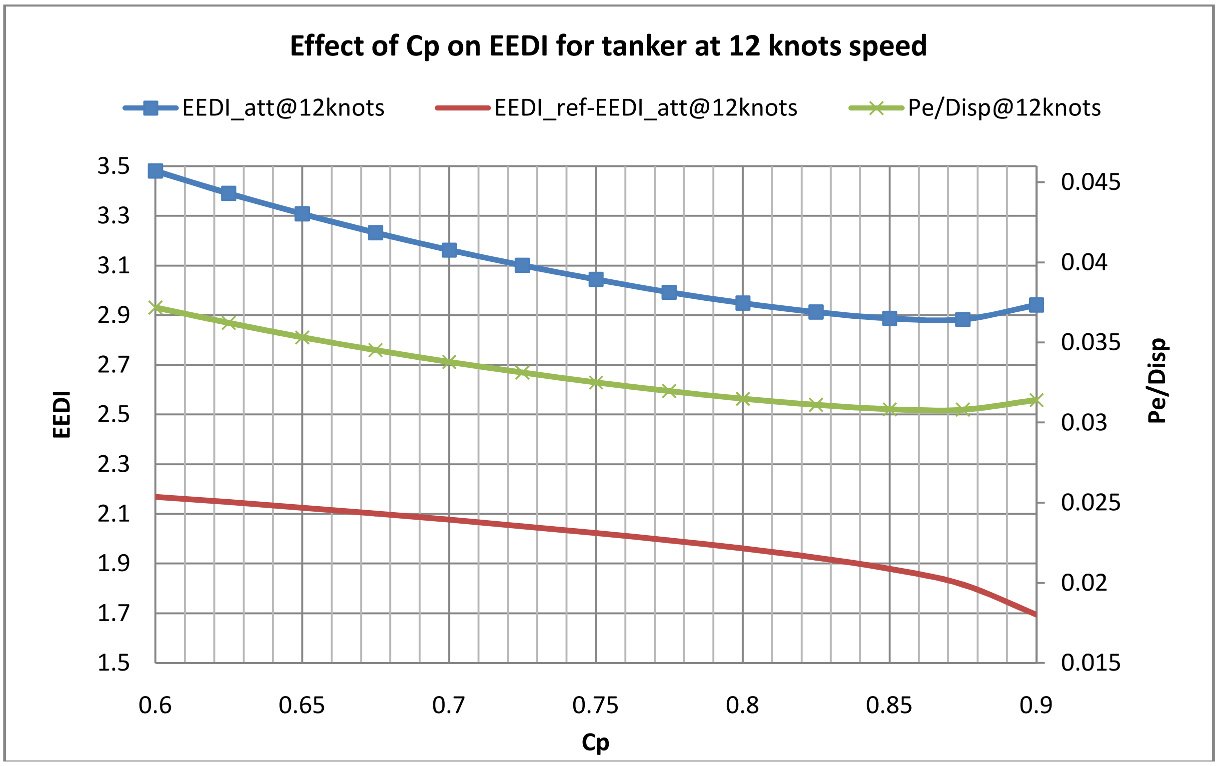

Figure 40: EEDI of Tanker at different Prismatic coefficient at 12 knot Speed

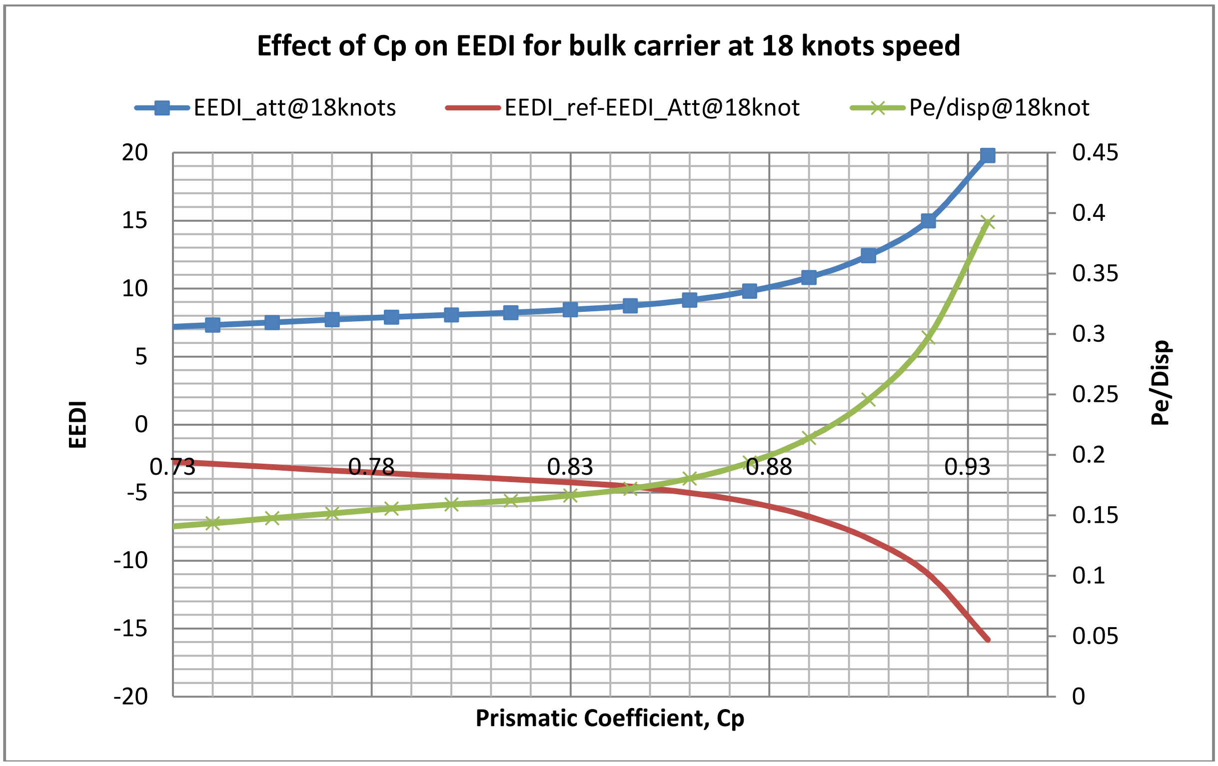

Figure 41: EEDI of Bulk carrier at different Prismatic coefficient at 18 knot Speed.

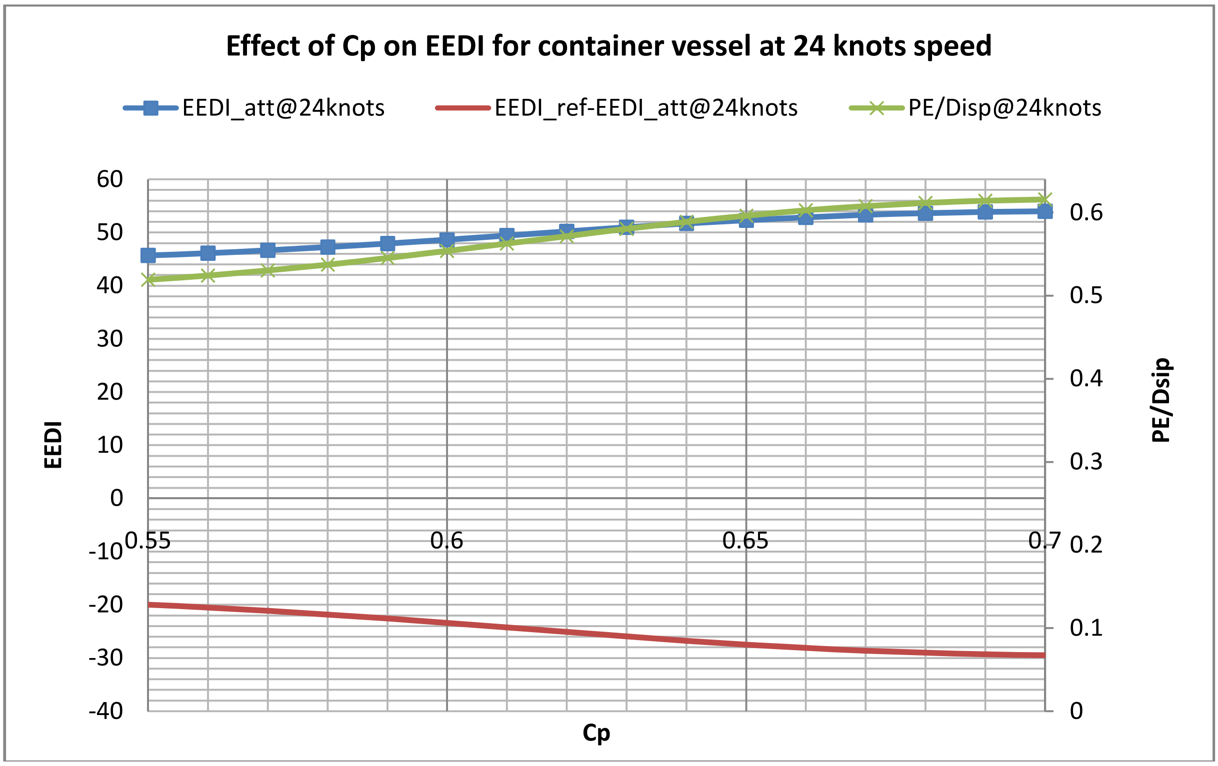

Figure 42: EEDI of Container vessel at different Prismatic coefficient at 24 knot Speed

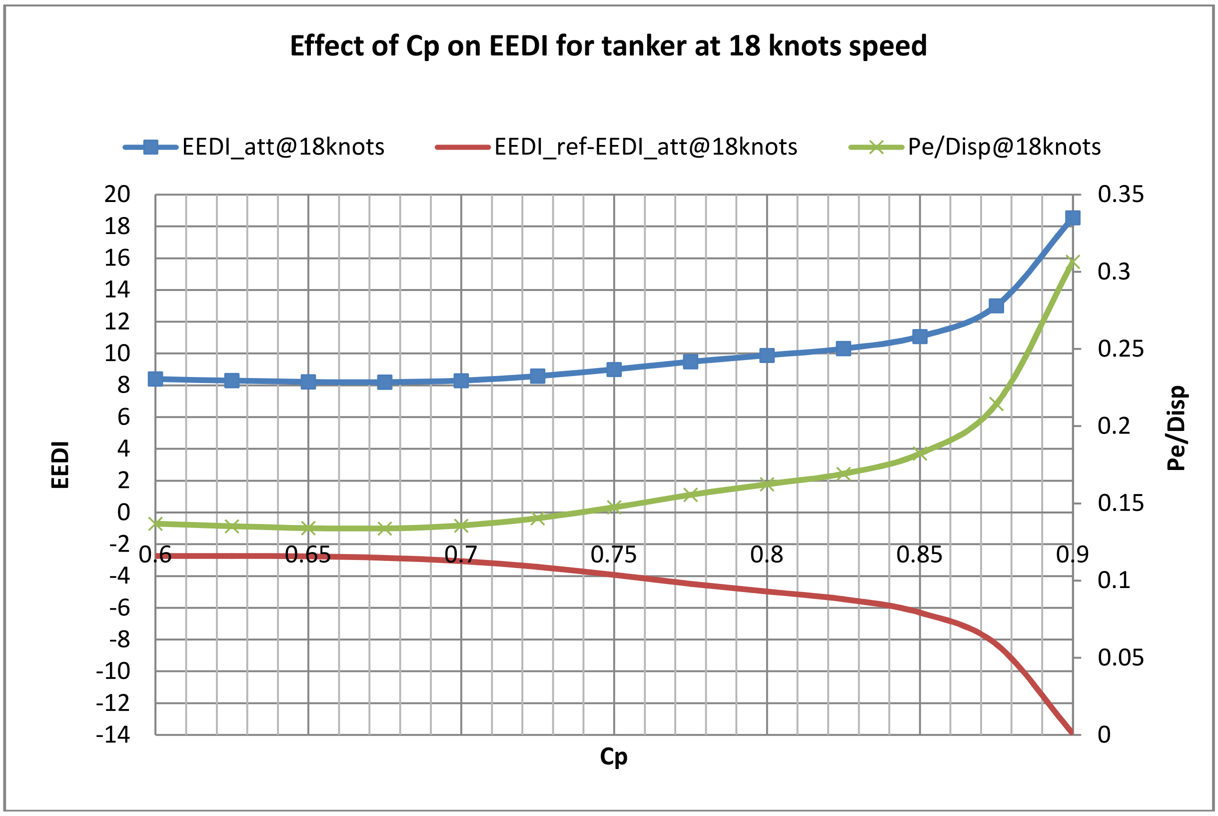

Figure 43: EEDI of Tanker at different Prismatic coefficient at 18 knot Speed

3.3.10 Summary of the analysis

The following table 13 will give the summery of the above analysis.

Table13: Suggestion to change the individual ship parameter to improve EEDI.

Vessel type	Speed	Length	Beam	Draft	L/B	B/T	Prismatic Coefficient, Cp (or, block coefficient, Cb)
Bulk Carrier	Decrease	Decrease (Low Speed), Increase (High speed)	Decrease (Low Speed), Increase (High speed)	Decrease (Low Speed), Increase (High speed)	Increase (Low Speed), decrease (High speed)	Increase (Low Speed), decrease (High speed)	Decrease
Container	Decrease	Decrease (Low Speed), Increase (High speed)	Decrease (Low Speed), Increase (High speed)	Decrease (Low Speed), Increase (High speed)	Increase (Low Speed), decrease (High speed)	Increase (Low Speed), decrease (High speed)	Decrease
Tanker	Decrease	Decrease (Low Speed), Increase (High speed)	Decrease (Low Speed), Increase (High speed)	Decrease (Low Speed), Increase (High speed)	Increase (Low Speed), decrease (High speed)	Increase (Low Speed), decrease (High speed)	Decrease

3.3.11 Best Design parameters for Bulk Carrier, Container and Oil Tanker

It is of interest, based on above analysis, what should be the best design parameters for a bulk carrier or tanker or an oil tanker? As mentioned before, individual impact of a ship parameter on EEDI could be different when a holistic approach is considered for optimization, because all the parameters are connected to each other in some way. So, it is possible to see the individual impact, but decision should be taken after doing a combined effort of all parameters.

In table 14-16, two different sized bulk carrier, container vessel and oil tanker have been analysed, to see maximum possible speed, where the combined impact of all the parameters are considered and optimized for the best result in terms of EEDI and speed.

Table 14: Maximum attainable speed for a large and small bulk carrier

Speed (knot)	Length (m)	Fn	L/B	Beam (m)	B/T	Draft (m)	Cp	Capacity (Tonne)	$EEDI_{ATT}$	$EEDI_{REF}$
15.35	300	0.15	7.1	42.3	2.4	17.6	0.73	135707.4	3.414	3.426
14.34	125	0.21	6.2	20.2	2.4	8.4	0.73	12873.7	10.53	10.537

Table 15: Maximum attainable speed for a large and small container vessel

Speed (knot)	Length (m)	Fn	L/B	Beam (m)	B/T	Draft (m)	Cp	Capacity (Tonne)	$EEDI_{ATT}$	$EEDI_{REF}$
25.9	250	0.27	6	41.66	3	13.8	0.55	52915.22	21.16	21.184
18.7	125	0.27	6	20.83	3	6.9	0.67	8057.545	30.58	30.866

Table 16: Maximum attainable speed for different range of oil tankers (for constant block coefficient of 0.72)

Vessel Type	Speed (Knot)	Length (m)	Fn	Beam (m)	Draft (m)	Capacity (Tonne)	MCR_{ME} (kW)	Allowed MCR_{ME} (kW)
Small Range Tanker	16.17	120	0.24	21.05	7.51	10093	4973	4983
General Purpose Tanker	16.77	160	0.21	28.07	10.02	23924	8027	8039
Medium Range Tanker	17	190	0.20	33.33	11.90	40062	10553	10611
Large Range Tanker_1+Panamax	17.21	230	0.18	40.35	14.41	71066	14401	14407
Large Range Tanker_2+Aframax	17.25	270	0.17	47.36	16.91	114966	18461	18473
Suezmax	17.22	300	0.16	52.63	18.79	157704	21665	21680
VLCC	17.1	350	0.15	61.40	21.92	250429	27249	27281
ULCC	16.78	450	0.12	78.94	28.19	532253	39340	39382

3.3.12 Comments on present EEDI reference line

Figure 44 and 45 gives the EEDI reference line and maximum allowable power at present condition for different types of vessels. It is very interesting to see that the reference line for the General Cargo vessel is intersecting the reference line for combination carrier, gas carrier, and bulk carrier. All the other lines look quite symmetric. The reason is the large scattered data in Lloyd's register's IHS Fair play database. The large scatter and poor correlation of the reference line values are due to the inclusion of highly specialized tonnage under the definition of cargo ships, as mentioned in MEPC documents 62/6/12, paragraphs 3 to 7, 9 and MEPC 62/INF.17.

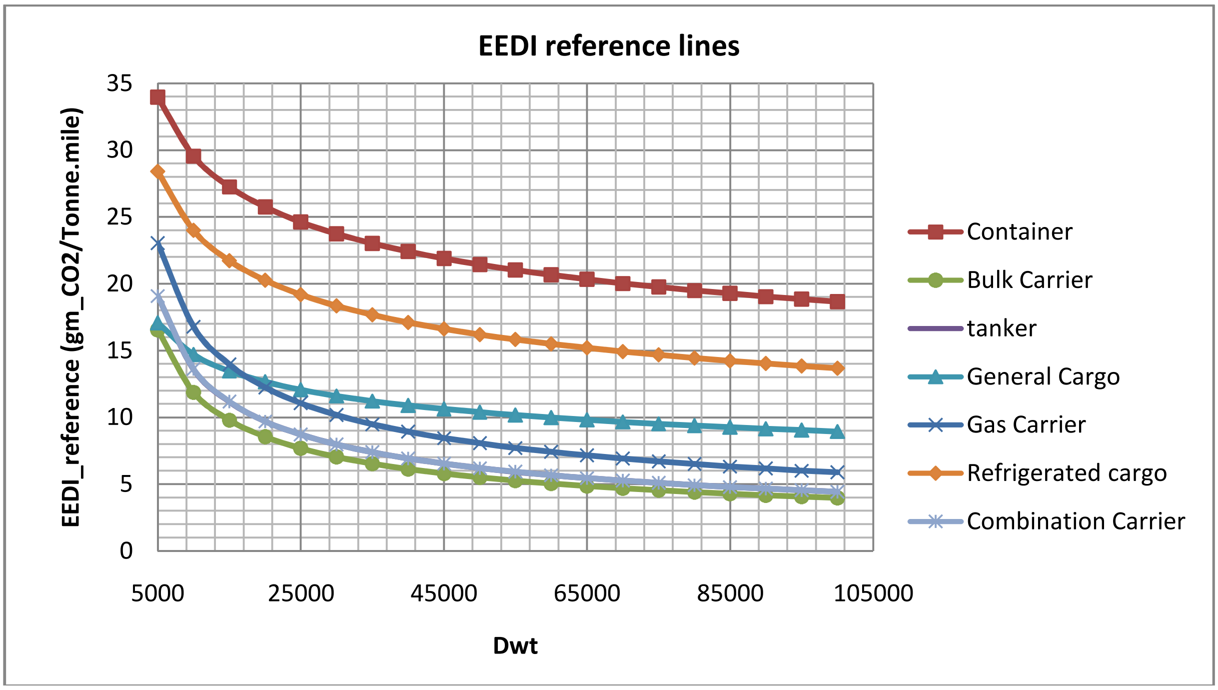

Figure 44: EEDI reference line at present for different types of vessels

Figure 45 gives a clear idea that, the container vessels are allowed to have higher engine power or higher speed. Historically, according to the database, container vessels are allowed to have higher engine power and speed but tankers or bulk carriers are not. Now, if a ship owner wants to have higher speed in his tanker or bulk carrier (especially in short shipping), he is not allowed to do that. In that case there is a possibility of cheating. The ship owner could declare the vessel as general cargo instead of bulk carrier. At this point, the question appears whether the reference line should be based on historical data or pure hydrodynamic calculations.

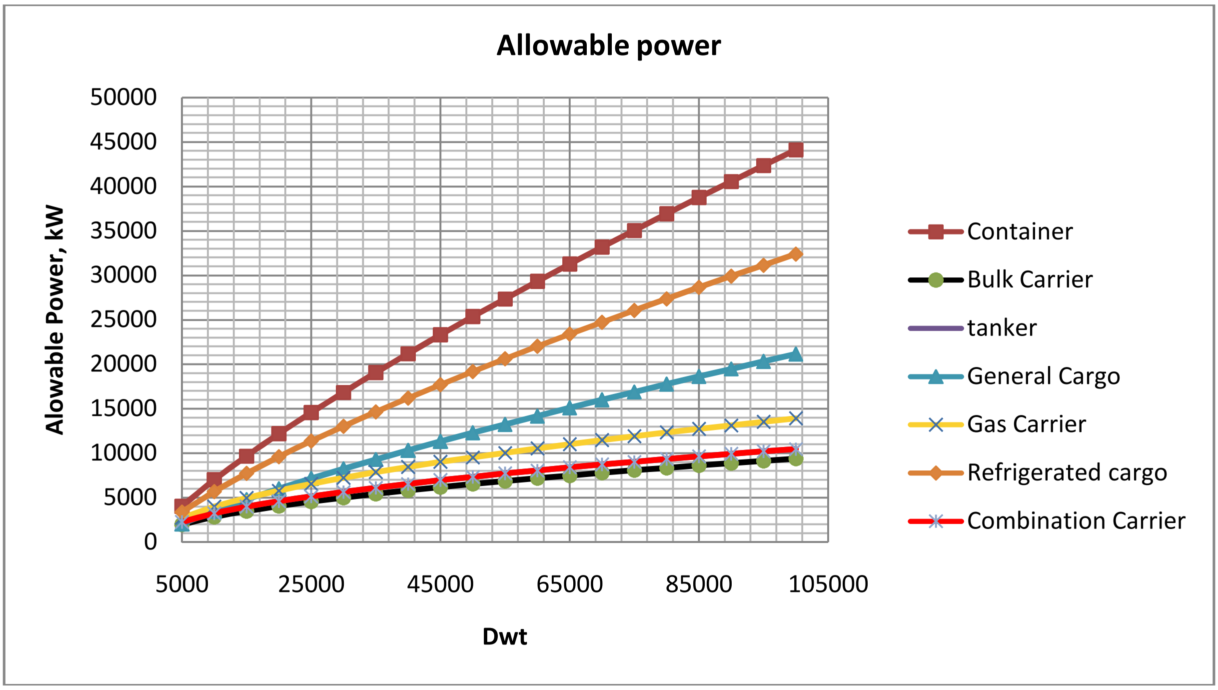

Figure 45: Maximum allowable power for types of vessels according to present reference line

3.3.13 Cost Effectiveness Analysis for a Panamax Tanker

The cost effectiveness for a Panamax tanker (75000 tonne dwt) is based on a supplied operational cost. With the principle dimension of that vessel, the total main engine power was calculated and the total fuel oil consumption was calculated for that specific main engine power. After that, the other maintenance costs are considered and it is all this costs are calculated for 15 years, with the assumption that, approximately a vessel has a 15 earning years. All the docking costs needed for 15 years are also included.

The vessel has the initial length of 235 meter and the above procedure was done for 240, 245, 250, 255, 260 meters of length, adjusting the block coefficient to have the same dead weight. The mission was to see the impact on fuel consumption, total cost and EEDI from the basic ship. The results are shown in figure 46-48.

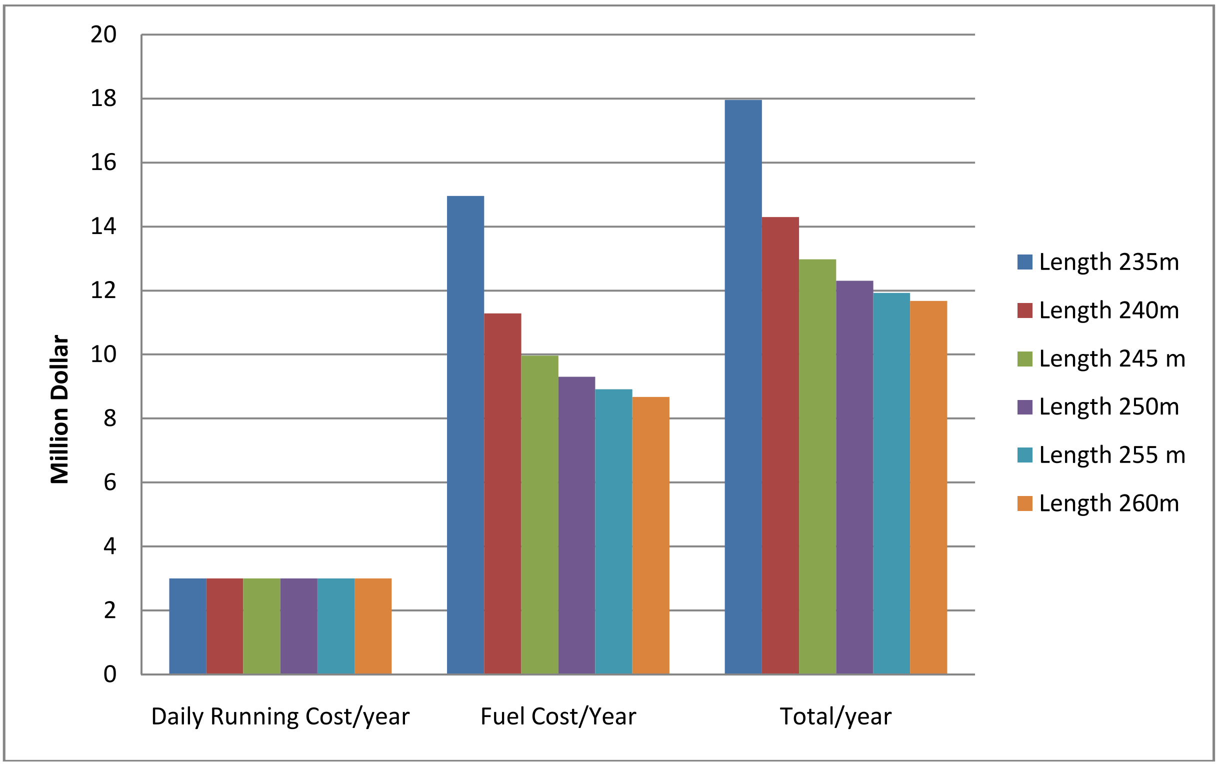

Figure 46: Daily running, Fuel cost and total cost per year for a 75000 TDW panamax tanker at different length at ship speed 16 knots.

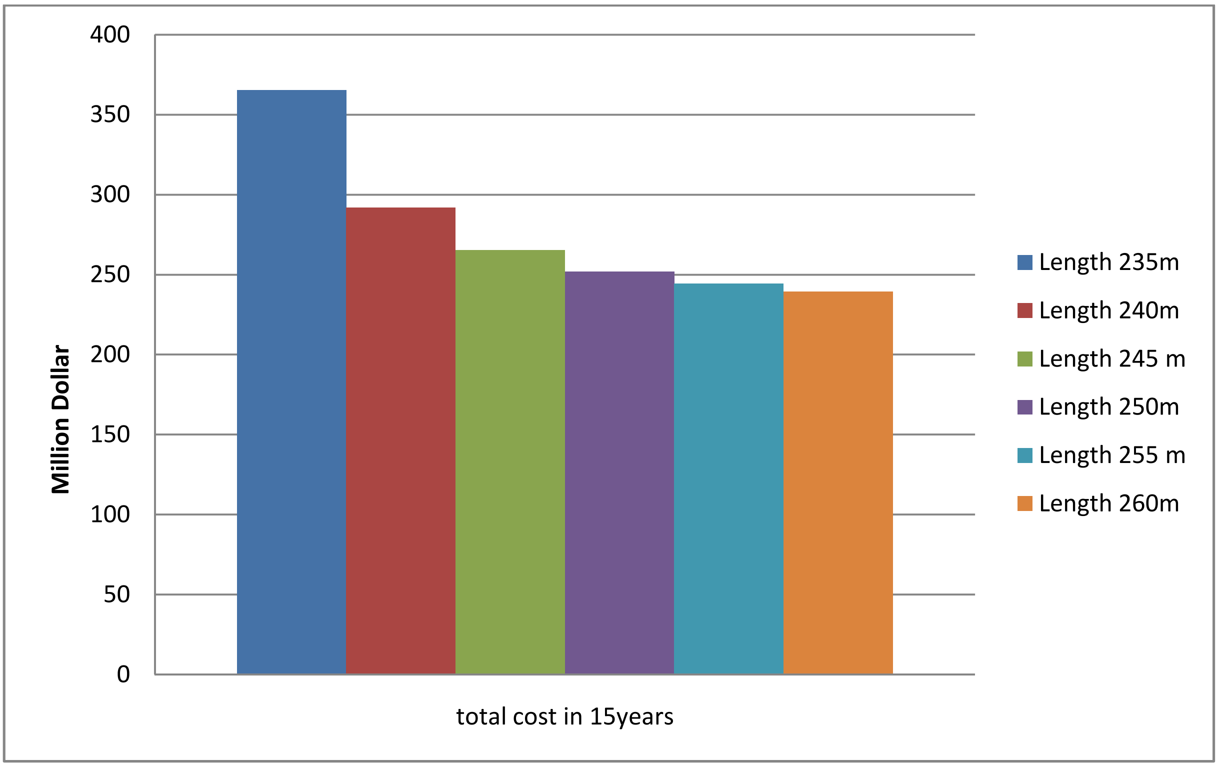

Figure 47: Total cost for a 75000TDW panamax tanker for 15 years at different length at ship speed 16 knots.

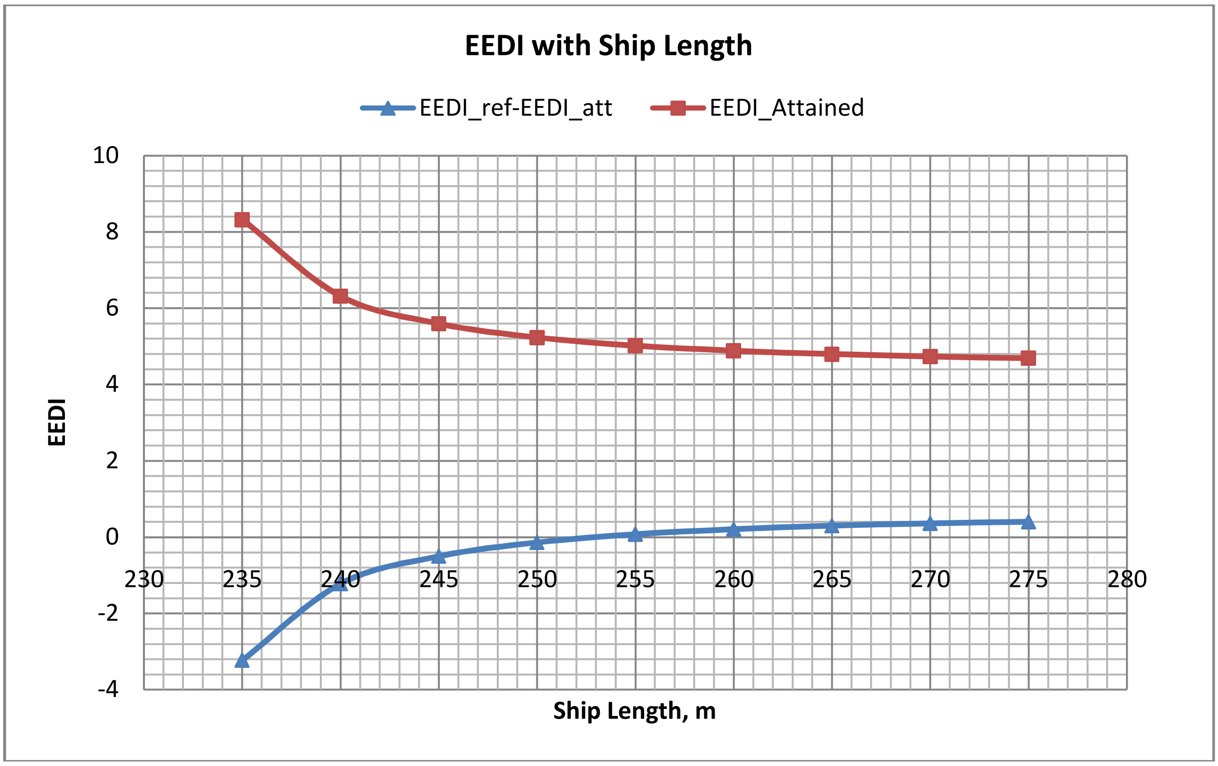

Figure 48: EEDI and EEDI_Reference – EEDI_attained with respect to ship length for a 75000 TDW panamax tanker at ship speed 16 knots.

4. Discussion

In this thesis, it was tried to find the background of the EEDI and application of other indexes than EEDI. But the most important part was to analyse the effect on ship design and hydrodynamics of ship. All the three types of ship that is shown in the analysis in section 3 has shown almost similar pattern of curves. A Ropax vessel was also analyzed in similar fashion, but it is not presented in this paper as in the adopted resolution by the IMO, Ropax vessel is not included.

Now the big question of this thesis was to find out, how EEDI will give impact on the ship design parameters. For all the three types of vessels, it can be said that, if the vessel is to be designed for slow speed (10-12knots), it is better to have small length, breadth, draft and the prismatic coefficient (Cp) for all speeds, as $EEDI_{reference} - EEDI_{attained}$ value decreases with the increase of these parameters. On the other hand, it is better to increase L/B and B/T at slow speed but, decrease at high speed. This means, the present EEDI formula will influence the designer and ship owner to build small ships (in terms of dimension) in low speed range.

When we investigate the curves for different ship parameters, it can be said that, influence of speed and length has the highest impact on EEDI, then the beam. Draft and prismatic coefficient does not have very high influence. So, it is clear from this point of view, if a designer wants to change the value of EEDI for a particular ship, he/she should look in to the speed and length first, then beam, draft and the prismatic coefficient.

An Effective power/Displacement curve is produced for every case to investigate the variation of $EEDI_{attained}$ and Effective power/Displacement curve with different ship design parameters. This ratio is actually composed of all hydrodynamic effect of ship. The variation of $EEDI_{attained}$ and Effective power/Displacement curve with different ship parameters has given the similar trend, that is either both decrease or both increase. It proves that, the present EEDI formula is not violating the hydrodynamic law of naval architecture.

5. Conclusions

The EEDI can be treated as a measure of transport efficiency, such that, the maximum amount of cargo that can be carried with minimum fuel consumption. Though the main intention of adopting EEDI is to reduce the CO_2 emission from the shipping industry, it also force the shipping industry to have more and more energy efficient ships, as CO_2 emission is almost proportional to fuel consumption and fuel consumption is the proportional reflection of total hull resistance. So, an improvement in EEDI of a vessel also means the improvement of ship hull resistance.

It can be criticised that small vessels are allowed to have higher EEDI (according to present reference line in figure 4). So it does not make sense when we compare a small and large vessel in terms of EEDI. If we only investigate the present reference line, it can be said easily that present EEDI is allowing small vessels to have higher EEDI and vice versa. It means smaller vessels are allowed to have higher speed than large vessel. But it is not true! Table 14, 15, and 16 describes it well, where it has been shown that larger vessel can achieve higher speed than smaller ones. The reason is, though the reference line allows having a higher EEDI for small vessels that does not mean that, small vessel can attain low EEDI. In table 14-16, all the physical aspects of ship has been considered and it shows that the attained EEDI for small vessel is also very high. So it can be concluded that the reference line allows higher EEDI for smaller vessels because at that range, the attained EEDI is also very high.

But it is true that, no matter how we modify or improve the hull design, it will not be enough to have a vessel that will have the same present speed with 30% reduction of EEDI (Phase 3 of CO_2 reduction). The present efficient hulls are good enough in most cases to comply the current phase 0 and, with some modification of hull parameters and improved hull design, phase 1 requirements can be achieved without reducing the speed, but it is not possible for further phases. So, at present status, it can be said that, it will cut off the ship speed and eventually the power requirement.

The power and speed cut off will definitely influence the shipping economy. The impact of EEDI on ship design should be treated for good, as it will save the fuel for the ship owners and, no doubt the bunker price will increase day by day. The ship owners/operators have to reduce the operating speed of ship anyway to save fuel.

An important aspect that is missing in current EEDI regulations is the sister vessel dilemma. Current EEDI regulations destroys the sister vessel concept. Let say, for a number of sister vessels, keel lay of one sister vessel is in phase 0 and another one is in phase 1. So, the 2nd vessel has to be modified in some way to achieve the EEDI requirements of Phase 1 and for this reason these two vessels cannot be sister anymore!

It is of real interests whether this regulation will really reduce the CO_2 emission or not. The present IMO regulations do not cover all types of vessels. Their plan is to finalize the current EEDI regulations and introduce appropriate reference line for the vessels that were not considered in the current regulations (RoPax and Passenger vessels are not covered yet) in the coming MEPC meetings. Again if we consider a vessel life of 25 years, the vessels built until phase 0 (no reduction required) will give service until 2038, emitting at the same rate. So, the real effect can be observed, perhaps after a decade! According to MEPC document number 63/INF.2 (ASSESSMENT OF IMO MANDATED ENERGY EFFICIENCY MEASURES

FOR INTERNATIONAL SHIPPING), 'the effect of EEDI will occur only as and when older, less efficient, tonnage is replaced by new, more efficient tonnage.'

Though EEDI is not an accurate emission indicator at present it is good in all aspect to have an emission control instrument at the design stage. In future, the formulation could be modified by introducing new coefficients or present coefficient values to make the EEDI more meaningful and efficient.

6. Future work

In this paper, only three types of vessels have been investigated. Other types of vessel should also be analysed to understand the impact of EEDI on design and hydrodynamics. It would be interesting to see and compare the hydrodynamically optimized result and EEDI optimized design. It was investigated here in this paper by comparing the Effective power/Displacement and $EEDI_{attatined}$ curves but, more hydrodynamic impacts can be analysed.

EEDI can be used only as a design parameter at present, not an accurate CO_2 emission indicator as the formulation considers the installed main engine's maximum continues rating. But a vessel has different loading conditions, (in terms of capacity, power and electric power consumption), which the present formulation does not cover. A vessel having an EEDI of 5 gm/tonne-mile does not mean that, she always emits at the same rate. It would be a good future work to analyse EEDI at different loading condition, to investigate the maximum achievable speed at different cargo loading cases.

The Energy Efficiency Operational Index is the actual indicator of CO_2 emission as it does not consider the installed power and maximum cargo capacity; rather it is based on operational data. It would be a nice to establish a relationship between EEDI and EEOI in a sense that, EEOI is always less than EEDI. As both the EEDI and EEOI have the same unit ($gram_{CO2}$/Tonne.mile) this relationship would be good to describe the actual CO_2 emission.

An import investigation can be made by analysing two existing vessels of same type where one vessel is above the reference line and another one is below. This practical investigation will help to describe what makes a vessel more efficient in terms of EEDI. This result can be compared with the suggestion made in this paper.

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