ANALYSIS OF THE EFFECTS OF CO_2 EMISSIONS SOURCED BY COMMERCIAL MARINE FLEET BY USING ENERGY EFFICIENCY DESIGN INDEX

by

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Environmentally friendly compared to other modes of transport, is still responsible for 1 billionns of CO_2 emissions per year and 2.7% of total global emissions, although it has the lowest CO_2 emissions per mile. In order to keep the world's surface temperature below the critical +2 °C, International Maritime Organization works with alternative methods especially in the energy efficiency design index, to increase the productivity depending on the type and operation of the ship to reduce current CO_2 emissions each tonne per mile basis. More energy-efficient vessels are necessary due to the increasing volume of maritime trade in parallel to meet the growing energy demands and reduce total CO_2 emissions. Measures to reduce CO_2 emissions also increase efficiency and fuel-savings. The most significant parameter of fuel economy is the speed of the ship. Sensitivity analysis was used to determine the ecological speed limits of vessels in terms of minimum commercial profitability by a gradual reduction in operating speeds. Consequently a solution methodology for the effects of slow steaming to the global environment is presented as a CO_2 emission reduction activity under the systematic analysis of human thought.

Key words: *optimum ship speed, ship emissions, bunker consumption, CO_2 emission*

Introduction

The atmospheric concentration of CO_2 has increased to 200-300 parts per million (ppm) over the past 400000 years. Especially since the beginning of the Industrial Revolution, CO_2 emissions from anthropogenic activities have increased these concentrations to 397 ppm. [1, 2]. The CO_2, which is one of the global GHG emissions contained in the atmosphere, has moved very recently beyond 400 ppm.

Maritime, which has an undeniable place in global trade, is considered an important emission source. Approximately 2.7% percent of global CO_2 emissions are produced by international shipping fleets [3]. In addition, estimates show that, in 2050, maritime transport will be responsible for 15% of total CO_2 emissions. Over time, various structural innovations such as hull design, materials, hydrodynamic performance of ships, engine and drive efficiency have become widespread to reduce emissions from ships. However, one of the best methods of

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reducing ship-based emissions today is freight-ship speed optimization. Corbett *et al.* [4] have studied the positive effects of slow steaming and/or speed reduction on emissions by fuel type. Some studies have proved that speed reduction can dramatically reduce fuel consumption in the case of long distances [5, 6] . Psaraftis and Konvas [7] suggested that speed reduction would increase transit times and ultimately exert pressure on the freight market.

In a globalizing world, increasing industrialization and consumer demands lead to an ever-increasing graph of foreign trade. Every day thousands of ships travel intercontinental, and play a key role in the continual increase of global trade by transporting all kinds of goods, primarily raw materials, industrial and agricultural products and petroleum products between ports.

In particular, maritime transport with trans-oceanic vessels contributes to the development of the global economy. On a sectorial basis, it is known that maritime transport carries 90% of the total tonnage and volume of products subject to world trade [8].

At the beginning of 2012, the total number of vessels, which is bigger than 300 GT (gross tons) in the world fleet, reached 48197 while the total tonnage of ships reached 146 billion DWT (deadweight tons) and the total fleet capacity reached 15.3 million TEU (twenty-foot equivalent unit) [9].

Rules in international maritime transport have a global dimension and are regulated by global organizations. One of these arrangements is the exhaust gas emission of ships because emissions from ships affect not only the regions where a country’s territorial waters run out, but all the regions it navigations along the ship’s route. Therefore, emissions adversely affect both the local and global environment. Moreover, they pass not only from sea to land but also from one continent to another with atmospheric phenomena [10].

The emissions from ships are regulated internationally within the scope of IMO’s international convention for the prevention of pollution from ships (MARPOL) 73/78 Annex VI of the Marine Pollution Agreement. This scope includes SO_x emission control area (SECA) and nitrous oxide emission standards for ships. As a result of the study conducted on a statistical approach on the fuel consumption and emissions of the international maritime trade fleet, total global anthropogenic emissions were reported to be 2.7% CO_2, 11% NO_x, and 2% SO_x [11].

In the maritime industry, it is a topic that is constantly being studied to optimize the fuel consumption of ships. In recent years in IMO, studies on reducing CO_2 emissions of ship-sourced greenhouse gases, especially gases from ship chimneys have yielded a result and EEDI has been implemented. Hughes, working for the IMO Air Pollution and Climate Change Department, described the EEDI as a, product created by a wide range of organizations to reduce greenhouse gas emissions from ships [12, 13].

The EEDI serves the efficiency of the global environment with fewer fossil fuel uses and associated GHG emissions, as it includes energy efficiency enhancing calculations. With the development of larger ship and optimized body designs with more efficient motors and propulsion systems, CO_2 emissions are reduced by ton-km capacity [14].

The EEDI is a figure value derived from the ship’s calculation of CO_2 emissions per tonne per mile, that is to say, with the formula based on the specific technical design parameters of the ship, in order to ensure more efficient energy use, which will lead to less fuel use. Smaller EEDI figure values are used as more energy efficient ship design. The implementation of the EEDI regulation is only for ships larger than 400 GT. The EEDI uses for seven different ship types [15]: Bulk Carriers, Tankers**,** Gas Tanker**,** Container Ships, General Cargo Ships**,** Refrigerated Cargo Ships**,** and Combination Carriers. But, EEDI is not used for ships with steam, diesel, electric and hybrid propulsion systems.

In order to find the amount of CO_2 emitted by a ship, it is necessary to multiply the specified CO_2 emission factor by the index coefficient. The EEDI formula has a grams of CO_2 per tons × nautical value, which can be considered scientifically correct. The lower EEDI value is less CO_2 emissions. The total emission of carbon dioxide released from a ship can be shown in grams:

$$\begin{gathered}\text{Ship's } CO_2 \text{ Emission} = \left(\text{Capacity} \times \text{ Speed}\right) \times CO_2 \text{ Emission index} = \\ CO_2 \text{ Emission index} = \frac{\text{Ship's } CO_2 \text{ Emission}}{\text{Capacity} \times \text{ Speed}}\end{gathered} \tag{1}$$

The CO_2 emission index is gCO_2 per tonne × mile and the ship's CO_2 Emission index is different for each ship.

Materials and methods

In this part of the study, the total annual CO_2 emission of a 150.000 DWT ship at 14.25 knots, 13.54 knots, and 12.83 knots speeds was calculated. In the second part of this analysis, EEDI Ship design index of ship which has EEDI value for full vessel is taken as 1.8 gCO_2 per tonne × mile. Nevertheless, if EEDI value for empty ship is taken as 2 gCO_2 per tonne × mile, how the system gives results is also indicated.

The EEDI formula is expressed [16]:

$$\begin{gathered}\frac{\Bigg(\prod_{j=1}^{M} f_j\Bigg)\Bigg(\sum_{i=1}^{nME} P_{ME(i)} C_{FME(i)} SFC_{ME(i)}\Bigg) + P_{AE} C_{FAE} SFC_{AE} + \Bigg\{\Bigg[\prod_{j=1}^{M} f_j \sum_{i=1}^{nPTI} P_{PTI(i)}}{f_i.Capacity.V_{ref} f_w} - \\ - \frac{\sum_{i=1}^{\text{neff}} f_{\text{eff}(i)} P_{AE\text{eff}(i)}\Bigg] C_{FAE} SFC_{AE}\Bigg\} - \Bigg[\sum_{i=1}^{\text{neff}} f_{\text{eff}(i)} P_{\text{eff}(i)} C_{FME} SFC_{ME}\Bigg]}{f_i.Capacity.V_{ref} f_w}\end{gathered} \tag{2}$$

where C_F is the non-dimensional conversion factor between fuel consumption and CO_2 emission. The $C_{FME} = C_{FAE} = C_F = 3.1144$ gCO_2/g as fuel. The CO_2 emission values of the C_F conversion factor according to different fuel types are presented in tab. 1. The V_{ref} is the speed of ship (no wind, no wave, speed of maximum loaded ship in knots in open water).

Table 1. The CO_2 emission values of different C_F conversion factors according to different fuel types [17]

Fuel	Reference	CO_2	CF
Diesel	ISO 8217 Grades DMX	0.875	3.206
LFO	ISO 8217 Grades RMD	0.860	3.151
HFO	ISO 8217 Grades RME	0.850	3.114
LPG	Propan, Butan	0.819 0.827	3.000 3.030
LNG		0.750	2.750

Specific fuel consumption (SFC) is the fuel consumption coefficient of the machines in g/kWh, SFC $SFCME$ = 190 g/kWh for the main machines, $SFCAE$ = 215 g/kWh for auxiliary machines. Capacity is the deadweight for conventional ships, Gross Tonne for Ro-Ro and cruise ships. Deadweight is the largest weight a ship can carry is the sum of the weights of the raw cargo, the fuel, the water, the food, the passengers and the ships themselves and their belongings. In other words, Lightweight is the difference between the tonnage and the highest displacement volume of the ship with a density value of 1.025 kg/m^3. The $PPTO$ (I) is the Shaft generator power in kW. The PME (I) is the PME (I) = 0.75 × ($MCRMEi$ – $PPTOi$). The PAE (I) is the power of the auxiliary machine in kW. The $PPTI$ (I) is the Shaft motor power in kW. The P_{eff} (I) is the 75% reduced power with innovation in mechanical energy efficiency technologies. The $PAE_{\mathrm{eff}}(I)$ is the measured value of the auxiliary machine in PME (I) with the innovation of electric energy efficiency technologies in kW. The f_j is the correction factor of the ship's design parameters. It is dimensionless. For Ice-class ships, the following tab. 2 is calculated according to the values.

Table 2. The f_j values of correction factor coefficient for different ice-class ships [17]

Ship type	f_i	Limit values for ice class ship			
		IC	IB	IA	IA SUPER
Tanker	$\dfrac{0.516L_{PP}^{1.87}}{\sum_{I=1}^{nME} P_{iME}}$	Max: 1.0 Min: 0.72 $L_{PP}^{0.06}$	Max: 1.0 Min: 0.61 $L_{PP}^{0.05}$	Max: 1.0 Min: 0.50 $L_{PP}^{0.10}$	Max: 1.0 Min: 0.40 $L_{PP}^{0.12}$
Bulk carrier	$\dfrac{2.150L_{PP}^{1.58}}{\sum_{i=1}^{nME} P_{iME}}$	Max: 1.0 Min: 0.89 $L_{PP}^{0.02}$	Max: 1.0 Min: 0.78 $L_{PP}^{0.04}$	Max: 1.0 Min: 0.68 $L_{PP}^{0.06}$	Max: 1.0 Min: 0.58 $L_{PP}^{0.08}$
Cargo ship	$\dfrac{0.0450L_{PP}^{2.37}}{\sum_{i=1}^{nME} PiME}$	Max: 1.0 Min: 0.85 $L_{PP}^{0.03}$	Max: 1.0 Min: 0.70 $L_{PP}^{0.06}$	Max: 1.0 Min: 0.54 $L_{PP}^{0.10}$	Max: 1.0 Min: 0.39 $L_{PP}^{0.15}$

For Cargo ships with mainframe vessels with 10000 kW and higher, the PAE is defined [17]:

$$P_{AE(MCRME>10000\,KW)} = \left(0.025 \times \sum_{i=1}^{nME} MCR_{ME(i)}\right) + 250 \tag{3}$$

For Cargo ships with mainframe vessels with 10000 kW and lower, the PAE is defined [17]:

$$P_{AE(MCRME<10000\,KW)} = 0.05 \times \sum_{i=1}^{nME} MCR_{ME(i)} \tag{4}$$

$$\frac{\left(\prod_{j=1}^{M} f_j\right)\left(\sum_{i=1}^{nME} P_{ME(i)} C_{FME(i)} SFC_{ME(i)}\right) + P_{AE} C_{FAE} SFC_{AE} + \Bigg\{\Bigg[\prod_{j+=1}^{M} f_j \sum_{i=1}^{nPTI} P_{PTI(i)}}{f_i \text{Capacity} V_{\text{ref}} f_w} - \\ - \frac{\sum_{i=1}^{\text{neff}} f_{\text{eff}(i)} P_{AE\text{eff}(i)} \Bigg]\Bigg\} C_{FAE} SFC_{AE\left[\sum_{i=1}^{\text{neff}} f_{eff(i)} P_{eff(i)} C_{FME} SFC_{ME}\right]}}{f_i \text{Capacity} V_{\text{ref}} f_w} \tag{5}$$

The EEDI formula, which at first glance looks very complex, is a rather simple representation of the ship's CO_2 efficiency, when combined in fact as separate factors. The EEDI unit is obtained from the formula as follows. When the CO_2 emitted per hour is divided by the nautical miles per hour, the clock in the formula is eliminated and the unit of the EEDI appears as gCO_2 per tonne × mile [18]:

$$EEDI = \frac{\text{gCO}_2}{tnm} \tag{6}$$

It can also be formulated for reference calculation [17]:

$$EEDI = 3.1144 \frac{190 \sum_{i=1}^{NME} P_{MEi} + 215 P_{AE}}{\text{Capacity} V_{\text{ref}}} \tag{7}$$

According to tab. 3, example of EEDI calculation for 150000 DWT bulk cargo (with and without additional mechanical or electrical energy efficient technologies) is given.

Table 3. Data of a 150000 DWT bulk cargo [13]

Manufacturer	Japan shipbuilding company
IMO number	9411XX
Type	Bulk carrier
LOA/LBP	250 m / 240 m
B/D	40 m / 20 m
Draft (summer)	14 m
DWT (summer draft)	150.000 ton
	Main engine
Manufacturer	Japan Heavy Industries Ltd.
Type	6J70A
MCR (Maximum continous rating)	15.000 kW × 80 rpm
SFC (at 50% MCR)	165.0 g/kWh
Number/Fuel type	1/Diesel

Auxiliary machine	
Manufacturer	Japan Diesel Ltd.
Type	5J-200
MCR (Maximum continuous rating)	600 kW × 900 rpm
SFC at 50% MCR	220.0 g/kWh
Number	3
Fuel type	Diesel
SPEED loaded in summer draft at 75% MCR	1425 kt
Propeller type	Fixed pitch propeller
Propeller radious	7 m
Number of pitch and number of propeller	4 and 1

Main generator	
Manufacturer	Japan electric
Rated output	560 kW (700 kVA) × 900 rpm
Voltage	AC 450 V
Number	3

According to the data, if EEDI formulas are put in place, the results:

Ship type: bulk carrier	
SFCME: 165 g/kWh	*SFCAE*: 220 g/kWh
Capacity: 150.000 tonne	*PME*: 11.250 kW
PAE: 625 kW	V_{ref}: 14.25 knot
Fuel: Diesel	*MCRME*: 15.000 kW
CFME: 3.206	*CFAE*: 3.206

EEDI = 2990 gCO_2 per tonne × mile [16] (1).

As a result of using additional mechanical and electric energy efficient technologies for the same vessel, the result is calculated:

P_{AEeff} (advanced electric energy efficiency technology): 600 kW

(As advanced electrical energy efficiency technology; waste heat recovery system was applied by using turbo generator.)

P_{eff} (advanced mechanical energy efficiency technology): 1500 kW

P_{MEeff} (advanced mechanical energy efficiency technology): –750 kW

EEDI Calculation index according to Annex 2 – MEPC 61/5/3 for waste heat recovery system [19], $f_{eff}(i)$ is taken as 1.0:

$$\sum_{i=1}^{\text{neff}} f_{\text{eff}(i)} \times P_{\text{AEeff}(i)} \times C_{FAE} \times SFC_{AE} = 1 \times 600 \times 3.206 \times 220 = 423.200 \tag{8}$$

As advanced mechanical energy efficiency technology, air lubrication system is used as air jets, P_{eff} = 1500 kW and PAE_{eff} = –750 kW [20]:

$$\sum_{i=1}^{\text{neff}} f_{\text{eff}(i)} \times P_{\text{eff}(i)} \times C_{FME} \times SFC_{ME} - \sum_{i=1}^{\text{neff}} f_{\text{eff}(i)} \times P_{AE\text{eff}(i)} \times C_{FAE} \times SFC_{AE} \tag{9}$$

EEDI = 2668 gCO_2 per tonne × mile [20]

As a result, can be seen that the *EEDI* value, which is found in the previous section without the use of additional mechanical and electrical energy efficiency technologies under the same conditions, is smaller than the *EEDI* value of 2.99 gCO_2 per ton-miles. This will demonstrate the energy efficiency that will result in less carbon dioxide emissions. Smaller EEDI values are said to be more energy efficient vessels, ie, less fuel consumption and less CO_2 emissions.

Effect of the speed to the emission of a ship

In this part of the study, three Scenarios were analysed and compared. The information of ship and cargo in these scenarios are given below:

Goods to be transported: Iron and steel
Annual Amount: 5000000 tons
Port of Loading: Ambarli, Istanbul
Evacuation Port: Yokohama, Japan
Ship Type: Bulk carrier (150.000 Dwt)
Cargo Capacity: 138.000 tonne (excluding fuel, storage, passenger, *etc.*)
Fuel: Diesel
Power of main engine: 15.000 kW × 80 rpm
SFC: 165 g/kWh
Distance: 8676 miles (nautical)

Let K be the amount of CO_2 released from the flue gas along the course of a ship between the two ports, Let K_1 be the amount of CO_2 released from the flue gas while sailing from Ambarli to Yokohama and let K_2 be the amount of CO_2 released from the flue gas while sailing from Yokohama to Ambarli.

Scenario 1: Annual total CO_2 emission at 14.25 knots cruising speed

The CO_2 index of full ship: 2 99 gCO_2 per tonne × mile, from eq. (1), (CO_2 index of light ship is taken 18 gCO_2 per tonne × mil) other information be found in the light of the aforementioned information:
Voyage number of a ship in a year: 360 day/60 day = 6
Annual transportation capacity of a ship: 6 × 138.000 tonne = 828.000 tonne per year
The number of vessels that are required to move from Turkey to Japan 5000000/828000 = 6038
Ship's CO_2 emission = (capacity × speed) × CO_2 Emission index
K_1 = CO_2 emission index of full ship × capacity × speed of ship
K_1 = 299 gr CO_2 per tonne × mile × 138.000 tonne × 1425 knot,
K_1 = 5879.835 gr CO_2 per hour
K_2 = CO_2 emission index of light ship × capacity × speed of ship
K_2 = 18 × 138.000 tonne x 1425 knot,
K_2 = 3539.700 gr CO_2 per hour
$K = K_1 + K_2 = 5879.835 + 3539.700 = 9419.535$ gCO_2 per hour
K = 942 tonne CO_2 per hour.

If the ship does 6 voyages with 1425 knots and a total of 6038 ships are used for this work, the total amount of CO_2 emitted in the transportation of 5000000 tons of iron and steel product from Ambarli port to the port of Yokohama, Japan:
K_{annual}: $V_{14,\,25} = 9419.535 \times 6 \times 6038$
$K_{\text{annual:}}$ $V_{14,\,25}$ =341250.914 gCO_2 per hour = 341 × 24 × 360 = 2946 mile × tonne CO_2

Scenario 2: Annual total CO_2 emissions at 13.54 knots cruising speed

Now if the aforementioned calculation is repeated in order to see what the total carbon dioxide amount change as a result of reducing the ship speed by 5% in the same example:
Ship speed 2: 1425 × 0.95 = 1354 knots.

Ship type: bulk carrier	
*SFCM*E: 165 g/kWh	SFCAE: 220 g/kWh
Capacity: 150.000 tons	PME: 9.000 kW
PAE: 625 kW	MCRME: 15.000 kW
CFME: 3.206	CFAE: 3.206

EEDI $V_{13,\,54}$ = 2.56 gCO_2 per tonne × mile (for full ship).

It can be seen that a 5% reduction in speed causes 15% decreasing. In our scenario, Yokohama – Ambarli voyage, which is empty, comes again at a speed of 14.25 knots and the CO_2 index is also taken into account as 1.8 gCO_2 per tonne tonne × mile miles:
CO_2 index of full ship: 256 gCO_2 per tonne tonne × mile mile, CO_2 Index of light ship: 18 gCO_2 per tonne tonne × mile mile
K_1 = CO_2 index of full ship × capacity × ship speed = 256 × 138.000 tonne × 13.54 knot
K_1 = 4783411.2 gCO_2 per hour

K_2 = CO_2 index of light ship × capacity × ship speed $K_2 = 1.8 \times 138.000$ tonne × 14.25 knot
$K_2 = 3.539.700$ gCO_2 per hour
$K = K_1 + K_2 = 4783411.2 + 3539.700 = 8323111.2$ gCO_2 per hour
$K = 8.32$ tonne CO_2 per hour
Departure time: 32 days (Ambarli – Yokohama), Return time: 30 days (Yokohama – Ambarli)
Voyage number of a ship in a year: 360 days/62 days = 5.8
Annual transportation capacity of a ship: 5.8 × 138.000 tonne = 800.400 tonne per year

The 5000000 tons of iron and steel load the number of ships needed for Japan to move jobs from Turkey 5000000 / 800400 = 6.25 total vessel is required in a year. If the ship does 5.8 voyages in a year with 13.54 knots for departure and 14.25 for return, a total of 6.25 ships are used for this work, the total amount of carbon dioxide emitted in the transportation of 5000000 tons of iron and steel product from Ambarli port to the port of Yokohama, Japan:
$K_{\text{annual}} : V_{13,54} = 8323111.2 \times 5.8 \text{ x } 6.25$
$K_{\text{annual}} : V_{13,54} = 301712781$ gr CO_2 per hour = 301 × 24 × 360 = 2,6 millionn CO_2

As a result, a total of 5000000 tons of iron and steel cargo is transported with 14.25 knots total annual emission is $K_{\text{annual}} : V_{14,25} = 2946$ millionn CO_2.

In the second calculation, if the ship is set to do the same job between Yokohama-Ambarli by decreasing its speed by 5% and it goes with 13.54 knots and empty ship returns with 14.25 knots, 2.6 millions of CO_2 emissions are calculated. If the results are to be shown in tab. 4 below, the 5% reduction in speed results in a 15% reduction in the CO_2 emission index and a 12% reduction in the total annual emissions of CO_2.

Table 4. Change of CO_2 emission rates by 5% reduction of cruise ship speed

Speed	Speed reduction ratio	Engine power	Emission index of full ship	Index reduction ratio	
12.25 knots		11.250 kW	2.99 gCO_2 per tonne × mile		
13.54 knots	5%	9.000 kW	2.56 gr CO_2 per tonne × mile	15%	
Speed	Departure time	Average number of ship	Number of ships required for annual transportation	Total emission in a year	Emission reduction rate
14.25 knots	30 days	6	6.038	22.946 millionn	
13.54 knots	32 days	5.8	6.25	2.6 millionn	11.7%

Scenario 3: Annual total CO_2 emission at 12.83 knot cruising speed

Now if the aforementioned calculation is repeated in order to look at the change in the amount of total carbon dioxide as a result of reducing the ship speed by 10% in the same example:
Ship speed 3: 14.25 × 0.90 = 12.83 knots.

Ship type: bulk carrier	
SFCME: 165 g/kWh	*SFCAE*: 220 g/kWh
Capacity: 150.000 tonnes	*PME*: 9.000 kW
PAE: 625 kW	V_{ref}: 12.83 knots
Fuel: Diesel	*MCRME*: 15.000 kW
CFME: 3.206	*CFAE*: 3.206

EEDI $V_{12,83}$ = 2,26 gCO_2 per tonmil (for full ship).

It can be seen that a 10% reducing of speed causing 25% decreasing on CO_2 emission. According to the scenario, the departure speed is 12.83 knots but return speed of the ship is 14.25 knots. So, the CO_2 index is taken as 1.8 gCO_2 per tonne × mile:
CO_2 index of full ship: 2.26 gCO_2 per tonne × mile
CO_2 index of light ship: 1.8 gr CO_2 per tonne × mile
$K_1 = 2.26 \times 138.000$ tonne × 12.83 knot $K_1 = 4.001.420, 4$ CO_2 per hour
$K_2 = 1.8 \times 138.000$ tonne × 14.25 knot $K_2 = 3.539.700$ gCO_2 per hour
$K = K_1 + K_2$
$K = 4.001.420, 4 + 3.539.700 = 7.541.120, 4$ gCO_2 per hour
$K = 7,541120$ tonne CO_2 per hour.
Departure time: 34 days (Ambarli – Yokohama), Return time: 30 days (Yokohama – Ambarli)
Voyage number of a ship in a year: 360 days/64 days = 5625
Annual transportation capacity of a ship: 5625 × 138.000 tonne = 776.250 tonne per year
5,000,000 tons of iron and steel load the number of ships needed for Japan to move jobs from Turkey 5,000,00 /776.250 = 6.44 total vessel is required in a year. So;
$K_{\text{annual}}\ V_{12,\,83} = 7541120.4 \times 5625 \times 6.44$
$K_{\text{annual}}\ V_{12,\,83} = 273.177.086$ gCO_2 per hour = 273 × 24 × 360 = 2358 millionn CO_2

As a result, it was calculated that the ship, which is suitable for the transportation of 5.000.000 tones of iron and steel cargo in Ambarli-Yokohama, has a total annual $K_{1\text{-}41.25} = 2946$ millionns of CO_2 annually with a total speed of 14.25 knots.

In the second calculation, if the ship is set to do the same job, it only decreases its speed by 14.25% by 5% and it goes with 13.54 knots and it is followed by the total of 14.25 knots at Yokohama-Ambarli. 2.6 millionns of CO_2 emissions are calculated.

In the third calculation, if the ship is set to do the same job, it only decreases its speed by 14.25% by 10% and it goes with 12.83 knots and it is followed by the total of 14.25 knots at Yokohama – Ambarli. 2.358 millionns of CO_2 emissions are calculated.

If looking at the results of 2.946 millionns of CO_2 and 2.358 millionns of CO_2, the speed can only reduce by 10%, and reduce the CO_2 emission by 25% in the course of the year (EEDI is taken as reference) and reduce the total emission of CO_2 per year by 20%. It is suitable.

Table 5. Change of CO_2 emission rates by 5% and 10% reduction of ship cruising speed (empty ship design index is 1.8%)

Speed	Speed reduction ratio	Engine power	Emission index of full ship	Index reduction ratio	
14.25 knots		11.250 kW	2.99 gr CO_2 per tonne × mile		
13.54 knots	5%	9.000 kW	2.56 gr CO_2 per tonne × mile	15%	
12.83 knots	10%	7.400 kW	2.26 gr CO_2 per tonne × mile	25%	
Speed	Departure time	Average number of ship	Number of ships required for annual transportation	Total emission in a year	Emission reduction rate
14.25 knots	30 days	6	6038	2.946 millionn	
13.54 knots	32 days	5.8	6.25	2.6 millionn	11.7%
12.83 knots	34 days	5.625	6.44	2.358 millionn	20%

The reduction in cruising speed by 10% only and the full shipment of CO_2 emissions by 20% compared to a 25% decrease in the full EEDI ratio will also save fuel. What is to be considered and calculated here is the annual and even the size of the savings from the fuel during the lifetime of the ship (average 20 or 30 years). The 20% CO_2 emission improvement between the aforementioned two different scenarios is of course an additional 0.4 (6.44-6.038 = 0.46) ships entering the service. Another point of view is to consider the relationship between the cost of the fuel and the cost of approximately 8 vessels to be carried during the 20-year period. As shown in tabs. 5 and 6, a 10% reduction in speed results in a 25% reduction in the CO_2 emission index and a 20% reduction in total annual CO_2 emissions.

Table 6. Change of CO_2 emissions rates by 5% and 10% reduction of ship cruising speed (when the empty ship design index is 2)

Speed	Departure time	Average number of ship	Number of ships required for annual transportation	Total emission in a year	Emission reduction rate
14.25 knots	30 days	6	6.038	23,067 millionn	
13.54 knots	32 days	5.8	6.25	2,721 millionn	11.3%
12.83 knots	34 days	5.625	6.44	2,479 millionn	19%

Results and discussion

During the journey of a ship between two harbours, the amount of CO_2 emissions emitted by the fuel produced by its main machine and auxiliary machines against the sea and air resistance can be calculated with certain formulas.

The amount of CO_2 released from a ship can also be measured by the carbon content of the fuel consumed on that ship. About 3.17 ton of CO_2 is released from the combustion of one ton of ship fuel [21]. In order to find the amount of CO_2 emission, the work which is done by the ship has to be multiplied by the index coefficient of CO_2 emission of that ship.

The scientific reference to the value (grams × CO_2)/(tones × nautical) calculated by the EEDI formula; the lower EEDI value is less CO_2 emissions.

The most important factor that reduces CO_2 emission is speed of the ship. Changing of speed also effects the fuel consumption. So, Reduction in ship speed always results in lower fuel costs.

On the other hand, as a result of decreasing the service speeds of different types and sizes of ships, the transit times generated by the additional vessels have been analysed due to the decrease in the number of voyages to be carried out annually. It was shown that the total amount of fuel has always resulted in less fuel costs with the vessels entering the service due to the decrease in cruise speed.

The CO_2 emissions from a ship can be calculated based on ship speed, fuel consumption and the amount of carbon in the content of the fuel. CO_2 emission savings at the lowest speed allowed by ship operating costs can also be calculated.

This study strongly emphasizes that speed is an important factor in maritime transport. Although it is considered as an environmental approach to reduce emissions by direct intervention the ship's machinery by technical methods, it is strongly demonstrated in this study that commercial speed optimization, optimum and proactive route planning and energy and capacity management can be a current and early approach. Determining the optimum change between fuel costs and costs resulting from time delays, precise adjustment of engine speeds and efficient operation of engines at low output levels for a long time is a dynamic process with two most important elements.

Considering the impact of fuel costs on revenue generated by ships, ship operators need to have an effective means of identifying optimum reduction in speed. In addition, in cases where fuel costs are high and market freight rates are low, the speed reduction option will be able to produce optimum results to ship operators commercially. The cost-saving benefits provided by a decline in shipping speeds must reach sufficient levels to ensure that the benefits are realized without the need for legal power. Therefore, the immediate and preventive implementation of the route planning, which will minimize the effects of air and sea conditions on the ship, should be considered as much as the minimum speed reduction. Assessing the emission reduction approach of fleet operations, managing fleets associated with a common hub, and how to manage commercial pressures for increased ship working hours will be an important task.

References

[1] Friedlingstein, P., *et al.*, Climate-Carbon Cycle Feedback Analysis: Results From the C4MIP Model Intercomparison, *Journal Clim.*, *19* (2006), 14, pp. 3337-3353

[2] Gazioglu, C., *et al.*, Connection between Ocean Acidification And Sound Propagation, *Int. J. Environ. Geoinformatics*, *2* (2015), 2, pp. 16-26

[3] Chang, C.-C., Wang, C.-M., Evaluating the Effects of Speed Reduce for Shipping Costs and CO_2 Emission, *Transp. Res. Part D Transp. Environ.*, *31* (2014), 3, pp. 110-115

[4] Corbett, J. J., *et al.*, The Effectiveness and Costs of Speed Reductions on Emissions from International Shipping, *Transp. Res. Part D Transp. Environ.*, *14* (2009), 8, pp. 593-598

[5] Cariou, P., Is Slow Steaming A Sustainable Means of Reducing CO_2 Emissions from Container Shipping, *Transp. Res. Part D Transp. Environ.*, *16* (2011), 3, pp. 260-264

[6] Tokuslu, A., Analyzing the Energy Efficiency Design Index (EEDI) Performance of a Container Ship, *Int. J. Environ. Geoinformatics*, *7* (2020), 2, pp. 114-119

[7] Psaraftis, H. N., Konvas, C.A., Balancing the Economic and Environmental Performance of Maritime Transportation, *Transp. Res. Part D Transp. Environ.*, *15* (2010), 8, pp. 458-462

[8] Inc, M., *et al.*, Modified Variational Iteration Method for Straight Fins with Temperature Dependent Thermal Conductivity, *Therm. Sci.*, *22* (2018), Suppl. 1, pp. S229-S236

[9] ***, Turkey Chamber of Shipping, Maritime Trade Analysis, General Directorate of Maritime Trade, Ankara, 2012

[10] Deniz, C., Durmusoglu, Y., Estimating Shipping Emissions in the Region of the Sea of Marmara, Turkey, *Sci. Total Environ.*, *390* (2008), 1, pp. 255-261

[11] Endresen, Ø., *et al.*, Emission from International Sea Transportation and Environmental Impact, *Journal Geophys. Res. Atmos.*, *108* (2003), D17

[12] ***, IMO, Main Events in IMO's Work on Limitation and Reduction of Greenhouse Gas Emissions from International Shipping, Londra, 2011

[13] Vasov, M. S., *et al.*, Reduction of CO_2 Emission as A Benefit of Energy Efficiency Improvement: Kindergartens in the City of Niš-Case Study, *Thermal Science Part B*, *22* (2018), 1, pp. 651-662

[14] ***, IMO COP15, UNFCCC 15. AD HOC Working Group on Long-Term Cooperative Action 8. 7-18 December 2009, *Proceedings*, Control of Greenhouse Gas Emissions from Ships Engaged in International Trade, Kopenhagen, Danmark, 2010, p. 44

[15] ***, IMO MEPC 63/23/10, 2012 Guidelines on Survey and Certificaitonne of the Energy Efficiency Design Index (EEDI), London, UK, 2012

[16] ***, IMO MEPC, 63/23/10, 2012 Guidelines on Survey and Certificaitonne of the Energy Efficiency Design Index (EEDI), London, UK, 2012

[17] ***, IMO MEPC.1 / Circ.681, Interim Guıdelines on the Method of Calculation of the Energy Efficiency Design Index for New Ships, London, UK, 2009

[18] ***, Deltamarin, EEDI Tests and Trials for EMSA (European Maritime Safety Agency), Finland, 2009

[19] ***, IMO, M. 61/5/3, Report of the Outcome of the Intersessional Meeting of the Working Group on Energy Efficiency Measures for Ships, London, UK, 2010

[20] ***, IMO, M. 62/INF. 3., Reduction of GHG Emissions from Ships, Detail Treatment of Innovative Energy Efficiency Technologies for Calculation of the Attained EEDI, London, UK, 2011

[21] Psaraftis, H. N., *et al.*, Speed Reduction as an Emissions Reduction Measure for Fast Ships, *Proceedings*, 10th International Conference on Fast Sea Transportation FAST, 2009, pp. 1-125

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