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Analysis of energy efficiency operational indicator of bulk carrier operational data using grey relation method

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According to the International Maritime Organization's regulations, there are factors that affect the energy efficiency of ship, cargo capacity and voyage distance. This document analyzes the information gathered from the detailed trials of the Energy Efficiency Operational Indicator of Taiwan's bulk carrier and uses it to investigate the influence of various characteristics of voyage on the indicator value. The course of bulk carriers is mostly irregular because of chart; it is often difficult to estimate its navigation route in advance. Due to the cargo loading port or others, the course changes temporarily. Therefore, navigation distance is one of the main factors that influence EEOI value of bulk carrier. Other secondary factors are different to some extent, depending on the size of the ship. For Capesize bulk carrier, cargo loading capacity may be influenced by season, but for Panamax size and Handysize bulk carrier, it could be due to oil consumption. Therefore, to use the source (existing bulk carriers) effectively and to meet ships' EEOI standard or the mutual recognition value, the optimum planning for navigation has to be reduced for it to be unexpectedly good.

Key words: Energy efficiency operational indicator, bulk carrier, Grey relation.

INTRODUCTION

Increased CO_2 content in the atmosphere leads to serious greenhouse effect, such as warming, melting glaciers, rising sea levels. These result in huge global economic losses. In fact, the most serious problem is the global warming that leads to melting glaciers. When other greenhouse gases are absorbed by the original glacier, methane is released, which can form an uncontrollable positive feedback effect that will result in the entire human race drowning disaster. This is the real reason for the current worldwide efforts to control CO_2 emissions.

In order to promote energy efficiency of ships and to reduce their greenhouse gas emissions, International Maritime Organization (IMO) proposed ship design / building (Ship Energy Efficiency Design Index, EEDI), operation of the ship (ship operational energy efficiency indicator, EEOI) (Class, 2011), carbon market mechanisms for establishing three key control measures, which the EEOI mainly uses for the operation of ships; they include establishing, implementing and maintaining a ship energy efficiency management plan (Ship Energy Efficiency Management Plan, SEEMP) as well as the publishing of MEPC.1/Circ.683, "ship Energy Efficiency Management Plan for guidelines development". Companies required to develop customized ship and to

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Table 1. Value of carbon factor.

Type of fuel	Reference	Carbon content	*CF* (t-CO2/t-Fuel)
1. Diesel/Gas oil	ISO 8217 Grades DMX through DMC	0.875	3.206000
2. Light fuel oil (LFO)	ISO 8217 Grades RMA through RMD	0.86	3.151040
3. Heavy fuel oil (HFO)	ISO 8217 Grades RME through RMK	0.85	3.114400
4. Liquified petroleum gas (LPG)	Propane	0.819	3.000000
	Butane	0.827	3.030000
5. Liquified natural gas (LNG)		0.75	2.750000

implement the ship Energy Efficiency operational indicator are under the jurisdiction of the SEEMP (Le Treut et al., 2007).

Shipping companies are required to report Energy Efficiency Operating Indicator from 2013. The IMO aims to reduce CO_2 emissions by 50 to 70% in the long term. To this end, it plans to introduce market based measures like Emission Trading System (ETS) and the Green House Gas (GHG) Foundation. Both measures are incentive schemes based on relative valuation, designed to generate high fuel efficiency competition among shipping companies (MEPC.1/Circ.684, 2009; Lars, 2009).

Grey analysis uses a specific concept of information. It defines situations without information as black, and those with perfect information as white. However, neither of these idealized situations ever occurs in real world problems. In fact, situations between these extremes are described as being grey, hazy or fuzzy. Therefore, a grey system is a system in which a part of information is known and the other part is unknown. With this definition, quantity and quality information forms a continuum from a total lack of information to complete information – from black through grey to white. Since there is always uncertainty, one is always somewhere in the middle, somewhere between the extremes, somewhere in the grey area.

ENERGY EFFICIENCY OPERATIONAL INDICATOR

EEOI is meant to enable operators to measure the energy efficiency of existing ships. This indicator is expressed as CO_2 per ton mile, for the efficiency of specific ship, thus enabling comparisons between similar ships. According to the definition of EEOI, the smaller the EEOI value, the higher the energy efficiency of the ship. Ship energy efficiency operational index is reduced by reducing the fuel consumption of ships per nautical mile, improving ship load or using low CO_2 emission factor of fuel.

Ship energy efficiency operational index is generally based on one or more statistical data of voyages obtained. The amount of fuel required for all vessels is moored in the harbor during the voyage; and the ship master and auxiliary machinery, boilers and other consumption statistics must establish an effective ship energy efficiency management system.

The basic expression for the EEOI of a voyage is defined as follows (MEPC 62/24):

$$EEOI = \frac{\sum_j FC_j \times C_{Fj}}{m_{cargo} \times D} \quad (1)$$

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

$$AvergeEEOI = \frac{\sum_i \sum_j (FC_{ij} \times C_{Fj})}{\sum_i (m_{cargo,i} \times D_i)} \quad (2)$$

Where: *j* is the fuel type; *i* is the voyage number; *FCi j* is the mass of consumed fuel *j* at voyage *i*; *CFj* is the fuel mass to CO_2 mass conversion factor for fuel *j*; *m*cargo is cargo carried (tonnes) or work done (number of TEU or passengers) or gross tonnes for passenger ships; and *D* is the distance in nautical miles corresponding to the cargo carried or work done.

CF is a non-dimensional conversion factor between fuel consumption measured in g and CO_2 emission also measured in g based on carbon content. The value of *CF* is presented in Table 1. The unit of EEOI depends on the measurement of cargo carried or work done, e.g., ton CO_2/(ton • nautical miles), ton CO_2/(TEU • nautical miles), ton CO_2/(person • nautical miles), etc. It should be noted that Equation 2 does not give a simple average of EEOI among number of voyage *i*.

GREY RELATION FOR EVALUATION

Grey analysis gives a clear set of statements about system solutions. At one extreme, no solution can be defined for a system without information. At the other

Table 2. Cape size bulk carrier EEOI.

Item	Voyage No.	EEOI
1	33C	4.40247E-06
2	34C	8.78904E-06
3	35B	4.64417E-06
4	36E	3.65096E-06
5	37B	1.30252E-05
6	38B	9.70918E-06
7	39B	6.40747E-06
8	40C	7.11695E-06

Table 3. Panamax size bulk carrier eeoi.

Item	Voyage No.	EEOI
1	1	1.18435E-05
2	2	1.19686E-05
3	3	1.17957E-05
4	4	1.04990E-05
5	5	1.54656E-05
6	6	1.05517E-05
7	7	3.45784E-06

extreme, a system with perfect information has a unique solution. In the middle, grey systems will give a variety of available solutions. Grey analysis does not attempt to find the best solution, but does provide techniques for determining a good solution, an appropriate solution for real world problems (Ma and Wong, 2005).

The basic steps of grey relational analytic method are as follows:

(1) To define reference (namely consulting) sequence, usually, we express the consulting sequence as $X_0(k)$, k =1, …, m (k is the consulting parameter)。

(2) To define comparative sequence, we express it as $X_i(k)$, i =1, …, n (i is the comparative parameter).

(3) To calculate the relational coefficient of the reference and comparative sequence, $\xi_i(k)$ is made the relational coefficient of reference and comparative sequence:

$$\xi_i(k)=\frac{\min_i\min_k|X_0(k)-X_i(k)|+\rho\max_i\max_k|X_0(k)-X_i(k)|}{|X_0(k)-X_i(k)|+\rho\max_i\max_k|X_0(k)-X_i(k)|} \quad (3)$$

The "ρ" is called distinguishing coefficient, usually setting ρ = 0.5, $\rho \in$(0-1).

(4) To calculate relativity (relational grade) γ_i,

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n}\xi_i(k) \quad (4)$$

"γ_i" is the relational grade of sequence X_i and X_0; the bigger its value is, the closer the relativity of sequence X_i and X_0.

(5) To construct the relational order based on relativity, we analyze the factors influencing the main behavior.

CALCULATION AND ANALYSIS OF EEOI

A voyage or period (example, day, data on fuel consumption/cargo carried and distance sailed in a continuous sailing pattern) could be collected from primary data sources selected. It could be the ship's log-book, such as bridge log-book, engine log-book, deck log-book and other official records. Even if the voyages with *m* cargo = 0, it is still necessary to include the fuel used during this voyage.

In this study, the rolling average can be calculated in a suitable time period, for example, a year closest to the end of a voyage for that period or number of voyages. Example includes seven or eight voyages, which are statistically relevant to the initial average period. The Rolling Average EEOI is then calculated for this period or number of voyages using Equation (2).

In the navigation data of Capesize, Panamax and Handys in Annex, the EEOI value is calculated with Equation (1) for single voyage; the result is shown in Tables 2 to 4. The rolling average EEOI is calculated for the number of voyages using Equation (2). The calculated result is shown in Table 5. According to the calculated result, the rolling averages can reflect actual EEOI of this ship. From the calculated result of the different types of ships seen in Table 5, the bigger cargo capacity has EEOI tons CO2/(tons • nautical miles), which is relatively small (4.40E-06). On the contrary, its trend curve is bigger (1.60E-05) as shown in Figure 1. This phenomenon is in line with the International Maritime Organization estimation in advance.

Equation (5) is used to analyze the navigation data in Annex (Annex Tables A to C) and EEOI value as shown in Tables 2 to 4. The result of grey relation grade will be calculated for every size of bulk carrier as shown in Tables 6 to 8.

For Cape-size bulk carrier, the influencing factors of energy efficiency operational indicator are navigation distance, cargo load capacity, heavy fuel/ oil consumption and marine diesel consumption; the grey relation grade of influencing factors are respectively navigation distance (0.7238), cargo load capacity (0.6754), heavy fuel/oil consumption (0.5637) and

Table 4. Handy size bulk carrier EEOI.

Item	Voyage No.	EEOI
1	284	1.37722E-05
2	285	2.11913E-05
3	286	2.84139E-05
4	287	1.92881E-05
5	288	8.59477E-06
6	289	9.50746E-06
7	290	1.10196E-05

Table 5. Rolling average EEOI.

Ship size	EEOI
Cape size	4.40E-06
Panamax size	8.44E-06
Handy size	1.60E-05

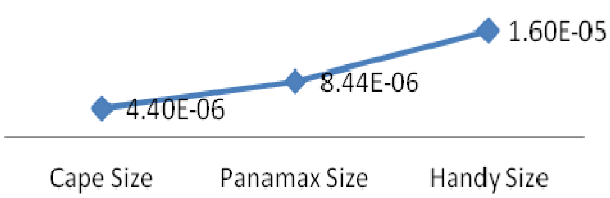

Figure 1. Rolling average EEOI of bulk carrier.

marine diesel/ oil consumption (0.5389). From the above result, the influencing factor associated with EEOI, the relation grade of voyage distance factor is maximum, cargo load capacity factor is second, heavy fuel/oil consumption factor is third and marine diesel/oil consumption factor is relatively little.

For Panamax bulk carrier, the grey relation grade of influencing factors are respectively navigation distance (0.8723), heavy fuel/oil consumption (0.6208), cargo load capacity (0.4854) and marine diesel/oil consumption (0.4578). From the above result, the influencing factor associated with EEOI, the relation grade of voyage distance factor is maximum, heavy fuel/ oil consumption factor is second, cargo load capacity factor is third and marine diesel/ oil consumption factor is relatively little.

For Handy-size bulk carrier, the grey relation grade of influencing factors are respectively navigation distance (0.8306), marine diesel/oil consumption (0.6371), cargo load capacity (0.5966) and heavy fuel/oil consumption (0.5686). From the above result, the influencing factors associated with EEOI, the relation grade of voyage distance factor are maximum, marine diesel oil consumption factor is second, cargo load capacity factor is third and heavy fuel oil consumption factor is relatively little.

The course of bulk carriers is mostly irregular because of chart. It is often difficult to estimate its navigation route in advance. Due to the cargo loading port or others, it changes its course temporarily. So, navigation distance is one of the main factors influencing EEOI value of bulk carrier. Other secondary factors are different to some extent, depending on the size of the ship. Like the cape size bulk carrier, it could be cargo loading capacity; for Panamax and Handy-size bulk carriers, it could be the factor of oil consumption. Therefore, to use the source (existing bulk carriers) effectively and to meet ships' EEOI standard or the mutual recognition value, the optimum planning for navigation has to be reduced for it to be unexpectedly good.

According to the above analysis, the voyage distance is the most influential factor affecting the EEOI of bulk carrier; therefore, the optimum navigation plan improves the effective method of the EEOI under voyage for bulk carrier.

Conclusion

In ships' operations, the first thing to consider is safety, since accidents resulting in casualties and environmental pollution are irreversible; second is to ensure that the contract of carriage is the reason for the existence of the ships; third is energy conservation, in order to protect the future of the earth and mankind. In energy conservation and emission reduction, energy efficiency is the most important. It reduces operating costs and greenhouse gas emissions radically.

The EEOI enables continuous monitoring of individual ship in operation and thereby the results of any changes made to the ship or its operation. The effect of retrofitting a new and more efficient propeller would be reflected in the EEOI value and the emissions reduction can be quantified. The effect of emissions by changes in operations, introduction of just on time planning or a sophisticated weather routing system will also be shown in the EEOI value.

From the EEOI equation and grey relation theory, from the computed result, navigation distance is the most influential on the EEOI for bulk carrier. So, the effective and optimum voyage planning is to improve the operation indicator for measuring ships' energy efficiency at each voyage or over a certain period of time. Certainly, besides navigation distance or voyage course factor, other factors are also noteworthy, for example cargo loading capacity or fuel consumption.

Table 6. Cape size bulk carrier Grey relation analysis.

Voyage	33	34	35	36	37	38	39	40	GRA grade
HFO(X_1)	0.3492	0.6341	0.3656	0.6819	0.7941	0.4662	0.4889	0.5149	0.5637
LFO(X_2)	1.0000	0.6858	0.5905	0.6820	0.3333	0.5149	0.4158	0.5497	0.5389
Cargo(X_3)	0.6034	0.5400	0.6824	0.4131	0.5308	0.8136	0.9263	0.8217	0.6754
Dist (X_4)	0.8895	0.9898	0.9740	0.4131	0.3610	0.5706	0.8204	0.9378	0.7238

Table 7. Panamax size bulk carrier Grey relation analysis.

Voyage	1	2	3	4	5	6	7	GRA grade
HFO(X_1)	0.7230	0.7471	0.3602	0.9127	0.4271	0.7538	0.4220	0.6208
LFO(X_2)	0.3598	0.4154	0.4710	0.6441	0.4938	0.4872	0.3333	0.4578
Cargo(X_3)	0.4507	0.4022	0.4688	0.3771	0.3428	0.3719	0.9845	0.4854
Dist (X_4)	0.8220	0.8733	0.7744	0.8370	0.8171	0.9825	1.0000	0.8723

Table 8. Handy size bulk carrier Grey relation analysis.

Voyage	284	285	286	287	288	289	290	GRA Grade
HFO(X_1)	0.7408	0.6857	0.3289	0.7958	0.4295	0.4550	0.7167	0.5686
LFO(X_2)	0.7786	0.4307	0.3880	0.4051	0.9192	0.7808	0.8987	0.6371
Cargo(X_3)	0.5125	0.3706	0.3333	0.4200	0.6776	0.7808	0.9975	0.5966
Dist (X_4)	0.9375	0.8413	0.7048	0.6956	1.0000	0.8090	0.9330	0.8306

Conflict of interests

The author has not declared any conflict of interests.

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Annex navigation data for bulk carrier

Annex Table A. Cape size Bulk Carrier (Sincere Navigation Corporation).

Item	Voyage No.	HFO+LSHFO	MDO+LSMGO	Cargoes (MT)	Distance (NM)
1	33A	597.4	0.10	0	3,842
2	33B	2507.00	0.20	162,953	13,420
3	33C	67.90	0.20	162,953	354
		3172.30	0.50	162,953	17,616
4	34A	826.50	0.10	0	4,622
5	34B	929.40	0.30	135,200	4,619
6	34C	51.60	0.30	75,603	215
		1807.50	0.70	210,803	9,456
7	35A	838.70	0.40	0	5,759
8	35B	2164.60	0.40	171,702	11,733
		3003.30	0.80	171,702	17,492
9	36A	118.20	0.20	0	699
10	36B	621.60	0.10	0	3,802
11	36C	2374.90	0.20	164,159	12,342
12	36D	329.78	0.20	164,159	1,726
13	36E	19.60	0.20	70,681	129
		3464.08	0.90	234,840	18,698
14	37A	276.97	25.60	0	1,234
15	37B	231.60	8.90	125,452	1,037
		508.57	34.50	125,452	2,271
16	38A	198.73	9.20	0	1,134
17	38B	220.90	8.60	134,690	1,043
		419.63	17.80	134,690	2,177
18	39A	828.28	14.90	0	4,914
19	39B	1265.60	0.30	170,070	6,029
		2093.88	15.20	170,070	10,943
20	40A	402.20	0.00	0	2,026
21	40B	664.80	0.20	0	4,075
22	40C	1266.30	0.30	169,003	6,043

Annex Table B. Panamamax size bulk carrier (U-Ming Marine Transport Corporation).

Item	Voyage No.	HFO	LFO	Cargoes (MT)	Distance (NM)
1	1	1145.400	3.035	59,240	5098
2	2	1201.639	3.575	67,114	4673
3	3	509.085	4.101	56,722	2389
4	4	1385.553	5.526	75,235	5485
5	5	672.170	4.805	75,200	1813
6	6	1112.215	4.065	76,236	4322
7	7	1118.866	14.875	75,758	13481

Annex Table C. Handy size bulk carrier (Taiwan Navigation Corporation).

Item	Voyage No.	HFO	LFO	Cargoes (MT)	Distance (NM)
1	284	504.03	118.21	34650	4070
2	285	452.19	72.63	36000	2146
3	286	254.25	73.98	36000	1002
4	287	710.49	65.72	33500	3745
5	288	465.73	64.21	30563	6292
6	289	514.17	62.28	36500	5180
7	290	394.31	84	28500	4753