ASSESSMENT OF ENERGY EFFICIENCY AND SHIP EMISSIONS FROM SPEED REDUCTION MEASURES ON A MEDIUM SIZED CONTAINER SHIP

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SUMMARY

Greenhouse gases and other emissions from vessels and related activities in maritime trade have caused significant environmental impacts especially global warming of the atmosphere. Consequently, the International Maritime Organization (IMO) concern significant care to the reduction of ship emissions and improvement of energy efficiency through operational and technical measures. The proposed short-term measure is ship speed reduction in which the ship speed is reduced below its designed value. Therefore, the present paper aims at evaluating the potential energy efficiency and environmental benefits from using speed reduction measure through energy efficiency design index (EEDI), energy efficiency operational indicator (EEOI) and ship emissions calculation models as recommended from IMO. As a case study, a medium sized Container Ship is investigated. The results show that, reducing ship speed by 12.6% will reduce CO_2 emissions by about 36%. Moreover, the attained EEDI value will be improved by 31.7% and comply with not only the current IMO requirements but also with the future ones. Additionally, reducing ship speed by 12.6% will reduce EEOI value from its value at design speed by 26.5%. Furthermore, it is noticed that SOx emission will comply with IMO 2020 limit if ship speed is reduced by 6.8% and above.

NOMENCLATURE

Symbol	Definition
CO_2	*Carbon dioxide*
CEAS	*Computerized Engine Application System*
D	*Distance of voyage*
E	*Pollutant emission rate*
EEDI	*Energy Efficiency Design Index*
EEOI	*Energy Efficiency Operational Indicator*
F	*Emission factor*
f_c	*Cubic capacity correction factor*
f_i	*Correction factor for any limitation in capacity*
f_j	*Ship specific design correction factor*
f_w	*Coefficient of reduction in speed*
GHG	*Greenhouse gases*
IMO	*International Maritime Organization*
m_{cargo}	*the weight of cargo carried on ship*
MCR	*Maximum continuous rating*
ME_{er}	*CO_2 emission reduction due to innovative*
NOx	*Nitrogen Oxide*
P_{AE}	*Auxiliary Engine power in EEDI*
P_{ME}	*Main Engine power in EEDI formula*
P_{PTI}	*75% of the rated mechanical power of the shaft motor divided by the weighted efficiency of the generators*
s	*Percentage of mass sulfur content in fuel*
SFC	*Specific fuel consumption*
SG_e	*CO_2 emissions from Shaft generators*
SOx	*Sulfur dioxide*
TEU	*Twenty-Foot Equivalent Unit*
V_{ref}	*The reference speed in EEDI*
x	*reduction rate of the EEDI*

1. INTRODUCTION

Global climate change moves us to change the manners by which we produce and use energy. Emissions reduction is important to maintain a strategic distance from critical changes in the world's climate (Bouman et al., 2017; IPCC, 2018). Therefore, the International Maritime Organization (IMO) has created and adopted progressively stringent regulations intended to essentially diminish emissions from vessels. The last study by IMO shows that maritime sector is responsible for 6.6%, 4% and 2.6% of Nitrogen Oxide (NOx), Sulfur dioxide (SOx) and Carbon dioxide (CO_2) emissions, respectively (El-Gohary, 2012).

CO_2 emissions from Container ships are almost 205 million tons which presents about (23%) of the CO_2 emissions from total shipping (Olmer et al., 2017). Therefore, Container ship is the core of study due to its huge contribution of total shipping emissions (N.R. Ammar et al., 2019).

In this regard, IMO has been effectively occupied with a worldwide approach to further improve marine energy efficiency and reduce emissions from ships through technical and operational measures. These measures included another Chapter 4 of International Convention for the prevention of pollution from ships (MARPOL) Annex VI which called "Regulations on energy efficiency for ships " and went into force on 1 January 2013 and applies to all vessels of 400 gross tonnages or more.

The regulation was issued to reduce CO_2 emissions, through applying energy efficiency indexes (Nader R. Ammar, 2018; Rehmatulla et al., 2017). The main indexes are the Energy Efficiency Design Index (EEDI) and Energy Efficiency Operational Indicator (EEOI) which can be used to assess the energy efficiency. EEDI sets a base energy efficiency level for the work attempted for various vessel types and sizes and gives a benchmark to compare the energy efficiency of vessels while setting a base required degree of efficiency for various vessel types and size. Mandatory execution of EEDI quickens the procedure of energy saving and emission reduction in maritime transportation, and higher prerequisites are proposed for the improvement of green vessels.

The operational -based measures to improve energy efficiency and reduce emissions are like speed reduction, weather routing, voyage optimization, auxiliary power reduction, trim/draft optimization, hull/propeller cleaning and hull coating (Rehmatulla et al., 2017). The operational short-term measure, which will be applied in this research paper is the speed reduction by using a lower speed than the deliberate design speed.

(Lavon & Shneerson, 1981) were among the first to talk about speed reduction measure in the wake of the oil emergencies of the 1970s. More recently, (J. Faber et al., 2009) assessed that up to 10% improvement in energy efficiency could be possible as a result of speed reduction measure. (Bazari & Longva, 2011) discovered that the potential went from roughly 10 to 20%, depending on vessel size and type. (Eide et al., 2011) found that an expansion in CO_2 reduction of beyond 33% by 2030 could be reachable by implementing measures with a minor expense beneath zero, for example, speed reduction measure which is among the measures with the greatest total savings potential. (Hoffmann et al., 2012) indicated that improving effectiveness by more than 50% by 2030 could be possible at zero net expenses and financially cost-effective measures such as speed reduction measure. It is found that for RO-RO cargo vessel by (Nader R. Ammar, 2018), reducing ship speed by 10% and 40% will reduce CO_2 emission by 27.05% and 78.39% with cost-effectiveness of 121.2 \$/ton CO_2 and 287.6 \$/ton CO_2, respectively.

The study of speed reduction practice in liner shipping became more frequent in the last years (Wong et al., 2015). Recently, there are significant advances in the speed reduction approach not only from the economic aspects (Wong et al., 2015) but also in others areas as resistance and environmental advantages (Tezdogan et al., 2016). Other studies found that slowing down is a cost-effective way to reduce greenhouse gas (GHG) emissions (Yuan et al., 2016). (Jasper Faber et al., 2017) found that CO_2 emissions could be reduced by 13, 24 and 33% if the ships reduced their speed by 10, 20 and 30%.

The present research aims at evaluating the potential energy efficiency, and environmental benefits of using speed reduction measure. The energy efficiency will be assessed by using EEDI and EEOI as recommended from IMO. The environmental benefits will be assessed by showing the effect of speed reduction measure on CO_2, NOx and SOx rates.

2. ENERGY-ENVIRONMENTAL MODELING FOR THE ASSESSMENT OF SPEED REDUCTION MEASURE

This section aims to present the environmental and energy efficiency models with emphasis on the calculation of EEDI EEOI which applied to analyse the effect of using speed reduction measure on ship emissions and energy efficiency.

2.1 ENERGY EFFICIENCY ASSESSMENT PROCEDURE

The IMO has approved vital energy efficiency rules for international ships underneath the EEDI and EEOI. EEDI is utilized to check associate degree energy-efficient design for explicit vessels. MARPOL Annex VI concern their regard for unique kind of vessels which have 400 metric gross tonnages and higher, for example, container ships, tankers, gas carriers, LNG carriers, bulk carriers, and passenger ships. EEDI Index is considered also for existing ships in service. The impact of maritime transportation on the environment can be shown in EEDI value. (American Bureau of Shipping, 2014; Ančić & Šestan, 2015; Bøckmann & Steen, 2016).

2.1.1 Required EEDI

Required EEDI is the restrictive limit for EEDI. It is determined for all vessel types utilizing 100 % of the deadweight (DWT) at summer load draft, except for passenger ships where gross tonnage is utilized. The required EEDI value can be calculated as presented in Eq. (1) (Ahmed G. Elkafas et al., 2021; Polakis et al., 2019).

$$EEDI_{required} = Baseline(1 - \frac{x}{100}) \quad (1)$$

The baseline is characterized as a curve indicating a mean value corresponded to a group of values for vessels from the same type. The baseline is created according to IMO guidelines using a group of ships from the same type with the corresponding capacity then a regression analysis is done to obtain the final form of the base line as shown in Eq. (2) (IMO, 2013).

$$Baseline = a \times Capacity^{-c} \quad (2)$$

Where a and c are constraints vary from vessel type to another, their values are 174.22 and 0.201, respectively, for container ships. Capacity is the deadweight tonnage (DWT) (IMO, 2013).

The reduction rate of the EEDI reference line value (x) is determined by the ship building year. It is between 10%, 20% and 30% in phase 1(1 Jan 2015-31 Dec 2019), phase 2 (1 Jan 2020-31 Dec 2024) and phase 3 (1 Jan 2025 and onwards), respectively (Germanischer-Lloyd, 2013).

2.1.2 Attained EEDI

Attained EEDI is the actual value for the case study and its value should be lower than required EEDI to be satisfied by IMO (IMO, 2018). Attained EEDI is a measure of energy efficiency for a ship and evaluated as presented in Eq. (3) (Polakis et al., 2019)

$$EEDI_{attained} = \frac{\prod_{j=1}^{M} f_j \left(\sum_{x=1}^{nME} P_{ME(x)} \times SFC_{ME(x)} \times C_{FME(x)}\right) + SFC_{AE} \times C_{FAE} \times P_{AE} + SG_e - ME_{er}}{f_i \times f_1 \times f_w \times f_c \times Capacity \times V_{ref}} \quad (3)$$

Where f_j is the ship-specific design elements correction factor, if elements aren't introduced, the factor is set to be 1. The power of the main engine (P_{ME}) is taken for EEDI procedure at 75% of Maximum Continuous Rating (MCR) for each main engine (x) in kilowatts. P_{AE} is the auxiliary power that is theoretically necessary to operate the main engine periphery and accommodation of the crew. Its value is a function of MCR of the main engine as presented in Eq. (4) in which P_{PTI} is 75% of the rated mechanical power of the shaft motor divided by the weighted efficiency of the generators (Nader R. Ammar, 2018; IMO, 2018).

$$P_{AE} = \left[0.025 \times \left(\sum_{i=1}^{nME} MCR_{ME} + \frac{\sum_{i=1}^{nPTI} P_{PTI(x)}}{0.75}\right)\right] + 250 \quad (4)$$

SFC is the specific fuel consumption measured in gram/kilowatt hour and C_F is a conversion factor between tons of fuel burned and tons of CO_2 produced for each main engine (ME) and Auxiliary engine (AE). The conversion factors of fuels used in the marine field are introduced in Figure 1 (Rehmatulla et al., 2017; Tran, 2017).

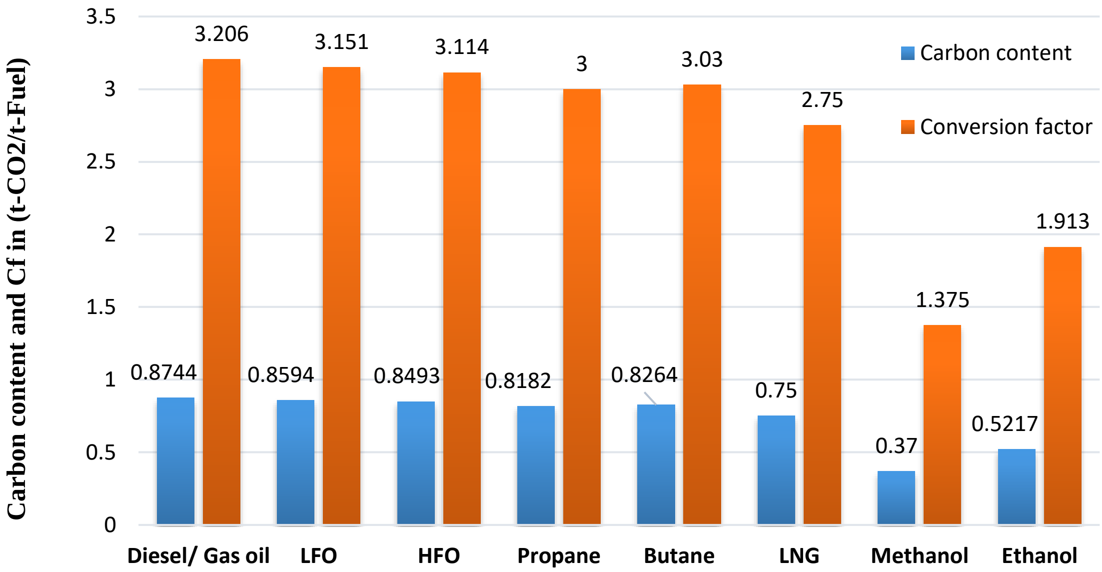

Figure 1. Conversion factors and carbon contents for marine fuels

For the dual-fuel engine, Eq. (5) is utilized to calculate the term of C_F×SFC for dual fuel (DF) case study depending on the value of each one for gas fuel and pilot fuel at the related load point (Ahmed G. Elkafas et al., 2021).

$$C_{F(DF)} \times SFC_{DF} = C_{F,pilotfuel} \times SFC_{pilotfuel} + C_{F,Gas} \times SFC_{Gas} \quad (5)$$

CO_2 emissions from Shaft generators (SG_e) and CO_2 emission reduction due to innovative technologies (ME_{er}) can be evaluated based on the power of the main engine as introduced in (Polakis et al., 2019). f_i is the capacity factor for any specialized limitation on capacity, and ought to be equal (1.0) if no need of the factor, f_1 is a correction factor for general cargo ships outfitted with cranes, f_w is a non-dimensional coefficient demonstrating the reduction in speed due to wave and wind conditions (Liu et al., 2011) and f_c is the cubic capacity correction factor for special types of ships and ought to be equivalent to one if no need of this correction exists.

Capacity depends on the ship type, for all ship types except passenger ships and container ships, the deadweight should be used as capacity while gross tonnage should be used for passenger ships and 70 % of the deadweight should be used for container ships.

The reference speed in EEDI conditions (V_{ref}) is calculated by assuming that the weather is calm with no wind or waves and measured according to the ITTC recommended procedure. The reference speed used in the calculation of attained EEDI must be estimated at 75% MCR (Germanischer-Lloyd, 2013).

2.1.3 Energy Efficiency Operational Indicator

EEOI is established by maritime Organization IMO following the International Convention for the Prevention of Pollution from Ships (MARPOL 73/78) Annex VI for prevention of air pollution from ships. The calculation of EEOI value is a fundamental work to determine this value at ship in research process. EEOI which called former operational CO_2 index, is a tool for measuring the CO_2 gas emission to the environment per the transport work. On the other hand, it represents the actual transport efficiency of a ship in operation. The unit of EEOI depends on the measurement of cargo carried or the transport work done, e.g., ton CO_2/ (tons/nautical miles), tons CO_2/ (TEU/nautical miles) or tons CO_2/ (person/nautical miles), etc. The EEOI is calculated by the following formula, in which a smaller EEOI value means a more energy efficient ship (Nader R. Ammar, 2019):

$$EEOI = \frac{\sum_i FC * C_F}{\sum_i m_{cargo} * D} \quad (6)$$

Where, i is the navigation voyage number, FC is the mass of consumed fuel at voyage, C_F is the conversion factor between fuel and CO_2 which can be calculated according to Figure 1, m_{cargo} is the weight of cargo carried on ship and D is the distance of voyage in nautical miles corresponding to the cargo carried or work done.

2.2 CALCULATION OF SHIP EMISSIONS RATES

The emissions from ships included many kinds of pollutants such as CO_2, SOx, and NOx emissions. The individual emission energy-based rate in g/kWh differs from type to another. When looking based on g CO_2 per kilowatt-hour, it is found that it is proportional to the specific fuel consumption and the conversion factor between fuel and CO_2 as discussed in Figure 1 which concluded that the quantity of CO_2 emission depends on the fuel type. On the other hand, SOx emissions are proportional to the specific fuel consumption (SFC) and the content of sulfur in the fuel (S) so that the SOX emission energy-based rate (E_{SOx}) in g/kWh can be calculated by Eq. (7) (Ahmed G Elkafas et al., 2021).

$$E_{SOx} = SFC \times 2.1 \times (S\%) \quad (7)$$

Where S is the percentage mass sulfur content in the fuel and SFC is in g/kWh. It is seen that lower the sulfur content in fuel is led to reduce the specific emission rate of SOx, which is the reason why more and more strict demands towards lower sulfur content are imposed on oil for marine diesel engines at the current time.

The emission rate of Nitrogen oxide (NOx) relays with the type of engine and fuel the Tier which depends on the date of ship construction as recommended by IMO as presented in Figure 1. As can be seen, the highest allowable specific NO_X emission rate (IMO Tier I level for engines manufactured before 2011) is 17 g NO_X/kWh for low-speed engines, while the rate for medium-speed engines (750 RPM) is approximately 12 g NO_X /kWh. For high-speed engines, at about 1100 RPM the allowable NO_X emission rate according to Tier I is approximately 11 g/kWh. IMO Tier II and III levels must be fulfilled corresponding to 15 % and 80 % NO_X reduction respectively, compared with the Tier I level, as shown in Figure 1.

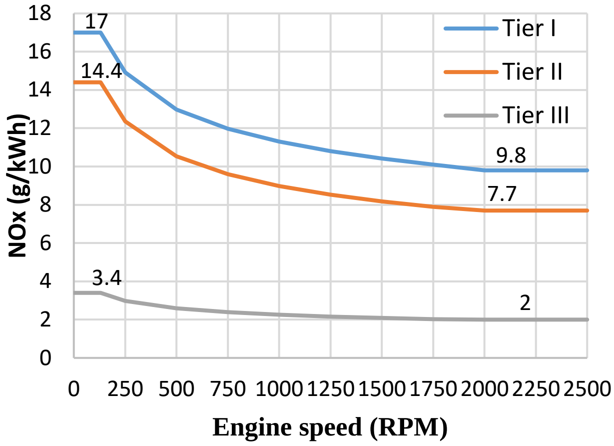

Figure 1. NOx limits in MARPOL Annex VI

The conversion factor of each emission type between fuel and pollutant type can be determined in g (pollutant)/g (fuel) through divided the energy-based rate by the specific fuel consumption value at the actual service condition. The important rate factor for emission is the rate of emission per hour which can be calculated as presented in Eq. (8).

$$F_i = \mathrm{FC} \cdot C_{F(i)} \tag{8}$$

Where F is the emission rate factor for each pollutant type (i) on t /hr, FC is the fuel consumption in t/hr however, C_F is the conversion factor for every emission type (i). The emission rate can be modified to be based on the ship deadweight and the transported nautical miles (g/dwt.nm) by dividing emission factor (F) by the speed and deadweight of ship.

3. SPEED REDUCTION MEASURE

The speed reduction measure is the one of the operational measures which can be applied for the ship by reducing the service speed in a noticeable amount. In the short term, limiting ship speeds can immediately reduce GHG emissions. Main engine power demand is proportional to the cube of the speed; as the ship's speed decreases, its main engine power demand falls even more rapidly, reducing fuel consumption and emissions.

Ships need to be able to escape from adverse weather conditions. Responding to concerns about whether the EEDI could result in underpowered ships, the MEPC has developed guidelines for determining the minimum propulsion power of ships (MEPC, 2017). All new ships need to comply with the minimum propulsion power standard. The minimum propulsion power is based on the speed that ships need to be able to attain when they encounter adverse weather conditions. It is not directly related to the speed at which ships sail, because they may operate their engines below the maximum continuous rate. Based on the ship shape, the minimum propulsion power can be based on minimum service speed in the range between 4-6 knots (MEPC, 2017).

The specific fuel consumption value corresponding to speed reduction measure should be varied from its value at design speed because it depends on the engine Continuous Service Rating (CSR) at actual loading condition. By developing a relation between engine loads with specific fuel consumption, the new SFC can be determined which corresponded to actual rating and new service speed. It should be assumed that the speed reduction measure is applied to the case study when it is in the same actual service condition (EEDI condition) which equals 70% DWT.

The exhaust emissions rate in (g/kWh) at the new service speed can be calculated by multiplying the resulted fuel consumption to the pollutant conversion factor. Therefore, the new emission rates corresponding to speed reduction measure can be determined. In the current research, the emission reduction potential will be determined by assuming that the baseline transport work is retained under speed reduction measure. The emissions reduction potential will be determined for CO_2, NOx, SOx and PM pollutants.

From energy efficiency point of view, when applying the speed reduction measure, the power of main engine will be reduced, therefore, EEDI value will be reduced. The reference speed in the EEDI formula is varying with the service speed and propulsion power, therefore, it should be recalculated at each proposed service speed.

4. CONTAINER SHIP CASE STUDY

The case study for the current paper is selected to be a Container ship (RIO GRANDE EXPRESS) which have IMO number (9301823). The ship is designed to contain 4250 TEU in the full load condition having maximum deadweight equal to 51741 tons at maximum draught 12.6 m. The ship was built in 2006 (15 years ago) by Samsung Heavy Industries Co. Ltd. Currently sailing under the flag of USA. Principal dimensions of the ship are given in Table 1 (A.G. Elkafas et al., 2019; Fleetmoon, 2020; Vesseltracking, 2020).

Table 1 Principal dimensions of the container ship case study

Particular	Value	Unit
Length over all	260	m
Length between perpendiculars	247	m
Breadth	32	m
Depth	19.3	m
Maximum draught	12.6	m
Service Speed	23.7	knots
Maximum continuous rating (MCR)	42504	kW

The container ship is propelled by a low-speed marine diesel engine (MAN B&W 8K90MC-C) with a MCR of 42504 kW which operated by HFO. Using the CEAS online calculation tool, the SFC and the engine speed are plotted on with various load factors as shown in Figure 2.

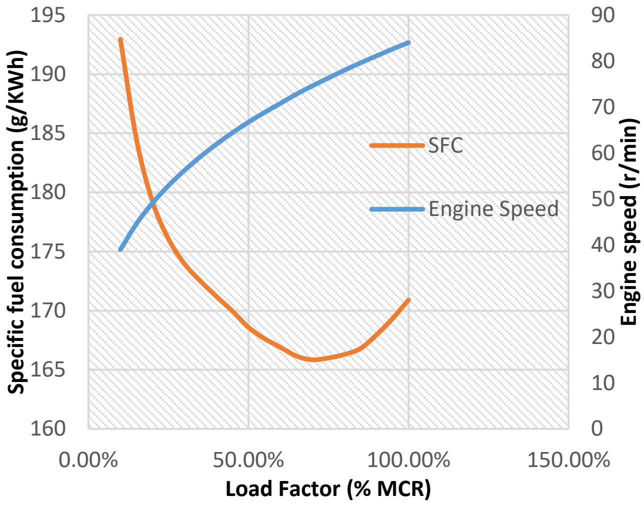

Figure 2. Specific fuel consumption and engine speed for various load factor

Based on MAN B&W 8K90MC-C main engine project reference with specifying the value of MCR equal to the required one for the case study, the correlation between the main engine power factor and specific fuel consumption can be found as presented in Figure 2 The SFC reduces at a part engine load and then go to increases again.

5. RESULTS AND DISCUSSIONS

The energy and environmental impacts of using speed reduction measure on the container ship case study are discussed. Firstly, the calculation of EEDI index at the operational design speed for the selected case study is presented. Secondly, the environmental benefits for using speed reduction approach are discussed including fuel saving percent at each speed reduction percent and selection of the optimized speed then compared the results of attained EEDI at each speed reduction with the required EEDI at all phases as recommended by IMO regulations.

5.1 CALCULATION OF ENERGY EFFICIENCY DESIGN INDEX AT DESIGN SPEED

IMO has introduced an index to measure the marine energy efficiency EEDI. The EEDI assesses marine energy efficiency. The required EEDI is the greatest suitable limit for the Index and can be determined by utilizing Eq. (1) and Eq. (2). For the case study, the maximum Deadweight is 51741 tons. The reduction factor (x) is determined by the fabricated year, it is about 10%, 20%, and 30% in 2015, 2020 and 2025 at Phase 1, 2 and 3 respectively for the case study.

Figure 3 shows the restrictive limit of EEDI for the container ship type for various deadweight values. For the case study at the Maximum deadweight, the baseline value of required EEDI is reduced from 19.66 gCO_2/ton-NM to 17.7, 15.73 and 13.76 gCO_2/ton-NM at the three phases, respectively.

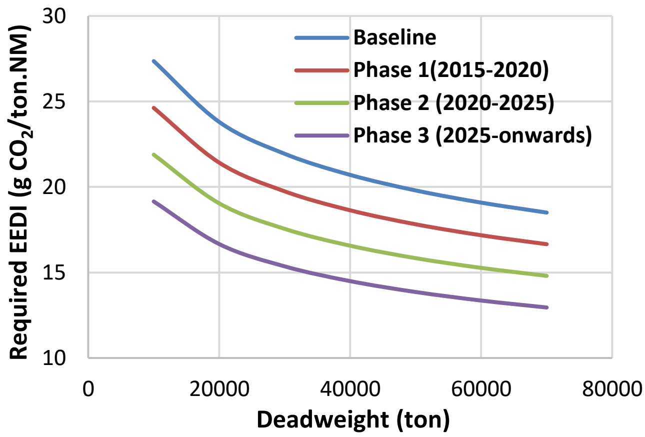

Figure 3. the restrictive limit of EEDI based on IMO regulations for container ship type

The attained EEDI at design service speed can be determined according to IMO regulations based on the technical data of the case study. As discussed in section 2 and according to Eq. (3), (f_j, f_i and f_c) for the case study are set to be 1.0. The ship is propelled by one main engine and only one generator is usually connected during normal sea going conditions to supply the required electric power. The ship uses Heavy fuel oil (HFO) as the main fuel for main engine, but marine diesel oil (MDO) is the fuel of auxiliary engines so that by using Figure 1, the conversion factor (C_F) for both main engine and auxiliary engine can be determined. The specific fuel consumption of main engine is determined at 75% MCR as recommended by IMO guidelines which can be determined from Figure 2. The attained EEDI shall be calculated for the container ship when the ship is carrying 70% of its maximum deadweight so that the reference speed which used in attained EEDI formula will be differ from the design service speed as the reference speed obtained at 75% MCR at a draught corresponding to 70% deadweight. The reference speed at 70% deadweight utilisation and 75% MCR in trial condition is calculated to be 24.46 knots. The other parameters of attained EEDI are calculated and presented at Table 2.

Table 2 Attained EEDI parameters calculated according to IMO regulations

EEDI Data	Values	Units
Main engine power (75%MCR)	31878	kW
Auxiliary power	1313	kW
Main engine SFC	166.37	g/kWh
Auxiliary engine SFC	190	g/kWh
Main engine C_F	3.114	gCO_2/g fuel

Auxiliary engine C_F	3.206	gCO_2/g fuel
Capacity (70% DWT)	36219	Tons
Reference speed	24.46	knots

The result of applying Eq. (3) for the attained EEDI is set to be 19.54 gCO_2/ton-nm at the design service speed. By comparing this value with the required EEDI values, it shows that attained value is lower than the baseline value of required EEDI by about 0.6% and should be decreased by 9.46%, 19.52% and 29.58% to be comply with EEDI values at phase 1, 2 and 3 respectively as recommended from IMO regulations. Figure 4 shows the required reduction percentage in the attained EEDI value for the case study relative to IMO phases.

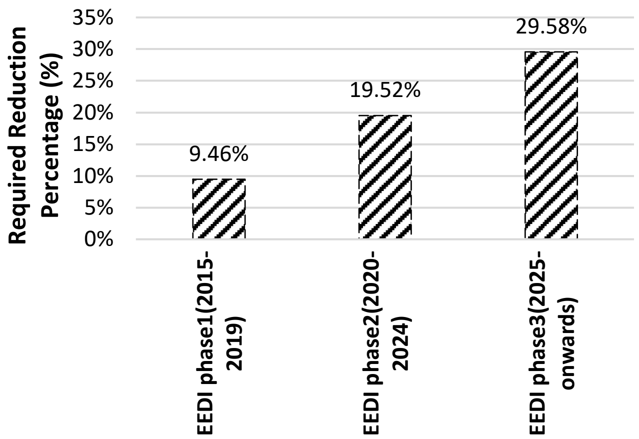

Figure 4. Required EEDI reduction percent at all phases

5.2 FUEL CONSUMPTION AND EXHAUST GAS EMISSIONS FOR THE ACTUAL CONDITION

The higher fuel prices encouraged the maritime field to decrease the quantity of used fuel and reduce CO_2 emissions and other exhaust emission types. To achieve this goal, the fuel consumption and the associated exhaust gas emissions shall be calculated for the so-called actual condition when the ship is not fully loaded as the cargo utilization in the design condition can be specified in percent of the design payload.

The specific fuel consumption (SFC) for the main engine is calculated as a function of the main engine loading in % MCR as discussed in Figure 2. The lowest fuel oil consumption occurs at approximately 75% MCR (EEDI power condition) for a normal engine tuning, while the SFC increases for higher and lower engine ratings, depending on the engine tuning.

For the actual condition of the case study, the engine is assumed to be normally tuned and the ship is assumed to be loaded at the actual draught of 10.33 m corresponds to 70% maximum deadweight (EEDI capacity condition). By using the same design speed (23.7 knots) to be in the actual service condition, the necessary main engine power at this condition is 32744 KW so that CSR can be calculated now by dividing the necessary power to maximum continuous rating of main engine. The specific fuel consumption at actual condition can be calculated from Figure 2 corresponds to the CSR (%MCR). Finally, the data corresponds to the actual condition can be shown in Table 3.

Table 3 Actual service condition data

Parameter	**Value**
Actual Deadweight (tons)	36219
Actual Draught (m)	10.33
Service speed (knots)	23.7
Necessary main engine power (kW)	32744
Engine rating in actual condition (CSR)	77%
Specific fuel consumption at CSR (g/kWh)	166.4
Main Engine fuel consumption (t/hr.)	5.45
Auxiliary Engine fuel consumption (t/hr.)	0.25

When multiplying the necessary propulsion power demand at actual condition with the SFC at constant continuous rating (%MCR), the fuel consumption of main engine at CSR is found and fuel consumption of auxiliary engine is calculated by multiplying the auxiliary engine SFC with its power demand at the actual condition and the results are shown in Table 3.

The values of diesel engine emission factors are shown in Table 4 (Banawan et al., 2010; Ahmed G. Elkafas et al., 2021; Seddiek & Elgohary, 2014; Speirs et al., 2020).

Table 4 Main engine and Auxiliary engine emission factors

Fuel type	**Emission factor (g/kWh)**	**CO_2**	**NO_X**	**SO_X**
HFO	Main Engine	518.1	13.6	3.49
MDO	Auxiliary engine	609.1	9.6	3.99

The exhaust gas emissions rates in g/dwt.nm can be calculated when multiplying the fuel consumption to the corresponded specific emission factor and the results are presented in Table 5.

Table 5 Exhaust emission factors at the actual sailing condition

Emission Type	**CO_2**	**NO_X**	**SO_X**
Emission Factor (g/dwt.nm)	20.72	0.534	0.14

5.3 SPEED REDUCTION IMPACT ON SHIP EMISSIONS AND ENERGY EFFICIENCY

The first concern is about the minimum propulsion power required to encounter adverse weather conditions set by

MEPC. By using the formula which appear in (MEPC, 2017) and specifying the actual deadweight of ship which equal to 36219 ton. The minimum propulsion power is equal to 8350 kW to make the case study able to encounter adverse weather conditions. Based on the value of minimum propulsion power, the speed reduction percent for the container ship could not be less than 33 %. Therefore, the analysis will be conducted to a range between 2-17% speed reduction percent to be on the safe side from the adverse weather requirement.

5.3.1 Speed reduction effect on fuel consumption and emissions rates

By using the relation between engine loads with specific fuel consumption in Figure 2, the new SFC can be determined which corresponded to actual rating and new service speed. The results of the total fuel consumption rate in t/hr corresponding to reduced service speed can be shown in Figure 5 which shows that the lower ship service speed, the less fuel consumption value because it depends mainly on the required power to propel the ship.

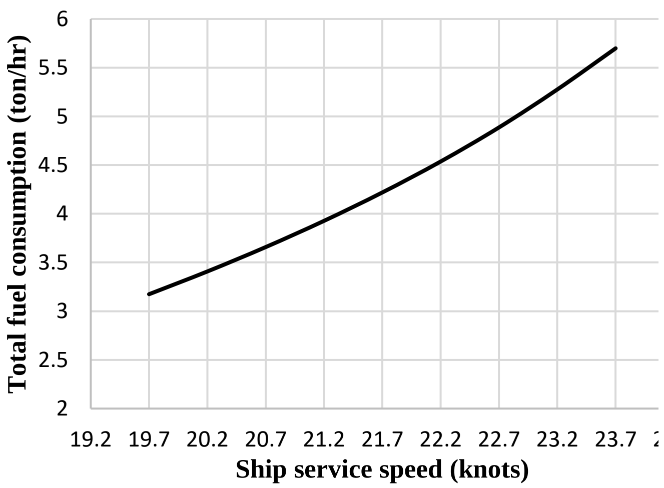

Figure 5. Total Fuel consumption rate for different ship speeds

By using the speed reduction measure, the quantity of fuel is saved by a noticeable percent as shown in Figure 6. When the service speed is reduced by 12.6% (20.7 knots), 14.7% (20.2 knots) and 16.8% (19.7 knots), the fuel consumption will be reduced by 35.81%, 40.2% and 44.3% respectively and thus will reduce the operation price of the ship.

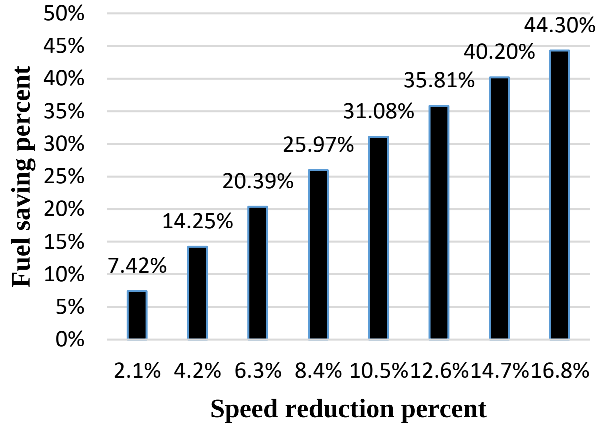

Figure 6. Fuel saving resulted from speed reduction measure

CO_2 emissions reduction percent corresponding to various speed reduction (% design speed) are shown in **Figure 7.** It shows the impacts of speed reduction on CO_2 emissions as follows, CO_2 emission rate at the operational design speed is 17.82 t/hr but when the design speed is reduced by 12.6%, 14.7%, and 16.8%, the CO_2 emission rate is reduced by 35.96%, 40.33%, and 44.41% respectively.

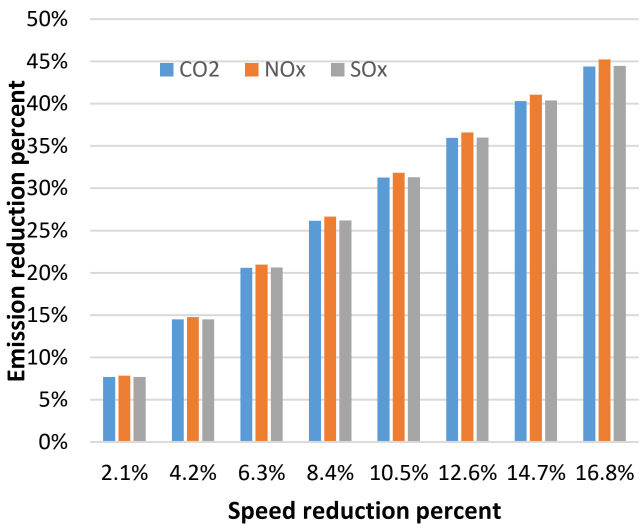

Figure 7. Speed reduction measure impacts on ship emissions

NOx emissions rates are 291.25 kg/hr, 270.79 kg/hr, and 251.69 kg/hr corresponding to speed reduction by about 12.6%, 14.7%, and 16.8% of design speed, respectively. These values are compared with NO_X emission rate at design speed (459.5 kg/hr) and found that speed reduction by these percent reduces the NO_X emissions rate by about 36.6%, 41.07%, and 45.22%, respectively as shown in Figure 7.

On the other hand, SOx emission rates are 76.8 kg/hr, 71.56 kg/hr, and 66.66 kg/hr corresponding to speed reduction by about 12.6%, 14.7%, and 16.8% of design speed, respectively. These values are compared with SOx emission rate at design speed (120 kg/hr) as shown in Figure 7 which shows that speed reduction by these percent reduces the SOx emission rates by about 36%, 40.4%, and 44.5% respectively. SOx emission rates have been compared with the IMO 2020 emission-limit rate. Figure 8 shows a comparative diagram between IMO SOx 2020 limit and the SOx emission rates at different ship speed reduction. It can be noticed that SOx emission will comply with IMO 2020 limit if ship speed is reduced by 6.8% and above.

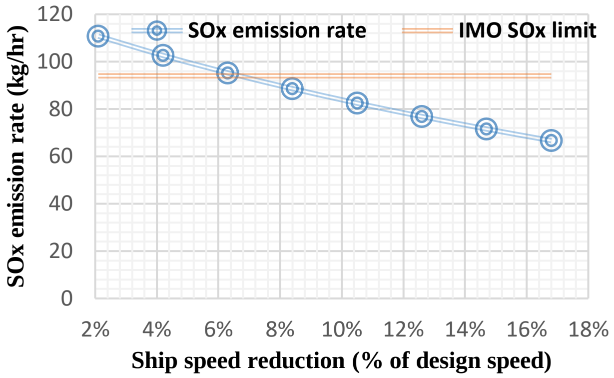

Figure 8. SOx emission rates at different ship speed reduction compared with IMO limit

5.3.2 Speed reduction effect on Marine Energy Efficiency

Ship speed reduction by a significant percentage reduces the main engine power, auxiliary engine power, and fuel consumption as discussed before. The energy efficiency level can be determined based on EEDI value performed at 70% DWT, therefore, the reference speed of EEDI when applying speed reduction measure will differ from its value in design speed. The results of attained EEDI corresponding to each speed reduction percent (% of design speed) are shown in Table 6.

Table 6 Attained EEDI values at different speed reduction percentages

Speed reduction percent (% of design speed)	**Attained EEDI (g/dwt.nm)**
2.1%	18.26
4.2%	17.08
6.3%	16.02
8.4%	15.05
10.5%	14.16
12.6%	13.34
14.7%	12.57
16.8%	11.85

The attained EEDI is reduced by a significant amount as shown in **Table 6** but it does not show the potential benefits regarding EEDI required phases. Therefore, **Figure 9** shows a comparison between the attained and the required EEDI values for the container ship at different speed reduction percentages.

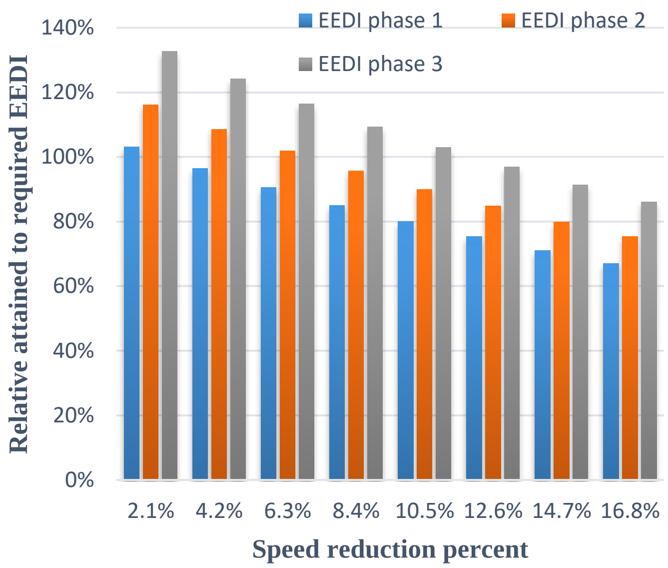

Figure 9. Comparison between attained and required EEDI values

Especially, at 20.7 knots which corresponds to 12.6% speed reduction percent of design speed, the attained EEDI is lower than its value at design speed by 31.73% and it also will be 75.4%, 84.8% and 96.9% of the required EEDI values at the first, second and third phases, respectively. On the other hand, at 20.2 knots which corresponds to 14.7% speed reduction percent of design speed, the attained EEDI is lower than its value at design speed by 35.67% and it also will be 71%, 79.9% and 91.35% of the required EEDI value of the first, second and third phases, respectively.

This means that the more speed reduction, the more improvement in energy efficiency as attained EEDI value is reduced and thus will comply not only with the current IMO EEDI requirement but also with the future ones.

On the other hand, EEOI can be utilized to assess the enhancement in energy efficiency resulted from speed reduction measure. The average EEOI is calculated using Eq. (6) by assuming the average transported cargo is 4250 TEUs each voyage over 11044 NM which is the distance between Hamburg-Germany and Busan–South Korea VIA Suez Canal. The average EEOI value is 0.0.000176-ton CO_2/TEU-NM corresponding to the design service speed. Figure 10 predicts the average EEOI values at different ship speed reduction as a percentage of design speed.

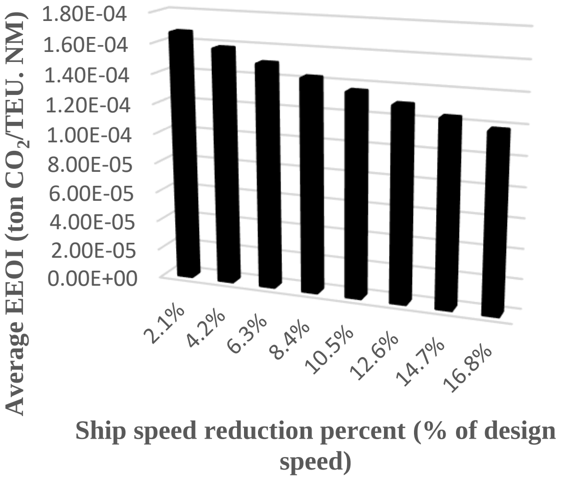

Figure 10. Average EEOI values at different speed reduction percentages

As shown in Figure 10, reducing ship speed by 12.6%, 14.7% and 16.8% will reduce EEOI value from its value at design speed by 26.5%, 29.8% and 33%, respectively.

6. CONCLUSIONS

IMO identifies many measures for reduction of ship emissions and improvement of marine energy efficiency through technical and operational viewpoint. One of the effective short term operational measures for reducing emissions and improving Energy Efficiency is presented in this paper. Speed reduction method is the operational measure which is selected to the study. The main conclusions from assessment of speed reduction measure on the container ship case study are as follows:

- From environmental perspective, when the ship speed is reduced by 12.66%, 14.7% and 16.8%, the fuel consumption will be reduced by 26.51, 29.84 and 32.99% respectively and thus will reduce the operation price of the ship. This reduction led to reduce CO_2 emissions by 35.96%, 40.33% and 44.41% respectively. Speed reduction approach by the same speed reduction percent reduce the SOx emission by about 36%, 40.4% and 44.5% respectively and reduce NOx emission rates by about 36.6%, 41.07% and 45.22%, respectively. It can be noticed that SOx emissions will comply with IMO 2020 limit if ship speed is reduced by 6.8% and above.
- From energy efficiency perspective, the attained EEDI of the case study should be reduced by 9.46%, 19.52% and 29.58% to satisfy the IMO three phases which set up to the required EEDI. When the speed reduction percentage equal to 12.6% from design speed, the attained EEDI will be lower than the attained EEDI at design speed by 31.73% and it also will be 75.4%, 84.8% and 96.9% of the required EEDI values at the first, second and third phases, respectively. The more speed reduction, the more improvement in energy efficiency as attained EEDI value is reduced and will comply with not only the current IMO EEDI requirement but also with the future ones. In addition to, reducing ship speed by 12.6%, 14.7% and 16.8% will reduce EEOI value from its value at design speed by 26.5%, 29.8% and 33%, respectively.
- Finally, speed reduction method is one of the effective operational measures to be applied to comply the IMO requirements for emissions reduction and marine energy efficiency improvement. Speed reduction can be easier to implement and enforce compared to other operational measures.

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