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Slow steaming application for short-sea shipping to comply with the CII regulation

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Summary

Slow steaming is an effective operational measure that reduces fuel consumption and thus emissions on board. With the Carbon Intensity Indicator (CII) regulation coming into force in 2023 from the International Maritime Organization (IMO), ships will have to reduce their CO_2 emissions even more. The practice of slow steaming is an important measure to comply with this regulation. In this study, real voyage data of a general cargo ship was used. The changes in fuel consumption, CO_2, CH_4, N_2O, and BC emissions, 20-year global warming potential (GWP20), and 100-year global warming potential (GWP100) of the ship were analysed under different scenarios (75%, 38%, 27%, and 19% main engine load), and the voyage expenses and cost-benefit ratio were calculated. At 38% main engine load, 31.5% less emissions were released than at 75% main engine load. At 27% and 19% main engine load, the emission reduction was 40.6% and 50.1%, respectively. The CO_2 reduction target of 40% by 2030 and 50% by 2050 compared to 2008 levels in the IMO Initial GHG Strategy was achieved with slow steaming. As CO_2 emissions decreased due to the application of slow steaming, this had a positive impact on the ship's CII rating and it remained at the A rating without further action. Nevertheless, it remains at the A rating with slow steaming, the amount of emissions varies depending on the rate of application of slow steaming in three different scenarios, and this shows that the environmental impact of each A rating is not the same. The results of the economic analysis show that operating costs increase and fuel costs decrease when the travel time is extended with slow steaming. As a result, the total voyage expenses decreased by up to 23.3%.

Keywords: *slow steaming; carbon intensity index; short-sea shipping; maritime transport*

Abbreviations

BC	:	black carbon
CII	:	Carbon Intensity Indicator
EEA	:	European Energy Agency
EEDI	:	Energy Efficiency Design Index
EEOI	:	Energy Efficiency Operational Indicator
EEXI	:	Energy Efficiency Existing Ship Index

GHG	:	greenhouse gas
GT	:	gross tonnage
GWP20	:	20-year global warming potential
GWP100	:	100-year global warming potential
HFO	:	heavy fuel oil
IMO	:	International Maritime Organization
LNG	:	liquefied natural gas
LOA	:	length overall
MCR	:	machinery continuous rating
MDO	:	marine diesel oil
MGO	:	marine gas oil
N_2O	:	nitrous oxide
NM	:	nautical miles
NT	:	net tonnage
PM2.5	:	particulate matter (size: 2.5 micron)
PM10	:	particulate matter (size: 10 micron)
SEEMP	:	Ship Energy Efficiency Management Plan
SEEMPII	:	Ship Energy Efficiency Management Plan Part II
SFC	:	specific fuel consumption

1. Introduction

Maritime transportation, the most important mode of transport, accounts for 90% of world trade [1]. It is well known that maritime transport is an efficient and environmentally friendly mode of transportation, considering carbon dioxide (CO_2) emissions per ton-mile of transport capacity. Although maritime transportation is an efficient and environmentally friendly mode of transportation, 300 million tons of low-grade fuels such as heavy fuel oil (HFO) and marine diesel oil (MDO) were burned annually, accounting for 7% of global fuel consumption and 3% of energy demand [2], and many pollutant emissions are being released into the atmosphere. The International Maritime Organization (IMO) stated that maritime transport accounted for 2.89% of global CO_2 emissions in 2018 [3]. According to the European Environment Agency (EEA) data, international maritime transport was responsible for 14.74% of NO_X emissions, 9.84% of SO_X emissions, and 6.75% of PM2.5 and 3.56% of PM10 emissions worldwide in 2017 [4]. These emission rates highlight the importance of shipboard emissions.

The IMO has worked on many types of emissions to reduce and control emissions from ships. NO_X, SO_X, and PM emissions are limited by regulations. This has led engine manufacturers to produce cleaner marine engines and improve fuel quality. For CO_2 emissions, numerous regulations and practices have been implemented in the past and continue to this day. In 2011, assuming that ship emissions have increased and will continue to increase, the IMO announced the Energy Efficiency Design Index (EEDI), Energy Efficiency Operational Indicator (EEOI), and Ship Energy Efficiency Management Plan (SEEMP) rules that will take effect in January 2013 [5]. The EEDI is an index that must be considered in the construction of ships larger than 400 gross tons and must be designed within the limits established for each ship. The purpose of the SEEMP regulation is to increase the operational energy efficiency of ships, and its unit is CO_2 production per nautical mile as in the EEDI. The SEEMP rule is mandatory, as is the EEDI rule, and every ship of more than 400 gross tonnage must have a plan designed to improve energy efficiency. The EEOI is a voluntary application and aims to reduce voyage-based CO_2 emissions from ships. In addition to these regulations, the IMO's Monitoring, Reporting and Verification (MRV) Regulation entered into force in 2015 and the IMO's Data Collection System (DCS) Regulation entered into force in 2018 for ships of 5000 gross tons and above. The goal of both regulations is to reduce CO_2 emissions from ships. However, the MRV regulation only applies to ships doing voyages in European ports, while IMO DCS is a regulation that must be followed by all ships calling at international ports. The IMO DCS requested that SEEMP Part II be added in addition to the existing SEEMP document, explaining the methods by which fuel consumption and emissions data are calculated and recorded. Along with these rules, the IMO's Initial GHG Strategy was enacted in 2018 and targets were set. At the IMO meeting, held in 2018, it was set to reduce CO_2 emissions released by ships by 40% by 2030 and 70% by 2050 compared to 2008 data [6]. Another target was to reduce greenhouse gas (GHG) emissions by 50% by 2050 compared to 2008 levels. To achieve these goals, various measures and strategies were announced that are classified under short-, medium-, and long-term. At the 75th meeting of the Marine Environment Protection Committee (MEPC), held in November 2020, two new regulations were announced to take effect in January 2023. The first of these rules is the Energy Efficiency Existing Ship Index (EEXI), which is applied to all commercial vessels over 400 gross tons [7]. As with the EEXI regulation, the goal is to reduce CO_2 emissions per nautical mile. Ship-specific EEXI calculations have been requested since November 2022. Another regulation announced at the same meeting is the Carbon Intensity Indicator (CII), which was entered into effect in January 2023. This rule will apply to all ships over 5000 gross tons. The amount of CO_2 produced annually by ships is calculated and graded between A and E [8, 9]. E is the lowest level, and once it is reached, the ship's International Air Pollution Prevention (IAPP) certificate is suspended and it is not allowed to sail until the proper precautions are taken. In addition, the IAPP certificate is suspended in the same manner if a grade of D is reached three times consecutively.

A look at the IMO's work shows that it has focused on reducing CO_2 and GHG emissions and has implemented various regulations to that end. The candidate measures outlined in IMO's Initial GHG Strategy guide how the industry can adapt to these practices. Slow steaming (speed reduction) is identified in the strategy as one of the short-term candidate measures. Slow steaming is an emissions reduction method in which a ship sails 15% or more below its normal speed [10]. It is the simplest way to reduce fuel consumption and emissions on board [11] and has been successfully used in the shipping industry for some time. A simulation study by Cepeda et al. [12] showed that fuel consumption could be reduced by 51% and 85% for slow steaming and ultra-low slow steaming, respectively, and that a 22% reduction in emissions was achieved for a fleet of 13 bulk carriers. Gurning et al. [10] conducted a decision-making study on the various types of slow steaming levels. According to their study, super slow steaming (extreme application of slow steaming) is the most favorable level of slow steaming due to lower emissions and operational costs. Another study looked at the effects of speed reduction in different weather and sea conditions on fuel savings [13]. A 30% speed reduction resulted in fuel savings of 2% to 45%, which varied depending on conditions. A study of the effects of slow steaming on reducing CO_2 emissions in the Mediterranean Sea was done by Degiuli et al. [14]. They applied both slow steaming and liquefied natural gas (LNG) as fuel on a case ship. The results showed that a 31% CO_2 reduction could be achieved by a 13.6% speed reduction, and that a 49% CO_2 reduction was achieved by a speed reduction on a ship fueled by LNG. Another study by Gospić et al. [15] shows the effects of slow steaming and gasification of fuel on a case ship that sails from Shanghai to Hamburg under various weather conditions. They calculated a significant fuel saving and reduction in CO_2 emissions, as well as a 16.5% reduction in the number of round trips per year due to the reduced speed. Glujić et al. [16] made a study to show the effect of slow steaming on CO_2 emissions using engine room simulators.

They used two different simulators with different main engines (one of them is MAN B&W 5MC90 and the other is Wartsila RT -Flex 82C L11) and different operating engine loads. The results show that CO_2 reduction up to 23% can be achieved when the main engine power is reduced to 60%. There are some studies in the literature that focus on the application of slow steaming to meet the new regulations. Goicoechea and Abadie [17] studied the optimal use of slow steaming for container ships under the European Union Emission Trading System (ETS). They created a model that calculates the optimal speed to achieve minimum ETS carbon prices for container ships from 2000 to 20,000 TEU. A study by Kalajdžić et al. [18] examined the EEXI compliance of 153 bulk carriers built between 2000 and 2020. They found that, on average, the entire fleet would need to make a 50% reduction in engine power at machinery continuous rating (MCR) and speed reduction of 15% on average to comply with the regulation. This shows that slow steaming is an effective method to meet current regulatory requirements.

A review of the studies clearly shows that slow steaming is an operational measure that can be used to reduce CO_2 emissions. Although there are many studies in the literature on slow steaming, there are few research papers that address the application of slow steaming and compliance with current maritime emissions regulations. To the best of the author's knowledge, there is no study in the literature on slow steaming and compliance with the recent CII regulation.

In this study, real voyage data of a general cargo ship doing short-sea shipping was used and a case study was made. The ship is currently operated by the ship management company using slow steaming. Four different scenarios were compared in the case study. These scenarios are the MCR case, the main engine load based on real voyage data, and two different slow steaming cases. In the study, firstly fuel consumption, CO_2 emissions, and other GHG emissions (CH_4, N_2O, and BC) were calculated and the effect of slow steaming application was revealed. Then, the scenarios were evaluated in terms of compliance with the CII regulation. In the final step of the study, voyage expenses were calculated and a cost-benefit analysis was performed.

2. Methodology

The Methodology section contains case study information, including case ship particulars, case ship voyage information, equations, assumptions, and data used for the study.

2.1 Ship specifications

The case ship in this study is a general cargo ship that has been under the management of Seahorse Shipping and Engineering Co. Ltd. The trade area of the case ship is the Black Sea, the Mediterranean Sea, and the Sea of Marmara. Table 1 shows the information about this vessel taken from the management company. The case ship is a medium-sized ship with 6,177 GT, which represents 43% of the total global fleet doing international voyages [19]. It has a deadweight capacity of 10,300 mt. The design speed of the ship is 12.3 knots and the installed power of the main engine is 2,500 kW. The main engine operates on both heavy fuel oil (HFO) and marine gas oil (MGO), but the management company operates the ship on MGO after the IMO Sulfur Cap regulation comes into effect.

Table 1 The case ship particulars.

Ship Particulars	
Ship type	General cargo
Keel laid date	2004
Gross tonnage (GT)	6,177
Net tonnage (NT)	3,680
Deadweight, mt	10,300
Length overall (LOA), m	128
Beam, m	18
Depth moulded, m	9.7
Draught, m	7.6
Main engine	S.X.D. – Daihatsu 8DKM-28 Max. 2,500 kW at 750 rpm
Diesel generator	2 x 220 kW at 800 rpm
Design speed, knot	12.3
Fuel type	HFO/MGO

2.2 Voyage data

The real voyage data between March 2020 and January 2021 are shown in Table 2. These data were taken from the management company. The case ship did eighteen voyages with the indicated ship speeds shown in the table. The voyage distances were calculated using the Netpas Distance 4.0 program. The program calculates the shortest route and voyage duration based on the departure and arrival ports entered and the average ship speeds.

Table 2 Voyage data of the case ship.

Voyage no	Departure port	Arrival port	Voyage distance (nm)	Average ship speed (knots)	Voyage duration (h)
01	Istanbul	Berdyansk	521	9.2	57
02	Berdyansk	El Dekheila	1250	7.9	158
03	El Dekheila	Berdyansk	1250	8.8	142
04	Berdyansk	Trabzon	385	7.8	49
05	Trabzon	Varna	551	8.8	63
06	Varna	Mariupol	527	7.6	69
07	Mariupol	Sousse	1572	7.6	207
08	Sousse	Galati	1367	8.5	161
09	Galati	Ravenna	1471	8.5	173
10	Ravenna	Ghazaouet	1496	7.6	197
11	Ghazaouet	Rijeka	1484	9.2	161
12	Rijeka	Sousse	869	8.6	101
13	Sousse	Nemrut	858	8.9	96
14	Nemrut	Haifa	648	8.0	81
15	Haifa	Nemrut	648	9.1	71
16	Nemrut	Haifa	648	7.6	85
17	Haifa	Nemrut	648	9.0	72
18	Nemrut	Haifa	648	7.0	93

2.3 Equations and assumptions

This sub-section explains voyage calculations, fuel consumption calculations, environmental calculations, and economic calculations. There are four scenarios in the case study. These scenarios in Table 3 are used to show the impact of slow steaming. The second scenario (S2) is the baseline scenario according to the real voyage data. Using the average ship speeds in Table 2, the main engine loads are calculated and shown in Figure 1. The calculation was performed using Equation 1 [20]. The average engine load is 38% for the baseline scenario (S2).

$$\frac{P_{\text{actual}}}{P_{\text{design}}} = \left(\frac{V_{\text{actual}}}{V_{\text{design}}}\right)^{\alpha} \tag{1}$$

Where P_{actual} and P_{design} are the actual main engine power in kW and the design power of the main engine in kW which is 2500 kW for the case ship, respectively. V_{actual} is the actual ship speed during the voyages and V_{design} is the design ship speed which is 12.3 knots for the case ship. α is the speed coefficient which is between 2.5 and 3 [21]. The speed coefficient depends on the ship block coefficient, propeller-engine interaction, and weather conditions [22]. This coefficient was taken as 2.5 according to the main engine power-ship speed data taken from ship noon reports.

In the case study, another scenario (S1) is at 75% main engine load, which is the normal machinery continuous rating (MCR) scenario, and the remaining scenarios are at 27% (S3) and 19% (S4) main engine load, resulting in 40% CO_2 emission reduction and 50% GHG reduction, respectively. Equation 1 was used to calculate V_{actual} for the voyage calculations of each scenario in the Netpas Distance 4.0 program. Instead of varying V_{actual} based on real ship speed data at the baseline scenario, ship speed is assumed to be constant for all voyages on S1, S3, and S4.

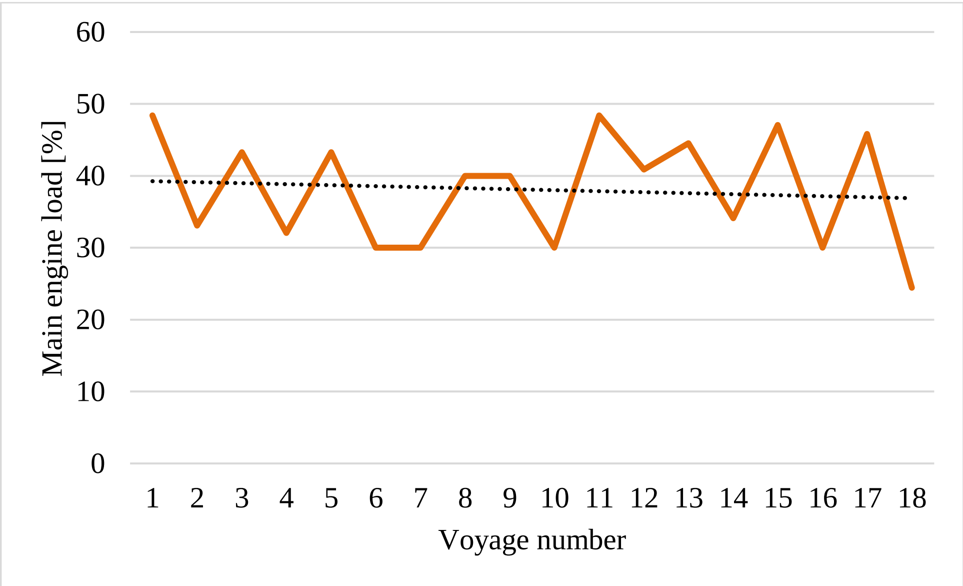


Fig. 1 Main engine load at the case ship voyages

Table 3 Voyage data of the case ship.

Scenario cases	Main engine load [%]	Ship speed [knots]	Voyage duration [days]
S1	75%	11	65.3
S2	38%	8.3	84.9
S3	27%	7.3	98.8
S4	19%	6.3	114.5

The reason for including 75% main engine load in the case study is this load is the most fuel-efficient point at the specific fuel consumption (SFC) curve with 200 g/kWh which was drawn by using consumption data indicated at the main engine manual of the case ship (Figure 2). The main engine load of 27% was selected since this engine load is the maximum engine load to comply with the IMO Initial GHG Strategy target of 40% CO_2 reduction. Lastly, 19% main engine load was selected hence it complies with the 50% GHG emission reduction target of the same strategy. This will be shown in the Results & Discussion section.

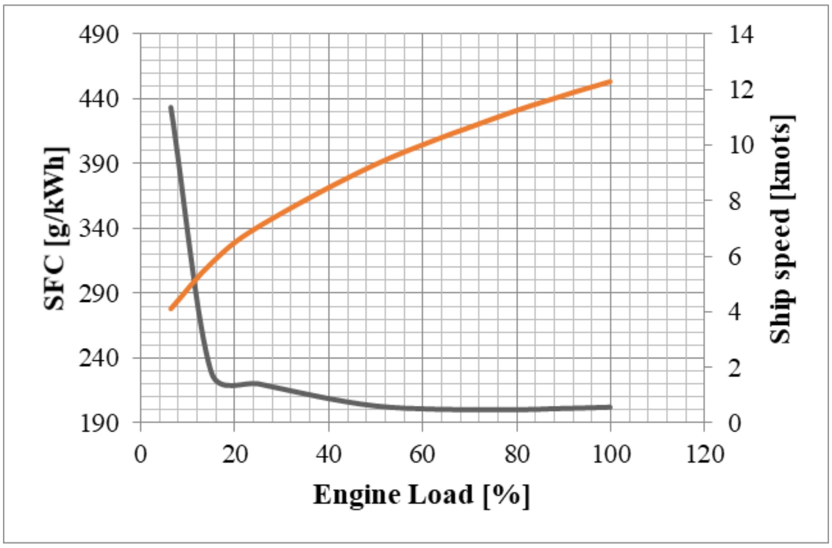


Fig. 2 The SFOC – ship speed graph of the case ship main engine

The next step is to calculate voyage-based fuel consumption and the total fuel consumption of the main engine. Equations 2 and 3 were used for the calculation.

$$FC_{\text{voyage}} = SFC \text{ x } P_{\text{actual}} \text{ x } D_{\text{voyage}} \quad (2)$$

$$FC_{\text{total}} = \sum_{i=1}^{i=18} FC_{\text{voyage}_i} \quad (3)$$

where FC_{voyage} is voyage-based fuel consumption in tons and D_{voyage} is voyage duration in hours. FC_{voyage_i} is the fuel consumption of i th number of voyage ($1 \leq i \leq 18$) and FC_{total} is the total fuel consumption of all voyages in the case study.

The main research focus is on the CII calculation of the case ship. Therefore, the calculation of the total CO_2 emissions is the primary importance. Firstly, the voyage-based CO_2 emissions are calculated by Equation 4, and the total CO_2 emissions are calculated by Equation 5.

$$V_{\text{CO2}} = FC_{\text{voyage}} \text{ x } C_{\text{f}_{\text{MGO}}} \quad (4)$$

$$V_{CO2_{total}} = \sum_{i=1}^{i\_18} V_{CO2_i} \tag{5}$$

where $C_{f_{MGO}}$ is the coefficient for the fuel carbon content of MDO that was also used by IMO [3], which is 3.206, and V_{CO2} is the voyage-based CO_2 emissions in tons. V_{CO2_i} is the CO_2 emissions of i th number of voyage ($1 \leq i \leq 18$) and $V_{CO2_{total}}$ is the total CO_2 emissions of all voyages at in case study.

To calculate the ship-specific CII, the first step is the CII_{ref} calculation that is done by using Equation 6. Further steps are the calculation of Required CII, Attained CII, and CII rating coefficient by using Equation 7 to 9 [23 – 26].

$$CII_{ref} = a \text{ x } capacity^{-c} \tag{6}$$

$$\text{Required CII} = \frac{100 - z}{100} \text{ x } CII_{ref} \tag{7}$$

$$\text{Attained CII} = \frac{V_{CO2_{total}}}{\text{capacity x distance}} \tag{8}$$

$$c_R = \frac{\text{Attained CII}}{\text{Required CII}} \tag{9}$$

where a and c are the coefficients that are given in Table A1 to calculate CII_{ref} for the specific type of ship, capacity is the deadweight of the case ship, CII_{ref} is the CII reference line value for the specific ship type in $gCO_2/t.NM$, z is the reduction factor in % that is given in Table 4. IMO determined z values until 2026, to achieve IMO's 2030 CO_2 reduction target, z values in the remaining years until 2030 are assumed in this study. The distance is the total voyage distance in nautical miles (NM), c_R is the rating coefficient. dd vectors (rating boundaries) in Table A2 are used to determine a rating of the ship according to the calculated c_R value. Figure 3 shows the rating boundaries. c_R value has to be under the dd value to stay at the specific rating.

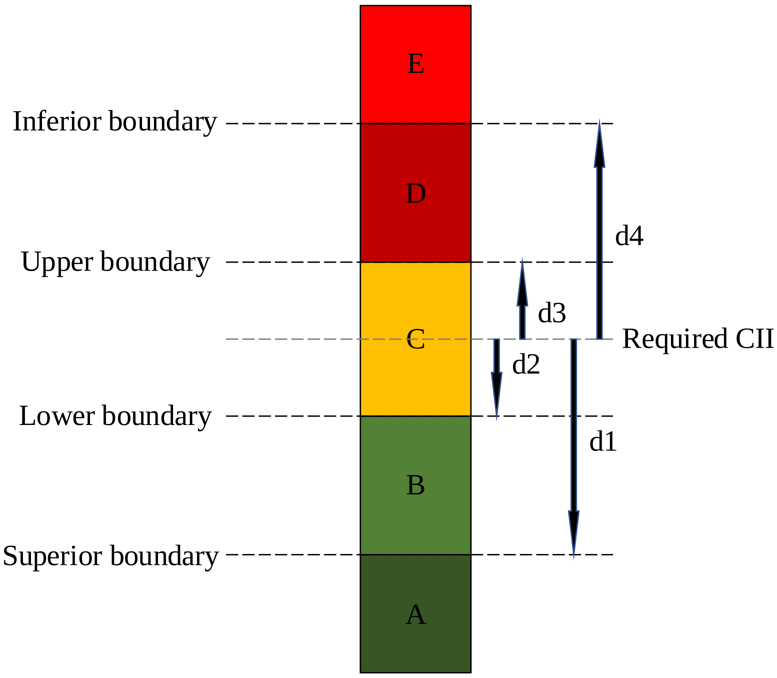


Fig. 3 CII Rating boundaries (derived from [26] and redrawn)

Table 4 Reduction factor according to years for the CII calculation [23].

Year	Reduction factor (z)
2023	5%
2024	7%
2025	9%
2026	11%
2027	18%*
2028	25%*
2029	32%*
2030	40%*

*Assumed for this study to comply with the IMO Initial GHG Strategy CO_2 reduction target

The secondary research focus under the environmental aspect of the study is GHG emissions and global warming potential in 20 years (GWP20) and 100 years (GWP100). The GHG emissions considered in this study besides CO_2 are nitrous oxide (N_2O), methane (CH_4), and black carbon (BC). The N_2O emissions are due to the chemical reactions during fuel combustion, the CH_4 emissions are due to unburned fuel, and the BC emissions are due to soot formation. The emission factors for these emissions are 0.36 mg/g fuel, 0.12 mg/g fuel, and 0.18 mg/g fuel for N_2O, CH_4, and BC for MGO, respectively [3]. It is known that the emission factors vary depending on the speed and load of the main engine. However, in this study, the emission factors are assumed to be constant, and the calculations are performed considering fuel consumption during voyages because of the lack of emission factors that vary with engine speed and load. GWP20 and GWP100 are the global warming impacts of different emissions within 20 years and 100 years, respectively. The unit of GWP is a ton.CO2e. To calculate the GWP20 and GWP100 of the scenarios, Equations 10 and 11 are used, respectively, using the derived coefficients [27 - 30].

$$\mathrm{GWP20} = \mathrm{CO_2} + 84\mathrm{CH_4} + 264\mathrm{N_2O} + 3200\mathrm{BC} \quad (10)$$

$$\mathrm{GWP100} = \mathrm{CO_2} + 28\mathrm{CH_4} + 265\mathrm{N_2O} + 900\mathrm{BC} \quad (11)$$

The last step of the study is the cost-benefit analysis of the slow-steaming operation in the scenario cases. The costs are running cost, which is 2500 USD/day (get from the ship management company), of the case ship; and voyage fuel expenses. The running cost includes crew salary, expenses related to the provision, supplies, crew and ship certification, lube oil, repair & maintenance, and ship insurance. The fuel price for MGO is 1002.5 USD/ton at the calculations [31]. The cost-benefit calculation is done by using Equation 12. The difference between total voyage expenses at 75% main engine load and other main engine load scenarios divided to the difference between 20-year global warming potential of 75% main engine load and other main engine load scenarios in the study. A lower value means a better cost-benefit result.

$$\mathrm{CBR} = \frac{\left(\left(RC_{\mathrm{daily}} \times D_{\mathrm{voyage_i}}\right)+\left(FP_{\mathrm{MGO}} \times FC_{\mathrm{total_i}}\right)\right)-\left(\left(RC_{\mathrm{daily}} \times D_{\mathrm{voyage_j}}\right)+\left(FP_{\mathrm{MGO}} \times FC_{\mathrm{total_j}}\right)\right)}{\mathrm{GWP20_i}-\mathrm{GWP20_j}} \quad (12)$$

where RC_{daily} is the daily running cost of the case ship, $D_{\mathrm{voyage_i}}$ is the total voyage duration by days at 75% engine load, FP_{MGO} is the fuel price of MGO, $FC_{\mathrm{total_i}}$ is the total voyage fuel cost at 75% engine load, $D_{\mathrm{voyage_j}}$ is the total voyage duration by days and $FC_{\mathrm{total_j}}$ is the total voyage fuel cost at 38%, 27%, and 19% engine loads, and $\mathrm{GWP20_i}$ and $\mathrm{GWP20_j}$ are 20 years global warming potential at 75%, and 38%, 27%, and 19% engine loads, respectively.

3. Results & Discussion

This section comprises environmental and economic analyses, as well as a discussion of the study's findings. The environmental analysis includes the total voyage GHG emissions and the CII values, and the voyage expenses calculation and the cost-benefit analysis form the economic assessment.

3.1 Environmental and economic analysis results

The first step of the environmental analysis is the calculation of the total voyage fuel consumption. Figure 4 shows the values for fuel consumption in the different scenarios. In the methodology section, it was explained that S2 is the baseline scenario with the 38% main engine load. The voyage data of the case ship was derived from the ship's management company and the calculations were performed accordingly. The baseline scenario (S2) has a total voyage fuel consumption of 402.4 tons. If the voyages were made with a 75% main engine load (S1), it would be 587.6 tons. These values show that slow steaming reduces fuel consumption by 31.5% and that the ship management company made a good choice to operate its ship at 38% main engine load to reduce fuel consumption. It can be observed that when the slow steaming operation is used more intensively, the total voyage fuel consumption will be 349.2 tons and 290.4 tons for S3 and S4, which equal to 40.6% and 50.1%, respectively.

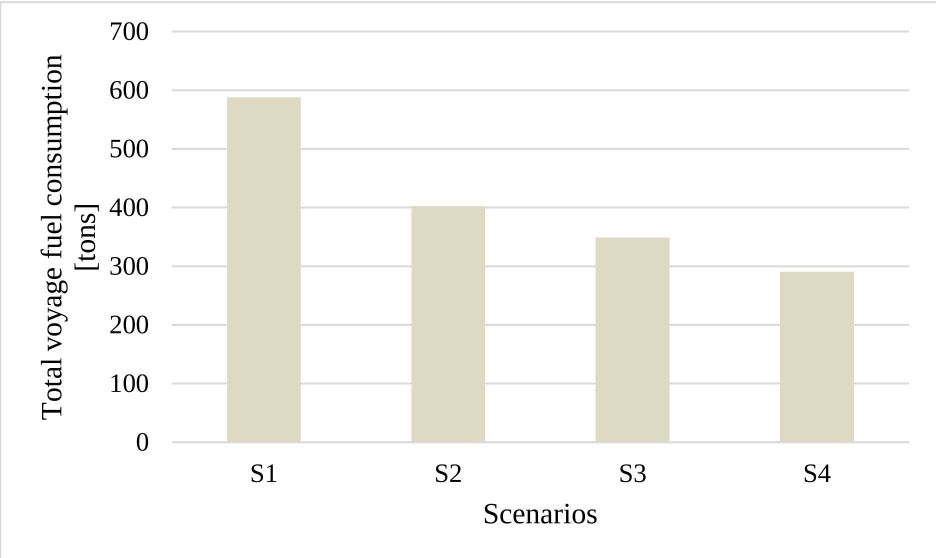


Fig. 4 Total voyage fuel consumptions at the case study scenarios

The environmental analysis results are shown in Figure 5. From the figure, S1 with 75% main engine load has the highest total voyage emissions of 1883.9 tons of CO_2, 0.212 tons of N_2O, 0.71 tons of CH_4, and 0.106 tons of BC. The GWP20 and GWP100 values are 2284.2 tons.CO_2e and 2037.2 tons.CO_2e, respectively. For the baseline scenario (S2), the emissions during the application of slow steaming at 38% load of the main engine are 1290.1 tons, 0.145 tons, 0.048 tons, and 0.072 tons for CO_2, N_2O, CH_4, and BC, respectively, due to the application of slow steaming by the ship management company. The baseline scenario has the GWP20 and GWP100 values of 1564.2 tons.CO_2e and 1395.0 tons.CO_2e, respectively. The slow steaming approach of the company results in a 31.5% reduction in both CO_2 emissions and GWP values. To achieve the IMO Initial GHG Strategy target of reducing CO_2 emissions by 40% by 2030, the slow steaming approach has to be applied more intensively. The main engine load of 27% in S3 results in a CO_2 reduction of 40.6%, meeting the 2030 target. The last scenario, S4, complies with another IMO Initial GHG Strategy target of a 50% reduction in GHG emissions by 2050. This scenario achieves a 50.6% reduction in GHG emissions by applying a higher rate of slow steaming approach with 19% main engine load. Although the economic life of the ship is far behind by 2050, general cargo ships are the oldest ship type in the global international fleet, with 58% of this ship type having an age of more than 20 years [32], and slow steaming is one of the effective decarbonization measures for this type of ships. The remaining emission levels are 0.126 tons of N_2O, 0.042 tons of CH_4, 0.063 tons of BC for S3; and 0.105 tons of N_2O, 0.035 tons of CH_4, and 0.052 tons of BC for S4. The GWP20 value is 1357.2 tons.CO_2e and 1128.9 tons.CO_2e, and the GWP100 value is 1210.4 tons.CO_2e and 1006.8 tons.CO_2e in S3 and S4, respectively. It can also be observed that the GWP20 values are higher than the GWP100 values in all cases.

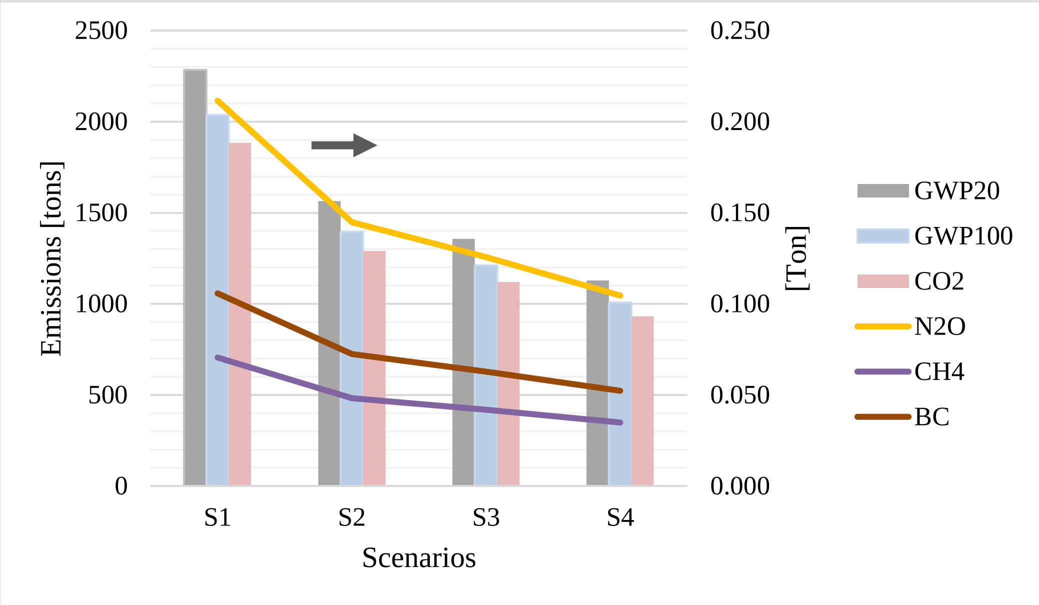
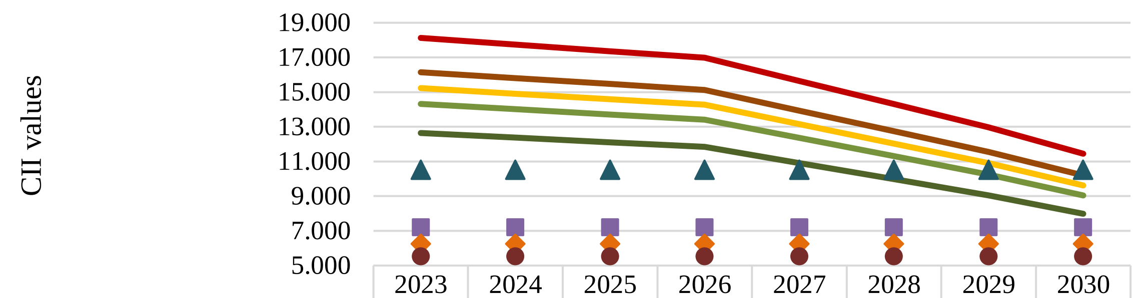


Fig. 5 Emission and GWP comparison of the case study scenarios

Figure 6 presents Attained CII and Required CII values of the case ship. Since there is no reduction factor for the Required CII after 2027, the reduction factors between 2027 and 2030 are assumed to be 18%, 25%, 32%, and 40%, respectively, to achieve the goal of 40% CO_2 reduction by 2030. It can be seen that in the S1 case, the CII rating is A between 2023 and 2027, B in 2028 and 2029, and C in 2030, if there is no improvement, and the Attained CII remains the same. The slow steaming approach in the baseline scenario (S2) results in a significantly lower Attained CII value of 7.205 gCO_2/t.NM and the ship will always be at the A rating until 2030. The slow steaming application of the ship management company stays under the A rating value of 12.643 to 7.985 gCO_2/t.NM from 2023 to 2030, respectively. Further intensive application of slow steaming on S3 and S4 results in lower Attained CII values of 6.252 and 5.521 gCO_2/t.NM and the ship remains at the A rating.

The economic analysis comprises voyage expenses and cost-benefit calculations. The possible loss of income by longer voyages and a lower number of voyages with slow steaming are not included in the analysis. The reason is the case ship has been doing tramp voyages, therefore the ship carries various bulk and packaged cargoes and there is no fixed freight rate. Nonetheless, the total voyage duration is 84.9, 98.8, and 114.5 days and the approximate annual income loss is 23%, 34%, and 43% at S2, S3, and S4 scenarios, respectively, when compared to S1. The voyage expense results are presented in Figure 7. Voyage fuel expense and voyage running cost are the voyage expense items. The majority of the voyage expenses consist of fuel expense, and reducing fuel expense increases the voyage profit [33]. According to the calculation results, voyage fuel expense decreases from 589,094 USD to 291,150 USD from S1 to S4 which equals 31.5%, 40.6%, and 50.1% of reduction at S2, S3, and S4, respectively, due to a lower fuel consumption amount by the application of slow steaming. On the other hand, the voyage running cost increases to 286,177 USD from 163,229 USD which corresponds to 23%, 34%, and 43% increase at S2 to S4, because of longer voyage durations by the application of slow steaming. The voyage fuel expense is the 78%, 66%, 59%, and 50% of the total voyage expenses at S1, S2, S3, and S4, respectively.



	2023	2024	2025	2026	2027	2028	2029	2030
Major Superior (A rating)	12.643	12.377	12.110	11.844	10.913	9.981	9.049	7.985
Minor Superior (B rating)	14.318	14.017	13.715	13.414	12.359	11.304	10.249	9.043
Moderate (C rating)	16.146	15.806	15.466	15.126	13.937	12.747	11.557	10.198
Minor Inferior (D rating)	18.126	17.745	17.363	16.981	15.646	14.310	12.975	11.448
Required CII	15.232	14.911	14.591	14.270	13.148	12.025	10.903	9.620
S1	10.522	10.522	10.522	10.522	10.522	10.522	10.522	10.522
S2	7.205	7.205	7.205	7.205	7.205	7.205	7.205	7.205
S3	6.252	6.252	6.252	6.252	6.252	6.252	6.252	6.252
S4	5.521	5.521	5.521	5.521	5.521	5.521	5.521	5.521

Fig. 6 Attained CII and Required CII of the case ship

Figure 8 shows the cost-benefit results in the different scenario cases. A lower cost-benefit ratio value means a more favorable scenario. Since 75% main engine load is the machinery continuous rating (MCR) and this load is the optimum load for the engine, other scenario cases are compared with this case to calculate the cost-benefit. The cost-benefit values are 190.0 USD/CO_{2e} at S2, 167.5 USD/CO_{2e} at S3, and 151.5 USD/CO_{2e} at S4. It is observed that a higher rate of slow steaming application leads to a higher CO_{2e} reduction, lower voyage expenses, and a lower cost-benefit ratio.

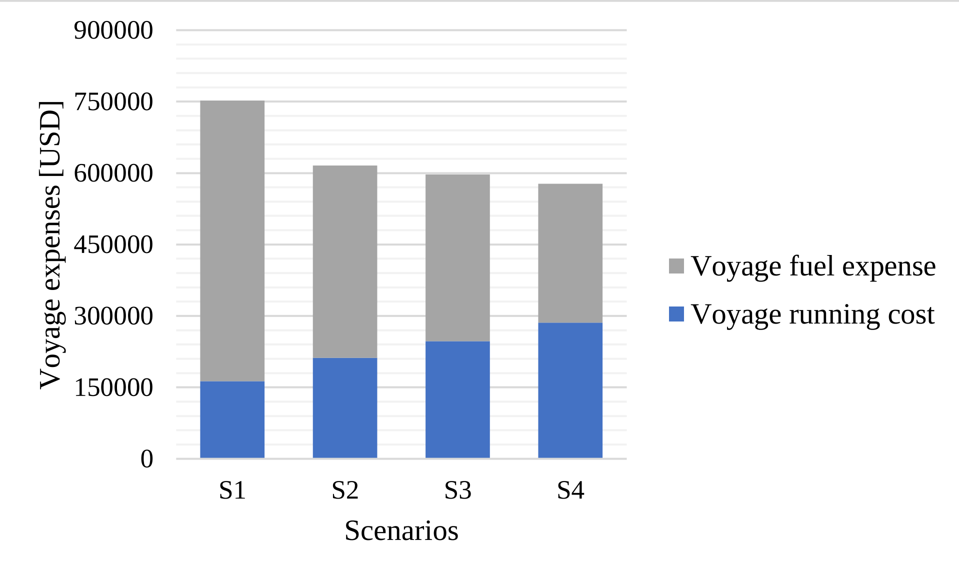


Fig. 7 Voyage expenses at different scenarios

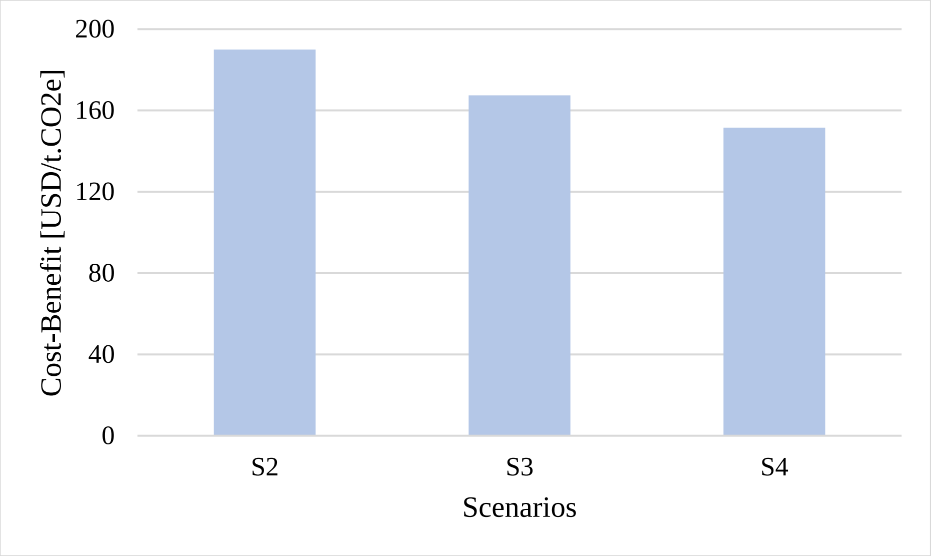


Fig. 8 Cost-benefit results at different scenarios

3.2 Discussion

In this study, environmental and economic analyses of case study scenarios from S1 to S4 were made and the effects of slow steaming were observed. The ship management company currently does not operate the case ship at MCR main engine load but applies slow steaming at the average of 38% main engine load. Accordingly, there has been a decrease in fuel consumption and emissions, and the positive effect of slow steaming has been visibly demonstrated. The GWP20 and GWP100 potentials also decreased due to the reduction in emissions. However, in this case, compliance with the IMO Initial GHG Strategy targets cannot be achieved. Compliance with the strategy was obtained by achieving a 40.6% CO_2 reduction at 27% main engine load in S3. In S4, the slow steaming application was further increased and 50.6% GHG emission reduction was achieved at 19% main engine load, and another target of the strategy was achieved before 2050. It has been revealed that slow steaming is a suitable emission reduction method for old ships and it will be a more logical choice compared to other emission reduction methods when the life span of the ship is considered. For example, retrofitting a ship to an LNG-fueled ship costs 1100 USD/kW. This results in a conversion cost of 2,750,000 USD for the retrofit of the case ship, resulting in a 25-30% CO_2 reduction. A cost of 275-385 USD/kW is incurred for retrofitting a ship to a methanol-fueled ship. This means a cost in the range of $687,000 - $962,500 for a 9-10% CO_2 reduction on board the case ship. If the ship is to be converted to a hydrogen fuel cell-powered ship, there will be a cost of 5,500,000 USD for the case ship with a unit price of 2200 USD/kW and a 100% CO_2 reduction will be obtained [34]. However, with slow steaming, significant CO_2 reduction can be achieved without any investment costs.

In terms of compliance with the CII regulation that will be in effect in 2023, the case ship drops down to a C rating even in the worst-case scenario S1 (75% engine load) without slow steaming and still does voyage in accordance with the regulation. Nonetheless, with the slow steaming application, the ship always remains at an A rating. This shows that the case ship, which applies slow steaming, will be in an advantageous position in different market-based measures that may be applied in the future. Another important point here is that although the ship remains at an A rating under slow steaming conditions in different scenarios when compared in terms of emissions, it has been seen that not every A rating will release the same emissions into the atmosphere. This shows that the environmental impact of every A rating will not be the same. For this reason, the CII regulation currently in force to reduce CO_2 and GHG emissions from ships may be reconsidered in the future and divided into narrower range ratings, e.g. A^+, A, and A^-. However, according to the results obtained from the study, it is seen that slow steaming is a very useful emission reduction method that complies with the CII regulation for a ship that does short-sea voyages.

From an economic point of view, the running cost of the ship increased due to the increase in the voyage duration with slow steaming, on the other hand, the fuel costs decreased significantly due to the decrease in fuel consumption. It is seen that total voyage expenses have decreased as a result. In this study, the freight lost due to the increase in voyage duration and the operational costs that may increase as a result of the slow steaming application are not included in the economic analysis. The ship management company has the decision to sail with slow steaming at 38% main engine load. The voyage duration is 84.9 days on S2. If 75% main engine load had been used, the voyages subject to the study could have been completed in 65.3 days and another voyage or voyages could have been made, but this loss has been accepted by the ship management company. Considering this situation, it is thought that the company may be willing to complete the specified voyages in 98.8 days at 27% main engine load in S3. In the last scenario (S4), voyages could be completed in 114.5 days at 19% main engine load. This increase in the voyage duration does not seem commercially reasonable. Environmentally viable S4 is not commercially viable as a result of the analysis. According to the cost-benefit analysis, the cost per t.CO_{2e} has decreased as the costs have decreased with a more intensive slow steaming application. The situation that should be noted again in this analysis is that the voyages that cannot be made due to the increased voyage duration due to slow steaming are not included in these calculations. As the ship makes tramp voyages, probable voyages and possible freight amounts cannot be estimated.

Another issue that should be considered together with the slow steaming application is increased operational cost. Diesel engines are not optimized for low loads. In general, 75-85% loads are suitable operating ranges for diesel engines. Therefore, slow steaming negatively affects engine performance. In a previous study, it was stated that during the long-term slow steaming application in ships, soot accumulation and fouling on the cylinder elements, turbocharger, and funnel would affect the engine performance [35]. In order to prevent the engine performance from being adversely affected, it has been recommended that routine checks should be carried out at shorter intervals than normal, especially parts such as piston ring, turbocharger, exhaust lines, and funnel should be inspected more frequently. The company has stated that they have been aware of these issues as they already apply slow steaming. In the case of a more stringent slow steaming application, controls can be increased, thereby maintaining engine performance.

4. Conclusions

With the case study in this paper, the slow steaming application of a ship that was doing short-sea shipping was analyzed in terms of environmental and economic aspects. The real voyage data were used in the study. In the environmental analysis, CO_2, N_2O, CH_4, and BC emissions were examined and the effect of slow steaming on the CII rating, which entered into force in January 2023, was examined. In the economic analysis, the varying voyage costs with the slow steaming application were examined and a cost-benefit analysis was made. Important findings obtained as a result of the study:

- The main engine load of the ship from which the real data retrieved is 38%. If the main engine load was 75% there would be more total voyage fuel consumption. With slow steaming, fuel savings of 31.5% at 38% main engine load, 40.6% at 27% main engine load, and 50.1% at 19% main engine load were achieved.

- As fuel consumption decreased with slow steaming, CO_2, N_2O, CH_4, and BC emissions decreased. Depending on this decrease, the GWP20 and GWP100 potential also decreased. Another point to note is that the GWP20 is higher than the GWP100. This is due to the greater impact of GHG emissions in the short-to-medium term.

- If the ship had sailed at 75% load, its CII rating would have dropped to C. However, it has always remained at the A rating with the slow steaming application. Although it remains at the A rating with slow steaming, the number of emissions vary according to the rate of slow steaming application in three different scenarios, and this shows that the environmental impact of each A rating will not be the same.

- As fuel consumption is reduced with slow steaming, fuel expenses have decreased. However, on the other hand, the running cost increased as the voyage duration increased. Considering the total voyage expenses, it was determined that there was a reduction of 18.2% in S2, 20.6% in S3, and 23.3% in S4 with slow steaming application compared to S1.

- According to the cost-benefit analysis, S4 is a scenario with more cost-benefit value than other slow steaming scenarios (S2 and S3). Low voyage expenses and a high emission reduction rate are effective in this result.

This study examined the effect of slow steaming on CII rating, CO_2, and other GHG emissions and concluded that it is an effective method for the old ships that do short-sea shipping to comply with the CII regulation, which came into force in January 2023. In addition, it has been observed that ships of this age, type, and voyage duration can achieve the 2030 and 2050 IMO Initial GHG Strategy targets with slow steaming. In terms of emissions, it has been seen that the same CII ratings can emit different amounts of emissions, therefore it has been suggested that more frequent rating ranges, for example, A+, A, and A-, may be more appropriate to evaluate ship-sourced CO_2 and GHG emissions. In the next study, a study can be done on the application of CII rating with a narrower range of ratings in a case study.

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Appendix

Table A1 CII reference line coefficient [24]

Ship type	Limitations	Capacity	a	c
Bulk carrier	DWT ≥ 279,000	279,000	4745	0.622
	DWT < 279,000	DWT	4745	0.622
Gas carrier	DWT ≥ 65,000	DWT	14405E+7	2.071
	DWT < 65,000	DWT	8104	0.639
Tanker		DWT	5247	0.610
Container ship		DWT	1984	0.489
General cargo ship	DWT ≥ 20,000	DWT	31948	0.792
	DWT < 20,000	**DWT**	**588**	**0.3885**
Refrigerated cargo ship		DWT	4600	0.557
Combination carrier		DWT	40853	0.812
LNG carrier	DWT ≥ 100,000	DWT	9.827	0
	100,000 > DWT ≥ 65,000	DWT	14479E+10	2.673
	DWT < 65,000	65,000	14479E+10	2.673
Ro-ro cargo ship (vehicle carrier)		GT	5739	0.631
Ro-ro cargo ship		DWT	10952	0.637
Ro-ro passenger ship		GT	7540	0.587
Cruise passenger ship		GT	930	0.383

Table A2 dd vectors for rating boundaries of different ship types [26]

Ship type		Capacity	dd vectors			
			d1	d2	d3	d4
Bulk carrier		DWT	0.86	0.94	1.06	1.18
Gas carrier	65,000 DWT and above	DWT	0.81	0.91	1.12	1.44
	Less than 65,000 DWT	DWT	0.85	0.95	1.06	1.25
Tanker		DWT	0.82	0.93	1.08	1.28
Container ship		DWT	0.83	0.94	1.07	1.19
General cargo ship		**DWT**	**0.83**	**0.94**	**1.06**	**1.19**
Refrigerated cargo carrier		DWT	0.78	0.91	1.07	1.20
Combination carrier		DWT	0.87	0.96	1.06	1.14
LNG carrier	100,000 DWT and above	DWT	0.89	0.98	1.06	1.13
	Less than 100,000 DWT	DWT	0.78	0.92	1.10	1.37
Ro-ro cargo ship (vehicle carrier)		GT	0.86	0.94	1.06	1.16
Ro-ro cargo ship		GT	0.76	0.89	1.08	1.27
Ro-ro passenger ship		GT	0.76	0.92	1.14	1.30
Cruise passenger ship		GT	0.87	0.95	1.06	1.16

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