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Ship energy consumption analysis and carbon emission exploitation via spatial-temporal maritime data

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HIGHLIGHTS

- Five indicators: CO_2 emissions, CO_2 index, fuel consumption, EEOI and FEEMI are selected to evaluate ship energy efficiency and environmental management.
- EEOI is evaluated together with the CO_2 emission to analyze the variation of EEOI via spatial-temporal maritime data.
- By quantitative analysis and designing different scenarios, the key factors affecting the change of EEOI are studied.

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ABSTRACT

Global greenhouse gas emission attracts significant attentions across varied communities, and carbon emission (CE) reduction has become hot topic in the maritime field considering that appropriately 3% CE come from the field. The prerequisite for fulfilling the task is to accurately quantify the ship CE. To achieve the aim, the study utilizes indicators, such as carbon dioxide (CO_2) emission, CO_2 index, fuel consumption, energy efficiency operational indicator (EEOI), fleet energy efficiency management index (FEEMI), to analyze ship energy consumption. We employ ship voyage data from container, oil tanker, bulk carrier and liquefied natural gas (LNG) carrier to evaluate ship energy consumption. We have testified EEOI variation tendency under different ship cargo loading volume states (i.e., full/partial load) and speed deceleration scenario. Moreover, the FEEMI indicator is used to determine energy efficiency for different ship fleets (container ship fleet, oil tanker fleet, bulk carrier fleet, LNG fleet). Experimental results suggest that EEOI is proportional to ship energy consumption when the sailing distance and cargo volume are constant. The ship EEOI indicator calculated in full-loaded status is obviously smaller than the counterpart under partial-load status. The fleet energy consumption efficiency shows a slight increase (at least 1%) due to release of ship energy efficiency management plan. The research findings can help maritime policy-makers provide more reasonable regulations for the purpose of ship energy consumption enhancement.

1. Introduction

Greenhouse gas (GHG) emission of global shipping industry has experienced a sharp increase in recent decades due to the global economic development [1–3]. It is noted that global climate change is mainly triggered by GHG carbon dioxide [58], whilst ship greenhouse gas emission accounts for a large proportion of global GHG emission [4]. Statistical indicators show that ship carbon dioxide emission raises from 701 million (in 2012) ton to 740 million (in 2018) ton, and it is found that about 2% global CO_2 emission come from the shipping industry [5–7]. The International Maritime Organization (IMO) has set the goal of reducing GHG emission of the global shipping industry in 2050 into

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half of the counterpart in 2008 [8]. A large number of international maritime regulations has been issued by IMO to achieve the goal [9]. Besides, the maritime community proposes different models and indictors to quantify ship GHG emission from the microscopic and mid-scopic levels. The energy efficiency operational indicator (EEOI) is proposed to determine ship CO_2 emission of main and auxiliary engines during anchoring and berthing procedure.

Ship energy efficiency improvement is an important way to fulfill low-carbon shipping goal considering that carbon dioxide emission mainly stems from ship fuel consumption [10,11]. Many studies have been conducted to exploit CO_2 emission variation tendency under different ship maneuvering conditions (e.g., varied engine working conditions, different sailing speeds) [12]. It is also noted that ship CO_2 emission level is quite low while she sails with low sulfur oil. Ship sailing at high speed also generates more GHG emission, and vice versa [13]. Many attempts have been paid to improve ship energy utilization efficiency, such as main engine operating condition controlling, ship travelling path optimization [14–16], hull curve design optimization [17], installing bubble lubrication system and propeller [18–21]. The above-mentioned studies try to improve ship energy efficiency by focusing on single factor, which may not be always the case in the real-world. Fan et al., proposed a novel framework by considering maritime policy, ship maneuvering operations, economy development, CO_2 emission reduction, maritime traffic safety, etc. [22]. Perez et al., proposed a novel system to collect both kinematic and static sailing parameters to fine-tune ship maneuvering operations in terms of calibrating EEOI and energy efficiency design index [23].

Overall, ship GHG emission reduction attracts numerous attentions in the maritime field, whilst intrinsic yet important factors for identifying ship energy efficiency fluctuation deserves more focuses. Firstly, we have conducted holistic literature survey by focusing on ship energy efficiency reduction topic, and we have proposed a novel framework to quantify ship energy consumption by integrating EEOI and CO_2 emission data. Secondly, we employ five indicators to conduct a comprehensive quantitative analysis of ship energy consumption under different spatial-temporal scales. Thirdly, we try to exploit crucial factors for determining ship EEOI variation, which can impose further impact on ship carbon emission levels. The remaining of the study is organized as follows. Section 2 provides a literature review about ship energy consumption analysis, and the section 3 describes methodology in detail. The section 4 demonstrates the experimental results and section 5 discusses both pros and cons about the study. The study is briefly concluded in the section 6.

2. Literature review

The primary goal of ship energy efficiency management is to reduce ship fuel consumption and exhaust emission in the real-world maritime activities. Previously studies try to improve utilization level of ship main engine energy to improve EEOI. The EEOI indicator is used to quantify ship main engine status, and the ship-borne sensory data is employed to verify statistical model performance [24]. It is found that ship moving speed plays an important role in fulfilling the task of ship energy utilization improvement and greenhouse gas emission reduction [25]. Hou et al., established a minimum EEOI optimization model by considering ship main engine rotational speed [26]. Sun et al., exploited performance for dynamic optimization models to analyze ship energy efficiency, and utilized genetic algorithm to optimize initial weights and thresholds of neural network nodes to predict ship fuel consumption and speed [27].

Previous studies mainly focus on determining single factor influence on EEOI variation. But, the EEOI may be simultaneously affected by different factors, such as ship cargo loading volume, sailing speed, sea condition, etc. [28,29]. It is a challenge to quantify ship energy under different maneuvering states, whilst some studies are conducted to explore multi-input variable model. Ship main diesel engine propulsion model is established to calculate ship life-cycle energy consumption assessment with the support of main engine speed, EEOI value, ship draught [30]. Liu et al., proposed a dynamic energy efficiency optimization model for a hybrid- electric ship under time-varying maritime environment inference [31]. The fast non-dominated sorting genetic algorithm II is applied to solve the above-mentioned optimization problem (i.e., obtaining ship optimal engine speed in a real-time manner). The experimental results demonstrate that ship EEOI can be significantly reduced at lower engine speed and smaller ship draft.

The newly development of machine learning and data mining technology stimulates ship energy efficiency enhancement by exploiting intrinsic relationship among different factors. The EEOI value can be calculated with the support of public-available AIS data, ship static data and environmental data, and the real-world ship fuel consumption is not essential for the EEOI calculation [32]. Shang et al., proposed a traffic energy consumption model based on macro and micro data, which can significantly improve the accuracy of energy consumption estimation [33]. Wu et al., estimated ship fleet energy consumption, voyage planning and speed optimization for linear shipping by formulating a multi-objective optimization problem [34]. Note that the study was implemented to exploit quantifiable factor influence such as departure/arrival ports, ship hull line, ship deadweight, etc. Additional studies are also conducted to exploit un-quantifiable factor influence (such as ship fouling) [35,36]. It was observed that the data mining related models can successfully quantify ship energy consumptions, which can obviously benefit ship EEOI monitoring, forecast and optimization.

The EEOI and CO_2 emission are commonly used to evaluate ship energy efficiency in the maritime community. Elkafas et al., measured ship speed reduction influence on the energy consumption and environment pollution energy efficiency design index (EEDI), EEOI and ship emission calculation models [37]. It was estimated that 12% ship speed reduction can result in 36% suppress of carbon dioxide emission. Ammar et al., studied the intrinsic relationship among ship speed, EEDI and EEOI with the support of empirical cargo ship data [38]. It was observed that ship speed reduction leads to increase of EEDI and EEOI decrease. With the help of oil tanker data, Seddiek et al., analyzed the EEDI and EEOI variation under scenarios of low steaming and waste heat recovery, respectively [39]. The experimental results indicated that 10% speed reduction can approximately suppress 30% CO_2 emission, and 20% speed cutting-down can result in more than 50% carbon emission reduction. The above-mentioned studies can benefit ship energy efficiency and environment protection, which were mainly conducted by focusing on single ship operation factor for CO_2. It was noted that previous ship energy consumption related studies were implemented in the way of specific ship type oriented. Thus, it is necessary to holistically determine crucial factors for exploiting ship energy efficiency.

3. Data and methodology

3.1. Data

We collect empirical ship static and kinematic data for the purpose of ship energy efficiency evaluation, and ship AIS data are collected with time span ranging from January 2021 to May 2023. The corresponding ship data are obtained with their latitude positions falling into the 30.33°S to 45.34°N, and the longitude data originates from 121.29°W to 129.03°E. Note that ship trajectory routes with ocean-going shipping voyages were selected to evaluate ship spatial-temporal carbon emission in a world-wide level. The raw ship data are downloaded from website www.hifleet.com, which provides ship AIS data around the world. The ship type consists of container ship, oil tanker, bulk carrier and LNG carrier (i.e., four typical merchant ships). Ships with similar structure, main engine power and deadweight ton are considered as sister-ship in our study. Four groups of sister-ship are obtained in our study, while each group of sister-ship contains four ships. In that way, four container ships are labeled as C1, C2, C3, C4. The four bulk carriers (LNG ships) are marked as B1 (L1), B2 (L2), B3 (L3), B4 (L4). More details for each ship are shown in Table 1.

3.2. Evaluation indicators

The carbon dioxide emission, carbon dioxide index, fuel consumption, EEOI and FEEMI are selected to evaluate ship energy consumption. The measurement unit for both of carbon dioxide emission and fuel consumption is ton, and carbon dioxide index is quantified with ton per nautical mile (ton/nm). The EEOI measurement unit is ton per ton nautical mile (ton/(ton•nm)), and measurement unit is applicable to that of the FEEMI. We define the term voyage while a ship departs and arrives at same port regardless the passing-by/anchoring port and goods information. The carbon emission coefficient (cec) usually refers to the emission coefficient of carbon dioxide and the measurement unit is same to that of carbon dioxide emission. Carbon proportion and carbon emission coefficient for different fuel types may vary in real-world. The calculation formula of CO_2 emission can be found in Eq. (1). Typical fuel types can be classified into five categories, which consist of diesel/gas oil, heavy fuel oil (HFO), light fuel oil (LFO), liquefied petroleum gas (LPG) and liquefied natural gas (LNG). The carbon content values for the five fuel types are 0.875, 0.86, 0.85, 0.819 and 0.75. The cec values for the above-mentioned five fuel types are 3.21, 3.15, 3.11, 3.03 and 2.75, respectively. It is noticed that LFO is commonly used for ocean-going ships during their voyages, while LNG carrier usually travels with LNG fuel [40].

$$E_{CO_2} = F_{con} \times cec \tag{1}$$

where *cec* is carbon emission coefficient, E_{CO_2} denotes CO_2 emission, and F_{con} is the fuel consumption.

The CO_2 index is an indicator to evaluate CO_2 emission, which demonstrates CO_2 emission per nautical mile (nm). The indicator is primary influenced by the CO_2 emission and ship sailing distance. The calculation formula of CO_2 index is shown in Eq. (2):

$$I_{CO_2} = \frac{E_{CO_2}}{S} \tag{2}$$

where S denotes ship sailing distance which can be found in navigation logbook, and the symbol I_{CO_2}denotes CO_2 index.

Fuel consumption data is collected from sensors installed on the main engine and auxiliary machines (boiler, radiator, lubrication oil pump etc.) [41]. Note that main engine energy consumption mainly refers to fuel instantaneous consumption calculation, such as ship oil and gas consumption during her moving or anchoring statuses. The main engine energy consumption heavily depends on main engine power and ship speed. This study mainly calculates fuel consumption of ship diesel engines. The ship auxiliary machine mainly refers to marine generator set, which provides power to varied ship-borne machines. The ship boiler generates steam by burning oil, which provides steam for the corresponding ship-borne facilities. The ship steam facilities mainly include oil heating facility, steam power plant, etc. F_m is fuel consumption of main engine, and the corresponding formula is shown in Eq. (3). The F_a and F_b denotes fuel consumption of auxiliary engine and boiler fuel consumption, respectively. Eq. (4) and Eq. (5) are used to calculate the F_a and F_b, respectively. The fuel consumption is calculated with Eq. (6) as follows:

$$\mathrm{F}_m = EF_m \times T_m \times W_m \tag{3}$$

$$F_a = EF_a \times T_a \times W_a \tag{4}$$

$$F_b = EF_b \times T_b \times W_b \tag{5}$$

$$F_{con} = F_m + F_a + F_b \tag{6}$$

where EF_m denotes the fuel consumption per kwh for ship main engine, and the measurement unit is kwh. The symbol T_m demonstrates time duration when the ship main engine is in working condition, and W_m demonstrates the main engine power. The EF_a illustrates fuel consumption per kwh of ship auxiliary engine, while T_a demonstrates time duration when the ship auxiliary engine is in working condition. The symbol W_a demonstrates auxiliary engine power. The EF_b is fuel consumption per kwh when the ship boiler is in working condition and the symbol T_b denotes boiler working time. The W_b demonstrate ship boiler power while the EF_b denotes boiler fuel consumption.

The EEOI is abbreviated as ship energy efficiency operation index, which refers to overall carbon dioxide emission for finishing a unit-cargo turnover operation (i.e., cargo loading volume multiplied by sailing distance) [42]. The EEOI is calculated with Eq. (7). Ship officials can evaluate ship energy efficiency with the help of EEOI values, and shipping company can take initiatives to improve ship energy efficiency, reduce carbon dioxide emission, lower down ship operation cost, etc. The FEEMI denotes energy efficiency management index for a ship fleet, which can measure fleet energy efficiency management capability [43]. A lower FEEMI value indicates higher energy efficiency, while a higher FEEMI value indicates lower energy efficiency. Fleet management participants can use FEEMI to identify ships with low energy efficiency, and thus further measurements can be taken to improve ship fleet energy utilization efficiency. Overall, we can obtain holistic view on the ship energy efficiency with help of the five indicators (carbon dioxide emission, carbon dioxide index, fuel consumption, EEOI and FEEMI). The FEEMI is calculated with Eq. (8).

$$EEOI = \frac{\sum_{i=1}^{N}\sum_{j=1}^{N} F_{coni} \times cec_j}{M \times S} \tag{7}$$

$$FEEMI = \frac{\sum_{i=1}^{N}\sum_{j=1}^{N} F_{coni} \times cec_j}{n\sum_{i}(M \times S_i)} \tag{8}$$

where i is ship voyage number, j is fuel type for the ship voyage, and N is maximum voyage number. The F_{coni} is the total fuel consumption for the i voyage. The S_i is the distance sailed by the ship for i voyage. The cec_j demonstrates carbon coefficient for the purpose of bridging fuel quantity into CO_2 quantity. The symbol M demonstrates cargo weight for a ship.

Table 1
details for each ship of sister-ship samples.

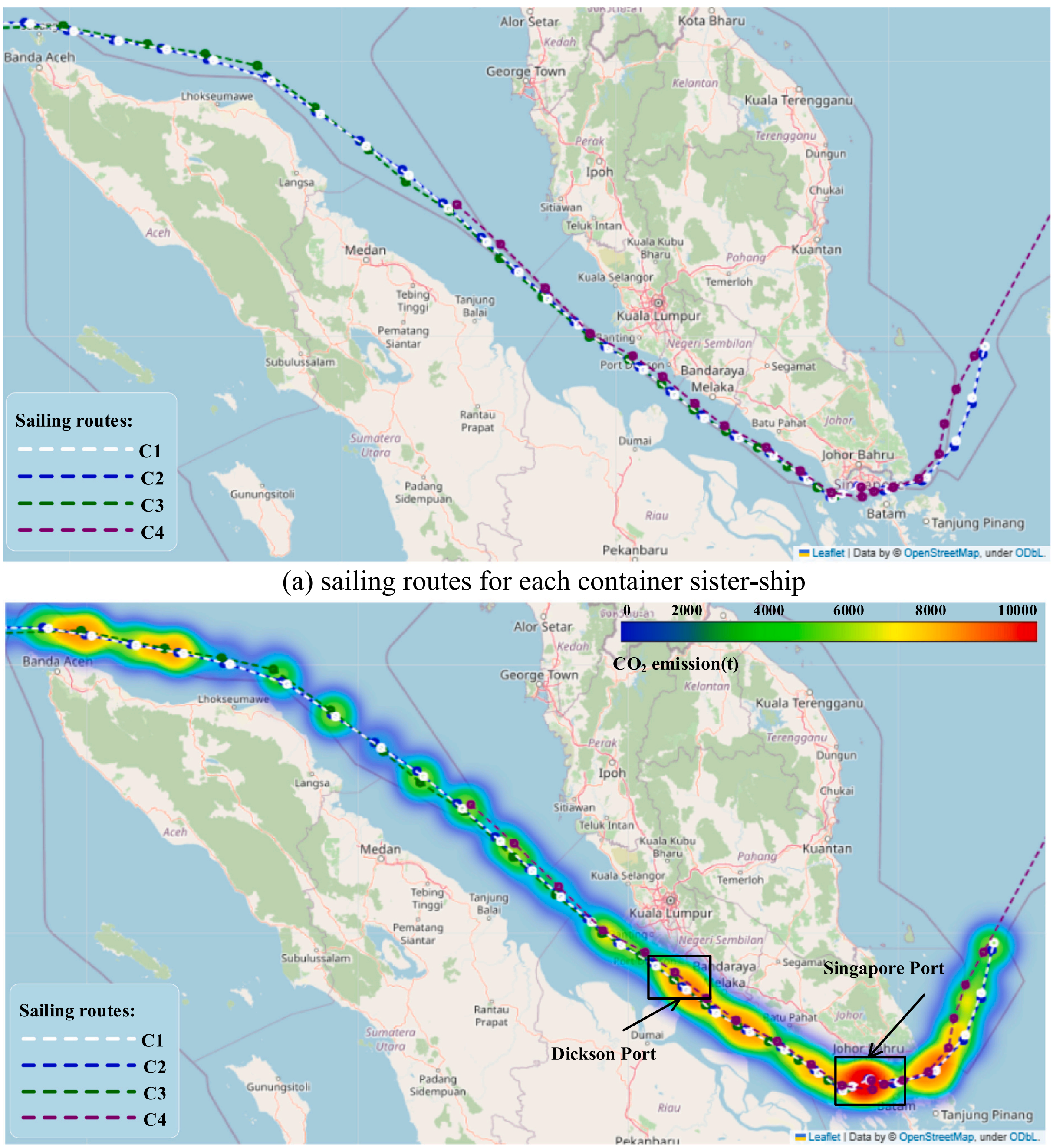
ship label	ship length (m)	hull beam (m)	design draft(m)	dead weight(t)	built year	main engine power(kw)
C1	368	51	16.025	145,368	2015	51,823
C2	368	51	16.025	145,388	2015	51,823
C3	368	51	16.025	145,551	2015	51,823
C4	368	51	16.025	145,401	2015	51,823
O1	190	32	12.8	56,877	2010	9480
O2	190	32	12.818	56,925	2010	9480
O3	190	32	12.818	56,956	2010	9480
O4	190	32	13	57,293	2010	9480
B1	150	25	10.167	22,430	2015	4860
B2	150	25	10.167	22,344	2019	4860
B3	150	25	10.167	22,396	2016	4860
B4	150	25	10.167	22,396	2015	4860
L1	225	37	12.022	54,732	2014	12,600
L2	225	37	12.022	54,684	2014	12,600
L3	225	37	12.022	54,675	2016	12,600
L4	225	37	12.022	54,645	2017	12,600

4. Experiment

4.1. EEOI evaluation of container sister-ship

The container sister-ship pairs C1, C2, C3, C4 are selected to analyze CO_2 emission, CO_2 index, fuel consumption, EEOI and FEEMI values. The C1, C2, C3, and C4 container ships are chosen as the sister-ship pair due to that the ship design parameters are almost identical. Firstly, we analyze the ship fleet monthly carbon dioxide emission and carbon dioxide index value. In addition, both of EEOI and carbon dioxide emission were further exploited from perspective of ship voyage. We have exploited potential reasons of EEOI variation in two scenarios by considering empirical ship navigation states and ship energy consumptions. The first scenario aims to testify EEOI variation tendency under different ship cargo loading volume states (full/partial load). The second scenario evaluated EEOI variation magnitude by suppressing 5%, 10%, 15%, 20% and 30% fuel consumption in the manner of speed controlling. The energy consumption efficiency for ship fleet is also verified with the FEEMI indicator.

Fig. 1 demonstrated CO_2 emission distribution of container sister-ship under same voyage. Fig. 1(a) showed sailing routes for each container ship, and the white, blue, green, purple curves in the subplot demonstrated the C1, C2, C3 and C4 sailing routes, respectively. Fig. 1 (b) indicated the CO_2 emission distributions in the way of heatmap, and the route color closer to red indicating that the carbon emission level was higher. It can be found that CO_2 emission around the Singapore waterways was obviously larger than other area. After carefully checking the raw AIS data near the Singapore waterways, the average ship



(a) sailing routes for each container sister-ship

(b) carbon emission distribution of container sister-ship

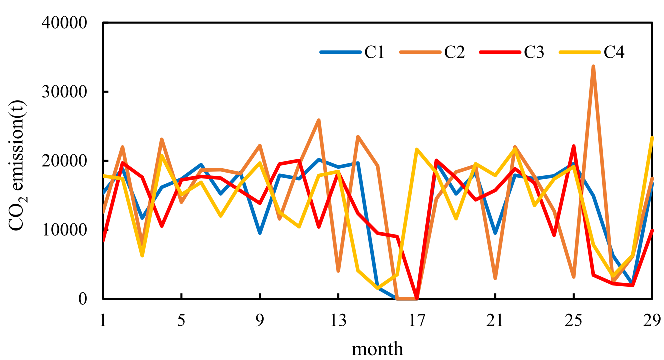
Fig. 1. Sailing routes and CO_2 emission distributions for the container sister-ship.

speed was smaller 0.6 knot and the ship berthing time was larger than the counterparts in other waterways. The main reason was that Singapore port was a transportation harbor of loading/unloading cargos in the world. The carbon emissions for different container sister-ship near the Dickson port varied by zooming out the CO_2 emission heatmap. The CO_2 emissions of C3 and C4 were marked with light yellow dashed lines, which indicated that the carbon emission of the two ships were small. The carbon emission of C1 and C2 was marked with dark and yellow dashed line, which suggested higher emission level compared to those of C3 and C4. In sum, sister-ship sailing with same trajectory may have different fuel consumptions and carbon emissions due to varied meteorological interference and traffic flow conditions.

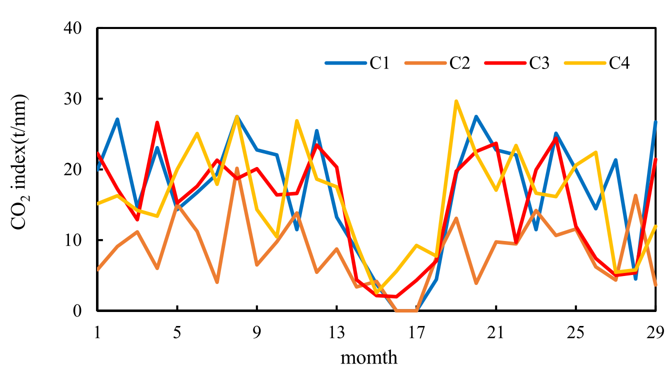
4.1.1. Monthly CO_2 emission and CO_2 index evaluation for container sister-ship

Fig. 2 showed the monthly carbon dioxide emission and carbon dioxide index values of four container sister-ship. Note that the x-axis label ranged from 1 to 12 in Fig. 2 demonstrated January 2021 to December 2021, and the labels marked from 13 to 24 denoted January 2021 to December 2021. The January 2023 to May 2023 was labeled from 25 to 29 in the x-axis label in Fig. 2. The above-mentioned x-axis label mark rule is also applicable in the following sections without further specification. From the perspective of monthly CO_2 emission, it can be found that the monthly CO_2 emission of the four ships was mainly concentrated in the range of 8000 to 24,000 ton. The CO_2 emission of ship C2 arrived at the peak value (i.e., 33,680.81 ton) in February 2023. Moreover, the CO_2 emission of the four ships was close to zero from March 2022 to May 2022.

The monthly CO_2 indicator distributions showed some unexpected variations. The maximum CO_2 index for the four ships was 29.65 ton per nautical mile, which was obtained by the container ship C4 in July 2022. It was also noted that ship carbon emission from March 2022 to May 2022 was quite close to zero, and a possible reason was that ship may utilize low-sulfur oil or cleaner energy during the period. The CO_2 index of ship C2 in March 2022 was close to zero, while the CO_2 emission in the same month was 19,256.8 ton. It can be safely inferred that a large amount of CO_2 emissions was generated by ship auxiliary diesel engines during ship anchoring and berthing states. The CO_2 emission of ship C2 reached the maximum in February 2023, whilst the corresponding CO_2 index was in a low level. Thus, we can infer that the CO_2 index was affected by both of CO_2 emission and ship sailing distance.



(a) monthly CO_2 emission of container sister-ship



(b) monthly CO_2 index of container sister-ship

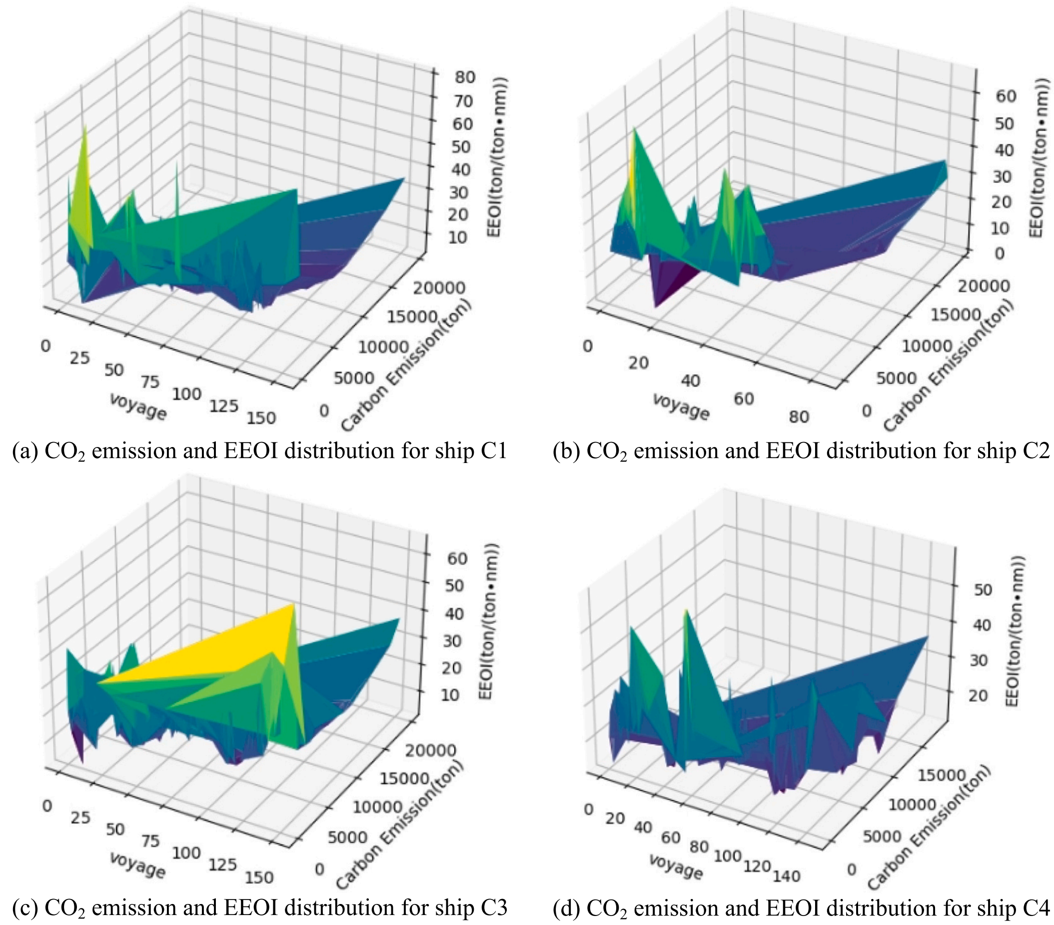
Fig. 2. Monthly CO_2 emission and CO_2 index of container sister-ship.

4.1.2. Voyage-based CO_2 emission and EEOI analysis of container sister-ship

To better analyze ship fuel consumption, we conducted voyage-based CO2 emission and EEOI exploitation for container sister-ship. We evaluated CO_2 emission variation from perspective of voyages together with EEOI. Fig. 3 illustrated the CO_2 emission and EEOI distributions with ship voyage data. Note that data samples marked with yellow indicating that EEOI value is larger than the counterparts with light-green color. The rule is applicable to the data samples labeled with light-green, dark-green and blue. It can be observed that EEOI values for the ship C3 were relatively larger than those of ship C1, C2, C4. Fig. 3 (a) showed that maximum EEOI was 80.27 ton/(ton•nm), which was found at the 16th voyage for ship C1. The corresponding CO_2 emission value reached 409.61 ton. The maximum EEOI value was 66.96 ton/(ton•nm), which was achieved by the ship C2 during her 11th voyage. Note that the CO_2 emission for the ship C2 were 497.74 ton in Fig. 3 (b). The maximum EEOI in Fig. 3(c) was obtained by ship C3 under the 131st voyage, while EEOI and CO_2 emission values were 65.34 ton/(ton•nm) and 6416.73 ton, respectively. Fig. 3(d) demonstrated that the maximum EEOI was obtained during the 53rd voyage, which was 59.32 ton/(ton•nm). It can be found that the EEOI values approximately ranged from 10 ton/(ton•nm) and 40 ton/(ton•nm). Besides, we did not find obvious quantitative relationship between ship CO_2 emission and EEOI.

From perspective of single ship CO_2 emission, the CO_2 emission of ship C2 was obviously larger than the counterparts in the 73rd voyage (which reached 29,824.14 ton). The voyage started from New York port to Singapore port, which was approximately 8300 nms. It is reasonable to generate large CO_2 emission under quite large sailing distance. From the perspective of CO_2 emission of multi-ship, the CO_2 emission of ship C2 was larger than other ships while counterpart of ship C1 was lower than additional ships. The CO_2 emission of four sister-ship was mainly concentrated from 0 to14000 ton, which showed similar sudden increase and decrease variation tendency. From the perspective of single ship EEOI, the EEOI of ship C4 reached the maximum on the 77th voyage (which was 78.67 ton/(ton•nm)). Cargo loading rate denotes the proportion between the loaded-cargo volume and maximum cargo capacity. The ship C4 transferred less cargo in the 77th voyage (i.e., the ship travelled from New York to Singapore), and the load factor was a little bit small. In that manner, the EEOI was larger and fuel consumption per unit of cargo was higher. From the view of multi-ship EEOI, the ship C4 EEOI was obviously larger than that of other ships and the ship C3 EEOI was lower than the counterparts. The average EEOI value of the four sister-ship was between 10 and 40 ton/(ton•nm). The ship C2 EEOI was 0 on the 18th voyage due to that the ship did not load cargos in the voyage.

We found that ship C2 EEOI reached a low level of 34.50 ton/(ton•nm) on the 73rd voyage, and the CO_2 emission reached the highest level (i.e., 29,824.14 ton). The ship C4 EEOI arrived at the maximum value on the 77th voyage which was indeed 78.67 ton/(ton•nm). Meanwhile, the maximum CO_2 emission for the ship C4 was 8773 ton. Overall, we cannot straightforwardly quantify relationship between CO_2 emission and EEOI value. The ship C2 EEOI reached a smaller value (14.54 ton/(ton•nm)) and larger value (49.38 ton/(ton•nm)) on the 24th voyage and the 72nd voyage, respectively. The carbon dioxide emission for the two voyages were quite similar due to that the origin and destination ports are same. In that way, EEOI varied in the two voyages considering that cargo loading data, ship movement data will



(a) CO_2 emission and EEOI distribution for ship C1 (b) CO_2 emission and EEOI distribution for ship C2

(c) CO_2 emission and EEOI distribution for ship C3 (d) CO_2 emission and EEOI distribution for ship C4

Fig. 3. Voyage-based CO_2 emission and EEOI distributions of container sister-ship.

change in real-world. Besides, the on-site sea and weather conditions can also impose unexpected influence on ship EEOI variation.

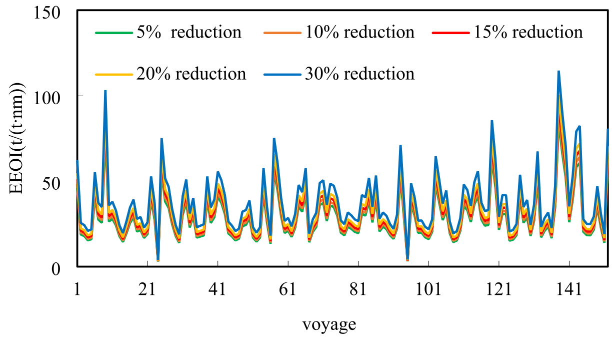
4.1.3. Voyage-based fuel consumption and EEOI analysis of container sister-ship

Fig. 4 showed EEOI variation along with fuel consumption reduction of for the container sister-ship. We have obtained the EEOI values by reducing fuel consumption with 5%, 10%, 15%, 20% and 30% magnitude. We employed the green, orange, red, yellow and blue curves to demonstrate EEOI values with 5%, 10%, 15%, 20% and 30% fuel consumptions. The assumption in the section is that fuel consumption deceleration is implemented in the manner of reducing ship speed. It is noticed that 5% speed reduction will increase additional 5% fuel consumption while cargo loading volume and sailing distance maintains same values. It can be found in Fig. 4(a) that the average EEOI for ship C1 was approximately 50 ton/(ton•nm). Moreover, the EEOI varied with same magnitude as that of the fuel consumption. The average EEOI may decrease 5% while the fuel consumption reduction ratio was 5%. The EEOI variations for the ship C2, C3 and C4 showed similar tendencies as those of ship C1, which can be found the subplots of Fig. 4(b), Fig. 4(c) and Fig. 4(d). From perspective of container sister-ship, there is a positive correlation between EEOI variation and ship consumptions.

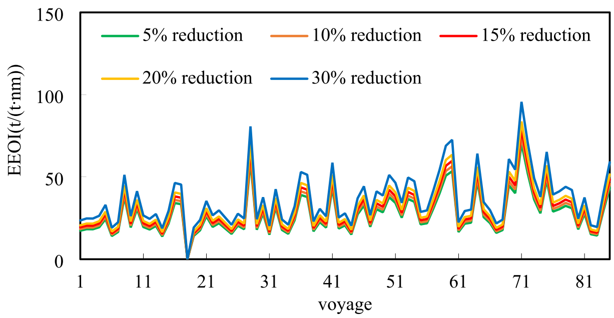
The voyage-based fuel consumption and EEOI variations can be found in Fig. 5. Top two EEOI values were obtained by the Ship C2 from perspective of single ship EEOI variation. The EEOI values were 9464.98 ton and 7453.62 ton, respectively. The peaking EEOI were obtained at the 49th and 73rd voyages, and the origin destination ports for the 49th (73rd) voyage were New York (New York) to Kaohsiung (Singapore). From perspective of sister-ship fuel consumption, ship C2 obviously required more oils than the other three ships while the ship C1 fuel consumption was lower than the counterparts. The fuel consumption for the container sister-ship mainly fell in the range of 0 to 3000 ton, while the ship fuel consumption variation curves were also quite similar.

The maximum EEOI for the ship C1 was 80.27 ton/(ton•nm), which was obtained at the 138th voyage. It can be observed that sea conditions, weather, and ocean currents can impose negative yet unexpected influence on the ship energy efficiency. In another word, ship may consume more fuel under adverse maritime conditions. It was noted that ship C1 sailed from Guangzhou port to Singapore port during the 138th voyage, and weather condition significantly varied under different route segments (such as storm, strong wins, other adverse weather conditions). It is quite challenging to obtain optimal ship maneuvering operations, which included ship speed reduction, ship heading change, etc. Ship may consume more fuel by adjusting ship maneuvering operations.

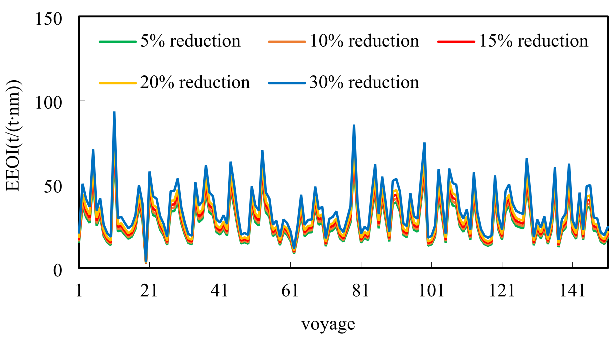
In that way, both of fuel consumption and EEOI showed significant rising tendency. From the point of sister-ship EEOI variation, the ship C4 EEOI was obviously larger than the counterpart of other three ships. Meanwhile, the ship C3 EEOI was smaller than the counterparts as well. The average EEOI value of the sister-ship ranged from 10 ton/(ton•nm) to 40 ton/(ton•nm). It was also noted that ship C4 reached the highest EEOI (i.e., 76.74 ton/(ton•nm)) during the 137th voyage. But, the fuel consumption for the ship C4 was approximately 128 ton, which was also smaller than the counterparts. The ship C1 obtained EEOI value was 66.96 ton/(ton•nm) and the highest fuel consumption was 9464.98 ton at the 71st voyage. In sum, the relationship between fuel consumption and EEOI cannot be easily quantified while the cargo loading volume and sailing distance change under different voyages.



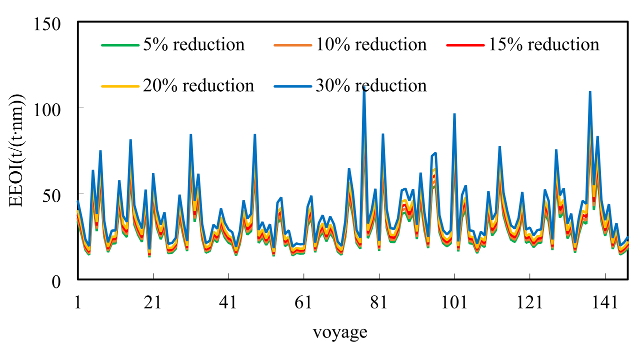
(a) ship C1 EEOI distributions under different fuel consumption reduction magnitudes



(b) ship C2 EEOI distributions under different fuel consumption reduction magnitudes



(c) ship C3 EEOI distributions under different fuel consumption reduction magnitudes

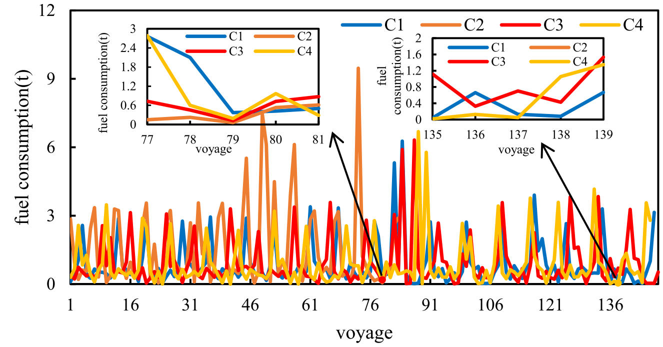


(d) ship C4 EEOI distributions under different fuel consumption reduction magnitudes

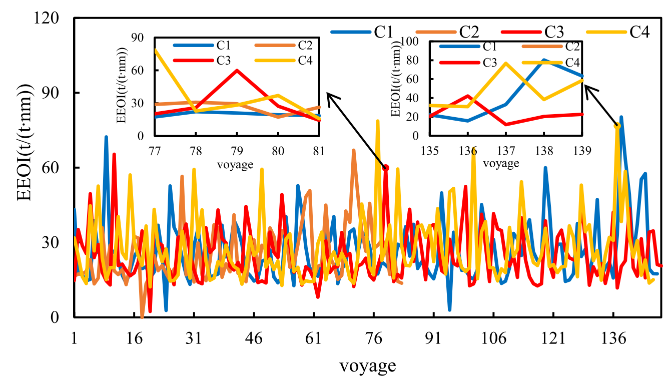
Fig. 4. EEOI variations under different fuel consumption reduction magnitudes for container sister-ship.

4.1.4. *Voyage-based cargo loading volume and EEOI analysis of container sister-ship*

Fig. 6 illustrated EEOI variations under different cargo loading rates for ship C2. The EEOI value obtained by empirical cargo loading data is marked with blue curve (labeled as empirical EEOI), while EEOI showed with orange curve demonstrated that ship was in full-loaded status (labeled as full-loaded EEOI). The figure showed that larger cargo loading volume will lead to lower EEOI. Fig. 6(a) showed that for empirical cargo loading volume ship C1 under the138th voyage was 94,341.79 ton while the corresponding EEOI was 80.27 ton/(ton•nm). The ship full-loaded cargo loading volume was 145,368 ton and her EEOI was 52.10 ton/(ton•nm). The ship C1 reached minimum loading rate which was 63.02%. The difference between empirical EEOI and full-loaded EEOI was 28.18 ton/(ton•nm), which was significantly larger than the counterparts of ship C2, C3, and C4. The ship empirical cargo loading volume was 139,874.28 ton on the13th voyage for ship C3, while the corresponding EEOI was approximately 17.81 ton/(ton•nm). In comparison, the EEOI value under full-loaded cargo volume condition was 17.12 ton/(ton•nm) while the maximum load rate was 96.22%. It can be found that the variation rate of energy efficiency index was different for each voyage, which may be affected by the cargo loading volume. It can be concluded that ship EEOI may vary with larger magnitude while the cargo loading volume is smaller. Experimental results suggested that average EEOI values of C1, C2, C3 and C4 decreased by 15.38%, 20.12%, 14.55% and 19.03%, respectively.



(a) relationships between fuel consumption and voyage

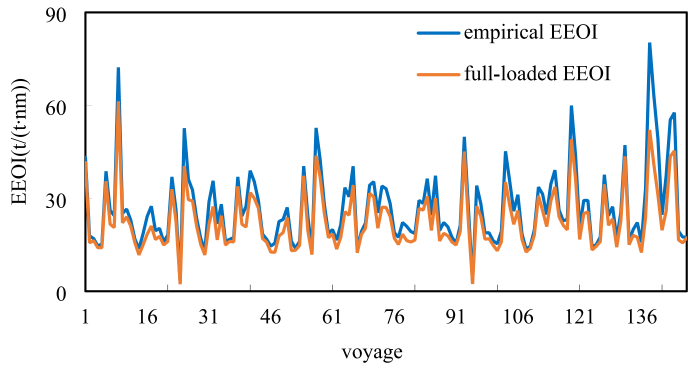


(b) relationships between EEOI and voyage

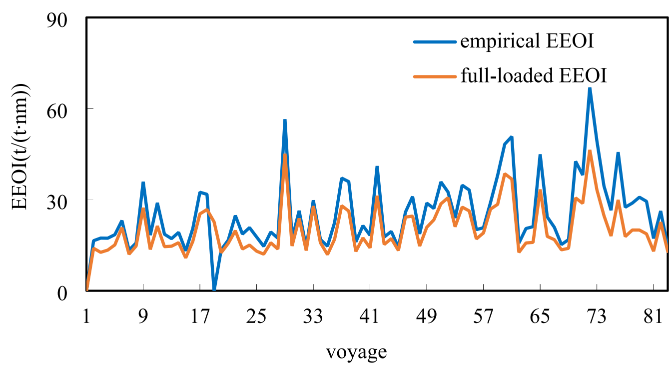
Fig. 5. Voyage-based fuel consumption and EEOI variations.

4.1.5. *FEEMI analysis for container sister-ship*

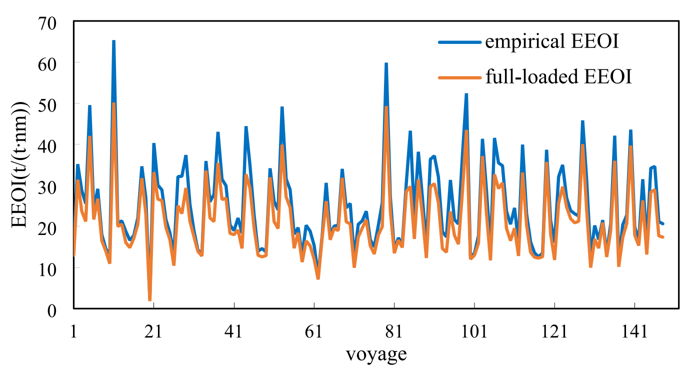
Table 2 showed the average EEOI value of four container sister-ship from 2021 to 2023. The ship C1 EEOI was larger than that of ship C2, while ship C3 EEOI was smaller than the counterpart of ship C4. The EEOI variation showed a decreasing tendency in recent four years. From the perspective of single ship EEOI, the maximum EEOI value of ship C1 in 2021 was 25.67 ton/(ton•nm), which was decreased by 0.08% (i.e., 25.65 ton/(ton•nm) in 2023). Besides, EEOI for ship C2 (C3, C4) in 2023 was 4.68% (3.5%, 0.48%) lower than the counterpart in 2021. It can be safely concluded that ship EEOI showed an obvious decreasing variation tendency from 2021 to 2023, which indicated that ship energy efficiency experienced a climbing tendency in the last three years. It was noted that minimum ship efficiency value was obtained by the ship C1 in 2021. In sum, ship EEOI increased due to long-term anchoring status and large cargo-loading volume. Fig. 7 showed that the FEEMI in 2021, 2022 and 2023 was 25.14 ton/(ton•nm), 24.86 ton/(ton•nm) and 24.59 ton/



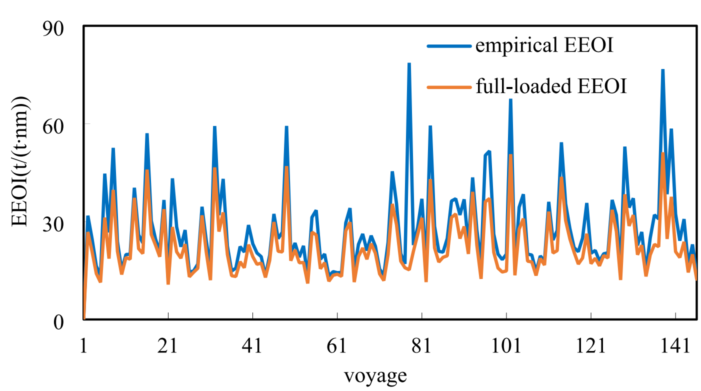
(a) EEOI variations for ship C1 under different cargo loading statuses



(b) EEOI variations for ship C2 under different cargo loading statuses



(c) EEOI variations for ship C3 under different cargo loading statuses



(d) EEOI variations for ship C4 under different cargo loading statuses

Fig. 6. EEOI variations under different cargo loading statuses for contain sister-ship.

Table 2
average EEOI of container sister-ship from 2021 to 2023.

year	C1 EEOI	C2 EEOI	C3 EEOI	C4 EEOI
2021	25.67	24.59	25.47	24.81
2022	25.66	24.41	24.81	24.55
2023	25.65	23.44	24.57	24.69

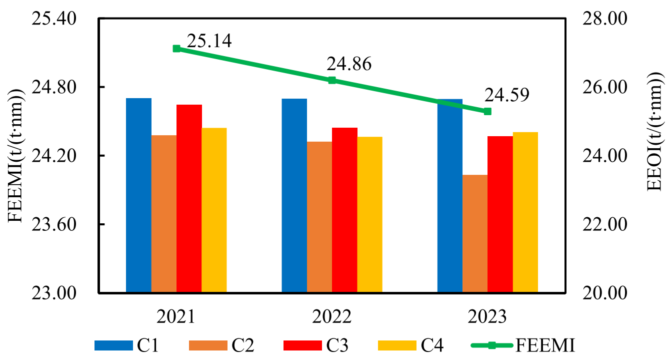


Fig. 7. FEEMI distributions for the container sister-ship.

(ton•nm), respectively. The FEEMI showed approximately 1% decreasing rate from 2021 to 2022, while the FEEMI decreasing rate was similar from 2022 to 2023. Ship energy efficiency can not only be measured with EEOI due to that ship loading volume and line may vary in real-world ship navigation activities. EEOI reduction is supposed to considered varied maritime factors, which included EEOI values, ship maneuvering condition, sea condition, etc. Both of EEOI and FEEMI values can be integrated to evaluate ship and ship fleet energy utilization performance.

4.2. EEOI evaluation for OBL fleet

The OBL fleet refers to a fleet of four sister-ship, which consists of oil tanker, bulk carrier and liquefied natural gas carrier. The OBL fleet for oil tanker (bulk carrier and liquefied natural gas carrier) indicates that the fleet involved with four oil tankers (bulk carrier and liquefied natural gas carrier). We collected AIS data for OBL fleet with time span ranging from 2021 to 2023. We firstly evaluated monthly CO2 emissions for the three ship types to identify peaking and peaking-off carbon emission period. After that, we exploited intrinsic relationship between EEOI and ship fuel consumption in a quantitative manner. We also testified EEOI variations under different cargo loading volumes. The SEEMP is introduced by IMO for the purpose of improving maritime energy consumption efficiency and mitigating greenhouse gas emission [40]. The SEEMP can be used to develop sustainable and resilience shipping industry by taking measurements of optimizing operations, introducing energy-saving facility and equipment, training sophisticated practitioners, etc. The ship fleet energy consumption was analyzed with FEEMI indicator under ship energy efficiency management plan (SEEMP).

4.2.1. Monthly CO_2 emission analysis of OBL fleet

Four sister-ship of oil tanker, bulk carrier and LNG carrier were selected to analyze monthly CO_2 emission. The CO_2 emission values for the four oil tankers (bulk carriers and LNG carriers) in each month were averaged for the purpose of better readability. To ensure data consistency in the study, we did only collect AIS data for the sister-ship from January to May of 2021, 2022 and 2023. The CO_2 emission distributions can be shown in Fig. 8. From perspective of single ship, the CO_2 emission of oil tanker and bulk carrier ranged from 0 to 2000 ton. Note that the CO_2 emission of LNG carrier was significantly larger than those of the oil tanker and bulk carrier, while the minimum and maximum CO_2 emission values were approximately 2000 and 6000 ton, respectively. The CO_2 emission of oil tanker sister-ship in January 2021 was lower than the counterparts. The main reason was that travelling distance for oil tankers may be short while corresponding ship speed was large. Fig. 8 also demonstrated that CO_2 emissions of bulk carriers and liquefied natural gas carriers were quite low (close to 0). After carefully checking the raw AIS data, it was observed that ship anchored in the inland port area for a long time which led to small CO_2 emission. It can be inferred that CO_2 emission was mainly generated by ship auxiliary diesel engine. The CO_2 emission of LNG carried fleet was larger than those of bulk carriers and oil tankers in terms of OBL fleet. It was also noted that CO_2 emissions of the ship three types were quite low in March, which indicated international trade in March was not active.

4.2.2. Voyage-based fuel consumption and EEOI analysis of OBL fleet

We selected 901 voyages from four sister-ship of oil tanker, bulk carrier and LNG carrier to identify ship fleet EEOI variations. Fig. 9 showed EEOI calculation of fuel consumption reduction for all ship. The green solid line in the figure represented the EEOI value calculated with empirical data. We obtained EEOI values by reducing fuel consumption at 5%, 10%, 15%, 20% and 30%, while the cargo loading volume and sailing distance remain constant. It can be found that EEOI value of OBL fleet showed a descending tendency along with fuel consumption decrease. We collected empirical EEOI data samples for the 901 voyages, and the EEOI data under fuel consumption reduction with 5%, 10%, 15%, 20% and 30% magnitudes were also obtained. For instance, ship

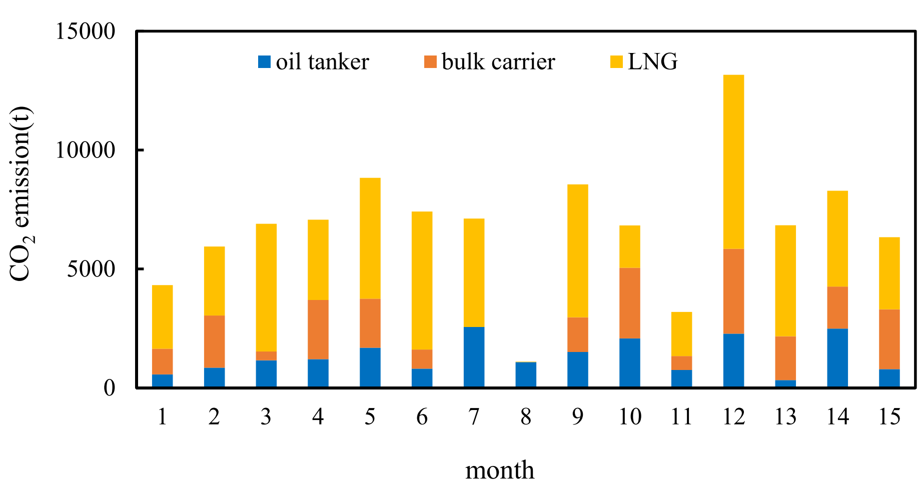


Fig. 8. Monthly CO_2 emission distributions of OBL fleet.

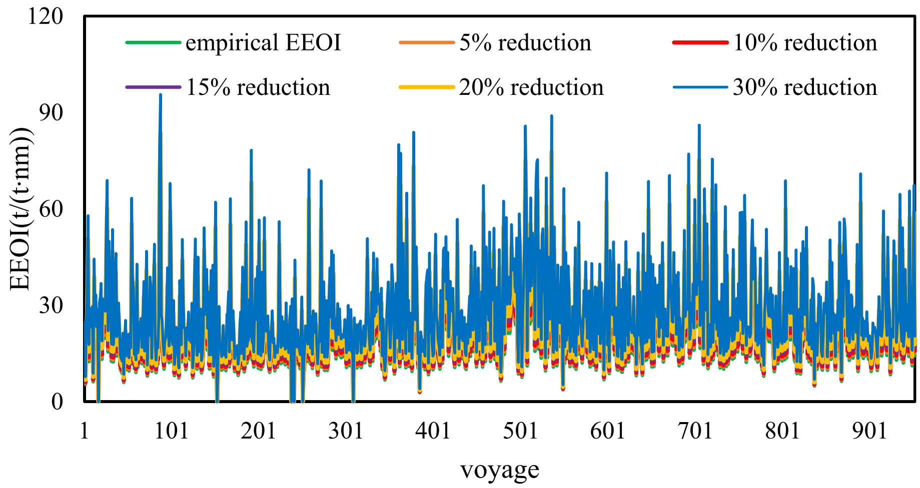


Fig. 9. EEOI variations under different fuel consumption reductions for OBL fleet.

travelling time for the 146th voyage was 302.22 h and ship speed arrived 11.12 nmile/h. The corresponding ship fleet EEOI was 17.24 ton/(ton•nm). We achieved fuel consumption reduction by shortening ship sailing time with same magnitude. In another word, we reduced 5% (10%, 15%, 20% and 30%) fuel consumption by decreasing ship sailing time with 5% (10%, 15%, 20% and 30%). In that way, ship sailing speed can be enlarged with 5% (10%, 15%, 20% and 30%), and the enlarged ship speed was 11.68 nmile/h (12.23 nmile/h, 12.79 nmile/h, 13.34 nmile/h, 13.90 nmile/h and 14.46 nmile/h). The EEOI with speed enlarged with 5% (10%, 15%, 20% and 30%) was updated as 17.24 ton/(ton•nm) (18.15 ton/(ton•nm), 19.16 ton/(ton•nm), 20.28ton/(ton•nm), 21.55ton/(ton•nm) and 24.63ton/(ton•nm)). The above-mentioned analysis indicated that EEOI had a linear positive correlation with fuel energy consumption while the cargo loading volume and sailing distance were constant.

4.2.3. Voyage-based cargo loading volume and EEOI analysis of OBL fleet

Four sister-ship of oil tanker, bulk carrier and LNG carrier were selected, while EEOI values for each type of sister-ship were averaged for the purpose of quantitative analysis. Fig. 10 showed that the EEOI value decreased while the load capacity increased. The larger difference between empirical and full-loaded cargo loading volume resulted in larger EEOI variation magnitude. It was noted that the lowest and largest load rates were 401rd and 307th voyages, respectively. The empirical and full-loaded EEOI values for the 401th voyage were 37.31 ton/(ton•nm) and 14.57 ton/(ton•nm), respectively. The variation ratio was 60.9%, which was obviously larger than other voyages. The empirical (full-loaded) EEOI value was 25.63 ton/(ton•nm) (25.58 ton/(ton•nm)), which suggested that the EEOI was almost same. We also noticed that the empirical EEOI for the 361st and 761st voyages were 0. It can be safely to draw the conclusion that ship cargo loading volume impose negative impact on the EEOI (i.e., large cargo loading volume leading to low EEOI). Moreover, EEOI value in different voyages may be varied, while ship in full-loaded status will result in minimum EEOI. The EEOI will experience very large variation tendency while cargo loading volume is quite small.

4.2.4. FEEMI analysis of OBL fleet

Table 3 showed the average EEOI value of OBL sister-ship from 2021 to 2023. The maximum EEOI for single oil tanker in 2021 was 24.42 ton/

Table 3
Average EEOI of OBL fleet from 2021 to 2023.

year	oil tanker EEOI	bulk carrier EEOI	LNG EEOI
2021	24.42	22.50	18.82
2022	22.41	21.25	17.41
2023	21.01	20.40	16.67

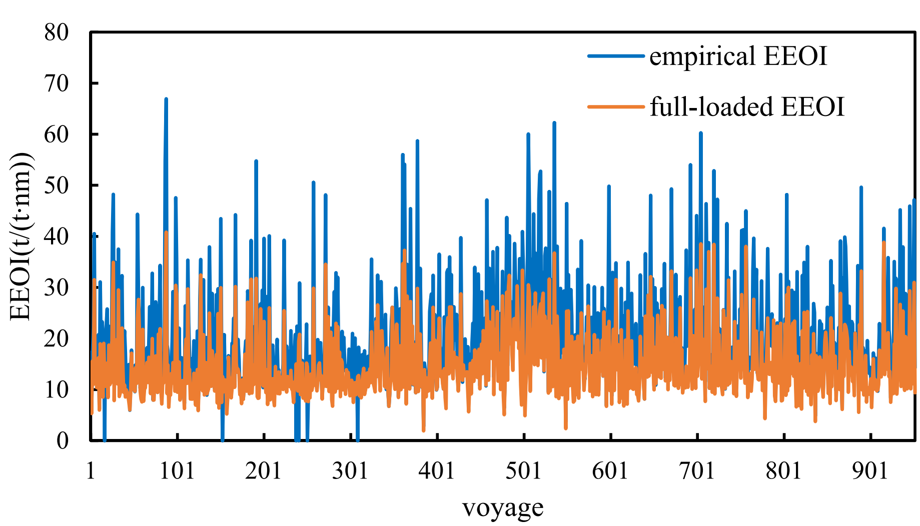


Fig. 10. EEOI variations under different cargo loading statuses for contain sister-ship OBL fleet.

(ton•nm), and the counterpart in 2023 was 21.01 ton/(ton•nm). The maximum EEOI for oil tanker experienced 13.96% decrease. The EEOI for bulk carriers lowered down by 9.3%, while the LNG carriers decreased by 11.42%. From perspective of ship fleet, the overall EEOI values of oil tankers were significantly larger than those of bulk carriers and LNG carriers. The main reasons can be ascribed into the following aspects: (1) oil tanker deadweight was obvious lower than that of the bulk carriers and LNG carrier; (2) oil tanker average sailing distance was relatively short. The energy efficiency for oil tanker was relatively lower than other ship types, and the minimum EEOI value for the oil tanker was obtained in 2021. Fig. 11 showed the FEEMI values of the OBL fleet. The FEEMI for the three ship types showed a downward trend, which showed that the ship EEOI experienced an increasing variation tendency (at least 1%). The shipping company can reduce the ship fleet energy consumption with the implementation of SEEMP plan in recent years. In another word, ship and ship fleet energy consumptions can be fine-tuned and evaluated under different operation measurements with the help of EEOI and FEEMI indicators.

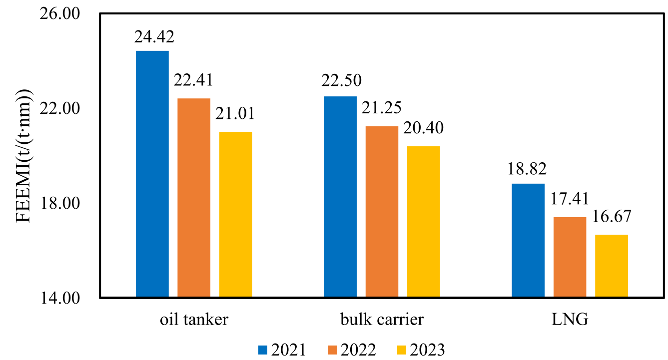


Fig. 11. FEEMI distributions of OBL fleet.

5. Discussion

Previous studies suggest that ship speed may be affected by different factors, which included oil price, cargo volume, freight fare, etc. [44–46]. The ship arrival in schedule and ship speed deceleration are considered as two crucial factors for suppressing ship fuel consumption [47,48]. Maritime traffic environments such as wind speed, wind direction, wave direction can impose severe yet negative impact on ship fuel consumption (i.e., larger overhead) [49]. It was also noted that economic and time costs of ocean-going ships travelling with different routes may significantly varied. In another word, ship travelling routes can be optimized according to the on-site weather and sea conditions [50]. In addition, ship fuel cost mainly depends on oil price, travelling distance, cargo loading volume, weather condition, ship speed, etc. The fuel consumption for ship propulsion system was mainly consumed by ship diesel engine. To reduce ship energy consumption, it is an efficient way to monitoring ship diesel engine performance and take initiatives to optimize fuel consumption [51,52]. Moreover, the regular maintenance of ship main and auxiliary engine can benefit ship fuel consumption [53].

Fuel consumption reduction is considered as an important factor for improving ship energy efficiency (i.e., EEOI). Fuel consumption may be optimized by fine-tuning ship attitude parameters (e.g., draft, ship trim, ship rolling angle). It was found that ship trim angle optimization can significantly reduce fuel consumption every year [54,55]. Moreover, the scuff magnitude for ship propeller and hull can also affect ship fuel consumption, which can further degrade ship diesel engine fuel utilization level. Some studies suggested that such disadvantages of can be mitigated by coating ship engines (such as propeller, hull) [56,57]. It was also found that hull condition can increase water resistance when a ship sails with bad hull condition. Algae and marine microorganisms may attach to ship bottom/side hull, which may obviously increase ship travelling resistance. In that way, it is necessary to clean ship hull periodically to suppress ship fuel consumption.

6. Conclusion

The study aims to accurately quantify the ship carbon emission distributions with support of five indicators (i.e., CO_2 emission, CO_2 index, fuel consumption, EEOI and FEEMI). We have simultaneously analyzed ship energy efficiency with support of CO_2 emission and CO_2 indicators. The EEOI is evaluated together with the CO_2 emission by considering ship kinematic data (e.g., voyage data, AIS data). We quantified EEOI variation in the way of controlling ship cargo loading volume statuses (full/partial load) and speed deceleration. At the same time, FEEMI is calculated to evaluate fleet operation efficiency. Finally, the research findings are applied to the OBL fleet for the purpose of model performance analysis. Experimental results show that EEOI for container ship (oil tanker, bulk carrier, LNG carrier) decreased by 2.19% (13.96%, 9.3%, 11.42%) from 2021 to 2023. The experimental results demonstrated that FEEMI also showed a decease tendency which was quite similar to that of the EEOI.

The following directions deserve our further attentions for the purpose of enhance our study. First, we estimated the five statistical indicators (EEOI, FEEMI, CO_2 emission, etc.) with average ship speed data. It is interesting to identify intrinsic relationship among fuel consumption and ship hull and propeller status. Second, we can also exploit instantaneous speed influence on the ship fuel consumption. Last but not least, we can also introduce cutting-edge artificial intelligence models to predict ship fuel consumption at different time scales.

CRediT authorship contribution statement

Xinqiang Chen: Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Siying Lv:** Writing – original draft, Methodology, Data curation. **Wen-long Shang:** Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Huafeng Wu:** Supervision, Funding acquisition, Formal analysis, Data curation. **Jiangfeng Xian:** Funding acquisition, Data curation, Conceptualization. **Chengcheng Song:** Software.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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