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Research Article

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Evaluation of the Impact of Energy Efficiency Design Index on Shipping Indicators to Improve Fuel Efficiency

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Abstract Ship energy efficiency plays a significant role in maritime industry where green shipping is becoming an important consideration now-a-days; especially where the world is facing great problems surrounding climate change from enhancement of economic and industrial activities, in parallel with population explosion. The idea of this research is to evaluate the impact of Energy Efficiency Design Index (EEDI) on shipping with focus on utilizing operational indicator EEOI (Energy Efficiency Operational Indicator) as a measurement of the energy efficiency of existing ships. In this research, we introduce a model for cost-efficient ship operation that will improve fuel efficiency and decrease EEOI. The model considers as input the following operational factors that could influence the overall ship operation (e.g.; ship speed, voyage distance, fuel consumption, voyage duration, and cargo weight). Saavedra-Tide vessel was used as a case study to determine the extent to which fuel-savings could be influenced by ship speed, deadweight, voyage distance, and duration. MATLAB software was employed to analyse the impact of energy efficiency operational index on the various operational parameters (ship speed, voyage distance, fuel consumption, voyage duration, and cargo weight). The data characterizing ships operational characteristics and voyage characteristics were obtained from the ships log. The ship log dataset is for the period May 2017 to November 2019. The research results revealed lower energy efficiency operational index (EEOI) values at lower ship speeds and higher EEOI values at higher ship speeds. We also went further to compare the result of the EEOI values obtained at various ship speed, with that of constant ship speed of 6 knots to further investigate ship speed impact on fuel consumption which is one of the most important factor in shipping business. It was found that, fuel consumption at 6 tonnes produced vessel records of 1.834×10^{-4} tonnes CO_2/tonnes EEOI value and with fuel consumption of 6.8 tonnes, EEOI value rises to 2.142×10^{-4} tonnes CO_2/tonnes. Mile.

Keywords Energy Efficiency, MATLAB, Index Analysis, Operational Indicator, IMO Guideline.

1. Introduction

To reduce the greenhouse gas emissions from the atmosphere as mandated by Imo in the Kyoto protocol, the EEDI was imposed on all ships that have gross tonnage over 400. According to IMO, ships engaged in international trade in 1996 contributed about 1.8% of the total world's C02 emissions which is approximated as 2.7% in 2007 and this percentage could go two or three times higher by 2050 if Present trend continues **[2]**. In order to control this CO2 emission from shipping, the ship Energy Efficiency Design Index (EEDI) has been formulated by the IMO Marine Environment Protection Committee (MEPC) as a measure of the CO2 emission performance **[3]**. The basic formulation of EEDI is based on the ratio of total CO2 emission per tonne mile. The amount of CO2 emission depends upon fuel consumption and fuel consumption depends upon the total power requirement which means the EEDI formulation eventually has certain impact on ship design parameters which are closely related to the economic performance of the ship. New ships (building contract as from 1st of January 2013 and the delivery of which is on or after 1 July 2015.) will have to meet a required Energy Efficiency Design Index (EEDI). In addition, all ships, new and existing, are required to keep on board a ship-specific Ship Energy Efficiency Management Plan (SEEMP) which may form part of the ship's Safety Management System (SMS). The SEEMP shall be developed taking into account guidelines developed by IMO. The regulations apply to all ships of 400 gross tonnages and above and were expected to enter into force on 1 January 2013 **[4]**. In the same regulation annex, the SEEMP (Ship Energy Efficiency Management Plan) recommends the use of the EEOI (Energy Efficiency Operational Indicator) as a measurement of the energy efficiency of existing ships. The EEOI, or annual fuel consumption divided by transport work, can be considered as the annual average carbon intensity of a ship in its real operating condition, taking into account actual speeds, draughts, capacity utilization, distance travelled, and the effects of hull and machinery deterioration and weather. Although the EEOI is referred to as an indicator of energy efficiency, it is technically more accurate to refer to the EEOI as a measure of carbon intensity as the units are in gCO2/t.nm **[9]**. There have been numerous new technologies and measures for fuel cost and emission reduction so far, which include speed optimisation, route optimisation, operations management and scheduling, optimisation of the ships draft, etc. [12] Among them, speed optimisation is an effective measure for improving ship energy efficiency, which has been widely studied in the past few years. The studies of [5]. Proved that by reducing speed only, the CO2 emission can be reduced by 19% at zero cost. [7] focused on the navigation planning of fishing boats, and pointed out the drawbacks of traditional speed control mode. [1] estimated the most economic speed to lower emission and demonstrated the feasibility of emission reduction by taking advantage of the tax rate. [8] constructed a cost model and designed a simple program to reduce the annual operating cost of a route by optimising the ship speed and ship number. [10] focused on inland ships and discussed the relation between EEOI and ship speed. The EEOI under different working conditions was calculated and analysed according to experimental data. Analysis in this study showed that operating at lower ship speed significantly increases the ship energy efficiency.

The potential for shipping to provide both fuel-efficient and low-polluting transport, however, depends on more widespread use of existing abatement techniques. Furthermore, although the fuel efficiency of shipping is already high, there is still room for improvement, which will be a competitive advantage in the future with expected high fuel prices.

Concept of EEDI

The ship "EEDI" has been formulated by the IMO's Marine Environment Protection Committee (MEPC) as a measure of the CO_2 emission performance of ships. The *EEDI* requires a specified energy efficiency that could be primarily, expressed by fuel consumption per capacity mile (e.g., tonne mile) for different ship types and sizes. With the level being tightened over time, the *EEDI* will stimulate continued technical development of all the components influencing the energy efficiency of a ship. Reduction factors are set until 2025 when a 30% reduction is mandated over the average efficiency for ships built between 1999 and 2009. The EEDI has been developed for the largest and most energy intensive segments of the world merchant fleet, and will embrace about 70% of emissions from new oil and gas tankers, bulk carriers, general cargo, refrigerated cargo and container ships as well as combination carriers (wet/dry bulk) – as shown in Fig 1.

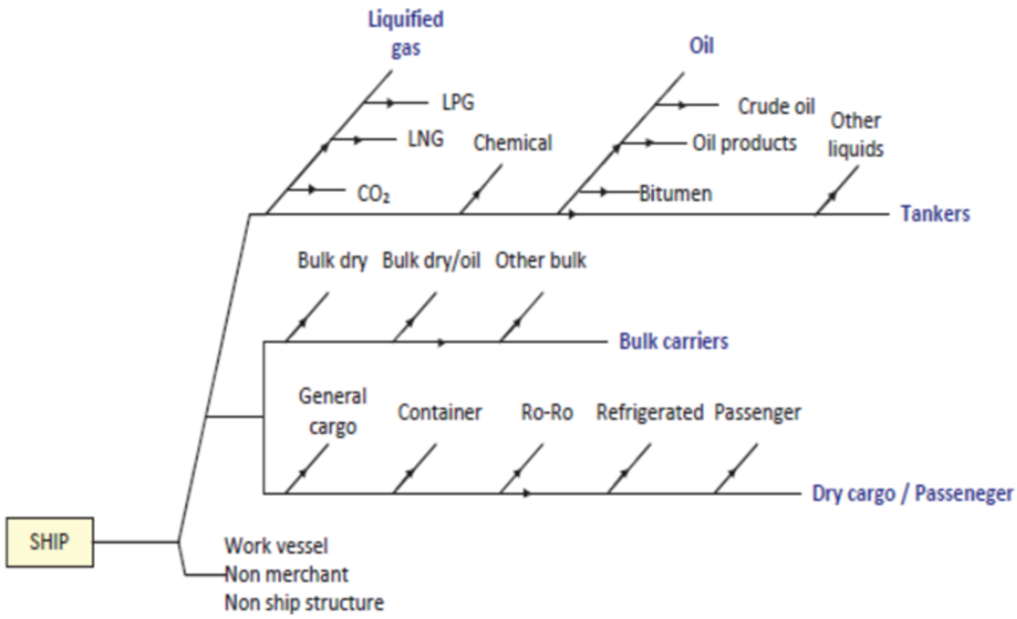

Figure 1: A graphical representation of cargo carrying vessels implementing EEDI [11].

2. Materials

The materials used to investigate the impact of energy efficiency design index on ship and operation are based on the data obtained from a case study offshore supply vessel, Saavedra Tide with four-stroke marine diesel diesel-electric, and a cargo carrying capacity of 4468 DWT. The ship voyage report data takes into account all voyages completed between June 2017, and November 2019.

The data include: voyage speed, voyage distance, fuel consumption, cargo weight, and voyage duration. The ship uses only marine diesel oil (MDO).

3. Methods

The carbon conversion factor (C_f) for MDO was selected as stipulated in MEPC.1/circ/684 ANNEX. Tables 2 and 3 presents extractions from data used for this research.

To investigate the impact of EEOI on variable ship speed, and fuel consumption, voyage parameters were selected for a specific voyage route (Onne-Akpo field), at different operating ship speed. Also, in order to analyse the impact of CO_2 emissions on repeated ship speeds, the voyage parameters were selected for a repeated ship speed (6knots), and voyage route (Egina-Akpo field). MATLAB application was employed to carry out the EEOI analysis of the data obtained from the case study vessel in order to investigate the impact of ship speed on fuel consumption, and carbon emissions.

Calculation of Energy Efficiency Operational Indicator (EEOI) Based on Operational Data

To compute EEOI values using the standard method specified in marine environmental committee **[6]** guidelines for energy efficiency calculations, voyages of Saavedra Tide taken between 2017 and 2019 were selected from two voyage routes of the ship. The voyage duration includes stops at anchorages, and ports. Voyages with similar cargo weight were carefully selected to ascertain the effect of changing ship speeds during operation. This study also investigates the relationship between fuel oil consumption, voyage duration, and ship speeds to enable ship owners achieve more fuel savings from their daily ship operations.

The basic expression for EEOI for a voyage is defined as:

$$EEOI = \frac{\sum_J FC_J \ X \ C_{Fj}}{m_{cargo} \ x \ D}$$

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

$$Average\ EEOI = \frac{\sum_i \sum_j \left(FC_{IJ}\ x\, C_{Fj}\right)}{\sum_i (m_{cargo,i}\ x\ D_i)}$$

j` = the fuel type;
i = the voyage number;
FCij = the mass of consumed fuel *j* at voyage *i*;
CFj = the fuel mass to CO_2mass conversion
factor for fuel *j*;
*M*cargo = cargo carried (tonnes) or work done (number of TEU or passengers) or gross tonnes for passenger ships; and *D* = the distance in nautical miles corresponding to the cargo carried or work done
The unit of EEOI depends on the measurement of cargo carried or work done, e.g., tonnes CO2/ (tonnes • nautical miles), tonnes CO2/ (TEU • nautical miles), tonnes CO2/ (person • nautical miles), e

Table 1: Reference value of CF for different fuel type

Type of Fuel	Reference	Carbon Content	C_F(t-CO2/t-Fuel
1. Diesel/Gas	Oil ISO 8217 Grades DMX through DMC	0.875	3.206000
2. Light Fuel Oil (LFO)	ISO 8217 Grades RMA through RMD	0.86	3.151040
3. Heavy Fuel Oil (HFO)	ISO 8217 Grades RME through RMK	0.85	3.114400
4. Liquefied Petroleum Gas (LPG)	Propane Butane	0.819 0.827	3.000000 3.030000
5. Liquefied Natural Gas (LNG)		0.75	2.750000

Table 1 shows the conversion factor for different fuel types. CF is a non-dimensional conversion factor between fuel consumption measured in g and CO_2 emission also measured in g based on carbon content.

Table 2: Ships Voyage Report Sheet for Onne-Akpo field

NAME OF VESSEL: Saavedra Tide						
Voyage Period	**Speed (knots)**	**Voyage Distance**	**Cargo Weight**	**Voyage Duration (hrs)**	**Fuel Consumption (MDO)**	**Draught**
July 5, 2018	6	30 NM	3495	11 hrs	6.0 m^3	5.0
July 29, 2018	7	30 NM	3392	10 hrs	6.8 m^3	5.0
Oct 9, 2018	6	30 NM	3481	11 hrs	6.0 m^3	5.0
Jan 18, 2019	10	30 NM	3511	7 hrs	9.1 m^3	5.0
March, 16, 2019	8.2	30 NM	3524	9 hrs	7.7 m^3	5.1

Tables 2 shows all the voyage parameters used to investigate variable ship speed impact on energy efficiency operational indicator.

Table 3: Ships Voyage Report Sheet for Egina-Akpo field

NAME OF VESSEL: Saavedra Tide						
Voyage Period	**Speed (knots)**	**Voyage Distance**	**Cargo Weight**	**Voyage Duration (hrs)**	**Fuel Consumption (MDO)**	**Draught**
May 11, 2017	6	20 NM	4162	8 hrs	4.7 m^3	5.0
June 26, 2017	6	20 NM	4142	8	4.8 m^3	5.0
October 2nd, 2017	6	20 NM	4173	8	4.7 m^3	5.0
October 28, 2017	6	20 NM	4153	8	4.7 m^3	5.0
Nov 19, 2017	6	20 NM	3991	8	4.7m^3	5.0

Tables 3 shows all the voyage parameters used to investigate the impact of constant ship speed on energy efficiency operational indicator. The ship voyage report for both routes takes into account all voyages completed between June 2017. And November 2019.

4. Results

In order to investigate the behaviour of CO^2 emissions on variable speed, and repeated constant speed, analysis was carried out on two different voyage routes. The first investigated the impact of variable speed, while the second investigated repeated constant speed impact.

A. Impact of EEOI on different ship speed

EEOI is a function of CO_2 emission, and distance sailed. And so, the higher the EEOI values, the higher the CO_2 emission, and ultimately increased fuel consumption. On this basis, Fig 2. Illustrates the relationship between speed, and energy efficiency operational indicator (EEOI). It can be seen that the EEOI values increases with the corresponding increase in ship speed for same voyage distance (30NM), and voyage route (Onne-Akpo Field). By utilizing this model, it is possible to estimate the CO_2 emissions during any given voyage.

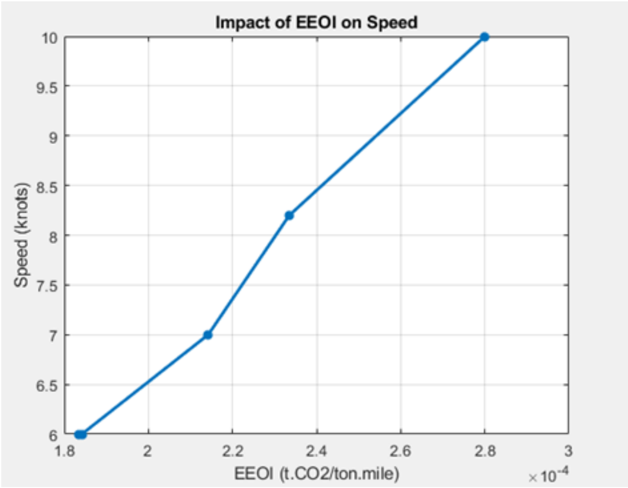

Figure 2: Impact of EEOI on Variable Ship Speed

B. Impact of EEOI on Fuel Consumption

Since this section was modelled by selecting all the voyage operations from Onne-Akpo field at different speeds of the vessel, and also, since speed is a function of fuel consumption, Fig 3 shows clearly that CO_2 emissions increases as fuel consumption increases. When the fuel consumption was at 6 tons, the vessel recorded EEOI value of about 1.834 x 10^{-4}. When fuel consumption was at 6.8 tons, EEOI value also increased to 2.142 x 10^{-4} t.CO_2/ton.mile.

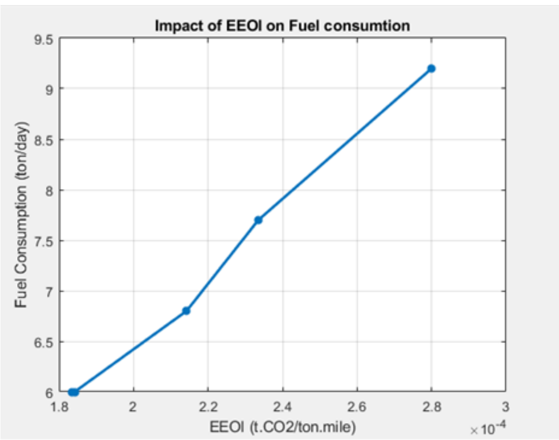

Figure 3: Graph of Correlation Between EEOI and Fuel Oil Consumption

C. Impact of speed on Fuel Oil consumption

The corresponding values of fuel oil consumption with changing speeds is illustrated in figure 4. When the vessel was operating at 6 knots, the fuel consumption was at 6 tons. When the vessel was operating at 7 knots in the same voyage route (Onne-Akpo field), the amount of fuel oil consumed increased to 6.8 tons with a significance difference of 10%-11% as can be observed from figure 4 below. This positive correlation illustrates that ship-owners, and ship operators can save a lot of fuel when operating at optimum speed.

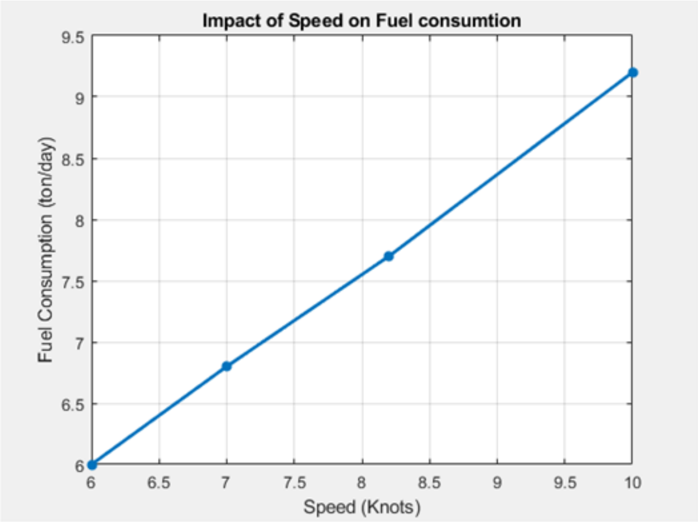

Figure 4: Graph of Correlation Between speed and Fuel Oil Consumption

D. Impact of Speed on voyage Duration

In order to shed more light on the impact of energy efficiency design index on ship operation, it is important to discuss the impact of speed on voyage duration. Figure 5, clearly indicates the arrival time of the vessel at different ship speed in (Onne-Akpo field). At the speed of 6 knots, the vessel arrived in about 11 hours, at 8.2 knots she arrived in about 9 hours. The result shows a negative correlation, meaning increase in ship speed will always reduce the duration of the voyage but, under normal/favourable operating conditions.

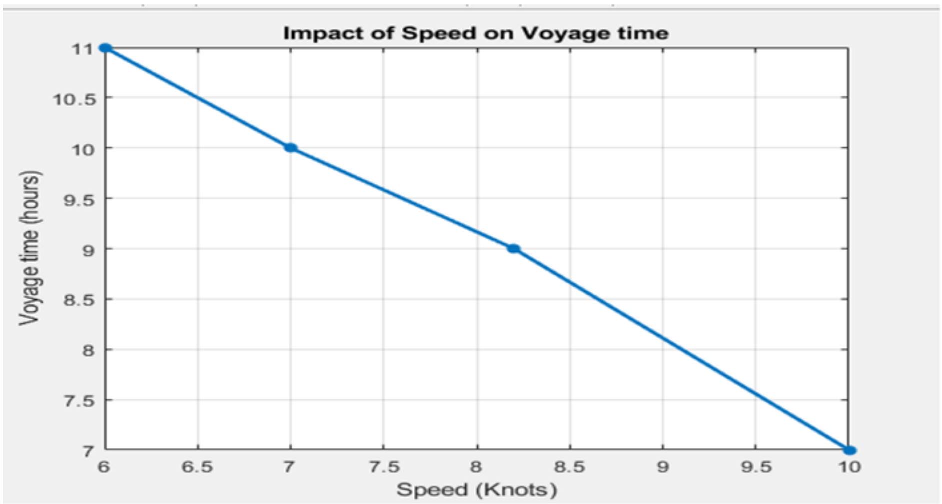

Figure 5: Graph of Correlation Between Speed and Voyage Duration

E. Comparison between the EEOI Values at Variable Ship Speed and EEOI Values at Repeated Ship Speed

This section attempts to compare the result of the EEOI values at variable ship speed, and that of constant ship speed of 6 knots to further investigate the impact of energy efficiency design index on ship operation. From Figure, the blue line chart indicates the EEOI values for the voyages from Onne to Akpo field, while the red line chart represents the voyage operations in Egina-Akpo field. It can be seen clearly that the EEOI values for the voyages at Onne-Akpo field increased significantly at different ship speeds, while the EEOI values for Egina-Akpo field operations remains at a steady level in all the five voyages as a result of constant ship speed during the operations. The significant increase in the EEOI values as can be seen in the blue line chart due to changing ship speed indicates increase in CO2 emissions, and fuel consumption at different ship speed, while the red line chart indicates steady emission levels, and steady fuel consumption at repeated constant speed.

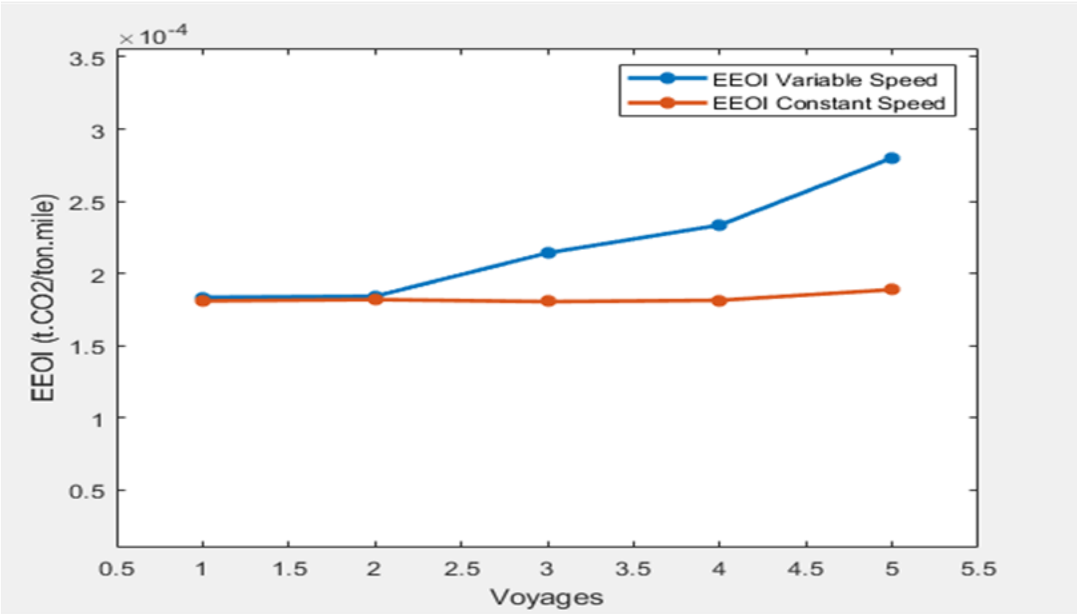

Figure 6: Comparison between EEOI (v speed) and EEOI (repeated constant speed)

5. Discussions

Ship energy efficiency design index EEDI plays a significant role in the shipping industry where fuel consumption is the biggest concern for all ship owners. Operations of marine machineries also cause the significant emissions of greenhouse gases (GHG) which aggravate ecotoxicology, global warming, and environmental degradation. This research was undertaken to minimise GHG emissions such as CO2, NOx, Sox, hydrocarbons, etc. which are ecotoxic, hazardous to human life, acidic to marine biology and responsible for rapid decay of social infrastructure and climate change. The research evaluates various ship's EEDI parameters that influence the energy efficiency operational indicator (EEOI) values of ships. It implements canonical formulae proposed by IMO, statistical relations and regression models for its analysis.

The results show a relationship between fuel oil consumption, and ship speed on one hand; and their impact on EEOI on the other hand. The linear relationship between fuel consumption, and carbon emissions was also observed in this research. As indicated, EEOI readily varies with changes in operating parameters (type of fuel, ship speed, sea state of route, deadweight, etc.). Hence, it is inappropriate to use the obtained value as a basis for generic comparison with the EEOI values of other ships. Since the amount of CO_2 emitted from ships is directly related to fuel consumption, the EEOI can also provide useful information on ships performance with regards to fuel efficiency, and the overall cost-efficient operation of the ship.

With bunker prices increasing steadily, it is necessary that ship-operators find out best practices for efficient ship operation. When the fuel consumption is at 6 tonnes, the vessel records EEOI value of 1.834 x 10^{-4} tonnes CO_2/tonnes. mile. Similarly, with fuel consumption of 6.8 tonnes, EEOI value rises to 2.142 x 10^{-4} tonnes CO_2/tonnes. mile. The potentials for shipping to provide both fuel-efficient, and low-polluting transport however, depends on more widespread use of existing abatement technologies. Furthermore, although the fuel efficiency of shipping is already high, there is still room for improvement, which will be a competitive advantage in a future with expected high fuel prices.

6. Conclusion

The research results revealed lower energy efficiency operational index (EEOI) values at lower ship speeds and higher EEOI values at higher ship speeds. It was found that, fuel consumption at 6 tonnes produced vessel records of 1.834 x 10^{-4} tonnes CO_2/tonnes EEOI value and with fuel consumption of 6.8 tonnes, EEOI value rises to 2.142 x 10^{-4} tonnes CO_2/tonnes. Mile

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