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Speed Optimization Strategies based on Sulfur Emissions Limitation and Fuel Cost

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Abstract

In order to meet the stricter requirements of the International Maritime Organization (IMO) on global sulfur limitation and promote the cost reduction and green development of shipping enterprises, this paper attempts to establish a comprehensive optimization model for container ship operations. The model is based on the current environmental protection regulations, taking the Trans-Pacific container ship "CMA CGM Argentina" as an example to combine the whole voyage of container ship's sailing and berthing organically. The model considers the relationship between fuel consumption and speed optimization, estimates the total fuel consumption cost and sulfur dioxide emissions of the ship, and determines the conditions that make the speed optimization strategy significantly effective.

Keywords

Emission Control Area (ECA); Fuel Cost; Sulfur Emission; Speed Optimization Strategy.

1. Introduction

Maritime transportation plays an important role in international commodity trade, and 90% of international cargo turnover is realized by maritime transportation. However, with the operation of ships, the problem of air pollution has attracted more and more attention [1] [2]. Due to the sulfur content of ship fuel, shipping is one of the important sources of sulfur dioxide in the world, which will aggravate the harm of acid rain and soil erosion. Therefore, the call for green shipping is getting higher and higher.

In recent years, the International Maritime Organization (IMO) has been promoting the process of "Reducing sulfur emissions". According to the requirements of IMO rules, the global sulfur limit order will be further strengthened from March 1, 2020. International ships are not allowed to carry non-conforming fuel (self-used fuel with sulfur content more than 0.50% m/M), unless the ship is equipped with a qualified exhaust gas purification system ("desulfurization tower"), which can effectively curb the use of high sulfur fuel from the source. In addition to the global upper limit of no more than 0.5% m/m, some countries and regions have formulated and implemented more stringent emissions control area standards. For example, in North America (designated areas along the coasts of the United States and Canada), the Baltic Sea and the Caribbean, the sulfur limit of 0.10% m/M has been adopted.

The further strengthening of the sulfur limit is bound to increase the fuel cost of shipping enterprises. Within the limit of 0.10% m/M, the pressure of fuel costs will be more significant. Therefore, shipping companies face two pressing issues: firstly, how does ECAs affect container shipping operations? Secondly, how can enterprises comply with the new environmental regulations at the least cost?

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2. Literature review

At present, many scholars generally believe that speed optimization is an effective measure to reduce fuel costs and sulfur emissions. Alderton[3]distinguished the speeds under different standards, and discussed the sensitivity of these speeds to the voyage, freight and fuel costs. Based on an actual case of an international liner company, Wang et al. [4] found that the speed of container ship has a significant impact on the total cost, and verified the cubic relationship between speed and fuel consumption through regression analysis. Psaraftis et al. [5] found that ship speed is a key factor in determining the sustainability of the marine economy and the marine environment, especially when the shipping market is depressed; "slow shipping" is a common and effective way to reduce costs and emissions. Wang et al. [6] studied ship speed decision-making models under different forms of carbon tax, as well as the resulting costs and total emissions. Doudnikoff et al. [7] found that when the speed of the ship in ECAs decreases, the total fuel cost will decrease. Fagerholt et al. [8] studied two kinds of speed optimization problems of ships entering and leaving the emissions control area, optimized the ship speed inside and outside the ECAs, and found the best entry point to optimize the route. These studies demonstrate the effect of speed optimization strategies on cost reduction from different perspectives. However, for a particular ship, it remains to be studied that under what circumstances the speed optimization strategy can significantly reduce the fuel cost.

Some scholars explore the different application environments of speed optimization strategies. Lindstad et al. [9] evaluated the cost of emissions reduction measures, and considered that the best emissions reduction scheme depends on the ship engine power, fuel price and fuel consumption in ECAs. Cao et al. [10] assumed that the voyage time of container ships remained unchanged, and studied the relationship between speed, fuel cost and sulfur dioxide emissions, and believed that proper slowing down in ECA can reduce costs. Dong et al. [11] comprehensively considered the dual environmental effects of emissions control zone and deceleration zone, and found that the combination of ECAs and deceleration strategy can significantly reduce the sulfur emissions of container ships and reduce the loss of profits compared with only establishing ECAs. However, few scholars further discuss the influencing conditions that make the speed optimization strategy more effective.

In order to make up for the shortcomings of current research, we propose a more urgent and realistic speed optimization problem of container liner transportation network on the basis of existing academic achievements. On the premise that the service frequency of ships remains unchanged, we try to minimize the cost of ship fuel and comply with environmental regulations. First of all, we construct a dual model of container ship costs and emissions. The model completely covers the entire voyage of container ship navigation, port activities and non-productive stays. Secondly, a case study of the container ship "CMA CGM Argentina" from East Asia (Pusan, South Korea) to North America (Savannah) is carried out. Finally, the sensitivity analysis of the ship's navigation distance within 0.10%m/m ECAs and the price difference between the two fuels is carried out, and we discuss the conditions that make the speed optimization strategy significantly effective. This will help shipping enterprises to use speed optimization strategies scientifically and adapt to the changes of environmental regulations dynamically.

3. Methodology

The first goal of the model is to minimize the total cost, as service revenue is assumed to be fixed. There are many costs involved in the process of container transportation. According to relevant literature, the choice of speed has little effect on some of the almost fixed costs, including maintenance costs, inventory costs and opportunity costs [12]. Therefore, this paper only considers fuel costs, because fuel costs can be affected by speed change, and fuel cost accounts for a large proportion of total operating costs. The second goal of the model is to make SO_2 emissions of ships comply with the new regulations of IMO and the original regulations of ECAs. This article mainly studies the changes in fuel costs and sulfur dioxide emissions brought about by fuel conversion and speed optimization.

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3.1 Basic assumptions

Considering the influence of ECA on the operation of container ships, in order to facilitate the establishment and solution of the model, the following basic assumptions are made in this paper

First, the main engine of the ship uses MGO (sulfur content is 0.1%) when sailing in the emissions control area, and switches to VLSFO (very low sulfur fuel refers to the fuel with sulfur content less than or equal to 0.5%, assuming sulfur content is 0.5%) when sailing outside the limit area. The main engine does not consume fuel during berthing.

Second, the auxiliary engine of the ship uses MGO during navigation and berthing.

Third, the ship operating cycle of shipping enterprises remains unchanged. The ship keeps constant speed during the voyage. The power factor at the port is not considered.

3.2 Model

3.2.1 Fuel cost

According to the relevant literature, the fuel consumption of the main engine is proportional to the cubic power of the speed [3,9,10], and has nothing to do with the type of fuel used. The fuel consumption of container ship's main engine sailing inside and outside ECA can be defined as:

$$F_{\mathrm{E}}^{\mathrm{M}} = F_{\mathrm{O}}^{\mathrm{M}} \left(\frac{V_{\mathrm{ECA}}}{V_{\mathrm{d}}}\right)^3 \frac{D_{\mathrm{ECA}}}{V_{\mathrm{ECA}}} [\alpha + (1-\alpha)L] \tag{1}$$

$$F_{\mathrm{N}}^{\mathrm{M}} = F_{\mathrm{O}}^{\mathrm{M}} \left(\frac{V_{\mathrm{NECA}}}{V_{\mathrm{d}}}\right)^3 \frac{D - D_{\mathrm{ECA}}}{V_{\mathrm{NECA}}} [\alpha + (1-\alpha)L] \tag{2}$$

In formulas 1 and 2, $F_{\mathrm{E}}^{\mathrm{M}}$ and $F_{\mathrm{N}}^{\mathrm{M}}$ signify main engine fuel consumption inside and outside ECAs per trip, respectively. $F_{\mathrm{O}}^{\mathrm{M}}$ is the rated constant of main engine fuel consumption(ton/h). V_{d} is the designed speed of container ship, V_{ECA} and V_{NECA} are the sailing speeds (nautical miles per hour) inside and outside ECAs. D is the single-trip navigation distance (nautical miles) of the container ship. D_{ECA} denotes distance of the ship sailing in ECAs. α is the influence coefficient of ship carrying capacity on fuel consumption of main engine. L is the payload rate of the container ship.

According to Cariou [13], we can get the following formula:

$$F_{\mathrm{O}}^{\mathrm{M}} = SFOM^{\mathrm{M}} EL^{\mathrm{M}} PS^{\mathrm{M}} \frac{1}{10^6} \tag{3}$$

In formula 3, $SFOM^{\mathrm{M}}$ represents the fuel consumption rate of the main engine; EL^{M} denotes the load coefficient of the main engine. PS^{M} represents the power of the main engine (kw).

Therefore, the main engine fuel cost function of a ship can be expressed as:

$$C^{\mathrm{M}} = F_{\mathrm{E}}^{\mathrm{M}} P_{\mathrm{MGO}} + F_{\mathrm{N}}^{\mathrm{M}} P_{\mathrm{VLSFO}} \tag{4}$$

In formula 4, P_{MGO} and P_{VLSFO} denote the price of MGO and VLSFO ($/ton), respectively.

Similarly, the total fuel cost function of marine auxiliary engine can be expressed as:

$$C^{A} = \left(F_{\mathrm{E}}^{\mathrm{A}} + F_{\mathrm{N}}^{\mathrm{A}} + F_{\mathrm{S}}^{\mathrm{A}}\right) P_{\mathrm{MGO}} \tag{5}$$

$$F_{\mathrm{E}}^{\mathrm{A}} = F_{O}^{A} \frac{D_{\mathrm{ECA}}}{V_{\mathrm{ECA}}},\ F_{\mathrm{N}}^{\mathrm{A}} = F_{\mathrm{O}}^{\mathrm{A}} \frac{D - D_{\mathrm{ECA}}}{V_{\mathrm{NECA}}},\ F_{\mathrm{S}}^{\mathrm{A}} = F_{\mathrm{O}}^{\mathrm{A}} S$$

In formula 5, $F_{\mathrm{E}}^{\mathrm{A}}$ and $F_{\mathrm{N}}^{\mathrm{A}}$ are the fuel consumption of auxiliary engine inside and outside ECA, F_{S}^{A} is the fuel consumption of auxiliary engine during berthing, S is the total port dwell time per trip (h).

$$F_{\mathrm{O}}^{\mathrm{A}} = SFOC^{\mathrm{A}} EL^{\mathrm{A}} PS^{\mathrm{A}} \frac{1}{10^6} \tag{6}$$

In formula 6, $SFOC^{\mathrm{A}}$ represents the fuel consumption rate of the auxiliary engine. EL^{A} denotes the load coefficient of auxiliary engine. PS^{A} represents the power of auxiliary engine (kw).

3.2.2 Sulfur dioxide emissions from the ship

When the ship sails outside the ECA, its main engine will switch to using VLSFO. In other cases, the main engine and auxiliary engine use MGO. According to the assumption of this paper, the ship has

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met the requirements of the existing environmental regulations through fuel conversion. Therefore, the SO_2 emissions from the ship can be expressed as follows:

$$E_{SO_2} = F_N^M \eta_{VLSFO} + \left(F_E^M + F_E^A + F_N^A + F_S^A\right)\eta_{MGO} \quad (7)$$

In formula 7, η_{MGO} denotes the SO_2 emissions coefficients of MGO, η_{VLSFO} denotes the SO_2 emissions coefficients of VLSFO.

3.3 Relationship between variables

This paper assumes that the operation frequency of the ship remains unchanged, that is, the one-way time T remains unchanged, so the relationship between the sailing time and the sailing speed inside and outside the ECA is as follows:

$$T = \frac{D_{ECA}}{V_{ECA}} + \frac{D - D_{ECA}}{V_{NECA}} + S \quad (8)$$

$$V_{NECA} = \frac{V_{ECA}(D - D_{ECA})}{V_{ECA}(T - S) - D_{ECA}} \quad (9)$$

When the speed optimization of the ship is not considered, the ship always sails at a constant speed, the following results are obtained:

$$V_{ECA} = V_{NECA} = \frac{D}{T - S} \quad (10)$$

3.4 Objective function

According to the above model and parameter relationship, the function of minimizing fuel cost for shipping enterprises is as follows:

$$\text{Min } C = \left\{F_O^M \left(\frac{V_{ECA}}{V_d}\right)^3 \frac{D_{ECA}}{V_{ECA}}[\alpha + (1-\alpha)L] + F_O^A \frac{D_{ECA}}{V_{ECA}} + F_O^A \frac{D - D_{ECA}}{V_{NECA}} + F_O^A S\right\} P_{MGO} + F_O^M \left(\frac{V_{NECA}}{V_d}\right)^3 \frac{D - D_{ECA}}{V_{NECA}}[\alpha + (1-\alpha)L] P_{VLSFO} \quad (11)$$

If the first derivative of the minimum cost function is set to zero, the optimal speed of the ship inside and outside of ECA can be obtained.

$$\frac{\partial C}{V_{ECA}} = 2F_O^M V_d^{-3} D_{ECA}[\alpha + (1-\alpha)L] P_{MGO} V_{ECA} - F_O^M V_d^{-3} (D - D_{ECA})^3 [\alpha + (1-\alpha)L] P_{VLSFO} \frac{2D_{ECA} V_{ECA}}{[(T-S)V_{ECA} - D_{ECA}]^3} \quad (12)$$

Where, $D > D_{ECA} > 0, V_{ECA}, V_{NECA} > 0, L \in (0,1), P_{MGO} > P_{VLSFO} > 0, T > S, \alpha \in (0,1)$。

4. Study

4.1 Case description

This paper selects the container ship on the East Asia to North America route as the research object. On the one hand, the route crosses emissions control areas for a long distance, which is greatly affected by ECA rules; On the other hand, there are a large number of ships on this route, so the route is representative.

Table 1. Voyage information of CMA CGM Argentina

Number	Port Calls	Arrival (UTC)	Departure (UTC)	Time in Port(h)	Sailing distance (nm)
1	Pusan	2020/12/07 22:07	2020/12/09 03:56	30	-
2	Panama City	2020/12/26 22:00	2020/12/27 17:00	19	8126.2
3	New York	2021/01/01 07:00	2021/01/04 08:00	73	2041.1
4	Norfolk	2021/01/05 07:00	2021/01/06 15:00	32	308.8
5	Savannah	2021/01/08 07:00	2021/01/10 07:00	48	534.2
Source: official website of CHINA COSCO SHIPPING GROUP					

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"CMA CGM Argentina" is a Panamax container ship, engaged in transportation from the East Asia to North America. The ship passes through ports such as Pusan, Panama City, New York, Norfolk and Savannah, including the US Caribbean emissions control area. According to port distance network (www.portdistance), the total voyage (D) from Pusan Port to Savannah port is 11010.3 nautical miles and the sailing distance inside ECA(D_{ECA}) is 1568.1 nautical miles. The total voyage time is 33.4 days, i.e. 801.6 hours, of which the dwell time is 202 hours. The recent voyage information of "CMA CGM Argentina" is shown in Table 1.

4.2 Parameter values

According to China's national standards, the influence coefficient α of container ship carrying capacity on main engine fuel consumption is 0.90 ~ 0.98. The "CMA CGM Argentina" was officially been named and put into use in 2019, so the hull is in good condition. In this paper, we set α=0.9 [14].

On December 25, 2020, the report of the container transportation market system of Shanghai Shipping Exchange showed that the container turnover was blocked due to the severe international COVID-19 epidemic, and a large number of containers were stranded at the docks, which made the port congestion increasingly serious and the shortage of containers never eased. The average utilization rate of ships in East Asia-North America route is close to full load level. Therefore, this paper assumes that the actual load is 90% of the rated load, that is, the payload L is 90%.

According to the conclusion of Wen et al. [15], the sulfur emissions coefficients of HFO (3.5%) and MGO (0.1%) are 70 kg/t and 2 kg/t, respectively. In this paper, we set η_{VLSFO}=10kg/t and η_{MGO}=2kg/t. The summary of ship parameter values are summarized in Table 2.

Table 2. Parameter values set in the case study

Parameter	Value
D	11010.3(nm)
T	801.6(h)
S	202(h)
D_{ECA}	1568.1(nm)
α	0.9
V_d	24(nm/h)
L	90%
PS^{M}	46360KW
$SFOC^{M}$	206g/(kW•h)
EL^{M}	0.8
PS^{A}	3840KW
$SFOC^{A}$	221g/(kW•h)
EL^{A}	0.5
P_{VLSFO}	411 $/t
P_{MGO}	442.5$/t
η_{VLSFO}	10kg/t
η_{MGO}	2kg/t
Source: Clarkson Database ; Port Distance; official website of CHINA COSCO SHIPPING GROUP	

4.3 Result analysis

This paper assumes that the operating cycle of the ship remains unchanged, so if the CMA CGM-Argentina slows down in one area, it will accelerate in other areas to make up for the time gap. In order to minimize the fuel cost, we set the first-order optimal cost function to zero, and the optimal cost speed is obtained V_{ECA}=17.98(nm/h). At this time, the speed outside ECA is 18.43 (nm/h), the total fuel cost is 99.28 million $.The total SO_2 emissions is 18.77 t. The results of the study at different speeds are shown in Table 3.

As shown in Table 3, when the company does not consider ship speed optimization, the container ship always sails at a constant speed during the whole voyage, with $V_{ECA} = V_{NECA} = 18.36\text{nm/h}$. This paper takes this speed as a baseline for analysis.

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Table 3. Fuel cost and SO_2 emissions at different speeds

Number	V_{ECA}/(nm/h)	V_{NECA}/(nm/h)	C/(million $)	E_{SO_2}/t
5	16	18.82	99.85	19.42
Variations	-12.87%	2.51%	0.56%	4.00%
No speed optimization	18.36	18.36	99.30	18.67
1	17.98	18.43	99.28	18.77
Variations	-2.07%	0.38%	-0.02%	0.53%
2	20	18.12	99.80	18.322
Variations	8.93%	-1.30%	0.50%	-1.88%
3	22	17.87	101.08	18.00
Variations	19.83%	-2.67%	1.79%	-3.59%
4	24	17.67	103.06	17.79
Variations	30.72%	-3.76%	3.79%	-4.71%

First of all, the V_{ECA} that minimizes the fuel cost is 17.98 nm/h. At this time, the fuel cost is reduced by 0.02% compared to the ship always sailing at a constant speed, which is almost negligible. But the SO_2 emissions has increased by 0.53%, which is about 0.1 t. Berechman et al. [16] regarded the treatment cost and economic loss of air pollutants as environmental costs, and estimated the comprehensive environmental cost of ships in Kaohsiung Port by bottom-up method, where SO_2 was 13,960 USD/t. It can be concluded that, although the total fuel cost decreases slightly due to the speed reduction of the ship in ECA, the speed optimization strategy has no significant effect on reducing the fuel cost at this time, and the cost of saving this cost is that the environmental cost of each voyage of the container ship increases greatly.

Secondly, the change of ship speed has more influence on SO_2 emissions than on fuel costs. On the basis of a constant speed, as the ship speed changes in ECAs, the variation range of SO_2 emissions is always significantly larger than that of fuel costs. The faster the ship speeds in the ECA, the lower the total SO_2 emissions.

4.4 Sensitivity analysis

The fuel costs and SO_2 emissions of container ships are not only affected by ship speed, but also influenced by many other factors. Firstly, this article uses the real-time fuel price on December 15, 2020. The price difference between VLSFO and MGO is not significant ($31.5/t), but fuel prices are changing. Secondly, the distance of navigation in ECAs will also have a direct impact on fuel costs and SO_2 emissions. In order to get further management suggestions, we used Mathematica 12 to draw three-dimensional parameter graph, and made sensitivity analysis on fuel price difference and navigation distance in ECAs.

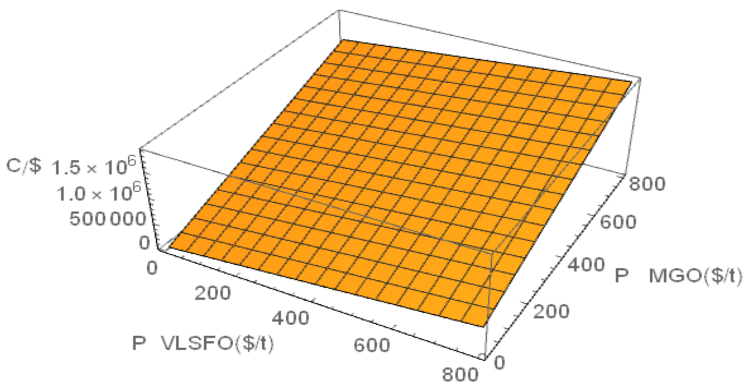

Figure 1. Fuel cost of the ship under different fuel prices

4.4.1 Sensitivity analysis of fuel price difference

Generally speaking, the price of MGO is higher than that of VLSFO, but there are occasional exceptions. For example, on December 25, 2020, the price of VLSFO in Zhou Shan Port was 419

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USD /t, which was higher than the price of MGO 405 USD/t (www.portdistance.com). In this case, shipping companies may adjust the use of fuel, but this rare situation is not considered in this paper. We assume that the price of VLSFO is always higher than that of MGO. The sensitivity analysis of fuel price is shown in Figure 1.

When the price of MGO fuel remains unchanged, the higher the price of VLSFO fuel, the greater the cost of ship fuel C. the higher the price of MGO fuel, the higher the cost of ship fuel, and the greater the price difference between the two fuels. At the same time, it can be observed that since the distance of ships sailing in ECAs is much shorter than that in non-ECA areas, the fuel cost is more sensitive to the fluctuation of the price of VLSFO.

4.4.2 Sensitivity analysis of navigation distance in ECA

As countries pay more and more attention to marine green development, it can be predicted that ECA area will expand in the future. To study the influence of ECA scope expansion on fuel costs and SO_2 emissions, we assume that other conditions remain unchanged, and only ECA scope is expanded.

We set $\frac{D_{\mathrm{ECA}}}{D} = R$, R is the ratio of ECAs to single-trip sailing distance. In this paper, R=0.14.

$$0 < V_{\mathrm{NECA}} = \frac{V_{\mathrm{ECA}}(D - D_{\mathrm{ECA}})}{V_{\mathrm{ECA}}(T - S) - D_{\mathrm{ECA}}} < 24, \therefore 7.6 < V_{\mathrm{ECA}} < 24$$

To analyze the dynamic influence of ECA distance and speed change on fuel costs and SO_2 emissions, we set $V_{\mathrm{ECA}} \in (8,24), R \in (0.14, 0.14 * 120\%)$. The corresponding sensitivity analysis results are shown in Figure 2 and Figure 3.

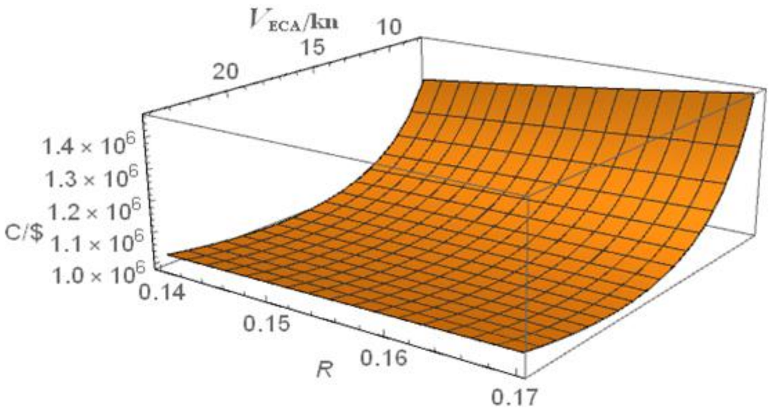

Figure 2. Fuel cost of the ship under different V_{ECA} and R

When the speed of the ship remains unchanged in the ECA, the longer the sailing distance of container ships in ECA, the higher the fuel cost, and there is a positive correlation between them. The lower the speed of a ship in ECA, the greater the impact of R on fuel costs .In addition, the best running speed in this case is 17.98 knots, which is significantly higher than the best running speed of 10.638 knots in Dong et al. [11] When the cost optimization speed V_{ECA} is 17.98 knots, the increase of R will not bring a significant increase in the fuel cost of the container ship .This means that even if the scope of ECA is expanded by 20% in the future, it will have little impact on the fuel cost of ships at the optimal speed.

There is a negative correlation between SO_2 emissions and ship speed, and SO_2 emissions are more sensitive to ship speed. Under the same R, the smaller the ship speed in ECAs, the more the total SO_2 emissions, which is very significant. At the optimal cost speed, with the expansion of ECA scope, SO_2 emissions show a downward trend. In other words, while considering optimizing the internal and external speed of ECA, the expansion of ECA will result in a slight decrease in the total SO_2 emissions. Therefore, in order to control the total SO_2 emissions, the dual effects of ECA rules and speed optimization should be considered at the same time. Simply reducing the speed or simply expanding the scope of ECA cannot effectively reduce SO_2 emissions.

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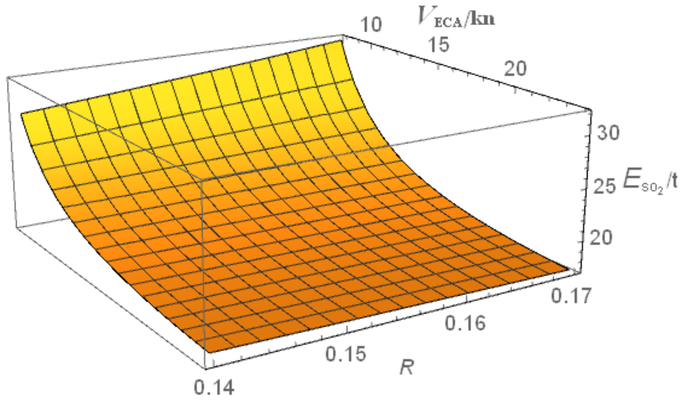

Figure 3. SO_2 emissions of the ship under different V_{ECA} and R

4.5 Significance range of speed optimization strategy

Fuel costs and SO_2 emissions are very sensitive to the changes of fuel price and the scope of ECA .But fuel price is an uncertain variable, and ECA range will probably be further expanded in the future. Therefore, for a specific ship, it is very important to comprehensively analyze and study the corresponding speed optimization strategy.

4.5.1 Fuel price

In order to further study the significance conditions of the speed optimization strategy and observe the changes of the optimal speed caused by the difference in the price difference between the two kinds of fuel, and its influence on the fuel costs and SO_2 emissions, we assume that other conditions remain unchanged, only the fuel price changes.

We set $P_{\text{MGO}}/P_{\text{VLSFO}} = A$, so $P_{\text{MGO}} = A * P_{\text{VLSFO}}$. In the case of this paper, A=442.5/411=1.08.

$$\frac{\partial C}{V_{\text{ECA}}} = 0, V_{\text{ECA}}^{*} = \frac{D_{\text{ECA}} + \dfrac{(D - D_{\text{ECA}})}{\sqrt[3]{A}}}{T - S}$$

According to the fluctuation of international oil prices in 2020, $A \in (1,2)$. When the fuel price ratio changes, the optimal cost speed also changes. The influence of fuel price changes on speed optimization strategy is summarized in Table 4.

Table 4. Influence of fuel price changes on speed optimization strategy

	V_{ECA}^{*}/(nm/h)	V_{NECA}^{*}/(nm/h)	changes in C	changes in E_{SO2}
No speed optimization (baseline)	18.36	18.36	-	-
A=1.08	17.98	18.43	-0.02%	0.53%
A=1.18	17.52	18.51	-0.10%	1.23%
A=1.2	17.43	18.53	-0.12%	1.37%
A=1.4	16.69	18.67	-0.42%	2.64%
A=1.6	16.08	18.81	-0.83%	3.84%
A=1.8	15.56	18.93	-1.32%	4.97%
A=2	15.11	19.04	-1.85%	6.03%

If the ratio of fuel price A is larger, the optimization speed in ECAs will be slower, and the impact of speed optimization strategy on fuel costs and SO_2 emissions will be greater. The fuel cost is (625.973A+1742.029) P_{VLSFO}, which is affected by A and the price of VLSFO, and is positively correlated with them.

In this case, A =1.08 and P_{VLSFO} is 441 \$/t .At the optimal cost speed, the fuel cost can only be reduced by about \$200, accounting for about 0.02% of the total cost. Even if the price of VLSFO rises, the cost reduction brought by speed optimization is relatively limited. Correspondingly, the change of

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fuel price ratio *A* has a more significant impact on fuel cost reduction. With the increase of *A*, the fuel cost is greatly reduced. When *A*=2, the fuel cost can be saved by $22,000, which is 1.85% of the total cost. To sum up, under other conditions unchanged, the larger *A* is, the more the speed optimization strategy can significantly reduce the fuel cost.

In contrast, as the fuel price gap *A* increases, the strategy of speed optimization will lead to a significant increase in SO_2 emissions at the same time. Compared with fuel cost, SO_2 emissions are more sensitive to the change of *A*. When the fuel cost is reduced by 1%, the SO_2 emissions increases by 4.24%. With other conditions unchanged, the higher the fuel price ratio *A* is, the more significant the speed optimization strategy will increase the SO_2 emissions of the ship.

4.5.2 Navigation distance in ECA

In order to further study the significance conditions of speed optimization strategy, we discuss the change of optimal speed caused by the expansion of ECA range and its impact on fuel costs and SO_2 emissions. The specific results are shown in Table 5.

Table 5. Influence of expanding ECA on speed optimization strategy

	V^*_{ECA}/(nm/h)	V^*_{NECA}/(nm/h)	changes in C	changes in E_{SO2}
No speed optimization (baseline)	18.36	18.36	-	-
R=0.14	17.96	18.43	-0.10%	0.58%
R=0.2	17.99	18.42	-0.35%	0.47%
R=0.3	18.04	18.42	-0.69%	0.29%
R=0.4	18.08	18.41	-0.93%	0.12%
R=0.5	18.13	18.40	-1.06%	-0.04%
R=0.6	18.18	18.39	-1.10%	-0.17%
R=0.7	18.22	18.39	-1.05%	-0.26%
R=0.8	18.27	18.38	-0.89%	-0.30%
R=0.9	18.32	18.37	-0.65%	-0.24%

Based on the same speed in the whole journey, the fuel cost is (66790.229*R* + 984319.83) dollars, which is only affected by *R*, and is directly proportional to it. With the increase of *R* value, the change trend of fuel cost and SO_2 emissions under the speed optimization strategy is first decreased and then increased, showing a "U" shape. Compared with SO_2 emissions, fuel cost is more sensitive to the change of *R*. Under other conditions unchanged, with the increase of *R* value, the speed optimization strategy can always reduce the fuel cost, and when *R*= 0.6, that is, ECA accounts for 60% of the total one-way voyage, the speed optimization strategy can reduce the fuel cost most effectively.

Because of the fixed sailing time and the complementarity of ship speed inside and outside ECA, when $R < 0.5$, the larger *R* is, on the contrary, the more the speed optimization strategies will increase the SO_2 emissions of ships. Under other conditions unchanged, when $R \geq 0.5$, with the increase of *R*, the speed optimization strategies can always reduce SO_2 emissions, and when *R*=0.8, the speed optimization strategy can reduce SO_2 emissions most effectively.

To sum up, under other conditions unchanged, when *R* value is lower than 0.5, the speed optimization strategy will not only reduce the cost but also increase the SO_2 emissions, but when $R \geq 0.5$, the speed optimization strategy will not only help to reduce the fuel cost, but also help to reduce the SO_2 emissions.

Through empirical analysis, this paper draws the following conclusions: (1) There is a sailing speed that minimizes the fuel cost. When V_{ECA} is 17.98 nm/h , the fuel cost is the lowest, but at the same time, the SO_2 emissions increases. (2) Other conditions affect the significance of speed optimization strategy in reducing fuel cost. Taking the container ship " CMA CGM Argentina " as an example, when other conditions are unchanged and the R=0.8, the speed optimization strategy can reduce the fuel cost most significantly; The larger the fuel price ratio *A* is, the more the speed optimization strategy will significantly reduce the fuel cost. (3) With the increase of fuel price gap, the speed optimization strategy will significantly increase the total SO_2 emissions of ships. However, with other

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conditions unchanged, after ECA accounts for more than half of the one-way voyage, the speed optimization strategy will not only help to reduce fuel costs, but also help to reduce SO_2 emissions from ships.

5. Conclusion

At present, ship cost control and emission control are widely concerned. In ECAs, the requirement of sulfur content less than 0.1% m/m for marine fuel in current regulations significantly increases the fuel cost of ships, which has a significant impact on the strategic choice of shipping enterprises. This paper focuses on how to reduce the voyage cost of ships by adopting the speed optimization strategy under the premise of meeting ECA rules. The analysis in this paper proves that under the current environmental regulations, this strategy can still play a role in reducing the fuel cost of ships.

The results of this paper are helpful for shipping enterprises and environmental management departments to solve the conflict between cost reduction and emissions reduction. In addition, with the new ships equipped with desulfurization device or LNG fuel system put into use, the significance of fuel conversion and speed optimization strategy will be weakened accordingly. This requires the shipping academia to continue to innovate, to explore other more effective solutions.

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