A Route Selection and Speed Optimization Method for Maritime Traffic with Emission Control Areas and Weather Conditions

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Abstract

Since Emission Control Areas (ECA) were established, IMO requested the use of low sulphur oil to achieve the goal of reducing sulfur emissions. However the cost of the low sulfur oil is much higher than the high Sulphur, thus the effective fuel saving solutions are eagerly required. A novel strategy for marine route selection and speed optimization is proposed by considering the limitations of the weather conditions and ECA. Firstly, an optimization model for ship route and speed selection is developed by combining the ship schedule with the weather conditions and ECA. Then, the proposed method is applied in three real voyages in which three similar vessels sailed through the same ECA in the west of the USA with the different voyage schedules and weather conditions. Finally, the experimental results showed that the proposed method is able to exactly estimate the fuel consumption and give an appropriate route advice under various voyage schedule and weather conditions, which significantly resolves the route selection and speed optimization problem in the ECA.

Keywords

Speed Optimization; Route Selection; Weather Routing; Ship Intelligence; Ship Energy Efficiency; Emission Control Areas.

1. Introduction

Obviously, shipping industry has played a significant role in the transportation industry. Compared with the land transportation, it has the advantages of larger volume, more mature development and lower cost. Therefore, over 95% of international trade is completed by shipping [1]. However, according to the data from IMO, the annual emission of SO_X has reached 6.34 million tons, accounting for about 4% of the world's total emissions. The national oceanic and atmospheric administration (NOAA) research has proved that shipping has become one of the most serious atmospheric pollution sources. Nearly 30% of nitrogen oxides gas was produced by navigation. Based on the will of Eco-friendly, the emission control area (ECA) has been established. Four Emission Control Areas (ECA) have been defined in MARPOL. They are the Baltic Sea, the North Sea and English Channel, and the North American and the US Caribbean coasts, as shown in Figure 1 Within the ECA, the sulphur content of emission should be lower than 1.5% m/m. In order to fulfill the requirements, there are several ways to be chosen. Such as installing a scrubber or using liquefied natural gas (LNG) as fuel [2,3]. Considering about the conveniences, practicability and economical efficiency, using low-sulfur fuel called MGO (Marine gas oil) instead of HFO (heavy fuel oil) seems like a better method than changing the ship's structure to meet the requirements of ECA. However, due to the high price of MGO and the existence of ECA, traditional sailing ways might cost more than before. Concerning about minimizing the cost, improving the sailing strategy is necessary [4,5].

On the aspect of sailing strategy, Perakis et al. had put forward the speed range of ship in full load and ballast in 1987 [6]. Wei et al. changed the speed optimization into a mathematical problem which could find the extreme value of the objective function [7,8,9,10]. Kim et al. considered about the fuel price, time cost and the change of carbon tax to optimize speed [11].

Because the total cost is closely related to the fuel consumption, Ronen et al. proposed that the bunker fuel consumption of the main engines is directly related to the third power of the speed [12]. Reducing the cruising speed by 20% will reduce the bunker consumption by 50% [13]. Fagerholt et al. developed an optimization model to be applied by ship operators for determining optimal routing and sailing speeds for a ship along a given sequence of ports, where some of the sailing is within ECA [14].

Figure 1 Four Emission Control Areas

In general, some of the researchers only put emphasis on mathematic models. However, the models are complicated and hard to be solved. Some of them only take speed optimization into consideration but ignore the weather factors and ECA. In fact, a comprehensive consideration in models of the factors that impact on the fuel consumption such as sea conditions, weather factors and ECA would be important to obtaining a precise result. A reasonable sailing strategy of the voyage is meaningful to avoiding the bad sea conditions, ships and cargo security threat and reducing the energy consumption as well as the environmental pollution.

The implementation of the ECA has a significant influence on making sailing plan, because the traditional route selection is mainly based on the meteorological conditions and energy efficiency but ignores the ECA factors. It might lead to a result that the selected route is short but covers a long distance in ECA [15]. If we didn't take ECA into account, the high price of MGO would increase the overall cost of navigation. How to reduce fuel consumption and achieve the goal of energy saving under the premise of safe is the focus in this paper.

We would conduct a research about the speed optimization and route selection of three vessels by the way of the same ECA in the west coast of the United States under different conditions. Meeting the required expected arrival time (Required ETA), how to save fuel consumption by adjusting the route and speed is the main focus in this paper [16].

2. Route Selection and Speed Optimization Method

The optimization model of fuel consumption is as follows:

$$\min\{\sum_{i\in r_j, r_j\in R} F_{ls}(v_i)\cdot t_i\cdot P_{ECA}\cdot\beta_i + F_{hs}(v_i)\cdot t_i\cdot P_{NECA}\cdot(1-\beta_i)\} \tag{1}$$

$$\text{s.t.}\ \ V_{\min}\le v_i\le V_{\max},\ \sum t_i\le T_{\max}, \tag{2}$$

$$\beta_i\in\{1,0\}, \tag{3}$$

$$t_i = D_i/(v_i-\Delta v_i) \tag{4}$$

where $F_{ls}(v_i)$ is the MGO fuel consumption rate under the actual speed v_i, and t_i is the sailing time in leg i under the speed of v_i, P_{ECA} is the price of MGO, and $F_{hs}(v_i)$ is the HFO fuel consumption rate under the actual speed v_i, P_{NECA} is the price of HFO, β_i is 0 or 1, it depends on whether the ship is inside ECA: 1 for inside ECA while 0 for outside ECA. D_i is the distance of the leg i, Δv_i is the speed loss, and r_j is route j, R is all the routes that can be chosen.

$\Delta v_i = \phi (W_f, W_d, W_h, C_{dir}, C_{spd}, ...S_l, S_h)$ where W_f is the wind speed, W_d is the wind direction, W_h is the wave height, and C_{dir} is the flow direction, C_{spd} is flow velocity, S_l is the state of ship loading(full load or in ballast), S_h is the ship heading.

And Δv_i can be expressed as:

$$\Delta v_i = C_\beta C_u C_{form} v_i / 100\%$$

Where,

C_β: Direction reduction coefficient, dependent on the weather direction angle such as W_f, W_d, W_h and the Beaufort Number (BN).

C_u: Speed reduction coefficient, dependent on the ship's block coefficient. The loading condition S_l and the Froude Number (FN).

C_{form}: Ship form coefficient.

We can obtain the the specific parameters of C_β, C_u *and* C_{form} by some reference to calculate Δv_i [17,18].

The baseline of ship fuel consumption and speed is obtained by analyzing the ship's history voyage data. The relationship of F_{ls} and v_i can be determined as:

$$F_{ls}(v_i) = 0.0658v_i^3 - 2.4816_i^2 + 40.226v_i - 206.51 \quad (5)$$

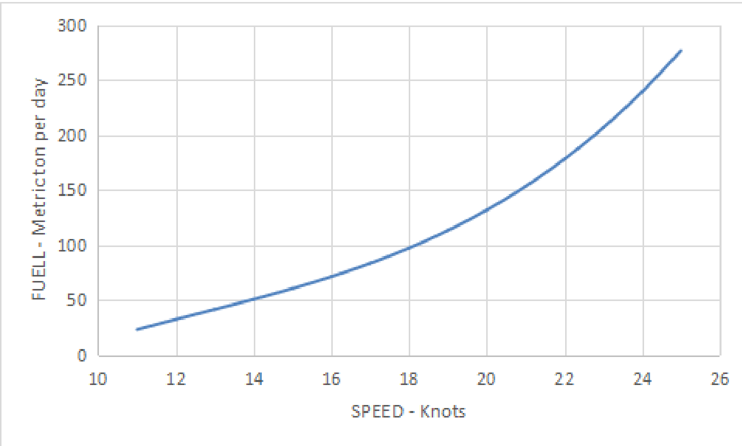

Figure 2 The baseline of the ships between the speed and the fuel consumption

3. Experiments and Results

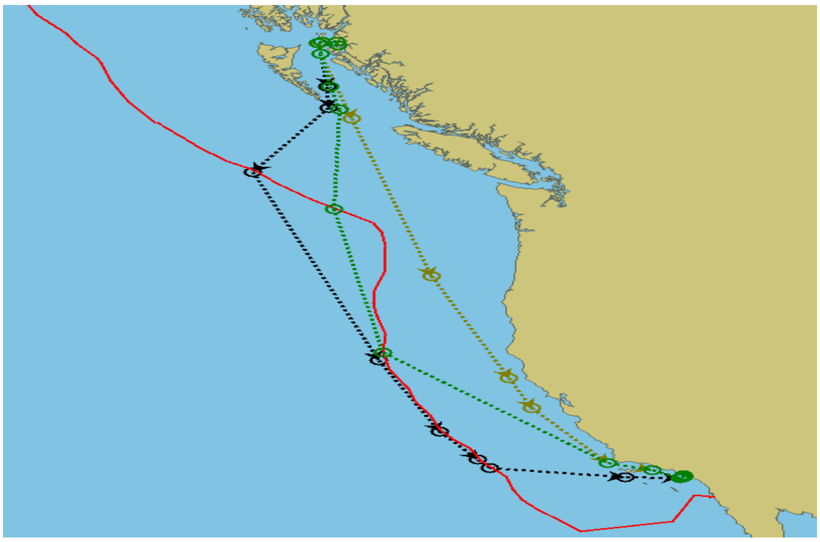

Figure 3 ECA and Route Selection

Since the models had been established,we can apply them into instance to select appropriate route and optimize speed. The above sections had mentioned that we would conduct a research of three vessels of various routes in the ECA located in the west coast of USA. The voyage is from Prince Rupert to Long Beach Port. There are 3 routes to be chosen (Figure 3):

The route which is totally inside ECA (right one in the picture).

The route which covers both inside and outside ECA (middle one).

The route which covers the area outside ECA as much as possible (left one).

We would analyze three cases under different conditions, in order to illustrate how to choose the route and optimize speed in various situations.

3.1 Case 1：Vessel A

In case 1, the vessel has insufficient MGO balance on board and the weather condition is good. The total distance of the voyage is 1667 sea miles, with 949.2 sea miles outside ECA and 718.8 sea miles inside ECA, and the sailing time is 84.8 hours. Due to the Green Flag Plan in California, there is a speed zone close to the coast of Long Beach port. In the speed zone, the speed should be less than 12 knots. Based on the method we have mentioned before, we can forecast the fuel consumption in Table 1. Therefore we recommend this vessel to navigate outside of ECA as much as possible.

Table 1 Fuel consumption for vessel A with different speed

		Outside ECA	IN ECA (Speed Zone)	IN ECA (Outside The Speed Zone)	
Distance(nm)		949.2	52.8	666	
Speed(kts)		21.5	12	18.5	19
Time(h)		44.15	4.4	36	35.05
MGO(mt)	Wx:-0.5kts	/	7.88	185.25	191.62
	Wx:-1	/	8.8	196.8	201.55
Total MGO(mt)	Wx:-0.5kts	/	/	193.13	199.50
	Wx:-1	/	/	205.6	210.35
Arr. Allowance ROB (mt)	Wx:-0.5kts	/	/	121.57	115.20
	Wx:-1	/	/	109.1	104.35

As we can see from table 1, we can reduce the fuel consumption by adjusting speed. Sailing at lower speed inside ECA would cut down the fuel consumption so as the cost.

3.2 Case 2: Vessel B

In case 2, we supposed that Vessel B reaches the destination port via three different routes from Jun 19th to Jun 23rd . The three options are:

OPT1: Fully inside ECA

OPT2: Inside ECA to ECA exit 4713N/13029W and entrance 4018N/12845W

OPT3: Similar to the Vessel A

The fuel price of MGO is 340 dollar, while HFO is 170 dollar, and the total sailing time should be in 89 hours. Comparing those sailing strategies under the condition of sufficient sailing time, good weather and sea state, we aimed at finding the economical one. The evaluation cost is shown in the table 2.

It seems like the option 2 is the best choice with the lowest cost. Without the heavy weather, the optimal sailing way is sailing at 17.23 knots inside ECA and 19 knots outside ECA. However, weather factors played an important role in the fuel consumption by affecting the speed, so it would also affect the choice of route. For example, there is a risk of encountering rough weather on the 22nd, as we can see in the weather overview (Figure 4). A thermal low is positioned over the California and is expected to affect the route and sign sea up about six meters. The weather factors are shown in Table 3.

Table 2 Fuel consumption for vessel B with different speed and routes

PRR TO LGB	Inside ECA				Outside ECA				Cost (USD)
	Speed (kts)	Distance (nm)	Time (h)	MGO (mt)	Speed (kts)	Distance (nm)	Time (h)	HFO (mt)	
OPT1	16.85	1449	86	387.00	0	0	0	0	131580
OPT2	17.57	1100	62.61	286.97	18	421	23.39	113.05	116787
OPT2	17.50	1100	62.86	282.86	18.50	421	23.14	119.09	116417
OPT2	17.23	1100	63.84	275.32	19.00	421	22.16	120.95	114167
OPT2	17.08	1100	63.41	277.77	19.50	421	21.59	125.49	115775
OPT2	16.94	1100	64.95	270.63	20.00	421	21.05	131.56	114378
OPT3	18.00	719	39.94	205.55	20.61	949	46.06	347.34	128933

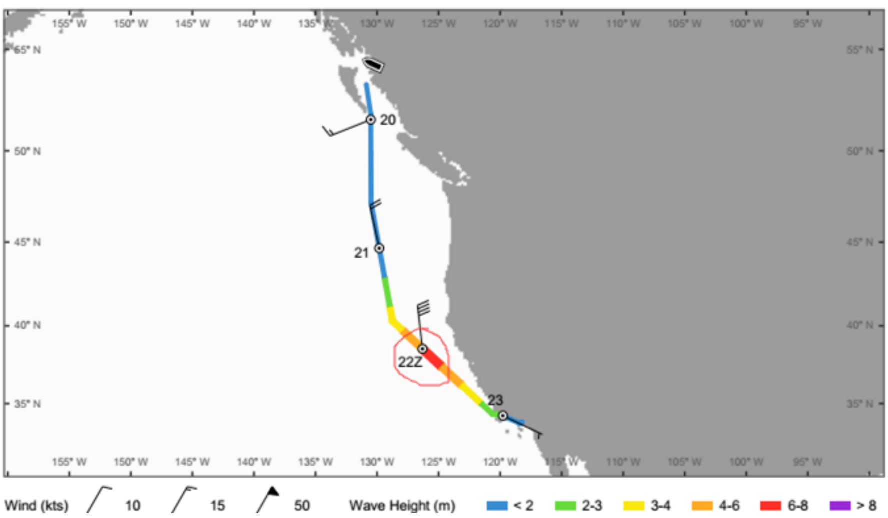

Figure 4 Weather overview of option 2

Table 3 Weather Factors and sea state of option 2

Date/Time	Ship speed (kts)	Current (fac-kts)	Weather (fac-kts)	Wind (deg)	Wind (kts)	Sign wave (m)	Wind wave (m)	Swell (m)	Current(kts)
20/18UTC	17.5	-0.1	-0.4	223	10	1.4	0.5	1.2	0.1
21/00UTC	17.3	-0.2	-0.6	248	15	1.5	0.7	1.3	0.2
21/06UTC	17.3	-0.2	-0.7	259	16	1.7	0.8	1.6	0.2
21/12UTC	17.5	-0.1	-0.4	277	14	1.7	0.5	1.6	0.1
21/16UTC	17.8	-0.1	-0.2	319	14	1.7	0.6	1.6	0.2
22/00UTC	17.7	-0.1	-0.2	348	18	1.9	1.1	1.6	0.2
22/12UTC	17.5	-0.1	-0.5	005	32	3.8	3.2	2.0	0.1
23/00UTC	16.3	-0.1	-1.7	354	40	6.1	5.6	2.2	0.1
23/12UTC	17.8	-0.1	-0.3	188	4	3.5	0.1	3.5	0.1

Due to the heavy weather in 22nd ,if we insisted sailing by the original route, the cost would increase a lot as well as the the risk. Therefore, we would like to take another route closer to the coast which is expected to decrease the sign sea with about one meter on the 22nd. We could reduce the influence of bad weather by re-planning route. The new route is shown in Figure 5, and the weather factors of this route is presented in Table 4.

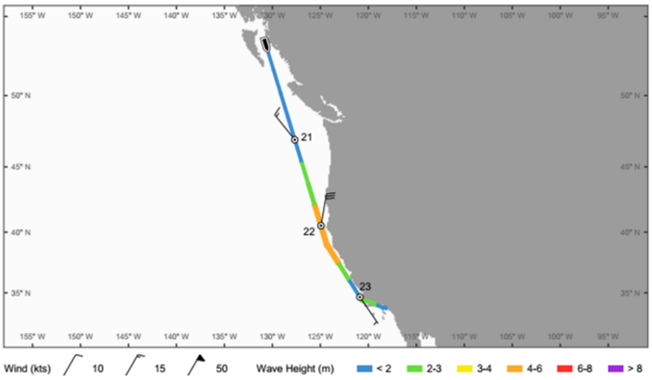

Figure 5 Weather overview of the new route

Table 4 Weather Factors and sea state of new route

Date/Time	Ship speed (kts)	Current (fac-kts)	Weather (fac-kts)	Wind (deg)	Wind (kts)	Sign wave (m)	Wind wave (m)	Swell (m)	Current(kts)
20/18UTC	16.1	-0.3	-0.7	223	17	1.5	0.9	1.1	0.3
21/00UTC	16.5	-0.2	-0.4	256	15	1.7	0.8	1.5	0.2
21/06UTC	16.9	0.0	-0.2	296	15	1.8	0.8	1.6	0.3
21/12UTC	16.9	0.0	-0.2	321	18	1.8	1.1	1.5	0.2
21/16UTC	17.0	0.1	-0.2	360	20	2.1	1.4	1.5	0.2
22/00UTC	16.8	0.0	-0.3	008	29	2.9	2.5	1.4	0.2
22/12UTC	16.7	0.1	-0.5	010	32	4.6	3.0	3.0	0.1
23/00UTC	16.8	0.0	-0.3	185	8	2.7	0.1	2.7	0.1
23/12UTC	16.7	-0.2	-0.2	146	4	2.2	0.0	2.2	0.2

So the route was changed due to the bad sea state and heavy weather since Jun.20th, the rest voyage is 1225 sea miles and the time is limited in 74 hours. We compared those two route and put forward a new strategy to replace the present optimal one. The fuel consumption was calculated in Table 5.

Table 5 Fuel consumption for vessel B of new route

	Outside ECA	IN ECA (Speed Zone)	IN ECA (Outside The Speed Zone)
Distance(nm)	/	1172	53
Speed(kts)	/	16.84	12
Time(h)	/	69.6	4.4
MGO(mt)	/	308.85	8.80
Cost(USD)	/	10500	2992
Total cost(USD)	108001		

Different with the previous route, we recommend vessels to navigate fully inside ECA and closer to the coast, with the speed of 16.84 knots inside the speed zone of ECA based on the combined consideration of weather condition, safety, ship's schedule, MGO balance and cost. Although the route is fully inside ECA,it would cost less than the route passed through the area of bad weather.

3.3 Case 3. Vessel C

In case 3, for Vessel C, the total sailing time is 79.3 hours, and the fuel price of MGO is 480 dollar instead of 340 dollar while the HFO is 357 dollar instead of 170 dollar. Based on sailing time not enough, sufficient MGO balance, and higher price of fuel, the optimal route would be fully inside ECA. It should be noted that even the time is not enough, sailing at a very high speed for more than 22 knots outside ECA is not safe. The three options are the same as case 2.

Table 6 Fuel consumption for vessel C with different routes

PRR TO LGB	INSIDE ECA				OUTSIDE ECA				Total Dis. (nm)	Cost (USD)
	Speed (kts)	Dis. (nm)	Time (h)	MGO (mt)	Speed (kts)	Dis. (nm)	Time (h)	HFO (mt)		
OPT1	18.34	1449	79	396.65	0	0	0	0	1449	190390
OPT2	18.98	1080	56.89	310.55	19	420	22.11	120.66	1500	192139
OPT2	18.80	1080	57.46	306.46	19.5	420	21.54	125.19	1500	191795
OPT2	18.62	1080	58.00	302.08	20	420	21.00	131.25	1500	191856
OPT2	18.31	1080	59.00	296.23	21	420	20.00	144.17	1500	193657
OPT3	21.27	719	33.82	243.71	21	949	45.19	325.75	1668	233273

As shown in the Table,6 if the fuel price rises, the previous optimal sailing way in Case 2 would be totally changed. Under the condition of time limits and higher fuel price, the best route would be sailing totally inside ECA,and the speed should be 18.34 knots.

Generally speaking, when the vessel has insufficient MGO balance and the weather condition is good, the optimal route usually is the one fully outside ECA. Under the condition of sufficient sailing time, good weather and sea state, it’s better to sail inside ECA to ECA exit 4713N/13029W and entrance 4018N/12845W. However, we should avoid the heavy weather by changing the route at any time. At last, when the sailing time is not enough, and the price of fuel is quite expensive, we recommend sailing inside ECA from beginning to the end. When the route is determined, on the premise of arriving on time, reducing the speed inside ECA and then adjusting the speed outside ECA would cut down the total cost.

4. Conclusion

Due to the existence of ECA, the route selection and navigation speed are affected. Aimed at finding out the most economical sailing strategy, this paper puts forward the improved fuel consumption calculation model, which takes both the ECA and weather factors into consideration. The model can calculate the fuel consumption of different routes passing through ECA, and provides a better navigation strategy based on it. Validated by testing result, comparing with the traditional typical constant speed navigation mode, the optimized way of sailing would reduce the cost, avoid the risks, such as stormy waves, and achieve the purpose of cost reduction and sulphur emission decrease.

However, in the actual voyage of ships, there are more detailed rules formulated by various countries inside ECA. Such as port time should be less than two hours in some EU countries, and the mandatory use of shore power in some ECA of California etc. Those rules may also affect the sailing strategies. This paper is not comprehensive enough, and further research will be carried out in the future.

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