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Influence of Design Parameters on the Energy Efficiency Design Index (EEDI)

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Abstract: Historically, the price of fuel has been the primary driver for improved efficiency and reduced fuel consumption on commercial ships. The highly competitive nature of the maritime industries meant that efforts to bring down fuel consumption were cost effective solutions, leading to overall optimization of the transport system. The IMO is developing the Energy Efficiency Design Index (EEDI) for new ships, which is a gauge of a ship's CO_2 efficiency. The EEDI is a simple formula that estimates CO_2 output per tonne-mile. Market mechanisms will be attached to the EEDI, providing ship owners with another economic driver for reducing CO_2 emissions. There are challenges in creating an EEDI and associated baseline that are straightforward enough to be enforceable and sophisticated enough to promote emissions reduction in a cost-effective manner.

ABS and HEC have jointly conducted a study which investigates the robustness of the EEDI and the potential shortcomings of the index by evaluating a parametric series of designs for three different ship types: tankers, containerships, and LNG carriers. By developing the series of "standard" designs based on good design practice and consistent assumptions, the analysis provides a comparative basis for assessing the relative impact of assumptions such as the ship's speed, deadweight and cargo carrying capability, and special features such as enhanced scantlings. By calculating CO_2 emissions for representative round trip voyages for each of the designs, the study provides a basis for assessing whether the EEDI correlates with expected CO_2 emissions. Finally, by evaluating the required freight rate per unit of cargo moved, the study provides background on the relative benefit-cost implications of various greenhouse reduction measures available to the ship designer. This report summarizes the findings from this study, which were submitted to SNAME T&R Ad Hoc Panel 18 tasked with investigating the EEDI. The results are summarized in document MEPC 60/4/34, which has been submitted to IMO for consideration.

1. Overview: IMO Energy Efficiency Design Index (EEDI)

The Energy Efficiency Design Index has been developed by the IMO over the past several years through a series of submissions to MEPCs 57-59 and the 1st and 2nd Working Groups on Greenhouse Gases.

After the 2nd intersessional meeting of the Working Group on Greenhouse Gas Emissions from Ships, the equation was refined to the following form,

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

The equation retains this form in the most recent MEPC .1/ Circ. 681, "Interim Guidelines on the Method of Calculation of the Energy Efficiency Design Index for New Ships."

For further details on the background to the EEDI and the proposed baseline, refer to reference 1.

Explanation of Terms

Conversion Factors (C_{FME} and C_{FAE})

Conversion factors are given for five categories of fuels used in the marine industry. The conversion factors were selected to be consistent with the Energy Efficiency Operator Indicator (EEOI) and the International Panel on Climate Change (IPCC) emission factors. The factors give the equivalent mass emission of CO_2 from combustion of a given mass of fuel. Specific values for fuel carbon contents and complete combustion are assumed. The type of fuel used in the calculation should be the same as the fuel burned in the determination of the specific fuel consumption on the Engine International Air Pollution Prevention (EIAPP) certificate.

Specific Fuel Consumption (SFC_{ME} and SFC_{AE})

Specific fuel consumption (SFC) is divided into two categories: main engine and auxiliary engine fuel consumption. Main engine fuel consumption is the SFC reported on the EIAPP Certificate for the parent engine in accordance with the NO_x Technical Code at 75% of the Maximum Continuous Rating (MCR). Auxiliary engine fuel consumption is the fuel consumption reported on the parent engine's EIAPP Certificate at 50% of the MCR. If different sized auxiliary engines are used, a single SFC is entered into the equation by taking the weighted average of the different engines.

Power (P_{ME}, P_{AE}, and P_{PTI})

Power from the main engine, P_{ME}, is 75% of the MCR of the engine, in kW, minus the output of any shaft generators. Power from auxiliary engines is determined by an empirical formula representing the hotel load and electrical needs for propulsion systems and machinery. Auxiliary power is taken as a function of the MCR of the main engine(s). This formula is adjusted slightly for vessels that have smaller propulsion engines with an installed power less than 10,000 kW. Additional shaft motor inputs are given at 75% of the rated power consumption divided by the weighted average of the efficiency of the generators.

$$P_{AE(MCRME>10000KW)} = \left(0.025 \times \sum_{i=1}^{nME} MCR_{MEi}\right) + 250$$

$$P_{AE(MCRME<10000KW)} = 0.05 \times \sum_{i=1}^{nME} MCR_{MEi}$$

Speed (V_{ref})

The speed used in the EEDI is the vessel's speed when operating at a draft corresponding to the specified capacity, at a trim as defined by the corresponding condition specified in the approved stability booklet. The speed assumes the vessel is operating at power level P_{ME}, in deep water and in calm weather (no winds or waves).

Capacity (*Capacity*)

Capacity is defined as deadweight for tankers, LNG carriers, and containerships. Capacity for tankers and LNG carriers is taken as the deadweight at the summer load line (SLL) draft.

Capacity for containerships is adjusted to be 65% of the SLL deadweight in order to better represent the normal design condition.

Innovative Energy Efficiency Technologies (P_{eff}, P_{AEeff}, and f_{eff})

Innovative technologies that provide mechanical or electrical power reductions are accounted for with the P_{eff} and P_{AEeff} terms respectively. An availability factor, f_{eff}, is given for each technology to estimate what percent of the time the technology is available during normal "at-sea" conditions.

Correction Factors (f_i, f_j, and f_w)

The correction factor f_i accounts for ship specific design elements and the factor, f_j, accounts for any technical or regulatory limit on capacity. Currently, these factors are only used for ships designed with an ice class notation. f_w is a factor representing the decrease in speed in certain sea conditions.

2. Analysis Approach

For each of the three ship types evaluated in this study (oil tankers, containerships, and LNG carriers), representative ship designs covering the more typical ship sizes have been developed (see Table 1).

Oil Tankers	Panamax Product	Aframax Crude	Suezmax Crude	VLCC Crude
100% Cargo Capacity (m^3)	54,000	132,000	180,000	360,000
Attained EEDI (EEDI$_A$)	5.95	3.73	3.14	2.53
Baseline EEDI (EEDI$_{BL}$)	6.11	3.86	3.19	2.32
%EEDI = (EEDI$_A$/EEDI$_{BL}$) - 1	-2.7%	-3.5%	-1.5%	9.2%

Containerships	Feedership	Panamax	Baby Neo-Panamax	Post-Panamax	Ultra Large
Slot Capacity (TEUs)	1,000	4,500	4,500	8,000	12,500
Attained EEDI (EEDI$_A$)	25.18	17.99	18.64	16.17	14.01
Baseline EEDI (EEDI$_{BL}$)	27.26	19.87	19.73	17.87	16.37
%EEDI = (EEDI$_A$/EEDI$_{BL}$) - 1	-7.6%	-9.5%	-5.6%	-9.5%	-14.4%

LNG Carriers Propulsion Plant Shafting Configuration	DFDE Single	DFDE Single	DFDE Single	DRL Twin	DRL Twin	DRL Twin
100% Cargo Capacity	150,000	180,000	215,000	180,000	215,000	265,000
Fuel Type (MDO)						
Attained EEDI (EEDI$_A$)	8.87	8.36	7.89	6.68	6.23	5.87
Baseline EEDI (EEDI$_{BL}$)	6.76	6.32	5.85	6.35	5.88	5.37
%EEDI = (EEDI$_A$/EEDI$_{BL}$) - 1	31.2%	32.2%	34.9%	5.2%	5.9%	9.4%
Fuel Type (LNG)						
Attained EEDI (EEDI$_A$)	5.93	5.59	5.28			
Baseline EEDI (EEDI$_{BL}$)	6.76	6.32	5.85			
%EEDI = (EEDI$_A$/EEDI$_{BL}$) - 1	-12.2%	-11.5%	-9.7%			

Table 1 Sizes for "Standard" Ship Designs

These designs are herein referred to as the "standard" designs. The basic steps taken in developing these standard ship designs and calculating their attained EEDI are described in Reference 1. For each standard design, a voyage was chosen that is representative of a typical voyage for existing ships of that type and size. The chosen voyages and their distances are listed in Table 2. For each roundtrip voyage, the total CO_2 production is calculated, as well as the Energy Efficiency Operating Index (EEOI), per MEPC.1/Circ. 684. These values are used to compare the actual carbon emissions of the ship to the cargo payload and distance moved. The total CO_2 production and EEOI are expected to differ somewhat from the EEDI as they include in-port emissions, ballast leg emissions, the actual type of fuel burned in lieu of the fuel type appearing on the EIAPP certificate, the SFC at the expected load on the main engine rather than 75% MCR, fuel consumption related to reefer containers, reliquefaction plants and other high electric load requirements not explicitly covered in the EEDI, etc. However, the trends in the values of total CO_2 production and the EEOI should follow the attained EEDI, and can be used to verify that the EEDI reasonably represents projected CO_2 emissions per tonne-mile.

The required freight rate was calculated when deemed useful for evaluating the cost-benefit of an alternative arrangement. The RFR is an estimation of the revenue per unit transport needed to cover costs (both capital and operational). As the inventory cost will vary with changes in transit time, the inventory cost is included in the RFR calculations. The RFR may be used as an indication of the ship owner's willingness to explore alternative designs as a reduction in RFR shows a potential for increased profit.

The following representative voyage itineraries are assumed for this study. Tankers and LNG carriers are assumed fully loaded outbound and in-ballast on the return voyage. Containerships are assumed loaded on all legs.

Tankers	Panamax Product 54,000 m^3	Aframax Crude 132,000 m^3	Suezmax Crude 180,000 m^3	VLCC Crude 360,000 m^3
Load Port	Puerto La Cruz	TEBAR	Bonny	Ras Tanura
Discharge Port	Houston	LOOP	LOOP	Chiba
Roundtrip Distance (nm)	4,212	10,290	11,754	13,132

Containerships	Feedership 1,000 TEUs	Panamax 4,500 TEUs	Baby Neo-Panamax 4,500 TEUs	Post-Panamax 8,000 TEUs	Ultra Large 12,500 TEUs
Leg 1 Ports	Singapore	Los Angeles	Los Angeles	Los Angeles	Los Angeles
	Jakarta	Oakland	Oakland		
Leg 2 Ports	Panjang	Ningbo	Ningbo	Shanghai	Shanghai
	Tanjung, Pelepas	Shanghai	Shanghai		
Roundtrip Distance (nm)	1,317	11,665	11,665	11,380	11,380

LNG Carriers	150,000 m^3	180,000 m^3	215,000 m^3	265,000 m^3
Load Port	Ras Laffan	Bonny	Ras Laffan	Ras Laffan
Discharge Port	Montoir	Sabine Pass	Inchon	Sabine Pass
Roundtrip Distance (nm)	11,890	12,130	12,238	19,316

Table 2 Round Trip Voyages for EEOI and RFR Analyses

Calculation of CO_2 Emissions

Carbon Content of Fuel Oil and Gas

The amount of carbon dioxide produced is directly related to the amount of fuel burned and the carbon content of the fuel. In order to maintain the calculations consistent with the Energy Efficiency Design Index (EEDI), the carbon content of fuels as defined by the EEDI method are applied for this study. The assumed carbon content of fuels is presented in Table 3.

Conversion Factors	Reference	Carbon Content	Cf (t-CO_2/t-Fuel)
Diesel / Gas Oil	ISO 8217 Grades DMX through DMC	0.875	3.20600
Light Fuel Oil	ISO 8217 Grades RMA through RMD	0.860	3.15104
Heavy Fuel Oil	ISO 8217 Grades RME through RMK	0.850	3.11440
Liquid Petroleum Gas (Propane)	2006 IPCC Guidelines Table 1.2 and 3.5.2	0.819	3.00000
Liquid Petroleum Gas (Butane)	2006 IPCC Guidelines Table 1.2 and 3.5.2	0.827	3.03000
Natural Gas	2006 IPCC Guidelines Table 1.2 and 3.5.2	0.750	2.75000

Table 3 Carbon Content of Fuels

The carbon content factors (*Cf*) were multiplied by the fuel consumed per voyage to determine the total tonnes of CO_2 produced.

Fuel Consumption Calculations

Total fuel consumption is taken as the sum of the fuel burned for each portion of the voyage (herein referred to as each voyage leg):

At Sea Loaded
At Sea Ballast
Maneuvering Loaded & Canal Transit
Maneuvering Ballast & Canal Transit
At Anchor
Port Loading
Port Discharging
Port Waiting

The CO_2 production for each leg of the voyage is calculated as follows:

$$CO_2 \text{ Production} = \text{Time} * [(ME_{LOAD} * SFC_{ME} * Cf_{ME}) + (SSDG_{LOAD} * SFC_{SSDG} * Cf_{SSDG})]$$

where

Time = duration of voyage leg
ME_{LOAD} = average main engine(s) output in kW
SFC_{ME} = specific fuel oil consumption for main engine at average loading
Cf_{ME} = carbon content of fuel being consumed by the main engine
$SSDG_{LOAD}$ = average output for auxiliary engines in kW

SFC_{SSDG} = specific fuel oil consumption for SSDG engines at average loading
Cf_{SSDG} = carbon content of fuel being consumed by the auxiliary generator engines

For propulsion plants that burn fuel oil, HFO is assumed for at-sea conditions outside of ECA's. Consumption of distillate fuel is assumed when the vessel is within an Emissions Control Area (ECA). These analyses assume compliance with the 200 nm ECA around North America scheduled for implementation in 2012.

For the tanker and containership slow speed diesel plants and for the LNG carrier slow speed diesel plus reliquefaction (DRL) plants, SFC rates for the main engine and auxiliary generator engines are based on the MAN B&W published consumption figures for the selected engines. The maker's quoted figures under ISO conditions are adjusted for the maker's tolerance and the heating value for HFO. SFC is calculated for the projected load anticipated for each voyage leg.

For LNG carrier DFDE propulsion plants, SFC rates for the medium speed dual fuel engines that provide power for the main propulsion motors and ship service generators are based on the MAN B&W published consumption figures for the selected engines. The maker's quoted figures under ISO conditions are adjusted for built-on pumps (LO pump, LT cooling pump, and HT cooling pump), the maker's tolerance and the heating value for the fuel oil. Electric output is taken as 97% of mechanical output. DFDE plants use an additional efficiency of 94.1% to calculate power out of the propulsion motor. This additional factor accounts for the efficiency of the transformers, frequency controllers, and electric motor.

A sample calculation of CO_2 production for the roundtrip transpacific voyage of an 8,000 TEU containership is presented in Table 4.

HFO Consumption	Time Days	Fuel Cons. kg/hr	Fuel Cons tonnes	CO_2 Emissions tonnes
At Sea - Westbound	9.21	8,824	1,950.9	6,076
At Sea - Eastbound	9.21	8,824	1,950.9	6,076
Maneuvering - Westbound	0.07	3,026	5.3	16
Maneuvering - Eastbound	0.07	3,026	5.3	16
At Anchor	0.00	1,098	0.0	0
Port - Cargo Ops	1.58	1,098	41.6	130
Port - Waiting Time	0.04	1,098	1.1	3
Sub Total (HFO)	20.19		3,955.1	12,318

MGO Consumption within ECA	Time Days	Fuel Cons. kg/hr	Fuel Cons tonnes	CO_2 Emissions tonnes
At Sea - Westbound	1.04	8,404	210.1	674
At Sea - Eastbound	1.04	8,404	210.1	674
Maneuvering - Westbound	0.00	1,786	0.0	0
Maneuvering - Eastbound	0.07	2,882	5.0	16
At Anchor	0.00	700	0.0	0
Port - Waiting Time	0.04	700	0.7	2
Port - Cargo Ops	0.13	700	2.1	7
Sub Total (MGO)	2.32		428.0	1,372
Total Voyage	22.51		4,383.0	13,690

Table 4 Sample Voyage CO_2 Production Calculation

Calculation of EEOI

The Energy Efficiency Operating Index (EEOI) is tool that has been developed by the IMO to "assist shipowners, ship operators, and parties concerned in the evaluation of the performance of their fleet with regard to CO_2 emissions". The current form of the EEOI is presented in MEPC.1/Circ. 684 as the "Guidelines for Voluntary Use of the Ship Energy Efficiency Operational Indicator (EEOI)." The EEOI is calculated by dividing the total trip carbon production by the transportation work. The equation, as presented in Circ. 684, for one voyage is:

$$\text{EEOI} = \frac{\sum_{j} FC_j \times C_{Fj}}{m_{cargo} \times D}$$

and for multi leg trips:

$$\text{Average EEOI} = \frac{\sum_{i}\sum_{j} (FC_{ij} \times C_{Fj})}{\sum_{i} (m_{cargo,i} \times D_i)}$$

Where:

- j is the fuel type;
- i is the voyage number;
- FC_{ij} 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.

The cargo payload has the units of tonnes for oil tankers and LNG carriers, and the units of TEU for containerships. Thus, the EEOI units are tonnes CO_2/t-nm for tankers and LNG carriers, and tonnes CO_2/TEU-nm for containerships. As these units produce rather large numbers, in this report EEOI values are presented in terms of grams CO_2 /t-nm and grams CO_2 /TEU-nm.

Calculation of RFR

The required freight rate (RFR) is calculated by taking the sum of the round trip voyage expenses and dividing by the cargo throughput. RFR is expressed in terms of U.S. dollars per barrel of oil moved ($/bbl) for tankers, U.S. dollars per million BTU moved ($/mBTU) for LNG carriers, and U.S. dollars per TEU moved ($/TEU) for containerships.

Round trip voyage expenses are taken as the sum of charter expenses, fuel oil costs, port charges, and canal tolls. Charter expenses are estimated by calculating the annual capital recovery related to ship construction costs and operating costs (crew costs, provisions, stores & supplies, lube oil, spare parts, maintenance & repair, drydocking costs, insurance, and management fees). Additionally an inventory rate is applied which accounts for the inventory cost of the cargo to the shipper.

For this study, the following fuel costs are assumed:

HFO = \$500 / tonne
MGO = \$750 / tonne
LNG = \$8/ mBTU

Sensitivity analyses were carried out for fuel at half of the above prices, and twice the above prices.

Total CO_2 Production and the EEOI for the Standard Ship Designs

The EEOI and the calculated total CO_2 emissions per voyage for each of the standard ship designs are shown in Table 5. In general, the EEOI tracks the EEDI. The primary reason that smaller vessels tend to have higher EEOI/EEDI ratios is that the smaller ships are typically used on shorter voyages, whereas large vessels are most suited for long haul trades. The large discrepancy between the EEOI/EEDI ratio for the Panamax and Baby Neo-Panamax containerships is discussed in Section 4.

Tankers		**Panamax Product**	**Aframax Crude**	**Suezmax Crude**	**VLCC Crude**
100% Cargo Capacity	m^3	54,000	132,000	180,000	360,000
Attained EEDI (*$EEDI_A$*)		5.95	3.73	3.14	2.53
Total CO_2 Emissions	tonnes	1545	5385	7375	12312
EEOI	g CO2/t-nm	14.6	8.5	7.5	5.6
EEOI/EEDI ratio		2.5	2.3	2.4	2.2

Containerships		**Feedership**	**Panamax**	**Baby Neo-Panamax**	**Post-Panamax**	**Ultra Large**
Slot Capacity		1,000	4,500	4,500	8,000	12,500
Attained EEDI (EEDIA)		25.18	17.99	18.64	16.17	14.01
Total CO_2 Emissions	tonnes	364	8576	9376	13604	17272
EEOI	g CO2/TEU-nm	578	434	382	318	281
EEOI/EEDI ratio		23.0	24.1	20.5	19.6	20.0

LNG Carriers		**DFDE Single**	**DFDE Single**	**DFDE Single**	**DRL Twin**	**DRL Twin**	**DRL Twin**
100% Cargo Capacity	m^3	150,000	180,000	215,000	180,000	215,000	265,000
Attained EEDI (LNG)		5.93	5.59	5.28			
Attained EEDI (MDO)		8.87	8.36	7.89	6.68	6.23	5.87
Total CO_2 Emissions	tonnes	8896	9987	11363	11967	13809	25080
EEOI	g CO2/t-nm	30	27	26	35	34	31
EEOI/EEDI ratio		5.0	4.9	4.8	5.2	5.4	5.3

Table 5 EEOI and CO_2 Production for the Standard Ship Designs (based on roundtrip voyages)

3. Tanker Studies

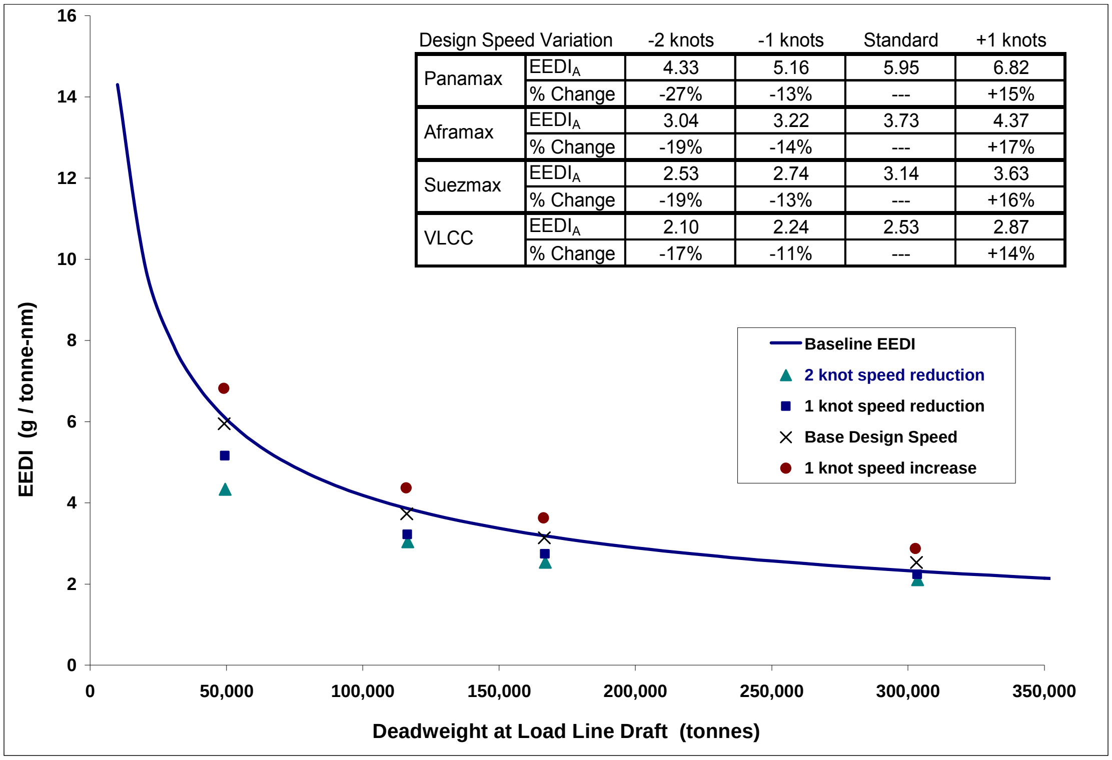
Influence of Service Speed on the EEDI

The EEDI is particularly sensitive to the service speed, as the required power increases by roughly the cube of the variation in service speed ($P \propto V^3$). As shown in Table 6 and Figure 1, increasing speed by 1 knot increases the EEDI by 14% to 17%, whereas reducing the speed by 1 knot reduces the EEDI by 11% to 14%.

When assessing the powering requirements, the most suitable MAN B&W engine was selected for each scenario. The engine is assumed to be de-rated to the power required to attain the design speed at 15% sea margin with the main engine operating at 90% MCR. The smaller engines associated with the slower service speeds may have higher rpm's. The propulsive coefficient is reduced at the higher rpm which somewhat mitigates the benefits of the lower service speed. Table 7 shows the selected main engines, % de-rating, and the associated SFC and RPM values that are applied for this matrix of tanker designs and speeds. Note that the SFC values assume the engine at 75% MCR, burning MDO under ISO conditions. A 3% margin above published SFC figures is included to reflect the anticipated difference between the published values and those shown in the EIAPP certificates.

Design Speed Variation		-2 knots	-1 knots	Standard	+1 knots
Panamax	Service Speed (design)	12.90	13.90	14.90	15.90
	DWT at SLL draft (tonnes)	49,498	49,360	49,203	49,039
	Main Engine MCR (kW)	5,685	7,291	9,222	11,361
	Attained EEDI ($EEDI_A$)	4.33	5.16	5.95	6.82
	Change vs. Standard Design	-27%	-13%	---	+15%
Aframax	Service Speed (design)	13.20	14.20	15.20	16.20
	DWT at SLL draft (tonnes)	116,453	116,337	116,135	115,889
	Main Engine MCR (kW)	9,564	11,073	13,822	17,378
	Attained EEDI ($EEDI_A$)	3.04	3.22	3.73	4.37
	Change vs. Standard Design	-19%	-14%	---	+17%
Suezmax	Service Speed (design)	13.20	14.20	15.20	16.20
	DWT at SLL draft (tonnes)	166,951	166,801	166,576	166,308
	Main Engine MCR (kW)	11,878	13,940	17,185	21,260
	Attained EEDI ($EEDI_A$)	2.53	2.74	3.14	3.63
	Change vs. Standard Design	-19%	-13%	---	+16%
VLCC	Service Speed (design)	13.80	14.80	15.80	16.80
	DWT at SLL draft (tonnes)	303,509	303,320	303,032	302,699
	Main Engine MCR (kW)	19,165	22,097	26,736	32,376
	Attained EEDI ($EEDI_A$)	2.10	2.24	2.53	2.87
	Change vs. Standard Design	-17%	-11%	---	+14%

Table 6 Influence of Service Speed on EEDI for Standard Oil Tankers



Design Speed Variation		-2 knots	-1 knots	Standard	+1 knots
Panamax	$EEDI_A$	4.33	5.16	5.95	6.82
	% Change	-27%	-13%	---	+15%
Aframax	$EEDI_A$	3.04	3.22	3.73	4.37
	% Change	-19%	-14%	---	+17%
Suezmax	$EEDI_A$	2.53	2.74	3.14	3.63
	% Change	-19%	-13%	---	+16%
VLCC	$EEDI_A$	2.10	2.24	2.53	2.87
	% Change	-17%	-11%	---	+14%

Figure 1 EEDI for Oil Tanker Standard Design

Main Engine Selection		-2 knots	-1 knots	Standard	+1 knots
Panamax	Service Speed (design)	12.90	13.90	14.90	15.90
	Reqd MCR (kW)	5,685	7,291	9,222	11,361
	MAN B&W ME Model	6S42MC7	7S42MC7	6S50MC-C8	5S60MC-C8
	% De-Rating	87.7%	96.4%	92.6%	95.5%
	RPM	136	136	127	105
	SFC at 75% MCR (g-kWhr)	182.4	182.4	177.3	176.3
Aframax	Service Speed (design)	12.90	13.90	14.90	15.90
	Reqd MCR (kW)	9,564	11,073	13,822	17,378
	MAN B&W ME Model	6S50MC-C8	5S60MC-C8	6S60MC-C8	8S60MC-C8
	% De-Rating	96.0%	93.0%	96.8%	91.3%
	RPM	127	105	105	105
	SFC at 75% MCR (g-kWhr)	177.3	176.3	176.3	176.3
Suezmax	Service Speed (design)	13.20	14.20	15.20	16.20
	Reqd MCR (kW)	11,878	13,940	17,185	21,260
	MAN B&W ME Model	5S60MC-C8	5S70MC-C8	6S70MC-C8	7S70MC-C8
	% De-Rating	99.8%	85.3%	87.6%	92.9%
	RPM	105	91	91	91
	SFC at 75% MCR (g-kWhr)	176.3	176.3	176.3	176.3
VLCC	Service Speed (design)	13.80	14.80	15.80	16.80
	Reqd MCR (kW)	19,165	22,097	26,736	32,376
	MAN B&W ME Model	6S70MC-C8	6S80MC-C8	7S80MC-C8	8S80MC-C8
	% De-Rating	97.7%	88.1%	91.4%	96.8%
	RPM	91	78	78	78
	SFC at 75% MCR (g-kWhr)	176.3	175.3	175.3	175.3

Table 7 Selected Main Engines for Matrix of Oil Tankers

Influence of Load Line Draft on the EEDI

When increasing displacement, the relative increase in power will generally be smaller than the relative increase in displacement, other factors being equal. This suggests that increasing the summer load line draft will tend to improve the EEDI.

Panamax tankers are beam restricted, and therefore tend to have a lower beam/depth ratio than larger tankers. The summer load line is not freeboard limited, but rather is selected based on the maximum expected cargo payload. On these ships, the summer load line draft can be increased at a nominal cost as most scantlings are adequate for deeper drafts. A deeper load line has no influence on the carrying capability of the vessel and therefore no impact on the expected CO_2 per tonne mile. As shown in Table 8, increasing the load line from 12.62 m to 13.90 m improves the EEDI relative to the baseline by approximately 4%.

Thus, for certain designs, increasing the load line draft can significantly reduce the EEDI at little extra cost and with little or no impact on the expected CO_2 emissions. For tankers, cargo cubic may be a better proxy for capacity than SLL deadweight, as increasing cargo cubic is expensive and could not be justified if done simply for the purpose of improving the EEDI.

Particulars	**Size Type**	**Standard Design**	**w/ increased SLL draft**
100% Cargo Capacity	m^3	54,000	54,000
Summer Load Line Draft	m	**12.62**	**13.90**
Deadweight at Load Line Draft	tonnes	49,203	55,220
Design Speed: 15% SM at 90% MCR	knots	14.90	14.90
Speed at SLL and 75% MCR (Vref)	knots	14.47	14.30
Calculated EEDI			
Attained EEDI ($EEDI_A$)		5.95	5.36
Baseline EEDI ($EEDI_{BL}$)		6.11	5.75
$\%EEDI = (EEDI_A / EEDI_{BL}) - 1$		-2.7%	-6.7%

Table 8 Influence of SLL Draft on EEDI for a Product Tanker

Influence of Block Coefficient on the EEDI

The Aframax tanker design was evaluated over a range of block coefficients, from Cb = 0.805 to Cb = 0.845. For this analysis, input parameters including design speed and the summer load line draft have been held constant. As Cb is reduced, the capacity is reduced as well as the required power. We find that the *%EEDI* (the attained/baseline EEDI ratio) improves by about 1% for each 0.1 reduction in Cb. This indicates that the changes in required power are more significant than the changes in capacity.

The expected CO_2 emissions for a roundtrip voyage between TEBAR terminal in Brazil and the Gulf of Mexico have been estimated for each design. Changes in CO_2 emissions with increase in Cb are in reasonable agreement with the respective change in EEDI.

AFRAMAX TANKER	Cb at Design Draft	0.805	0.815	Standard 0.825	0.835	0.845
100% Cargo Capacity	m^3	130,720	131,358	132,000	132,634	133,272
Summer Load Line Draft	m	15.06	15.06	15.06	15.06	15.06
Deadweight at Load Line Draft	tonnes	113,073	114,604	116,135	117,668	119,197
Design Speed: 15% SM at 90% MCR	knots	14.90	14.90	14.90	14.90	14.90
Req'd Power (MCR)	kW	13,426	13,611	13,822	14,066	14,355
Speed at SLL and 75% MCR	knots	14.46	14.45	14.44	14.44	14.43
Calculated EEDI						
Attained EEDI ($EEDI_A$)		3.72	3.72	3.73	3.74	3.77
Baseline EEDI ($EEDI_{BL}$)		3.92	3.89	3.86	3.84	3.81
Difference from.Baseline (*%EEDI*)		-5.2%	-4.5%	-3.5%	-2.5%	-1.1%
% Change vs. Standard Design		-1.7%	-0.9%	---	1.1%	2.6%
CO_2 Emissions for Tebar-GoM Service						
Total CO_2 Emissions	tonnes	5,216	5,294	5,385	5,489	5,613
CO_2 Emissions per BBL Oil Moved	t/bbl	6.34	6.41	6.49	6.58	6.70
% Change vs. Standard Design		-2.2%	-1.2%	---	1.5%	3.2%

Table 9 Influence of Cb on EEDI for Aframax Tanker

At the lower block coefficients, the construction cost is reduced, primarily due to reduced powering requirements. As shown in Table 10, the reduced powering requirements also result in a significant reduction in fuel consumption for the voyage. However, the benefits of the lower Cb are not sufficient to offset the loss in cargo throughput due to the reduced capacity, and therefore the RFR increases as the Cb is reduced.

AFRAMAX TANKER	Cb at Design Draft	0.805	0.815	Standard 0.825	0.835	0.845
Ship Construction Cost	million $	$62.6	$62.9	$63.1	$63.3	$63.6
Ship Operating Cost	million $	$3.18	$3.18	$3.18	$3.19	$3.19
Charter Rate	$/day	$28,914	$28,988	$29,068	$29,155	$29,252
Fuel Oil Consumption (for voyage)	MT	1,672	1,697	1,726	1,759	1,799
Required Freight Rate (HFO=$500/t)	$/bbl	$3.07	$3.05	$3.04	$3.03	$3.03

Table 10 Influence of Cb on RFR for Aframax Tanker

Influence of Hull Steel Weight on the EEDI

Concerns have been raised that the influence of hull steel weight on the EEDI may discourage introduction of more robust scantlings in future designs. It is also recognized that most of the existing fleet utilized to develop the EEDI proposed baseline were constructed prior to the implementation of the IACS Common Structural Rules (CSR) for Tankers by the major classification societies. The CSR can add 3% to 8% to the hull steel weight.

To gain an understanding of the impact of increased steel weight on the EEDI, a 5% increase in hull steel weight was assumed for each of the standard designs. Two scenarios have been evaluated: (1) holding the Cb at the design draft constant, leading to a reduction in deadweight, and, (2) adjusting the Cb such that the deadweight at the SLL draft is maintained constant. As shown in Table 11, a 5% increase in hull steel weight increases the %EEDI (the attained/baseline EEDI ratio) by between 0.5% and 1.4%.

			5% add'l hull steel weight	
		Standard Design	Constant Cb	Constant DWT @ SLL
Panamax	DWT at SLL draft (tonnes)	49,203	48,829	49,203
	Attained EEDI ($EEDI_A$)	5.948	5.994	6.029
	Baseline EEDI ($EEDI_{BL}$)	6.110	6.135	6.110
	$\%EEDI = (EEDI_A/EEDI_{BL}) - 1$	-2.7%	-2.3%	-1.3%
	% Change vs. Standard Design	---	0.4%	1.4%
Aframax	DWT at SLL draft (tonnes)	116,135	115,355	116,135
	Attained EEDI ($EEDI_A$)	3.727	3.752	3.758
	Baseline EEDI ($EEDI_{BL}$)	3.864	3.868	3.864
	$\%EEDI = (EEDI_A/EEDI_{BL}) - 1$	-3.5%	-3.0%	-2.7%
	% Change vs. Standard Design	---	0.6%	0.8%
Suezmax	DWT at SLL draft (tonnes)	166,576	165,509	166,576
	Attained EEDI ($EEDI_A$)	3.140	3.160	3.163
	Baseline EEDI ($EEDI_{BL}$)	3.187	3.198	3.187
	$\%EEDI = (EEDI_A/EEDI_{BL}) - 1$	-1.5%	-1.2%	-0.8%
	% Change vs. Standard Design	---	0.3%	0.7%
VLCC	DWT at SLL draft (tonnes)	303,032	301,199	303,032
	Attained EEDI ($EEDI_A$)	2.529	2.544	2.542
	Baseline EEDI ($EEDI_{BL}$)	2.316	2.323	2.316
	$\%EEDI = (EEDI_A/EEDI_{BL}) - 1$	9.2%	9.5%	9.8%
	% Change vs. Standard Design	---	0.3%	0.5%

Table 11 Influence of 5% Increase in Hull Steel Weight on EEDI

Influence of Electronic Engine on the EEDI

The B&W MAN ME series engines which are arranged with electronically controlled fuel valves and exhaust valves represent the state of the art in slow speed diesel design. The ME series of electronically controlled engines have specific fuel consumption (SFC) values that are equal to the mechanically controlled engines at the optimizing point, but lower over a wide range of powers because the electronic controls can match fuel and exhaust setting to the engine load. Figure 2 shows the relative performance of an electronically controlled engine and a mechanically controlled engine optimized for the 100% MCR point.

The ability to match fuel and exhaust settings to load allows better control of emissions over a wider range of power. Although the ME series of engines presently cost more than the MC engines (approximately 10% premium), it is anticipated that this premium will decrease over time.

As shown in Table 12, the electronically controlled ME series engines provide a 2.2% improvement in the EEDI as compared to the mechanically controlled MC series engines.

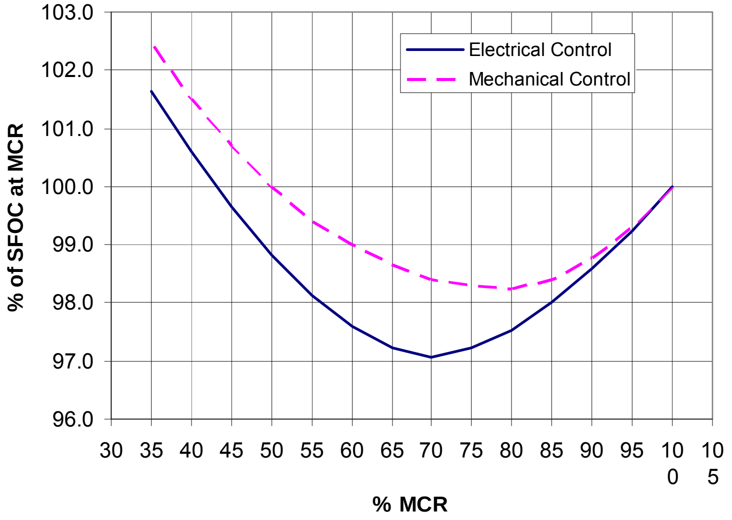


Figure 2: Specific Fuel Consumption of Mechanically Controlled and Electronically Controlled Two-Stroke Diesel Engines

		Standard Design w/ MC engine	with ME engine
Panamax	MAN B&W ME Model	6S50MC-C8	6S50ME-C8
	RPM	127	127
	SFC at 75% MCR (g-kWhr)	177.3	173.3
	Attained EEDI $(EEDI_A)$	5.948	5.822
	Baseline EEDI $(EEDI_{BL})$	6.110	6.110
	$\%EEDI = (EEDI_A/EEDI_{BL}) - 1$	-2.7%	-4.7%
	% Change vs. Standard Design	---	-2.1%
Aframax	MAN B&W ME Model	6S60MC-C8	6S60ME-C8
	RPM	105	105
	SFC at 75% MCR (g-kWhr)	176.3	172.3
	Attained EEDI $(EEDI_A)$	3.727	3.647
	Baseline EEDI $(EEDI_{BL})$	3.864	3.864
	$\%EEDI = (EEDI_A/EEDI_{BL}) - 1$	-3.5%	-5.6%
	% Change vs. Standard Design	---	-2.2%
Suezmax	MAN B&W ME Model	6S70MC-C8	6S70ME-C8
	RPM	91	91
	SFC at 75% MCR (g-kWhr)	176.3	172.3
	Attained EEDI $(EEDI_A)$	3.140	3.072
	Baseline EEDI $(EEDI_{BL})$	3.187	3.187
	$\%EEDI = (EEDI_A/EEDI_{BL}) - 1$	-1.5%	-3.6%
	% Change vs. Standard Design	---	-2.2%
VLCC	MAN B&W ME Model	7S80MC-C8	6S80ME-C9
	RPM	78	78
	SFC at 75% MCR (g-kWhr)	175.3	171.2
	Attained EEDI $(EEDI_A)$	2.529	2.473
	Baseline EEDI $(EEDI_{BL})$	2.316	2.316
	$\%EEDI = (EEDI_A/EEDI_{BL}) - 1$	9.2%	6.8%
	% Change vs. Standard Design	---	-2.2%

Table 12 Influence of Electronic Engines on the EEDI

AFRAMAX Tanker Parametric Study

A series of parametric designs have been developed in order to evaluate the influence of variations in length, beam, depth, and Cb on the EEDI, CO_2 emissions, and required freight rates.

Designs covering the following range of proportions have been evaluated:

• LBP / Beam (L/B)	5.0 to 6.5
• LBP / Depth (L/D)	10.0 to 13.0
• Beam / Depth (B/D)	1.8 to 2.3
• Scantling Draft / Depth (T_S/D	≤ 0.76

Historical data on L/B, B/D, L/D and T_S/D ratios are presented in Figure 3 and Figure 4. The range of ratios applied in the parametric study was selected to extend beyond current practice. Extending this analysis to this broad range of dimensions is helpful in illustrating trends.

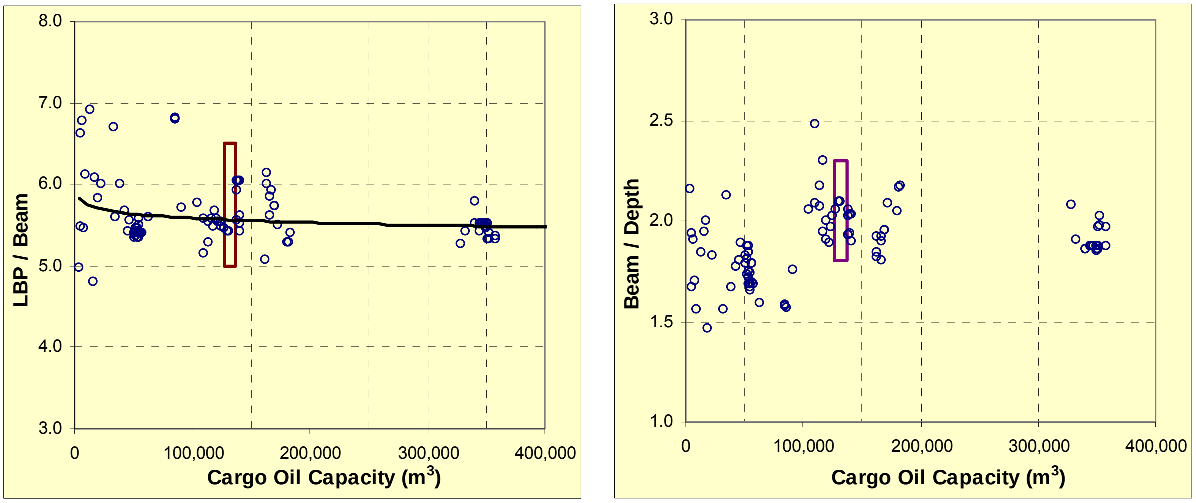


Figure 3 L/B and L/D Ratios (for double hull tankers build since 1990)

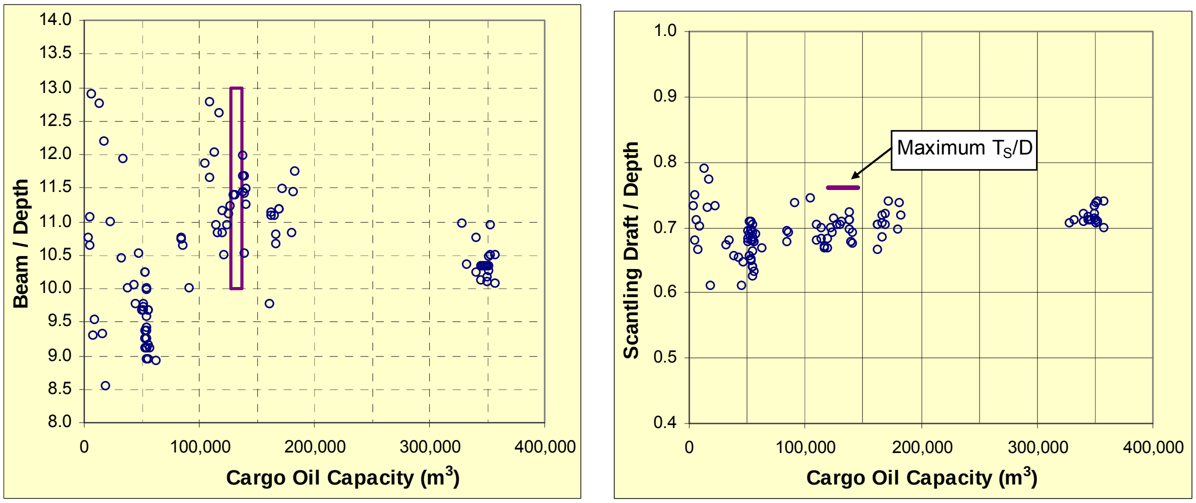


Figure 4 B/D and T_S/D Ratios (for double hull tankers build since 1990)

The following particulars are maintained constant for all designs, consistent with the standard Aframax tanker design:

- Cargo Cubic = 132,000 m^3
- Design Draft = 13.60 m
- Scantling Draft = 15.05 m
- Service Speed at the Design Draft = 14.9 knots

For each combination of L/B and L/D rations evaluated, the particulars (LxBxD) are developed that satisfy the L/B and L/D ratios while maintaining constant volume. The block coefficient is adjusted to maintain constant deadweight at the design draft. The particulars and required installed power to achieve the design speed with 15% sea margin and the main engine operating at 90% MCR are shown in Table 13.

			Length / Beam								
			4.75	5.00	5.25	5.432	5.50	5.75	6.00	6.25	6.50
Length / Depth	10.00	LBP (m)	220.80								
		Beam (m)	46.48								
		Depth (m)	22.08								
		Cb	0.841								
		ME MCR (kW)	14,423								
	10.50	LBP (m)	225.02	227.83	230.52						
		Beam (m)	47.37	45.57	43.91						
		Depth (m)	21.43	21.70	21.95						
		Cb	0.812	0.833	0.855						
		ME MCR (kW)	13,959	14,140	14,528						
	11.00	LBP (m)	229.10	231.99	234.77	236.71	237.43				
		Beam (m)	48.23	46.40	44.72	43.58	43.17				
		Depth (m)	20.83	21.09	21.34	21.52	21.58				
		Cb	0.785	0.805	0.825	0.840	0.845				
		ME MCR (kW)	13,780	13,795	13,909	14,074	14,159				
	11.274	LBP (m)	231.28	234.21	237.03	239.01	239.74	242.34	244.85		
		Beam (m)	48.69	46.84	45.15	44.00	43.59	42.15	40.81		
		Depth (m)	20.52	20.78	21.03	21.20	21.27	21.50	21.72		
		Cb	0.771	0.791	0.811	0.825	0.830	0.849	0.868		
		ME MCR (kW)	13,740	13,704	13,743	13,826	13,871	14,132	14,590		
	11.50	LBP (m)	233.05	236.02	238.87	240.88	241.61	244.25	246.79		
		Beam (m)	49.06	47.20	45.50	44.35	43.93	42.48	41.13		
		Depth (m)	20.27	20.52	20.77	20.95	21.01	21.24	21.46		
		Cb	0.760	0.779	0.799	0.813	0.818	0.837	0.855		
		ME MCR (kW)	13,728	13,659	13,656	13,693	13,718	13,872	14,162		
	12.00	LBP (m)		239.93	242.85	244.91	245.66	248.37	250.98	253.51	
		Beam (m)		47.99	46.26	45.09	44.67	43.20	41.83	40.56	
		Depth (m)		19.99	20.24	20.41	20.47	20.70	20.92	21.13	
		Cb		0.756	0.774	0.788	0.793	0.810	0.828	0.845	
		ME MCR (kW)		13,626	13,555	13,535	13,534	13,559	13,648	13,828	
	12.50	LBP (m)				248.82	249.60	252.37	255.05	257.64	260.14
		Beam (m)				45.81	45.38	43.89	42.51	41.22	40.02
		Depth (m)				19.91	19.97	20.19	20.40	20.61	20.81
		Cb				0.764	0.769	0.786	0.803	0.820	0.836
		ME MCR (kW)				13,481	13,466	13,427	13,427	13,470	13,576
	13.00	LBP (m)					253.42	256.26	259.00	261.65	264.22
		Beam (m)					46.08	44.57	43.17	41.86	40.65
		Depth (m)					19.49	19.71	19.92	20.13	20.32
		Cb					0.748	0.764	0.780	0.796	0.812
		ME MCR (kW)					13,463	13,384	13,335	13,315	13,327

Table 13 Particulars: Parametric Series of Aframax Tankers

The *%EEDI* (the attained/baseline EEDI ratio) for the series of tankers is given in Table 14. The change in the EEDI relative to the standard design is provided in Table 15. We find that a reduction in the EEDI of about 3.4% is achieved in the designs with high L/B and L/D ratios.

	Length / Beam								
Length / Depth	4.75	5.00	5.25	5.432	5.50	5.75	6.00	6.25	6.50
10.00	0.61%								
10.50	-2.49%	-1.27%	1.27%						
11.00	-3.72%	-3.63%	-2.80%	-1.72%	-1.20%				
11.381	-3.97%	-4.22%	-3.97%	-3.38%	-3.06%	-1.38%	1.73%		
11.50	-4.10%	-4.50%	-4.53%	-4.31%	-4.13%	-3.11%	-1.16%		
12.00		-4.74%	-5.23%	-5.33%	-5.32%	-5.17%	-4.59%	-3.40%	
12.50				-5.71%	-5.80%	-6.07%	-6.10%	-5.76%	-5.08%
13.00					-5.90%	-6.38%	-6.73%	-6.82%	-6.77%

Table 14 %EEDI for parametric series of Aframax Tankers
(where EEDI% = $\text{EEDI}_{\text{ATTAINED}}$ / $\text{EEDI}_{\text{BASELINE}}$ -1)

	Length / Beam								
Length / Depth	4.75	5.00	5.25	5.432	5.50	5.75	6.00	6.25	6.50
10.00	3.99%								
10.50	0.89%	2.11%	4.65%						
11.00	-0.34%	-0.25%	0.58%	1.66%	2.18%				
11.381	-0.59%	-0.84%	-0.59%	---	0.32%	2.00%	5.10%		
11.50	-0.72%	-1.12%	-1.15%	-0.93%	-0.75%	0.27%	2.22%		
12.00		-1.37%	-1.85%	-1.95%	-1.94%	-1.79%	-1.21%	-0.02%	
12.50				-2.33%	-2.42%	-2.69%	-2.72%	-2.38%	-1.70%
13.00					-2.52%	-3.00%	-3.35%	-3.44%	-3.39%

Table 15 Change in EEDI relative to the Standard Design

The expected CO_2 production for a roundtrip voyage between TEBAR terminal and the Gulf of Mexico has been estimated for each design in accordance with the methodology described in Section 2. Changes in CO_2 emissions relative to the standard ship (Table 16) correlate well with the changes in the EEDI (Table 14).

	Length / Beam								
Length / Depth	4.75	5.00	5.25	5.432	5.50	5.75	6.00	6.25	6.50
10.00	3.96%								
10.50	0.88%	2.09%	4.68%						
11.00	-0.32%	-0.20%	0.56%	1.66%	2.24%				
11.381	-0.59%	-0.80%	-0.55%	0.00%	0.31%	2.06%	5.14%		
11.50	-0.68%	-1.11%	-1.14%	-0.89%	-0.72%	0.33%	2.28%		
12.00		-1.35%	-1.81%	-1.95%	-1.96%	-1.78%	-1.17%	0.05%	
12.50				-2.32%	-2.42%	-2.67%	-2.67%	-2.36%	-1.65%
13.00					-2.45%	-2.97%	-3.29%	-3.41%	-3.32%

Table 16 Total CO_2 Production relative to the Standard Design

The required freight rates for the round trip voyage, expressed in terms of US$ per barrel moved from TEBAR to the Gulf of Mexico are shown in Table 17. The RFR values are relatively constant for all designs, slightly favoring the designs with higher L/B and L/D ratios.

		Length / Beam								
		4.75	5.00	5.25	5.432	5.50	5.75	6.00	6.25	6.50
Length / Depth	10.00	$3.07								
	10.50	$3.03	$3.04	$3.08						
	11.00	$3.02	$3.02	$3.03	$3.04	$3.05				
	11.381	$3.02	$3.01	$3.01	$3.02	$3.02	$3.05			
	11.50	$3.02	$3.01	$3.01	$3.01	$3.01	$3.03	$3.05		
	12.00		$3.02	$3.01	$3.00	$3.00	$3.00	$3.01	$3.03	
	12.50				$3.01	$3.00	$3.00	$3.00	$3.00	$3.01
	13.00					$3.01	$3.00	$2.99	$2.99	$2.99

Table 17 RFR's for Parametric Series of Tankers
(assumes HFO at $500/tonne and cargo value at $70/barrel)

Extending this analysis over a broad range of dimensions is helpful in illustrating trends. However, it should be noted that L/D ratios above 12 exceed current practice and the more elastic hull girders of such ships raises structural concerns. The LBP of these designs far exceeds traditional Aframax tanker practice, and will not fit at many existing berths. Considering the relatively modest improvements in EEDI achieved with such designs, it is not expected that future newbuildings will go to these extremes, although some increase in length and reduction in Cb beyond current practice may be appropriate.

4. Containership Studies

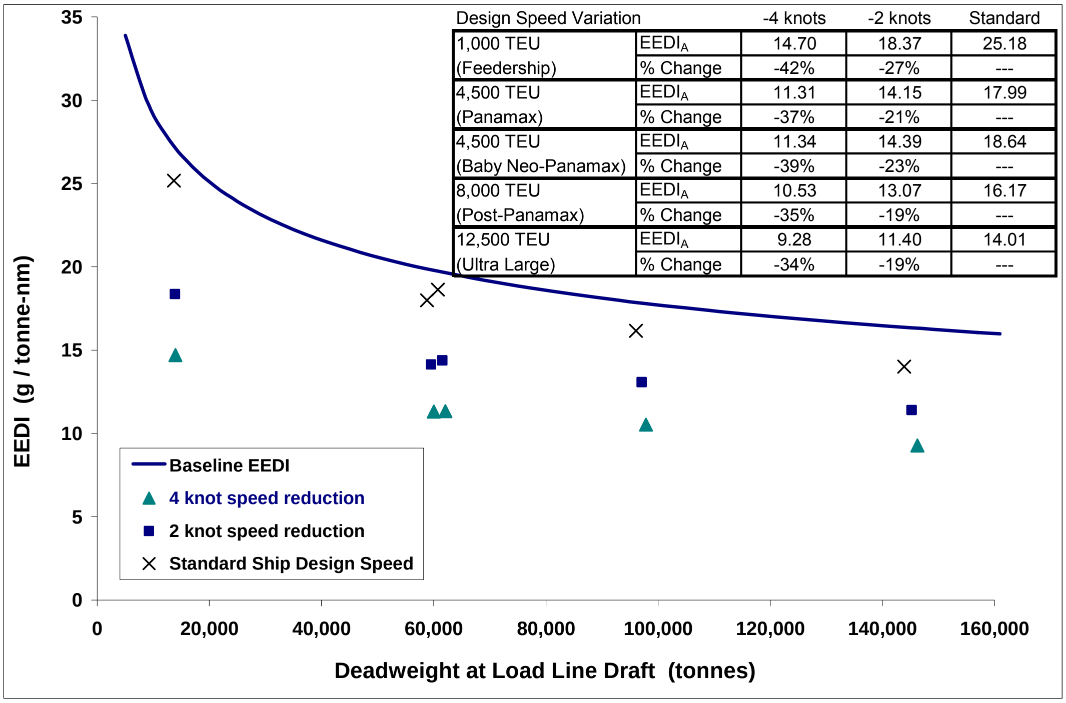
Influence of Service Speed on the EEDI

As shown in Table 18 and Figure 5, reducing speed by 4 knots reduces the EEDI by 34% to 42%, whereas reducing the speed by 1 knot reduces the EEDI by 19% to 27%.

When assessing the powering requirements, the most suitable MAN B&W engine was selected for each scenario. Consistent with recent practice for containerships, ME series engines were selected. The engine is assumed to be de-rated to the power required to attain the design speed at 15% sea margin with the main engine operating at 90% MCR. The smaller engines associated with the slower service speeds may have higher rpm's. The propulsive coefficient is reduced at the higher rpm which somewhat mitigates the benefits of the lower service speed. Table 19 shows the selected main engines, % de-rating, and the associated SFC and RPM values that are applied for this matrix of tanker designs and speeds. Note that the SFC values assume the engine at 75% MCR, burning MDO under ISO conditions. A 3% margin above published SFC figures is included to reflect the anticipated difference between the published values and those shown in the EIAPP certificates.

Design Speed Variation		-4 knots	-2 knots	Standard
1,000 TEU (Feedership)	Service Speed (design)	14.50	16.50	18.50
	DWT at SLL draft (tonnes)	13,960	13,856	13,669
	Main Engine MCR (kW)	4,232	6,090	9,337
	Attained EEDI ($EEDI_A$)	14.70	18.37	25.18
	Change vs. Standard Design	-42%	-27%	---
4,500 TEU (Panamax)	Service Speed (design)	20.50	22.50	24.50
	DWT at SLL draft (tonnes)	60,008	59,519	58,817
	Main Engine MCR (kW)	20,484	28,040	38,532
	Attained EEDI ($EEDI_A$)	11.31	14.15	17.99
	Change vs. Standard Design	-37%	-21%	---
4,500 TEU (Baby Neo-Panamax)	Service Speed (design)	20.50	22.50	24.50
	DWT at SLL draft (tonnes)	62,079	61,539	60,747
	Main Engine MCR (kW)	21,279	29,575	41,330
	Attained EEDI ($EEDI_A$)	11.34	14.39	18.64
	Change vs. Standard Design	-39%	-23%	---
8,000 TEU (Post-Panamax)	Service Speed (design)	21.00	23.00	25.00
	DWT at SLL draft (tonnes)	97,857	97,086	96,068
	Main Engine MCR (kW)	31,982	43,341	57,843
	Attained EEDI ($EEDI_A$)	10.53	13.07	16.17
	Change vs. Standard Design	-35%	-19%	---
12,500 TEU Ultra Large)	Service Speed (design)	21.00	23.00	25.00
	DWT at SLL draft (tonnes)	146,238	145,221	143,865
	Main Engine MCR (kW)	42,699	57,202	75,920
	Attained EEDI ($EEDI_A$)	9.28	11.40	14.01
	Change vs. Standard Design	-34%	-19%	---

Table 18 Influence of Service Speed on EEDI for Standard Containership Designs



Design Speed Variation		-4 knots	-2 knots	Standard
1,000 TEU (Feedership)	$EEDI_A$	14.70	18.37	25.18
	% Change	-42%	-27%	---
4,500 TEU (Panamax)	$EEDI_A$	11.31	14.15	17.99
	% Change	-37%	-21%	---
4,500 TEU (Baby Neo-Panamax)	$EEDI_A$	11.34	14.39	18.64
	% Change	-39%	-23%	---
8,000 TEU (Post-Panamax)	$EEDI_A$	10.53	13.07	16.17
	% Change	-35%	-19%	---
12,500 TEU (Ultra Large)	$EEDI_A$	9.28	11.40	14.01
	% Change	-34%	-19%	---

Figure 5 EEDI for Standard Containership Designs

Main Engine Selection		-4 knots	-2 knots	Standard
1,000 TEU (Feedership)	Service Speed (design)	14.50	16.50	18.50
	Reqd MCR (kW)	4,232	6,090	9,337
	MAN B&W ME Model	5S35ME-B9	5S46ME-B8	6S50ME-C8
	% De-Rating	97.3%	88.3%	93.7%
	RPM	167	129	127
	SFC at 75% MCR (g-kWhr)	178.4	175.3	173.3
4,500 TEU (Panamax)	Service Speed (design)	20.50	22.50	24.50
	Reqd MCR (kW)	20,484	28,040	38,532
	MAN B&W ME Model	6K80ME-C6	8K80ME-C6	7K90ME-C9
	% De-Rating	94.6%	97.1%	96.1%
	RPM	104	104	104
	SFC at 75% MCR (g-kWhr)	175.3	175.3	175.3
4,500 TEU (Baby Neo-Panamax)	Service Speed (design)	20.50	22.50	24.50
	Reqd MCR (kW)	21,279	29,575	41,330
	MAN B&W ME Model	6K80ME-C6	7K80ME-C9	7K98ME-C7
	% De-Rating	98.2%	93.3%	98.1%
	RPM	104	104	104
	SFC at 75% MCR (g-kWhr)	175.3	175.3	175.3
8,000 TEU (Post-Panamax)	Service Speed (design)	21.00	23.00	25.00
	Reqd MCR (kW)	31,982	43,341	57,843
	MAN B&W ME Model	9K80ME-C6	10K80ME-C9	10K98ME-C7
	% De-Rating	98.4%	95.7%	96.1%
	RPM	104	104	104
	SFC at 75% MCR (g-kWhr)	175.3	175.3	175.3
12,500 TEU (Ultra Large)	Service Speed (design)	21.00	23.00	25.00
	Reqd MCR (kW)	42,699	57,202	75,920
	MAN B&W ME Model	12K80ME-C6	10K90ME-C9	14K98ME-C7
	% De-Rating	98.6%	99.8%	90.1%
	RPM	104	104	104
	SFC at 75% MCR (g-kWhr)	175.3	175.3	175.3

Table 19 Selected Main Engines for Matrix of Containership Designs

Influence of Load Line Draft on EEDI

For containerships, the summer load line draft is set deeper than the design draft, to allow for the occasional need to move heavier containers or additional quantities of ballast. The summer load line is not freeboard limited, and can be increased at a nominal cost. For the standard designs, the SLL draft was set 12% greater than the design draft (Ts / Td = 1.12). This factor was derived from analysis of existing containerships. To better understand the implications of further increases in the design draft, each standard design was also evaluated for a Ts / Td ratio of 1.20.

As shown in Table 20, increasing the Ts/Td ratio from 1.12 to 1.20 improves the attained EEDI by 9.6% to 9.8%.

			Standard Design	w/ increased SLL draft
1,000 TEU (Feedership)	Summer Load Line Draft	m	8.51	9.12
	Deadweight at Summer Load Line Draft	tonnes	13,669	15,299
	Draft at 65% Summer Load Line Deadweight	m	6.65	6.66
	Service Speed: 15% SM at 90% MCR	knots	18.50	18.50
	Speed at 65%SLL DWT and 75% MCR (Vref)	knots	18.71	18.53
	Attained EEDI ($EEDI_A$)		25.18	22.70
	Change vs. Standard Design		-9.8%	---
4,500 TEU (Panamax)	Summer Load Line Draft	m	13.22	14.16
	Deadweight at Summer Load Line Draft	tonnes	58,817	65,773
	Draft at 65% Summer Load Line Deadweight	m	10.30	10.32
	Service Speed: 15% SM at 90% MCR	knots	24.50	24.50
	Speed at 65%SLL DWT and 75% MCR (Vref)	knots	24.73	24.50
	Attained EEDI ($EEDI_A$)		17.99	16.24
	Change vs. Standard Design		-9.7%	---
4,500 TEU (Baby Neo-Panamax)	Summer Load Line Draft	m	13.22	14.16
	Deadweight at Summer Load Line Draft	tonnes	60,747	67,872
	Draft at 65% Summer Load Line Deadweight	m	10.27	10.30
	Service Speed: 15% SM at 90% MCR	knots	24.50	24.50
	Speed at 65%SLL DWT and 75% MCR (Vref)	knots	24.78	24.53
	Attained EEDI ($EEDI_A$)		18.64	16.85
	Change vs. Standard Design		-9.6%	---
8,000 TEU (Post-Panamax)	Summer Load Line Draft	m	14.56	15.60
	Deadweight at Summer Load Line Draft	tonnes	96,068	107,478
	Draft at 65% Summer Load Line Deadweight	m	11.37	11.39
	Service Speed: 15% SM at 90% MCR	knots	25.00	25.00
	Speed at 65%SLL DWT and 75% MCR (Vref)	knots	25.22	24.99
	Attained EEDI ($EEDI_A$)		16.17	14.58
	Change vs. Standard Design		-9.8%	---
12,500 TEU (Ultra Large)	Summer Load Line Draft	m	15.90	17.04
	Deadweight at Summer Load Line Draft	tonnes	143,865	160,377
	Draft at 65% Summer Load Line Deadweight	m	12.30	12.32
	Service Speed: 20% SM at 90% MCR	knots	25.00	25.00
	Speed at 65%SLL DWT and 75% MCR (Vref)	knots	25.46	25.26
	Attained EEDI ($EEDI_A$)		14.01	12.67
	Change vs. Standard Design		-9.6%	---

Table 20 Influence of SLL Draft on EEDI for Containerships

Influence of Hull Steel Weight on EEDI

To gain an understanding of the impact of increased steel weight on the EEDI, a 5% increase in hull steel weight was assumed for each of the standard designs. Two scenarios were evaluated: (1) holding the Cb at the design draft constant, leading to a reduction in deadweight, and, (2) adjusting the Cb such that the deadweight at the SLL draft is maintained constant. As shown in Table 21, a 5% increase in hull steel weight increases the %EEDI (the attained/baseline EEDI ratio) by between 0.9% and 1.2%.

		Standard Design	5% add'l hull steel weight Constant Cb	 Constant DWT @ SLL
1,000 TEU (Feedership)	SLL DWT (MT)	13,669	13,523	13,669
	Attained EEDI ($EEDI_A$)	25.18	25.46	25.39
	% Change vs. Standard Design	---	1.1%	0.9%
4,500 TEU (Panamax)	SLL DWT (MT)	58,817	58,184	58,845
	Attained EEDI ($EEDI_A$)	17.99	18.20	18.14
	% Change vs. Standard Design	---	1.1%	0.8%
4,500 TEU (Baby Neo-Panamax)	SLL DWT (MT)	60,747	60,123	60,747
	Attained EEDI ($EEDI_A$)	18.64	18.85	18.81
	% Change vs. Standard Design	---	1.1%	0.9%
8,000 TEU (Post-Panamax)	SLL DWT (MT)	96,068	94,991	96,068
	Attained EEDI ($EEDI_A$)	16.17	16.36	16.33
	% Change vs. Standard Design	---	1.2%	1.0%
12,500 TEU (Ultra Large)	SLL DWT (MT)	143,865	142,202	143,865
	Attained EEDI ($EEDI_A$)	14.01	14.18	14.17
	% Change vs. Standard Design	---	1.2%	1.1%

Table 21 Influence of 5% Increase in Hull Steel Weight on EEDI (for containerships)

Post-Panamax Containership Service Speed vs. Cb Study

This study investigates the influence of slower speed designs with fuller hull forms on the EEDI, CO_2 emissions, and the required freight rate. A 40 m beam vessel with approximately 5,500 TEU slot capacity is evaluated. A series of designs have been developed with block coefficients ranging from 0.56 to 0.81. CO_2 emissions (expressed in terms of tonnes CO_2 production per TEU moved) and the RFR for these designs has been determined for a transpacific voyage with two load ports and two discharge ports.

Design Dimensions and Data

The following assumptions were made when determining the dimensions of each design:

- Design Parameters:
  16 rows on deck x 16 bays
  14 rows in holds x 8 high
- Range of Cb to be evaluated: 0.55 to 0.80
- Operating draft varied with change in Cb (i.e. shallower draft at higher Cb)
- Average container weight = 9 tonnes/TEU
- A linear relationship between Cb and speed is assumed, where:
  Design Service Speed = 17.8 knots at Cb = 0.80
  Design Service Speed = 27.8 knots at Cb = 0.55
- For the purposes of the RFR analysis, the voyage speed is taken as 2 knots less than design speed

The principal dimensions for all seven designs are as follows:

LBP (m)	264.0
Beam (m)	40.0
Depth (m)	24.0
Design Draft (m)	12.0
Scantling Draft (m)	13.4

Table 22 Post-Panamax Principal Dimensions

The following table provides basic design data for each combination of block coefficient and service speed considered in the study. The design service speed assumes a 15% sea margin with the main engine at 90% MCR and the vessel at its design draft. The slot capacity is based on standard (8'-6" high) container stowage with 7 tiers on deck (subject to visibility restrictions). The methodologies for developing slot capacity and loadable capacity are described in Addendum I to HEC Report 2008-20-1, "Parametric Study of Baby Neo-Panamax Containerships".

Block Coefficient	0.56	0.61	0.63	0.66	0.71	0.76	0.81
Design Speed (Knots)	27.8	25.8	25.0	23.8	21.8	19.8	17.8
Slot Capacity (TEUs)	5,607	5,721	5,765	5,830	5,935	6,039	6,141
Lightship (tonnes)	25,537	24,853	24,566	24,220	23,749	23,288	22,989
Main Engine MCR (MW)	70.1	57.5	52.3	45.6	36.0	26.3	19.0
Construction Cost ($ millons)	109.6	102.9	100.0	96.2	90.7	84.8	79.4
Loadable TEUs @ 9.0t/TEU	4,982	5,086	5,130	5,196	5,302	5,376	5,480
Loaded Draft	13.0	12.4	12.1	11.8	11.0	10.1	9.1
Cb at Loaded Draft	0.58	0.62	0.63	0.66	0.70	0.74	0.79

Table 23 Post-Panamax Containership Design Data

EEDI, CO_2 Production and EEOI Calculations

The EEDI and EEOI for each design are presented in Table 24. Figure 6 shows total CO_2 production plotted as a function of design speed. We find that reducing design service speed from the typical value of about 25 knots to 17.8 knots reduced CO_2 production and the EEOI by 47%.

Block Coefficient	0.56	0.61	0.63	0.66	0.71	0.76	0.81
Design Speed (Knots)	27.8	25.8	25.0	23.8	21.8	19.8	17.8
Slot Capacity (TEUs)	5,607	5,721	5,765	5,830	5,935	6,039	6,141
Loadable TEUs @ 9.0t/TEU	4,982	5,086	5,130	5,196	5,302	5,376	5,480
Attained EEDI ($EEDI_A$)	28.2	22.3	20.0	17.3	13.5	10.1	7.4
CO_2 Production (tonnes/voyage)	15120	12559	11641	10511	8960	7519	6378
CO_2 per TEU Moved (tonnes/TEU)	1.52	1.25	1.15	1.04	0.88	0.73	0.61
EEOI (g CO_2/TEU-nm)	520	428	396	355	300	250	210

Table 24 EEDI, EEOI, and CO_2 Production
(Approx. 5,500 TEU Containership in Transpacific Service)

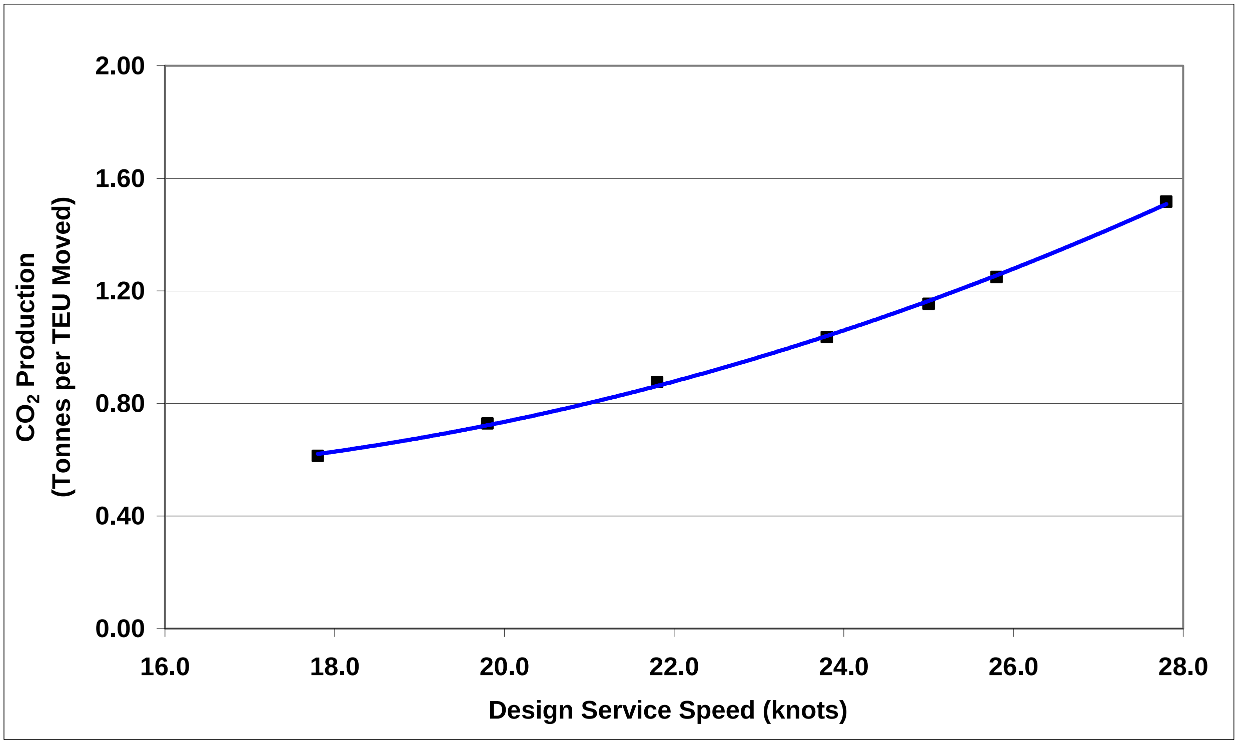


Figure 6 CO_2 Production per TEU Moved
(Approx. 5,500 TEU Containership in Transpacific Service)

RFR Calculations

The RFR is computed by dividing total voyage expenses by the number of TEU's moved. The "loadable" containers are calculated assuming an average weight of 9 tonnes/TEU. 100% ship utilization is assumed both eastbound and westbound. Therefore, the "number of TEU's moved" for the roundtrip is taken as two times the "loadable" TEU's. The "loadable container" count is the theoretical useable capacity, given the average container weights and mix of containers. Actual utilization may vary, depending on various factors such as the service, shipping company philosophy, seasonality, and market conditions.

The calculated RFR's are presented in Figure 7.

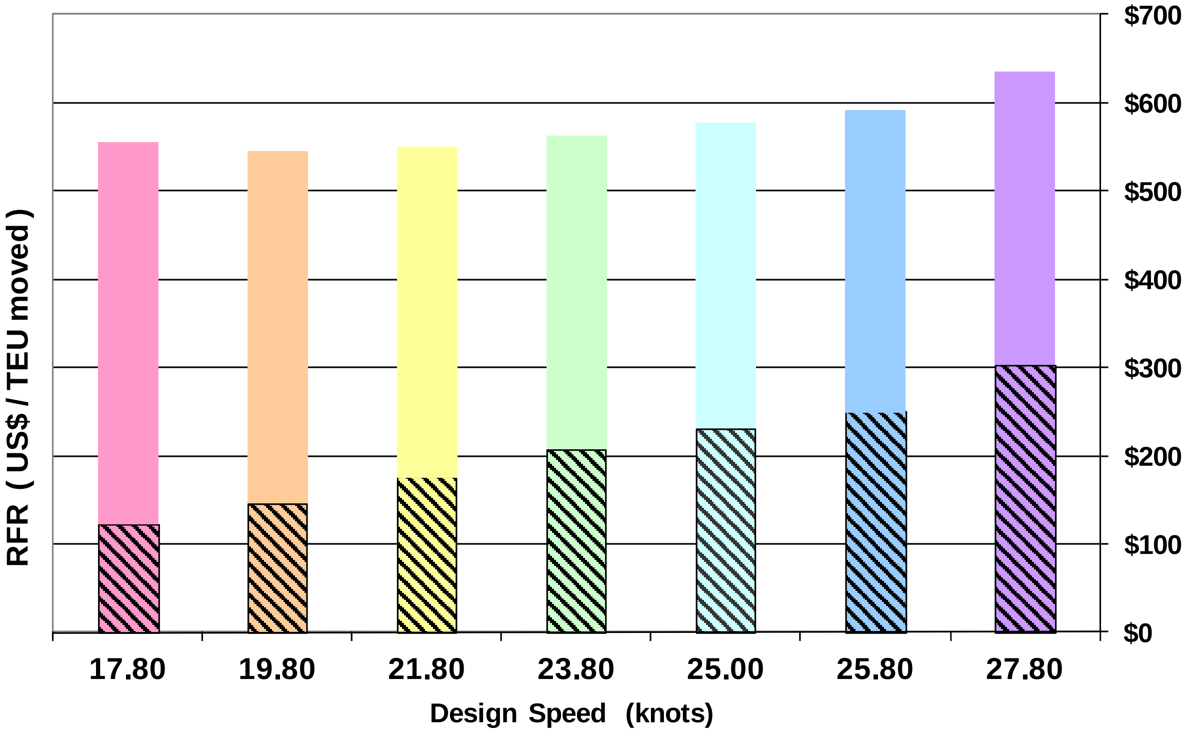


Figure 7 Post-Panamax Required Freight Rate (US$ per TEU moved) (assume HFO at $500 per tonne)

The shaded regions in Figure 7 designate the contribution of fuel oil consumption to the RFR. Although the increases in voyage duration associated with the slower, high Cb designs result in charter costs and inventory costs having a higher contribution to RFR, this increase in cost is more than offset by the lower fuel consumption. As shown, a reduction in RFR is realized as the design speed is reduced, with the 19.8 knot service speed (0.76 block coefficient) design having the lowest RFR.

The RFR calculation includes an inventory cost, to account for the lost value to the shipper related to slower transit times. To calculate inventory cost, the value of the containers is taken at $30,000 per TEU and a 10% discount rate is applied.

As block coefficient is increased and ship speed is reduced, a number of factors come into play that influences the RFR. These include:

- For higher Cb designs, the weight and cost of hull steel increases. For the slower ships, the installed main engine power and machinery costs decrease. The machinery cost reduction has the bigger impact and therefore the high Cb / reduced speed designs have lower construction costs.

  Although the daily charter rates are lower for the high Cb designs, this is offset by the longer voyage time associated with these slower ships. The net effect is that the overall voyage charter costs (including amortization of the vessel construction cost and operating costs) is higher for the high Cb / reduced speed designs.

- Fuel oil consumption is significantly lower on the high Cb / reduced speed designs. Even when the longer voyage time is factored in, the overall fuel costs are much less with the slower vessels.
- The high Cb designs have increased container capacity. This is primarily due to the additional containers that can be accommodated within the fuller hull form. Another factor is that the reduced fuel consumption allows for reduced fuel oil storage capacity. As fuel oil storage tanks are fully double hulled and located within the cargo block region, the smaller fuel tanks translate into an increase in cargo slots in the holds.

The various components of voyage expense are shown graphically in Figure 8. Fuel costs comprise approximately 41% of the RFR. If inventory rate is omitted from the calculation, the contribution of fuel costs to the RFR increases to 60%.

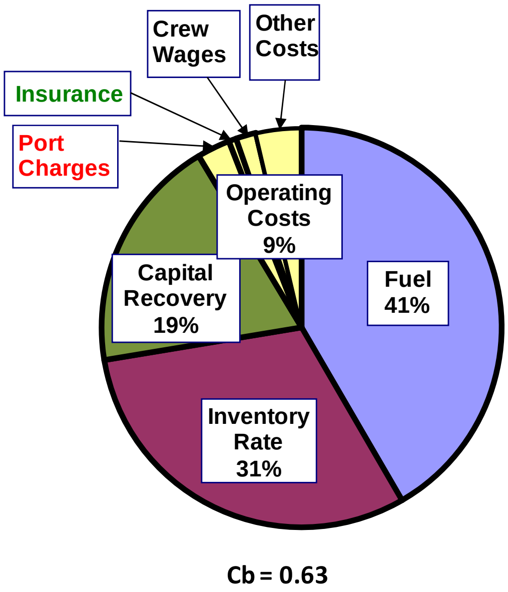


Figure 8 Components of Voyage Expense
(5,500 TEU containership, 25 knot design speed and Cb=0.63)

Influence of Fuel Oil Price on RFR

HFO prices were approximately $500 / tonne during the first half of 2008. By year end, HFO prices ranged between $200 and $250 per tonne. Continued volatility can be expected with a longer term trend of increasing prices. Figure 9 presents RFR plots for HFO prices of $250, $500 and $1,000 per tonne. Lower fuel costs tend to flatten the curve and shift the optimal point towards faster vessels with finer hull forms.

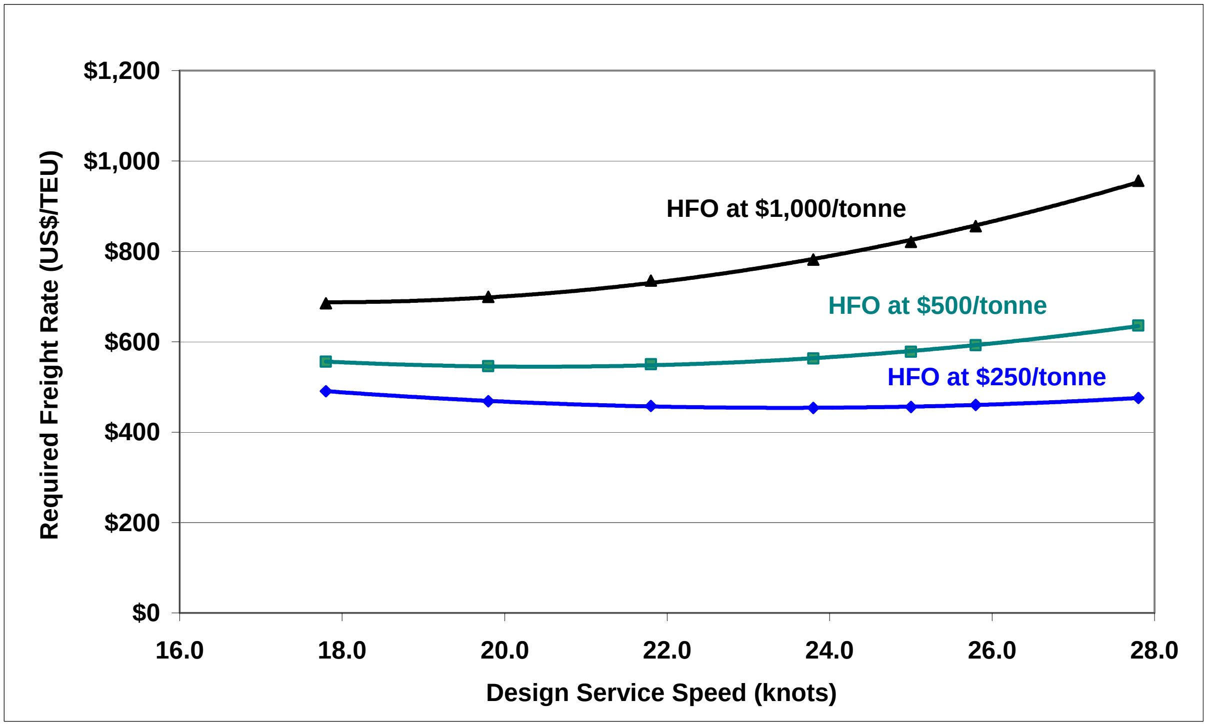


Figure 9 Sensitivity of RFR to Fuel Oil Price
(Approx. 5,500 TEU Containership in Transpacific Service)

Comparison: Panamax and Baby Neo-Panamax Designs

Historically, the principal dimensions of containerships in the 3,500 to 4,500 TEU range have been adjusted from their optimum in order to allow transit through the Panama Canal. These designs have a length to beam ratio that does not enable efficient cargo stowage, and they must carry significant quantities of ballast water in order to maintain stability while maximizing cargo payload. An alternative design is the Baby Neo-Panamax containership which has an increased beam that allows for more efficient cargo stowage. Slated for completion in 2014, the expansion of the Panama Canal will allow transit of containerships up to approximately 12,500 TEU in capacity.

To understand the impact of the shift from Panamax to Baby Neo-Panamax on the EEDI, standard designs of each class with similar displacements have been analyzed. A comparison of two designs, each having a 4,500 TEU slot capacity but different beams, is presented in Table 25.

Particulars		Panamax	Baby Neo-Panamax
Slot Capacity	TEU	4,500	4,500
Loadable Capacity (9t/TEU)	TEU	3,385	4,209
Length Overall	m	295.625	280.145
LBP	m	275.000	260.600
Beam	m	32.200	34.800
Depth	m	21.000	19.300
Design Draft	m	11.80	11.80
Summer Loadline Draft	m	13.22	13.22
Lightship	tonnes	19,119	19,071
Design Block Coefficient		0.630	0.630
Deadweight at Design Draft	tonnes	48,524	50,206
Deadweight at Loadline draft	tonnes	58,817	60,747
Design Speed: with SM at 90% MCR	knots	24.50	24.50
Required Engine Power (MCR)	kW	38,532	41,330
Attained EEDI ($EEDI_A$)		17.99	18.64
Change in EEDI for Neo-Panamax			+4%
CO_2 Production (tonnes/voyage)	tonnes	8,576	9,376
CO_2 Production per TEU Moved	t/TEU	1.27	1.11
EEOI	g CO_2/TEU-nm	434	382
Reduction in EEOI for Neo-Panamax			-12%
RFR (with HFO at $500/tonne)	$/TEU	$453	$390
Reduction in RFR for Neo-Panamax			-14%

Table 25 Comparison: Panamax and Baby Neo-Panamax Designs

As the designs have similar deadweights, the majority of the difference in EEDI is caused by the required engine power. The decreased length to beam ratio of the Baby Neo-Panamax ship increases the power required to achieve the design speed. The increased power increases the EEDI of the Baby Neo-Panamax over the Panamax design by 3.6%.

Though the slot capacities of the designs are the same, the loadable capacity for the Panamax design is significantly lower than the Baby Neo-Panamax design. Due to the instability of the Panamax design, large amounts of ballast water must be carried which increases the deadweight of the vessel. Whereas the deadweights of the two designs are roughly equivalent, the ballast water results in 24% less loadable containers for the Panamax design. The EEDI does not take into account the amount of deadweight utilized by cargo as opposed to ballast water. Thus, the EEDI considers the Panamax design a 3.6% better performer than the Baby Neo-Panamax design, whereas CO_2 emissions per unit mile (expressed in terms of the EEOI) are 12% higher for the Panamax design as compared to the Baby Neo-Panamax design.

5. LNG Carrier Studies

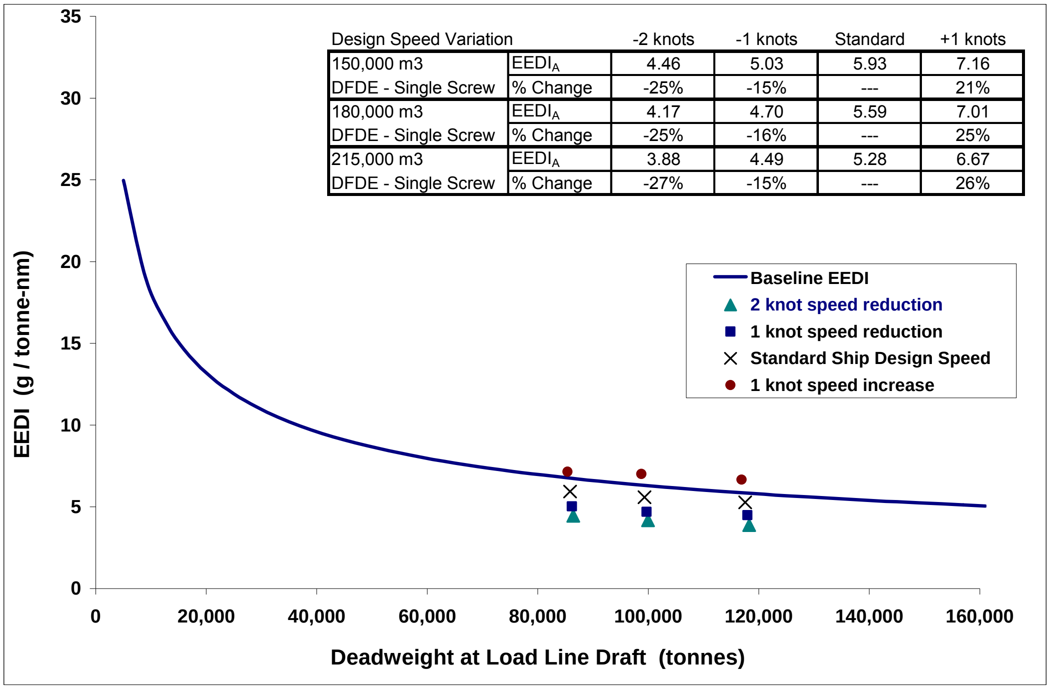
Influence of Service Speed on the EEDI

As shown in Table 26 and Figure 10 and Figure 11, reducing speed by 1 knot reduces the EEDI by 34% to 42%, whereas reducing the speed by 2 knot reduces the EEDI by 19% to 27%.

When assessing the powering requirements, the most suitable MAN B&W engines have been selected for each vessel with DRL propulsion. Consistent with current practice for LNG carriers with DRL propulsion, ME series engines are selected. The engine is assumed to be de-rated to the power required to attain the design speed at 20% sea margin with the main engine operating at 90% MCR. For DFDE propulsion, the propulsion motor rating is that required to attain the design speed at 20% sea margin.

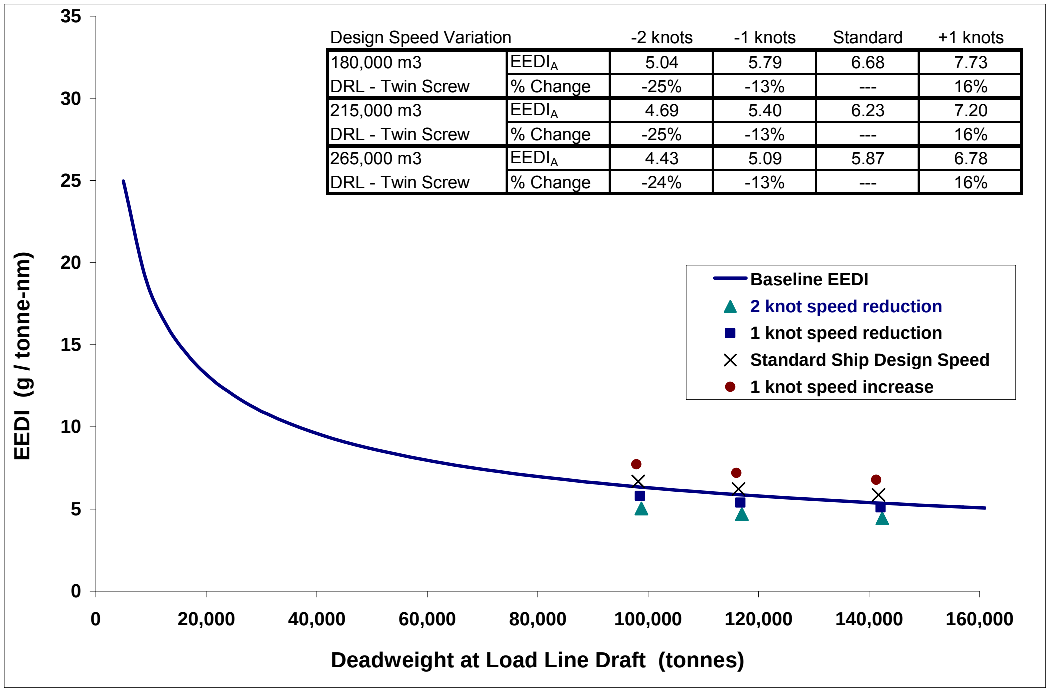
Design Speed Variation		-2 knots	-1 knots	Standard	+1 knots
150,000 m3 DFDE - Single Screw	Service Speed (design)	17.80	18.80	19.80	20.80
	DWT at SLL draft (tonnes)	86,431	86,188	85,837	85,385
	Prop.Motor Rating (kW)	17,490	20,858	25,930	32,788
	Attained EEDI ($EEDI_A$)	4.46	5.03	5.93	7.16
	Change vs. Standard Design	-38%	-30%	-17%	---
180,000 m3 DFDE - Single Screw	Service Speed (design)	17.80	18.80	19.80	20.80
	DWT at SLL draft (tonnes)	99,954	99,697	99,309	98,738
	Prop.Motor Rating (kW)	18,964	22,599	28,317	37,221
	Attained EEDI ($EEDI_A$)	4.17	4.70	5.59	7.01
	Change vs. Standard Design	-42%	-34%	-22%	---
215,000 m3 DFDE - Single Screw	Service Speed (design)	17.80	18.80	19.80	20.80
	DWT at SLL draft (tonnes)	118,261	117,937	117,537	116,899
	Prop.Motor Rating (kW)	20,893	25,604	31,696	41,960
	Attained EEDI ($EEDI_A$)	3.88	4.49	5.28	6.67
	Change vs. Standard Design	-46%	-37%	-26%	---
180,000 m3 DRL - Twin Screw	Service Speed (design)	17.80	18.80	19.80	20.80
	DWT at SLL draft (tonnes)	98,754	98,501	98,205	97,861
	Main Engine MCR (kW)	19,878	24,172	29,353	35,609
	Attained EEDI ($EEDI_A$)	5.04	5.79	6.68	7.73
	Change vs. Standard Design	-30%	-19%	-7%	---
215,000 m3 DRL - Twin Screw	Service Speed (design)	17.80	18.80	19.80	20.80
	DWT at SLL draft (tonnes)	116,967	116,690	116,366	115,988
	Main Engine MCR (kW)	22,097	26,867	32,637	39,618
	Attained EEDI ($EEDI_A$)	4.69	5.40	6.23	7.20
	Change vs. Standard Design	-34%	-25%	-13%	---
265,000 m3 DRL - Twin Screw	Service Speed (design)	17.80	18.80	19.80	20.80
	DWT at SLL draft (tonnes)	142,371	142,065	141,710	141,296
	Main Engine MCR (kW)	25,404	30,843	37,406	45,333
	Attained EEDI ($EEDI_A$)	4.43	5.09	5.87	6.78
	Change vs. Standard Design	-38%	-29%	-18%	---

Table 26 Influence of Service Speed on EEDI for Standard LNG Carrier Designs



Design Speed Variation		-2 knots	-1 knots	Standard	+1 knots
150,000 m3	$EEDI_A$	4.46	5.03	5.93	7.16
DFDE - Single Screw	% Change	-25%	-15%	---	21%
180,000 m3	$EEDI_A$	4.17	4.70	5.59	7.01
DFDE - Single Screw	% Change	-25%	-16%	---	25%
215,000 m3	$EEDI_A$	3.88	4.49	5.28	6.67
DFDE - Single Screw	% Change	-27%	-15%	---	26%

Figure 10 EEDI for Standard LNG Carrier Designs
(for Single Screw, DFDE Propulsion)



Design Speed Variation		-2 knots	-1 knots	Standard	+1 knots
180,000 m3	$EEDI_A$	5.04	5.79	6.68	7.73
DRL - Twin Screw	% Change	-25%	-13%	---	16%
215,000 m3	$EEDI_A$	4.69	5.40	6.23	7.20
DRL - Twin Screw	% Change	-25%	-13%	---	16%
265,000 m3	$EEDI_A$	4.43	5.09	5.87	6.78
DRL - Twin Screw	% Change	-24%	-13%	---	16%

Figure 11 EEDI for Standard LNG Carrier Designs
(for Single Screw, DFDE Propulsion)

Influence of Load Line Draft on the EEDI

The design draft for LNG carriers is generally based on limitations at the discharge terminals. The density of LNG has a relatively narrow range, from about 0.44 tonnes/m^3 to 0.47 tonnes/m^3, so the draft does not vary significantly with cargo payload. The summer load line draft is set deeper than the design draft, to allow for the potential need for ballast to provide suitable clearances for loading arms. The summer load line is not freeboard limited, and can be increased at a nominal cost. For the standard designs, the SLL draft was set 8% greater than the design draft (Ts / Td = 1.08). This factor was derived from analysis of existing LNG carriers. To better understand the implications of further increases in the design draft, each standard design was also evaluated for a Ts / Td ratio 0f 1.16. As shown in Table 20, increasing the Ts/Td ratio from 1.08 to 1.16 improves the attained EEDI by 9.6% to 9.8%.

			Standard Design	**w/ increased SLL draft**
150,000 m3 DFDE - Single Screw	Summer Load Line Draft	m	12.45	13.34
	Deadweight at Load Line Draft	MT	85,837	95,449
	Design Service Speed: 20% SM at 90% MCR	knots	19.80	19.80
	Speed at 75%SLL DWT and 75% MCR (Vref)	knots	19.10	18.95
	Attained EEDI ($EEDI_A$)		5.93	5.38
	Change vs. Standard Design		-9.4%	---
180,000 m3 DFDE - Single Screw	Summer Load Line Draft	m	12.70	13.63
	Deadweight at Load Line Draft	MT	99,309	110,530
	Service Speed: 15% SM at 90% MCR	knots	19.80	19.80
	Speed at 75%SLL DWT and 75% MCR (Vref)	knots	19.11	18.97
	Attained EEDI ($EEDI_A$)		5.59	5.06
	Change vs. Standard Design		-9.5%	---
215,000 m3 DFDE - Single Screw	Summer Load Line Draft	m	13.00	13.92
	Deadweight at Load Line Draft	MT	117,537	130,149
	Service Speed: 15% SM at 90% MCR	knots	19.80	19.80
	Speed at 75%SLL DWT and 75% MCR (Vref)	knots	19.12	19.00
	Attained EEDI ($EEDI_A$)		5.28	4.80
	Change vs. Standard Design		-9.1%	---
180,000 m3 DRL - Twin Screw	Summer Load Line Draft	m	12.70	13.63
	Deadweight at Load Line Draft	MT	98,205	109,426
	Service Speed: 15% SM at 90% MCR	knots	19.80	19.80
	Speed at 75%SLL DWT and 75% MCR (Vref)	knots	19.58	19.38
	Attained EEDI ($EEDI_A$)		6.68	6.06
	Change vs. Standard Design		-9.3%	---
215,000 m3 DRL - Twin Screw	Summer Load Line Draft	m	13.00	13.92
	Deadweight at Load Line Draft	MT	116,366	128,978
	Service Speed: 20% SM at 90% MCR	knots	19.80	19.80
	Speed at 75%SLL DWT and 75% MCR (Vref)	knots	19.59	19.41
	Attained EEDI ($EEDI_A$)		6.23	5.67
	Change vs. Standard Design		-8.9%	---
265,000 m3 DRL - Twin Screw	Summer Load Line Draft	m	13.00	13.92
	Deadweight at Load Line Draft	MT	141,710	156,790
	Service Speed: 20% SM at 90% MCR	knots	19.80	19.80
	Speed at 75%SLL DWT and 75% MCR (Vref)	knots	19.64	19.48
	Attained EEDI ($EEDI_A$)		5.87	5.35
	Change vs. Standard Design		-8.9%	---

Table 27 Influence of SLL Draft on EEDI for LNG Carriers

Influence of Single Screw vs. Twin Screw Arrangements on the EEDI

All LNG standard designs have a maximum design draft of not more than 12 m, due to draft restrictions at LNG terminals. For the larger ships (>= 180,000 m^3 capacity), the draft limit results in relatively high beam / design draft (B/Td) ratios, which tends to favor the twin skeg arrangement. For the twin screw design, the propellers can be the nearly the same diameter as for the single screw propeller, allowing for lower RPM and higher efficiency. The modern twin skeg designs also have excellent wake fields, further contributing to the propulsive efficiency. The higher propulsive coefficient more than offsets the increased resistance due to the greater wetted surface of the twin skeg hull form.

For these larger ships, the EEDI is 5% to 6% lower (more favorable) for the twin screw arrangement as compared to the single screw arrangement.

Propulsion Plant		**DFDE**	**DFDE**	**DFDE**	**DFDE**	**DFDE**	**DFDE**
Shafting Configuration		**Single**	**Single**	**Single**	**Twin**	**Twin**	**Twin**
100% Cargo Capacity	m^3	150,000	180,000	215,000	180,000	215,000	265,000
Rated Power of Propulsion Motors	KW	25,930	28,317	31,696	26,417	29,374	33,665
Main Engine Electrical Efficiency		91.3%	91.3%	91.3%	91.3%	91.3%	91.3%
Main Engine Power (P_{ME})	kW	21,303	23,264	26,040	21,703	24,132	27,658
Aux. Engine Power (P_{AE})	kW	898	958	1,042	910	984	1,092
Deadweight at SLL (Capacity)	tonnes	85,837	99,309	117,537	98,351	116,443	141,898
Speed at SLL and 75% MCR (V_{ref})	knots	19.10	19.11	19.12	19.04	19.06	19.10
Fuel Type (LNG)							
SFC, Main Engine (SFC_{ME})	g-KWhr	159.3	159.3	159.3	159.3	159.3	159.3
SFC, Diesel Generators (SFC_{AE})	g-KWhr	159.3	159.3	159.3	159.3	159.3	159.3
Fuel Conv Factors (C_{FME} and C_{FAE})	t CO_2	2.750	2.750	2.750	2.750	2.750	2.750
Attained EEDI ($EEDI_A$)		**5.93**	**5.59**	**5.28**	**5.29**	**4.96**	**4.65**
Baseline EEDI ($EEDI_{BL}$)		6.76	6.32	5.85	6.35	5.87	5.36
%EEDI = ($EEDI_A$/$EEDI_{BL}$) - 1		-12.2%	-11.5%	-9.7%	-16.7%	-15.6%	-13.4%
Fuel Type (MDO)							
SFC, Main Engine (SFC_{ME})	g-KWhr	204.2	204.2	204.2	204.2	204.2	204.2
SFC, Diesel Generators (SFC_{AE})	g-KWhr	204.2	204.2	204.2	204.2	204.2	204.2
Fuel Conv Factors (C_{FME} and C_{FAE})	t CO_2	3.206	3.206	3.206	3.206	3.206	3.206
Attained EEDI ($EEDI_A$)		**8.87**	**8.36**	**7.89**	**7.91**	**7.41**	**6.95**
Baseline EEDI ($EEDI_{BL}$)		6.76	6.32	5.85	6.35	5.87	5.36
%EEDI = ($EEDI_A$/$EEDI_{BL}$) - 1		31.2%	32.2%	34.9%	24.6%	26.2%	29.5%

Table 28 EEDI for LNG Carrier Designs with DFDE Propulsion (comparison of single and twin screw designs)

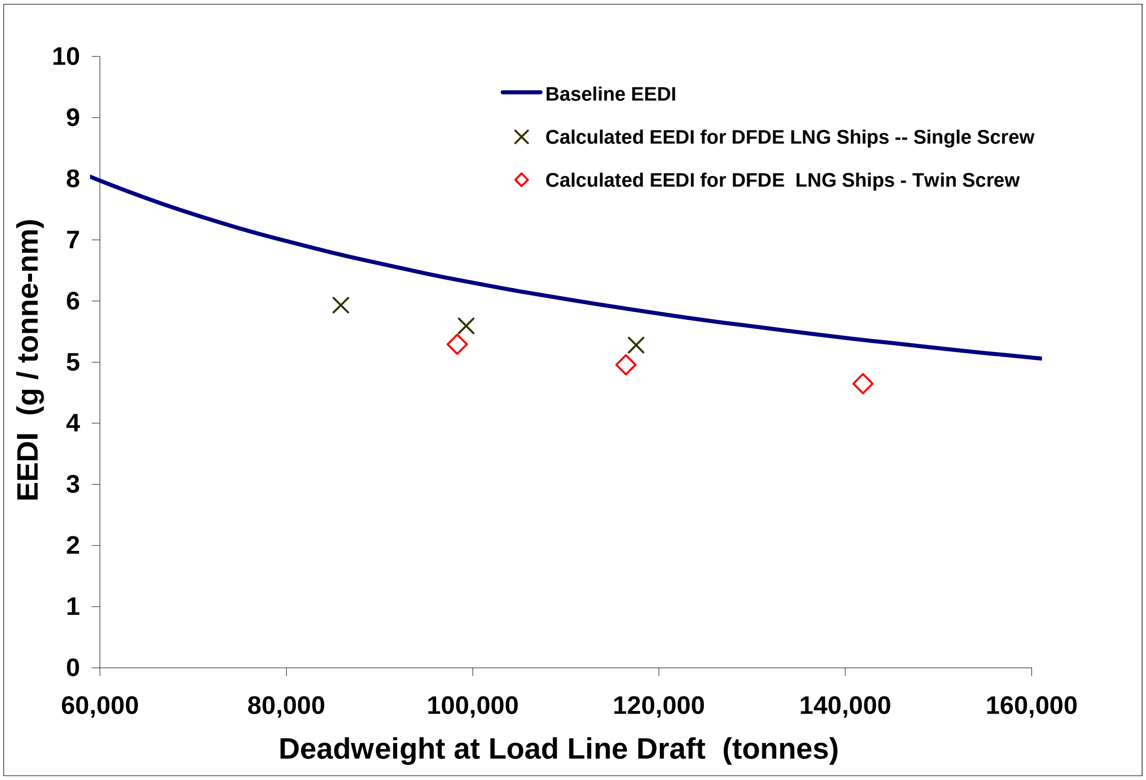


Figure 12 EEDI for LNG Carrier Designs with DFDE Propulsion (comparison of single and twin screw designs)

Alternative Power Plant Study

The 215,000 m^3 LNG carrier has been evaluated with three different propulsion arrangements: DRL, DFDE, and COGES. The attained EEDI for these alternative propulsion configurations are presented in Table 29. Ship particulars and data applied in the calculation of the EEDI are summarized in Table 30.

The DRL propulsion arrangement has two HFO burning main engines, each driving a fixed pitch propeller. There are typically 4 or 5 HFO burning ship's service diesel generators provided to supply the power requirements of the reliquefaction plants, main cargo pumps, and other ship services. The power required for reliquefaction on a 215,000 m^3 ship can average 6 MW on the laden voyage and 5 MW on the ballast voyage. Reliquefaction is not required while offloading cargo as the gas is returned to shore. A gas combustion unit (GCU) is provided to dispose of the boil off gas (BOG) whenever the reliquefaction plant is not available.

The DFDE propulsion plant consists of dual fuel diesel engines driving electrical generators that supply all of the ship's electrical power for both propulsion and ship's services. Power is typically generated at 6,600 Volts and distributed through transformers to the propulsion control system driving the propulsion motor or motors. Power is also supplied to a 440 Volt system that distributes power for the ship's auxiliary machinery and electrical services. Each of the propellers may be driven by a single slow speed electric motor, or through two medium speed electric motors geared to the propeller via a single stage reduction gear. The medium speed motors are smaller, lighter, and more efficient, but a reduction gear and its associated lubrication oil and cooling systems are required. The dual fuel diesel engines may be operated on boil-off gas (BOG), marine diesel oil (MDO) or HFO. BOG is collected from the cargo tanks, compressed to about 6 bar, and delivered to the engines in a double wall piping system. A small amount (about 1%) of MDO is also required as a pilot fuel when operating on gas. The largest dual fuel engines available develop 950 to 1000 kW per cylinder and are available as in-line configurations of 6 to 9 cylinders or “V” configurations of 12 to 18 cylinders. The number of engines and cylinder configuration are selected so as to provide as near optimal loading as possible for the engines required to be in service during the various operating modes of the ship. In 2009 new developments in diesel technology have made it possible to burn diesel fuel and gas simultaneously in any proportion in the dual fuel diesel engines.

Several arrangements of gas turbine and steam turbines are possible. A plant that is suitable for LNG service has a single large aero-derivative gas turbine driving a 36 MW electric generator, a heat recovery steam generator (HRSG), a steam turbine driving an 11 MW generator, and a pair of medium speed diesel generators each driving 6 MW generator. Normally, only the gas turbine, HSRG, and steam turbine would be in service, and the diesel generators would provide backup and take home power. Variable speed electric motors would drive the propellers as in the DFDE ships. The gas turbine would be located above the main deck in a gas tight enclosure and be supplied with BOG at 40 to 46 bar by two-stage compressors in the ship’s compressor room through a double wall pipe. Power would be generated at 11 kV and distributed to the propulsion system at 6.6 kV. Several variations of this plant are possible such as substituting a HRSG with provision for firing with BOG for one of the diesel generators; and two smaller gas turbines each exhausting into its own HSRG plus steam turbine.

When burning boil off gas, the DFDE and COGES alternatives have significantly lower EEDI ratings than the DRL alterative. This is because of the higher heating value and lower relative carbon content of natural gas as compared to fuel oil. When fuel oil is burned in the DFDE and COGES propulsion systems, the EEDI is significantly higher than for the DRL design. This is due to the higher efficiency of the slow speed diesel engines utilized in the DRL design, and the electrical losses associated with the DFDE and COGES diesel electric propulsion systems. If the DFDE and COGES systems burn 50% boil off gas and 50% fuel oil, their EEDI is roughly equivalent to the DRL EEDI rating.

	DRL	DFDE	COGES
when burning Fuel Oil			
Attained EEDI ($EEDI_A$)	6.23	7.41	6.96
Comparison to DRL		19.0%	11.8%
when burning Boil Off Gas			
Attained EEDI ($EEDI_A$)		4.96	5.16
Comparison to DRL		-20.4%	-17.2%
when burning 50% Fuel Oil and 50% Boil Off Gas			
Attained EEDI ($EEDI_A$)		6.18	6.06
Comparison to DRL		-0.7%	-2.7%

Table 29 EEDI for 215,000 m^3 LNG Carrier Designs (comparison of alternative propulsion systems)

Propulsion Plant		**DRL**	**DFDE**	**COGES**
Shafting Configuration		**Twin**	**Twin**	**Twin**
100% Cargo Capacity	m3	**215,000**	**215,000**	**215,000**
Length Overall	m	**315.000**	**315.000**	**315.000**
LBP	m	**303.000**	**303.000**	**303.000**
Beam	m	**50.000**	**50.000**	**50.000**
Depth	m	**27.000**	**27.000**	**27.000**
Design Draft	m	**12.00**	**12.00**	**12.00**
Summer Loadline Draft	m	**13.00**	**13.00**	**13.00**
Lightship	tonnes	41,029	40,952	40,391
Design Block Coefficient		**0.770**	**0.770**	**0.770**
Deadweight at Design Draft	tonnes	102,731	102,808	103,369
Deadweight at Load Line draft	tonnes	116,366	116,443	117,003
Design Speed: 20% SM at 90% MCR	knots	**19.80**	**19.80**	**19.80**
Rated Power of Propulsion Motors	KW	0	29,374	29,374
Main Engine Electrical Efficiency		0.0%	91.3%	91.3%
Installed Main Engine Power (MCR)	kW	32,638	0	0
Main Engine Power (P_{ME})	kW	24,478	24,132	24,132
Aux. Engine Power (P_{AE})	kW	1,066	984	984
Deadweight at SLL (Capacity)	tonnes	116,366	116,443	117,003
Speed at SLL and 75% MCR (V_{ref})	knots	19.59	19.06	19.06
Fuel Type (LNG)				
SFC, Main Engine (SFC_{ME})	g-KWhr		159.3	166.5
SFC, Diesel Generators (SFC_{AE})	g-KWhr		159.3	166.5
Fuel Conv Factors (C_{FME} and C_{FAE})	t CO_2	2.750	2.750	2.750
Attained EEDI ($EEDI_A$)			**4.96**	**5.16**
Baseline EEDI ($EEDI_{BL}$)			5.87	5.86
$\%EEDI = (EEDI_A/EEDI_{BL}) - 1$			-15.6%	-12.0%
Fuel Type (MDO)				
SFC, Main Engine (SFC_{ME})	g-KWhr	172.3	204.2	192.8
SFC, Diesel Generators (SFC_{AE})	g-KWhr	196.9	204.2	192.8
Fuel Conv Factors (C_{FME} and C_{FAE})	t CO_2	3.206	3.206	3.206
Attained EEDI ($EEDI_A$)		**6.23**	**7.41**	**6.96**
Baseline EEDI ($EEDI_{BL}$)		5.88	5.87	5.86
$\%EEDI = (EEDI_A/EEDI_{BL}) - 1$		5.9%	26.2%	18.8%

Table 30 EEDI for 215,000 m^3 LNG Carrier Designs (comparison of alternative propulsion systems)

6. Findings and Conclusions

Many of the findings and conclusions listed below are incorporated into IMO MEPC 60/4/34. This document was peer reviewed by SNAME Ad Hoc Panel No. 18 tasked with evaluating the EEDI, and submitted to IMO by the professional society IMarEST on behalf of SNAME. IMarEST has NGO status at IMO. MEPC 60/4/34 is attached as Appendix 1 to this paper.

Findings related to design optimization and the EEDI

1. The EEDI is particularly sensitive to the service speed, as the required power increases by roughly the cube of the variation in service speed ($P \propto V^3$). Reducing service speed by one knot reduces the EEDI by between 10% and 15%.
2. The scantling draft / design draft ratio (Ts/Td) for existing containerships is about 1.12 for existing LNG carriers is about 1.08. To gain an understanding of the impact of the selected load line draft on the EEDI, calculation were also run with Ts/Td=1.20 for containerships and Ts/Td=1.16 for LNG carriers. Increasing the scantling drafts for containerships and LNG carriers to Ts/Td=1.20 and Ts/Td=1.16 respectively reduces the EEDI as compared to the standard design by between 9% and 10%.
3. For tankers, containerships, and LNG carriers, a 5% increase in hull steel weight increases the attained index by between 0.5% and 1.4%. To put this in perspective, a speed reduction of between 0.05 and 0.10 knots would offset the impact of a 5% increase in hull steel weight.
4. For the Aframax tanker, the *%EEDI* (the attained/baseline EEDI ratio) improves by about 1% for each 0.1 reduction in Cb. The relative change in the EEDI with change in Cb was compared to the relative change in calculated CO_2 emissions for a representative roundtrip and found to be in reasonable agreement.
5. Improvements in the EEDI of 2% to 3% could be realized for an Aframax tanker by increasing the LBP/Beam ratio to 6.0 and above and the LBP/Depth ratio to 12.5 and above. However, these small improvements in the EEDI come at a price, as construction cost increases, the vessel’s length exceeds the berthing capability at many terminals, and the more flexible hull girder associated with the higher LBP/Depth ratios raises structural concerns.
6. The influence of ship size on overall efficiency is illustrated in Table 5. By utilizing deadweight as a surrogate for Capacity, the EEDI does not encourage optimization through more effective utilization of the vessel, employment of larger vessels which benefit from economies of scale, and vessels specially designed for alternative backhauls. Rather, the EEDI may penalize such alternatives should they involve increased lightship weight or influence powering optimization.
7. For containerships, the combination of reducing design service speed from the typical value of about 25 knots to 17.8 knots and increasing block coefficient for the slower design reduces CO_2 production and the EEOI by 47%. Whereas the optimal design speed (representing the minimum RFR) is calculated as 24-26 knots when HFO is $250/tonne, it is 20-21 knots with HFO at $500/tonne and 17-18 knots with HFO at $1,000/tonne.

8. The Baby Neo-Panamax design evaluated in this study has the same slot capacity as the Panamax design but has a substantially larger "loadable" capacity than the beam-restricted Panamax design. The CO_2 emissions per TEU for the Baby Neo-Panamax design is 13.8% lower as compared to the Panamax containership. However, the Panamax design has a 3.6% more favorable EEDI as the EEDI does not account for the amount of deadweight utilized by ballast water as opposed to cargo.
9. For large LNG carriers (>= 180,000 m^3 capacity), the EEDI is 5% to 6% lower (more favorable) for a highly optimized twin screw/ twin skeg arrangement as compared to the single screw arrangement. These designs are draft restricted. For the twin screw design, the propellers can be nearly the same diameter as for the single screw propeller, allowing for lower RPM and higher efficiency.
10. For LNG carriers, the DFDE and COGES propulsion alternatives burning boil-off gas offer significant reductions in CO_2 emissions as compared to DRL propulsion or DFDE propulsion plants burning fuel oil.

Conclusions related to design optimization and the EEDI

1. This study demonstrates the high sensitivity of the EEDI to service speed.
2. Utilizing the deadweight at the summer load line draft as a proxy for cargo carried could lead to "gaming" of the EEDI by increasing the load line draft beyond current practice. At least for LNG carriers, cargo volume may be a better indicator of cargo carrying capability.
3. Increasing steel weight by implementing more robust scantlings has a relatively modest impact on the EEDI.
4. The parametric Aframax tanker study indicates that, although slightly longer ships with reduced block coefficient may be worth considering in the future, relatively little improvement in the EEDI can be achieved through adjustment of the main particulars (length, beam, and depth) to minimize required power.
5. It should be recognized that the EEDI encourages optimization through improvements in hydrodynamic and aerodynamic performance and improvements in the power plant, but does not necessarily encourage the use of an optimized vessel for a given trade.

7. References

1. Larkin, J., Ozaki, Y., Tikka, K., Michel, K., "An Evaluation of the Energy Efficiency Design Index (EEDI) Baseline for Tankers, Containerships, and LNG Carriers", SNAME Symposium, Climate Change and Ships: Increasing Energy Efficiency, Feb. 16-17, 2010.
2. MEPC .1/Circ 681 - "Interim Guidelines on the Method of Calculation of the Energy Efficiency Design Index for New Ships," 17 Aug 2009.
3. MEPC 58/4/8 - "Methodology for Design CO_2 Index Baselines and Recalculation thereof," 21 Jul 2008, submitted by Denmark.
4. GHG-WG 2/2/7 - "Recalculation of the Energy Efficiency Design Index Baselines for Cargo Ships," 4 Feb 2009, submitted by Denmark.
5. MEPC 60/4/7 - "Guidelines for Calculation of Baselines for Use with the Energy Efficiency Design Index," 18 Dec 2009, submitted by Denmark and Japan.
6. MEPC 60/4/14 - "Consideration of the Energy Efficiency Design Index for New Ships – Recalculated Baseline for Containerships," 12 Jan 2010, submitted by Denmark, Marshall Island, and World Shipping Council.
7. MEPC 60/4/33 – "Energy Efficiency Design Index Baseline Evaluation for Tankers, Containerships, and LNG Carriers," 15 Jan 2010, submitted by IMarEST.
8. MEPC 60/4/34 – "Influence of Design Parameters on the Energy Efficiency Design Index for Tankers, Containerships, and LNG Carriers," 15 Jan 2010, submitted by IMarEST.

Appendix 1 MEPC 60/4/34

Influence of Design Parameters on the Energy Efficiency Design Index for Tankers, Containerships, and LNG Carriers