MIDDLE POMERANIAN SCIENTIFIC SOCIETY OF THE ENVIRONMENT PROTECTION

Rocznik Ochrona Środowiska

Volume 22. Year 2020 ISSN 1506-218X 549-560

Energy Efficiency Operational Indicator as an Index of Carbon Dioxide Emission from Marine Transport

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1. Introduction

International shipping is the reason of emission about 2.5-3.0% of the carbon dioxides (CO_2) in the worldwide pollution. In 2015, it was 932 million tons and percentage of 2.6%. Transport accounts for 24% of global emission. CO_2 emission depends on total fuel consumption and carbon concentration in used fuel. CO_2 is one of green-house gases (GHG) (Olmer et al. 2017). Due to emission other GHGs like: black carbon, nitrogen and sulfur oxides from marine diesel engines, equivalent CO_2 (CO_{2e}) emission is sometimes used. The difference between CO_2 and CO_{2e} is rather small, about 7-9% more for CO_{2e} and is quite stable.

There are 223 flag states in the world. The most CO_2 emission can be attributed to ships flying six flags: Panama (15%), China (11%), Liberia (9%), Marshall Islands (7%), Singapore (6%) and Malta (5%). About 66% of the global shipping fleets' deadweight tonnage is registered to them (Olmer et al. 2017).

To ensure that shipping is cleaner and greener, International Maritime Organization (IMO) has adopted regulations to reduce the emission. The aim is zero-carbon shipping. In that aim, by adding a new Chapter 4 to Annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL 73/78 Convention) on the regulation of energy efficiency of ships, it was introduced making mandatory from 1st January 2013 the energy efficiency design index (EEDI) for new built ships and the Ship Energy Efficiency Management Plan (SEEMP) for all ships (IMO 2012a, IMO 2012c). The required EEDI is determined by equations (IMO 2012d, IMO 2012e) include several factors to suit specific types of vessels, their configurations and operating conditions. The level of CO_2 emission is to be tightened every 5 years (about 10% less, going to next number of required EEDI Phase) from 1st January 2015 (IMO 2012e, Polish Register 2019, Polish Register 2020). It is expected to stimulate continued innovation and technical development of all the components influencing the engine fuel consumption and hull resistance from its design phase.

The EEOI is the total carbon dioxide emission (in g CO_2) in a given time period per unit of transport effect (ton-km or ton-mile). A lower EEOI means a ship more efficient in its operation (IMO 2009, Acomi et al. 2013). An application of Ship Energy Efficiency Management Plan (SEEMP) requires to perform some actions. As an example, the calculating of EEOI is voluntary but from 1st January 2018 the ship-owners of large vessels over 5,000 gross tonnage loading or unloading cargo or passengers at ports in the European Economic Area (EEA) should monitor and report their related CO_2 emission and other relevant information (Directive 2015, Directive 2018). From 30th April 2019 of each year, shipowners shall submit first to States in which those ships are registered and after approving to the European Commission, a satisfactory verified emissions report for each ship that has performed activities in the EEA in the previous reporting period (last calendar year). It shall be done through a THETIS MRV platform (a special basis prepared by European Maritime Safety Agency for Paris Memorandum of Understanding) (Elliot 2009).

Total consumption reports of each type of fuel and emissions reports in marine transport allow to recognize the possibility for formulation new regulations for efficiency increasing and emissions restrictions.

Advantages and disadvantages from enforcing emission restrictions within emission control areas is analyzed in (Dulebenets 2016) and an evaluating the effects of speed reduce for shipping costs and CO_2 emission is presented in (Chang & Wang 2014).

2. Energy Efficiency Design Index as the primary requirement

EEDI is a first step of IMO's drive to reduce the CO_2 emission from shipping and a benchmarking scheme aiming to provide an indication of a merchant ship's CO_2 output in relation to its transport work.

EEDI is provided by formula (1) where in the numerator is CO_2 emission from main engines and auxiliaries (calculating as a product of fuel factor c_{Fi}, engine load P_i and specific fuel consumption SFC_i at this load) and the denominator is a product of ship's deadweight DWT and the ship's reference speed V_s (IMO 2012e):

$$EEDI_i = \left(\sum_i c_{Fi} \cdot P_i \cdot SFC_i\right)/(DWT \cdot V_s) \quad (1)$$

The reference speed means ship's speed at 75% Maximum Continuous Rating of main engine. The units used for EEDI are: g CO_2 /(ton-mile).

The EEDI is an estimated measure of transport energy efficiency of a ship, which is currently under the design stage. It should be estimated for designed vessel and it is an important index for designers and builders of ships (IMO 2012b, IMO 2012d).

Goal of EEDI:

- mitigate CO_2 emissions,
- increase cargo carrying capacity to maximal possible ship's deadweight,
- enhance ship's speed performance,
- design and use the most efficient equipment,
- design the ship's hull with the lowest resistance,
- design the marine power plant as much efficient as possible.

3. EEOI calculation

The calculation of EEOI needs to measure some parameters during vessel operation, like:

- the distance sailed as recorded in ship's Bridge Log Book,
- the cargo mass as per Bill of Lading and Deck Log Book,
- the total fuel consumption as recorded in Engine Log Book.

It should be known the fuel coefficient c_F depending on the type of used fuel. The c_F is presented in Table 1 (Elliot 2009, on base: Acomi & Acomi 2014).

Table 1. Fuel coefficient for different types of fuel

Type of fuel		Reference	Carbon content	c_F [kg-CO_2/kg-fuel]
1	Diesel/gas oil	ISO 8217 grades DMX through DMC	0.875	3.20600
2	Light fuel oil	ISO 8217 grades RMA through RMD	0.860	3.15104
3	Heavy fuel oil	ISO 8217 grades RME through RMK	0.850	3.11440
4	Liquefied Petroleum Gas (LPG)	propane butane	0.819 0.827	3.00000 3.03000
5	Liquefied Natural Gas (LNG)	methane	0.750	2.75000
6	Hydrogen	hydrogen	0	0.0
7	Biofuels	Biodiesel, renewable diesel, F-T diesel, FP bio-oil	different	0.0

An equation (2) for *EEOI* calculation shows the idea of index term.

$$EEOI = \frac{actual\_CO2\_emission}{performed\_transport\_work} \tag{2}$$

EEOI is provided by other formulas for ships being into operation. The examples are presented in formulas (3) and (4).

The EEOI for a voyage is calculated as follows:

$$EEOI = \frac{\sum_{j=1}^{j} FC_j \times \boldsymbol{c_{Fj}}}{m_{cargo} \times D} \tag{3}$$

For a number of voyages the index *Average_EEOI* is expressed by formula (4):

$$Average\_EEOI = \frac{\sum_{i=1}^{i} \sum_{j=1}^{j} FC_{ij} \times \boldsymbol{c_{Fj}}}{\sum_{i=1}^{i} m_{cargo,i} \times D_i} \tag{4}$$

where:

j – is the fuel type,

i – is the voyage number,

FC_i – is the mass of consumed fuel at voyage i,

c_{Fj} – is the fuel mass to CO_2 mass conversion factor for fuel j (fuel factor),

$m_{cargo,i}$ – is mass cargo carried (in tons) or work done (number of TEU or passengers) or gross tons for passenger ships,

D_i – is the distance (in nautical miles) corresponding to the cargo carried or work done.

The EEOI depends strongly on vessel capacity. At the same speed and type of a vessel, EEOI will decrease about twice when the capacity increases four times. So the EEDI is determined among others by ship capacity (IMO 2012b, Polish Register 2014). It is presumable that the EEOI will be smaller during operation than required EEDI in design phase.

Approximate EEOI for different types of ships is presented in Table 2 (on base: Acomi & Acomi 2014).

Table 2. Comparison of EEOI for chosen different types of vessels

Type of vessel	EEOI [g-CO_2/ton-km]	EEOI [g-CO_2/ton-mile]
Ro-ro	33	18
Container ship	18	9.8
General cargo	14	7.6
Product tanker	11	5.9
Bulk carrier	4.5	2.4
VLCC tanker	4.2	2.3

The EEOI reaches different values depending on type and size of vessel, cargo capacity, area of sailing etc. For definite vessel the comparison between individual voyages in different condition may be done. The aim is minimizing the index. This is a task for crew members and shipowners.

4. Expected effects of EEDI and EEOI introduction

A wide variety of design, operational and economic solutions is presented in Fig.1.

Looking at Fig.1 it may be seen that we have many possibilities to decrease the EEOI near zero. If we cannot do it till now means it will exist many troubles for introducing those solutions. Of course, the best solution is using hydrogen, other synthetic fuels and bio-fuels (till c_F will be calculated as zero).

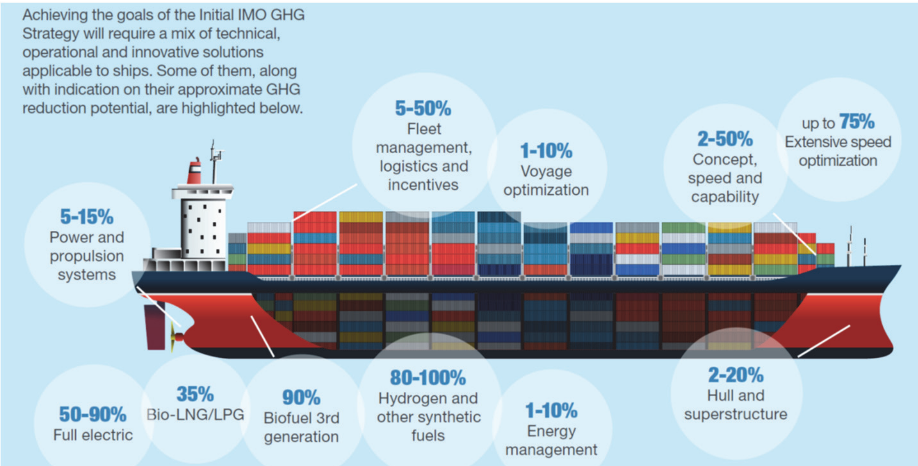

Fig. 1. A wide variety of design, operational and economic solutions (IMO Action 2018)

In reality into ship's operation there are much less possibilities. Methods like: energy or power management systems (EMS, PMS), voyage optimization (special computer programs, improved voyage planning) and extensive speed optimization (conducive for slow steaming) (MAN 2012) are still into consideration.

The IMO idea "zero carbon" in shipping in 2050 (and as soon as possible in this century) is the target for next steps. The timetable of IMO Action to reduce GHG emissions from ships is (IMO Action 2018):

- 2020 – EEDI phase 2: up to 20% reduction in carbon intensity of the ship,
- 2023-2030 – mid-term measures to reduce carbon intensity of the fleet by at least 40%,
- 2025 – EEDI phase 3: up to 30% reduction in carbon intensity of the ship. Note: early entry into effect (2022) for several ships types with up to 50% carbon intensity reduction for largest containerships,
- 2030-2050 – long term measures to reduce carbon intensity of the fleet by at least 70%,
- 2050 – at least 50% reduction of total annual GHG emissions (requires approximately 85% CO_2 reduction per ship).

The EEDI introduction in 2013 has an influence on all design processes. Better designed and equipped vessel allows to reach lower EEOI (Polish Register 2014). Due to IMO Action program (phases of decreasing required EEDI) the EEOI will have a possibility to decrease it for vessels built later. But the index is more complicated. It requires a co-operation between technical superintendent office and crew members, depends on mass cargo and other operational conditions like: estimated time of arrival, route of voyage (distance), hull resistance, sea conditions, wind force and direction, sea current etc. (Elliot 2009, Herdzik 2017). Analyzing the variation of EEOI with respect to different voyage parameters it could be noticed that the most preferred parameters that result in major beneficial changes decreasing that factor are: increasing the quantity of mass cargo maintaining the same route (optimization the route and speed in time constraint) and decreasing the fuel consumption maintaining a medium vessel speed or using waste heat recovery systems (WHRS) (Herdzik 2014b, IMO 2018, IMO 2019).

The Life Cycle Assessment (LCA) is the other point of view on EEOI. There are four main phases in whole life of a ship: building, operation, maintenance and scrapping. The CO_2 emission during design phase is negligible. During three main phases the CO_2 is emitted due to consuming a large of electricity and other forms of energy. Only during scrapping process the balance of CO_2 emission may be different (possible less than zero) because a part of materials would be recycled. The ship produce benefits only in operation phase. Knowing the benefits (total work transport) it may be estimated the real EEOI or as a correction factor introduces to the *Average_EEOI*.

The other proposition is Energy Efficiency Technical Indicator (EETI) (UCL Energy 2015) defined as the energy efficiency (g-CO_2/(ton-mile) of a ship in a reference operating condition (speed and draught). It seems to be a better indicator for comparison different voyages of the same vessel because disposing the changing operating conditions.

We should try to adopt for shipping other ideas (e.g. from ashore transport) (Jachimowski et al. 2018) for improving the all transport cycle of cargo.

5. Slow steaming of a vessel as the primary method of EEOI decreasing. Main engine operational problems

Slow steaming of a vessel decreases the fuel consumption. The main engine load (and fuel consumption) depends on the third power (cubic dependency) of vessel speed (propeller characteristics) but the vessel speed is in linear dependency to propeller rotational speed (Faber et al. 2012, Herdzik 2017). So the overwhelming reason for adopting slow steaming is the promise of fuel savings and decreasing the EEOI. Slow steaming practices introduced after a slowdown in global trade in 2008. Between 2013 and 2015 there has been an increase in speed for some of the largest vessels. The observed vessel speed decreasing after 2015 and respectively the main engine (ME) load has an effect on the its operation. ME are designed to work at 70-85% of maximum continuous rating (MCR). Now the ME load is in a range of 10-50% MCR (see Table 3).

Table 3. Typical engine load in slow steaming vessels (percentages) (MAN 2012)

Type of vessel/ME load	10-30%	20-40%	30-50%
Container	17.8	25.8	56.4
Bulk/Tank/others	5.9	11.9	82.2

There are the following concerns with regards to slow steaming (Faber et al. 2012, Herdzik 2014a, MAN 2012):

- frequent and thorough scavenge system and under piston inspections must be carried out,
- till the engine has a load dependent cylinder lubrication system which is suited for slow steaming it may work properly, unless the engine has not such system the cylinder lubrication rate must be adjusted to optimal value as per manufacturer’s advice,

- slow steaming causes fouling of the turbochargers and loss of efficiency of turbochargers and engines, requires more often washing processes,
- turbochargers operating outside their designed range produce less air flow leading to more deposits,
- increased carbon deposits on the injectors compromises with their performance,
- causes fouling of the exhaust gas economizer resulting in reduction of capacity as well as increased danger of soot fire,
- causes reduction in scavenge air pressure resulting in improper combustion,
- leads to improper atomization of the fuel as well as leads to knock combustion or misfire,
- maintenance intervals have to be modified,
- causes low temperature corrosion of cylinder liners,
- increases the risk of scavenge fires and needs extra scavenge and under piston draining,
- cause loss of heat transfer due to carbon deposits and failure of components due to thermal stresses, etc.

When main engine is run at full load (periodically, according to manufacturer's advice, as an example: four hours of slow steaming and one hour of full load) after long periods of slow steaming the risk of engine damage becomes imminent. But this is infeasible in many cases.

To overcome the mentioned concerns it requires performing many actions like: proactive on-board servicing, manual cleaning, manual adjustments, fuel adjustments, enhanced engine room staff training, engine upgrade kits etc. It means additional works and competencies for engine room staff.

The approach for long-term slow steaming requires the preparedness of main engine like: engine retrofit, derating and upgrade measures taken to minimize the return on slow steaming (MAN 2012).

A ship can be designed to have an optimal hull form, rudder and propeller to sail in a certain speed, while it may redundant power in order to manoeuvre safely in adverse conditions.

When ships are designed to sail at lower speed, their design may change. In (Faber et al 2012), it has presented the Germanisher Lloyd (GL) example for comparison of the designs of an typical existing post panama container ship (6500 TEU) with a design speed of 26 knots and a ship with a design speed of 22.5 knots. The latter ship is shorter and broader and has a higher block coefficient. Due to introduced changes its water resistance increases but its main engine power decreased by 21.5% (but less than square).

6. EEOI as carbon dioxide emission index

The EEOI may perform a role of carbon dioxide emission index from shipping. A basic problem is its proper understanding and application. It should be used all possibilities for decreasing that indicator but only reasonable. One simple example: during voyage knowing the estimated time of arrival (ETA) and a distance to sail, it is easy to calculate the required medium speed of a vessel to reach the ETA – it is a reasonable method. In other case, if we will sail with bigger speed and the saved time we will spend in standing in a drift or sail in a circulation with low speed (the distance will be longer and the EEOI lower) is unreasonable.

Knowing the mass cargo, distance to sail, types of vessels and their capacity it is possible to estimate the total carbon dioxide emission to the atmosphere from shipping due to monitor, report and verification (MRV) systems.

Introducing the EEDI and EEOI, IMO has an aim to decrease the total CO_2 emission from shipping to zero. This is a laudable goal. But it must be remembered that all imposed limitations, requirements and regulations provide to increasing the cost of transport and shipping.

7. Final remarks

Total shipping fuel consumption is on a level of 300-330 million tons yearly with CO_2 emission about 0.9-1.0 billion tons.

The expectation is minimizing the CO_2 emission from shipping. A limitation of other GHG emission from marine diesel engines provides to increasing the specific fuel consumption (according to IMO about 2%, but probably more) and respectively to increasing the CO_2 emission.

Slow steaming method is the most perspective but required to research preferable solutions and propositions to minimize its effects.

Energy storage through use the batteries and cold ironing (shoreside electrical power to a ship at berth) are still under development.

Introducing through IMO the regulations of EEDI and EEOI is reasonable but should be the first step to other actions.

The decarbonization process in global shipping was started. The supreme hope is marine fuel switch to lower (up to zero) carbon in fuel for propulsion.

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Abstract

The paper presents Energy Efficiency Operational Index (EEOI) introduced through International Maritime Organization (IMO) which defined the carbon dioxide emission as a result of transport specific cargo mass on specific distance. The total fuel consumption from all elements of vessel energetic system causes the carbon dioxide emission. Ship-owners should inform the marine administration about the fuel consumption from all vessels of 5000 tons of gross tonnage or more from 1st January 2018. In marine transport about 85% of carbon dioxide emission comes from such vessels. The calculating of EEOI is voluntary now but it is indicated to do it. It allows on an assessment the differences between the Energy Efficiency Design Index (EEDI) obligatory during design process of a vessel and its power plant and EEOI. Due to it may be estimated the correctness of vessel and power plant operation in exploitational conditions.

The basic way of EEOI decreasing is slow steaming of a vessel. The power demand for propulsion (and fuel consumption) is proportional to the third power of vessel velocity (according to the propeller characteristics) on the other hand the hull resistance (the demand for thrust by propeller) is proportional to the second power of vessel velocity. As a result it causes the decreasing of total fuel consumption for covering the same distance but increasing the time of voyage. It is for acceptance during a bad economic situation. Although it will be no acceptable during a good economic situation when it will be required the increasing of vessel velocity (decreasing the time of voyage).

The other effective methods are under research which allows to reach the same aim. It is known such methods of vessel operation which leading to the decreasing of that index. The paper shows these methods with their characteristics.

Keywords:
marine transport, emission to atmosphere, carbon dioxide, energy efficiency operational indicator, ship operation, shipping

Eksploatacyjny indeks efektywności energetycznej statku jako wskaźnik emisji dwutlenku węgla w transporcie morskim

Streszczenie

W artykule omówiono wprowadzony przez Międzynarodową Organizację Morską (IMO) wskaźnik zwany eksploatacyjnym indeksem efektywności energetycznej statku (EEOI), który określa emisję dwutlenku węgla w wyniku transportu jednostki masy ładunku na jednostkową odległość. Za emisję CO_2 odpowiada zużycie paliwa przez wszystkie elementy okrętowego układu energetycznego. Od 1 stycznia 2018 r. armatorzy muszą zgłaszać do administracji morskiej ilość zużytego paliwa przez poszczególne statki o tonażu od 5000, które odpowiadają za 85% zużycia paliwa w transporcie morskim. Wyznaczanie wskaźnika EEOI jest obecnie dobrowolne, ale wskazane, aby go wyznaczać. Pozwala to na określenie różnic między projektowym indeksem efektywności energetycznej statku (EEDI), który jest obligatoryjny w procesie projektowania statku i elementów układu energetycznego, a eksploatacyjnym. Dzięki temu można oszacować poprawność eksploatacji siłowni i statku w warunkach rzeczywistych.

Podstawowym sposobem zmniejszenia wskaźnika EEOI jest zmniejszenie prędkości eksploatacyjnej statku. Zapotrzebowanie na moc napędu (i zużycie paliwa) jest proporcjonalne do trzeciej potęgi prędkości statku (wg tzw. charakterystyki śrubowej), natomiast opór kadłuba (zapotrzebowanie na siłę naporu przez śrubę okrętową) jest proporcjonalny do potęgi drugiej prędkości statku. Skutkuje to zmniejszeniem zużycia paliwa na pokonanie tej samej drogi, ale wydłuża czas podróży. W okresie dekoniunktury na rynku żeglugowym jest to do przyjęcia. Jednak wraz z pojawieniem się oznak koniunktury, które będą wymagać wzrostu prędkości statku (skrócenia czasu podróży) będzie to niemożliwe.

Poszukuje się więc innych skutecznych metod, które pozwolą osiągnąć ten sam cel. Znane są możliwości takich sposobów eksploatacji statku, które prowadzą do zmniejszenia tego wskaźnika. W artykule wskazano na te metody wraz z ich charakterystyką.

Słowa kluczowe:
transport morski, emisja do atmosfery, dwutlenek węgla, eksploatacyjny wskaźnik efektywności energetycznej, eksploatacja statku, żegluga