The influence of the SO_2 emission limit in ECA emission control area on liner route speed and route selection

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Abstract

In order to study the influence of the establishment of emission control area on the route choice of ships, this paper established a two-objective optimization model to minimize the total fuel cost and the total sulfur dioxide emissions. the model is implemented by MATLAB, and a domestic route including 8 ports of call in China is taken as an example, and then the commercial software CPLEX is used to solve the problem so as to verify the feasibility of the model. The results show that different route choices can be obtained by using the dual-objective optimization model, which has certain practical significance for the route choice of some liner shipping companies: The length of route distance in the emission control zone has a significant influence on the route selection and speed optimization of the entire route. In this paper, Epsilon constraint method is also used to obtain Pareto solution set, and different optimal route path selection is obtained according to different weight allocation of the two objective functions, which is of certain reference significance for liner operators to select routes.

Keywords

Emission control area, dual objective optimization, epsilon constraint method.

1. Introduction

As a major shipping country, China has always attached great importance to promoting the development of green shipping and ship energy conservation and emission reduction. In December 2015, the Ministry of Transport issued the Implementation Plan for Ship Emission Control Zones in the Pearl River Delta, Yangtze River Delta and Bohai Sea Rim, setting up ship emission control zones in China's three coastal waters. At the end of 2018, the Ministry of Transport upgraded and improved the above plan, and issued a new implementation plan to extend the scope of China's ship emission control zone to the country's coastal areas and major inland river waters. Thereafter, ships within the DECA range must use bunker fuel with a sulphur content of not more than 0.5%. In this paper, we will focus on route and speed optimization with the goal of minimizing the total fuel cost and SO2 emissions when adopting the fuel conversion method. In reference to some existing literature, we assume that fuel conversion is an instantaneous process for simplicity. The rest of the paper is arranged as follows. In the second part, we review the relevant literature. In section 3, we describe the problems and data used in this article. The fourth section introduces the mathematical model and algorithm. In the fifth section, the results of numerical experiments are given and discussed. The last section is the conclusion.

2. Literature Review

Many scholars have studied the optimization of ship navigation scheme based on the ECA or "green shipping" concept. Under the shipping background of ECA and carbon tax policy, Lin Guihua, Gao Jie et al. (2020-5-26) used fuel consumption function based on speed and ship load to build a mixed integer nonlinear model for liner company revenue maximization to study issues such as speed optimization, shipping line allocation and cargo distribution. Sheng D(2019) established a mixed integer convex cost minimization model to determine the optimal ship speed and fleet size. Through numerical study, the economic and environmental impacts of ECA regulations on several representative industrial transportation services were investigated. Chen LY through the Mediterranean may ECA of liner shipping route choice behavior modeling, studies have shown that the establishment of ECA will be quite a number of ships will be rerouted around it, and small vessels divert tendency was stronger than large ships, Dai WL (2018) study shows that the fuel price, port loading and unloading cost and emission charges and cargo transport demand patterns across different markets, to influence the shipping company's network configuration reveals the regulatory costs and the possibility of the relevant market distortions and regional emissions system, and highlights the market dynamic complex influence of international environmental policy.

3. Problem Description

After the introduction of ECA, the global Marine environment has been improved, but it has also brought some new problems to the shipping industry. For example, how to design the sailing plan under ECA's policy and how to minimize the discharge of ships are important issues for the shipping industry to consider. To solve the above problems, this paper proposes a two-objective optimization mathematical model of container liner route design and speed optimization based on ECA strategy. Considering multiple port cities and arrival time, the total fuel cost and total SO2 emissions can be minimized by optimizing ECA internal and external routes and speeds. There are many costs involved in container transportation. According to the literature, the choice of path and speed has little impact on some almost fixed costs, including labor costs, maintenance costs, and inventory costs. Therefore, this paper only considers fuel costs, which are affected by changes in routes and speeds and account for a large proportion of total operating costs.

In addition, the main pollutants discharged by container liners during their voyage are sulfur dioxide, carbon dioxide and nitrogen oxides. The SO2 emissions from ocean-going ships are proportional to the sulfur content and fuel consumption of the fuel used, and a proportionality constant called the "sulfur index" is calculated by multiplying the total fuel consumption (ton) by the percentage of sulfur in the fuel and then multiplying by 0.02. The calculation formula of SO2 emissions is as follows:

SO2 emissions =0.02× total fuel consumption × the percentage of sulfur in the fuel.

According to IMO regulations, since 2012, ships around the world have been required to use fuels with a sulphur content of not more than 3.5% (such as HFO) (Kontovas, 2014). After ECA was introduced in 2015, ocean-going vessels will need to use MGO rather than HFO for ECA trips in the Baltic, North Sea, North America and the Caribbean. From January 1, 2019, China's seagoing ships entering DECA shall use Marine fuels with a sulfur content of not more than 0.5% (such as MGO). Therefore, we studied MGO with a sulfur content of less than 0.1% and HFO with a sulfur content of 3.5% in the experiment.

Since the current emission control area is mainly for sulfur emission restriction, this paper mainly studies SO2 emission, and the second goal of the model is to minimize the total SO2 emission.

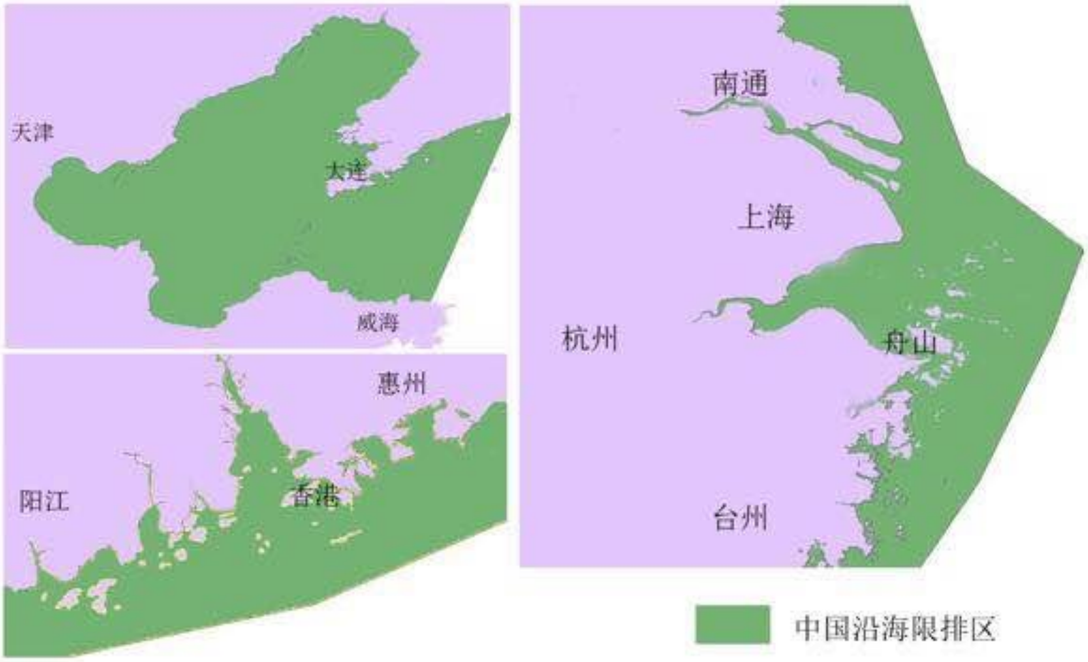

Figure 1: China's domestic Ship Emission Control zone

4. Mathematical Model

Index and collection

i, j	Port index
k	Number of days of voyage from port $\boldsymbol{i}$ to port j
v	Speed of vessel
r	Index of ship path selection
A	Collection of ports visited
G	A collection of two ports of continuous access
K	A collection of the number of days of voyage from port $\boldsymbol{i}$ to port j
V	The set of velocities at discrete points
$R_{i,j}$	Set of path options from port i to port j
$RE_{i,j}$	A set of path options that contain port i to port j within the ECA
$RN_{i,j}$	A set of path options that contain port i to port j outside the ECA

The input parameters

p^{ECA}	The ECA's internal fuel prices
p^{N}	Fuel prices outside the ECA
F_{ijrv}^{ECA}	When choosing a route r and speed v ,fuel consumption within the ECA from port i to port j
F_{ijrv}^{N}	When choosing a route r and speed v ,fuel consumption outside the ECA from port i to port j
T_{ijrv}^{ECA}	Choose the path r and speed v when sailing from port i to port j within the ECA sailing time.

T^{N}_{ijrv}	When choosing the path r and speed v, the non-ECA sailing time from port i to port j
C^{ECA}_{ijrv}	When choosing the route r and speed v, the SO2 emissions within the ECA during the journey from port i to port j
C^{N}_{ijrv}	Sulfur dioxide emissions outside ECA during port i to port j travel when choosing route r and speed v
w_i	Waiting time of ship in port i
L_{jk}	The lower limit of the time window when the ship arrives at the port j on the first k day
E_{jk}	The upper bound of the window of time at which a ship arrives at port j on day k
M	A sufficiently large positive number

The decision variables

t_j	Time of arrival at port j
s_{ij}	Time of vessel between port i and port j
y^{ECA}_{ijrv}	Weight of sailing speed v from port i to port j in ECA under route choice r
y^{N}_{ijrv}	Weight of sailing speed v from port i to port j in ECA outside route choice r
z_{ijr}	Binary variable, when the ship sails from port i to port j, if the path r is chosen, it is 1, otherwise it is 0
β_{jk}	The binary variable is 1 if the ship arrives at Port j on day k, otherwise 0

Mathematical model:

$$\min F_1 = \sum_{i,j\in G}\left(\sum_{r\in RE_{ij}}\sum_{v\in V}P^{ECA}F^{ECA}_{ijrv}y^{ECA}_{ijrv} + \sum_{r\in RN_{ij}}\sum_{v\in V}P^{N}F^{N}_{ijrv}y^{N}_{ijrv}\right) \tag{1}$$

$$\min F_2 = \sum_{i,j\in G}\left(\sum_{r\in RE_{ij}}\sum_{v\in V}C^{ECA}_{ijrv}y^{ECA}_{ijrv} + \sum_{r\in RN_{ij}}\sum_{v\in V}C^{N}_{ijrv}y^{N}_{ijrv}\right) \tag{2}$$

The constraint:

$$s_{ij} = \sum_{r\in R_{ij}}\sum_{v\in V}(T^{ECA}_{ijrv}y^{ECA}_{ijrv} + T^{N}_{ijrv}y^{N}_{ijrv}) \quad \forall i,j\in G \tag{3}$$

$$t_i + \gamma_i + s_{ij} \le t_j \quad \forall i,j\in G \tag{4}$$

$$t_j - M(1-\beta_{jk}) \le E_{jk} \quad \forall j\in A, k\in K \tag{5}$$

$$t_j + M(1-\beta_{jk}) \ge L_{jk} \quad \forall i,j\in G \tag{6}$$

$$\sum_{k\in K}\beta_{jk} = 1 \quad \forall j\in A \tag{7}$$

$$\sum_{v\in V}y^{ECA}_{ijrv} = z_{ijr} \quad \forall i,j\in G, r\in RN_{ij} \tag{8}$$

$$\sum_{v\in V}y^{N}_{ijrv} = z_{ijr} \quad \forall i,j\in G, r\in RN_{ij} \tag{9}$$

$$\sum_{r\in R_{ij}}z_{ijr} = 1 \quad \forall i,j\in G \tag{10}$$

$$y^{ECA}_{ijrv} \ge 0 \quad \forall i,j\in G, r\in RE_{ij}, v\in V \tag{11}$$

$$y_{ijrv}^{N} \geq 0 \quad \forall i, j \in G, r \in RE_{ij}, v \in V \tag{12}$$

$$t_i \geq 0 \quad \forall i \in A \tag{13}$$

$$\beta_{jk} \in \{0,1\} \quad \forall j \in A, k \in K \tag{14}$$

$$z_{ijr} \in \{0,1\} \quad \forall i, j \in G, r \in R_{ij} \tag{15}$$

Objective (1) is to minimize the sum of fuel costs inside and outside the ECA. Because there is a nonlinear relationship between speed and fuel consumption, So according to the decision variables y_{ijrv}^{ECA} and y_{ijrv}^{N} ,A piecewise linear interpolation method is used to estimate fuel consumption at a certain speed， Objective (2) is to minimize total emissions within and outside the ECA. Constraints (3) and (4) ensure that the time to arrive at a port plus the waiting time of the port and the sailing time to the next port do not exceed the time to arrive at the next port. Constraint conditions (5) - (7) Ensure that the arrival time of the port is within the time window. The constraints (8) and (9) relate the range speed weight to the path option, that is, if the path option is selected, the sum of the speed weights inside and outside ECA is equal to 1 respectively. Constraint condition (10) Ensures that a path option must be chosen from port i to port j .The constraint (11) - (13) ensures that the velocity weights and time of arrival are non-negative. Constraints (14) and (15) guarantee 0-1 variables.

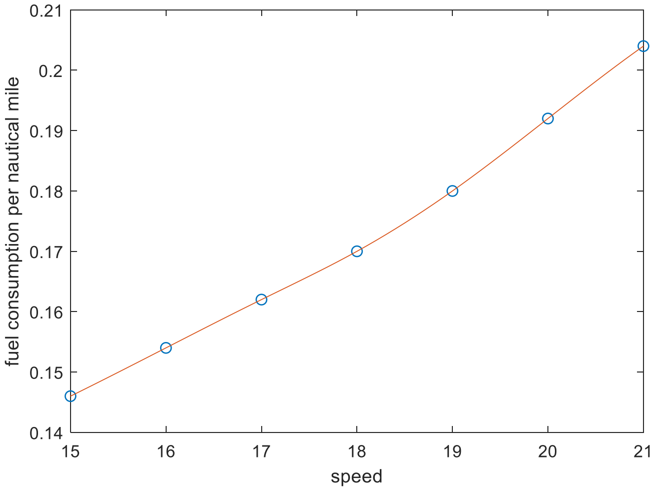

Figure 2: Fuel consumption propagated at different speeds

Epsilon Constraint algorithm Design

In order to accurately solve the dual objective optimization problem and obtain Pareto frontier, Epsilon constraint algorithm is introduced below to solve the problem. The so-called Pareto front means that when an object is dominant or determined, under the condition of not increasing resources, the optimal solution of another object can be obtained. The values of these two solutions form a coordinate, and a series of such coordinates form a curve, which is Pareto Front. This method was founded by Berube et al. [11]. The main idea is to form Pareto front by transforming one of the objectives into constraints and then optimizing the other.

The specific process of Epsilon constraint law, namely pseudocode, is described below:

First of all, three categories:

1)ideal point. target first ideal point use f_1^l said, $f_1^l = \min\{f_1(X)\}$,target second ideal point use f_2^l said, $f_2^l = \min\{f_2(X)\}$, 2)nadir point. target first nadir point use f_1^N said, $f_1^N = \min\left\{ f_1(X): f_2(X) =_2^l \right\}$ target second nadir point use f_2^N said, $f_2^N = \min\left\{ f_2(X): f_1(X) =_1^l \right\}$.

3)extreme point. Set up the $f^E = \left\{ (f_1^l, f_2^N), (f_1^N, f_2^l) \right\}$ as two points in Pareto frontier.

The pseudocode of the Epsilon constraint algorithm can be expressed as follows:

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Step 1 Calculation ideal point $f^l = (f_1^l, f_2^l)$ 和nadir point $f^N = (f_1^N, f_2^N)$;
Step 2 Setup $f^{'} = \{(f_1^N, f_2^N)\}$,and let $\varepsilon = f_2^N - \Delta$;
Step 3 While $\varepsilon \geq f_2^l$,do:
    Solve the Epsilon constraint problem, where epslion constraint is $\sum_k \sum_i D_k * x_{ik} \leq \varepsilon$,And the single objective of optimization is $\sum_k \sum_i (d_{ik} - s_{ik})$。The single objective optimization problem is solved to the optimal solution and the optimal solution is obtained $(f_1^*, f_2^*)$ Add to the collection $f^{'}$,Among them $f_2^* = \sum_k \sum_i D_k * x_{ik}$.
    set up $\varepsilon = f_2^* - \Delta$。
Step 4: Pareto front F is obtained by removing the dominant point from the set.
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5. Case Analysis

The model was solved by yalmip calling CPLEX 12.8 solver on MATLAB.

5.1. The performance of the model considers the influence of ECA

This study takes an airline in China as an example. In this case, the ship starts from Tianjin and visits Yantai, Qingdao, Shanghai, Ningbo, Xiamen, Hong Kong, Shenzhen and finally returns to Tianjin.(See Table 1)

Table 1: Line lengths selected by different paths

ECA/ Non-ECA (sea mile)	option1	option2	option3
leg1	226/0	183/43	106/121
leg2	72/143	57/196	43/212
leg3	164/160	127/214	63/257
leg4	285/0	212/128	125/375
leg5	276/53	185/192	113/216
Leg6	167/124	146/195	329/288
Leg7	77/0	54/36	36/59
leg9	348/1368	326/1547	285/1788

Without considering the path and speed of ECA's influence, the solution is as follows: First, we do not consider the restriction of ECA's emission control area on sulfur emission. Option 1 provides the shortest distance between any two ports, with a total distance of 3,259 nautical miles. Taking into account the different fuel types used within and outside ECA, total fuel costs and so2 emissions were calculated. The results are shown in Table 2. The total cost of fuel is approximately us $360,770 and the total sulfur dioxide emissions are 24.68 tons. The internal fuel consumption of the ECA is 295.17 tons, while the external fuel consumption of the ECA is 344.16 tons, with a total fuel consumption of 639.33 tons.

When the weights of the two targets are the same, the result considering the influence of the emission control area is shown in Table 3. As you can see, the cost of fuel is about $335,150. Compared to fuel costs without taking ECA's impact into account, the savings were approximately $25,620 (7.10%). Total sulfur dioxide emissions increased to 29.49 tons, an increase of 4.81 tons. As shown in Table 3, the fuel consumption of the ship inside the ECA is 222.84 tons, and that outside the ECA is 414.87 tons, with a total fuel consumption of 637.71 tons. The route has a total range of 3,460 nautical miles. In this case, it means that container liners are more inclined to choose the route with a longer total voyage but a shorter one within the ECA, so as to reduce costs. However, the internal fuel price (MGO) of the ECA is higher than the external fuel price (HFO), and the external speed of the ECA is greater than or equal to the internal speed of the ECA. For example, in the section from Tianjin to Yantai, the ship sails at the minimum speed of 15 in the ECA to reduce fuel consumption. When the ship sails outside the ECA, the speed needs to be increased to make up for the extra time in the ECA. The results of the optimization model verify the impact of ECA on the shipping industry mentioned in the introduction.

Table 2: Does not consider route selection in the case of emission control area

Leg	speed		Fuel consumption			Fuel cost	So_2 emissions
	Within ECA	Outside ECA	Within ECA	Outside ECA	Total fuel consumptiom		
1	15	15	33	/	33	360770	24.68
2	20	21	13.82	29.17	42.99		
3	20.83	21	33.12	32.64	65.76		
4	21	/	58.14	/	58.14		
5	21	21	56.30	10.81	67.11		
6	21	21	34.07	25.30	59.37		
7	15.42	/	11.50	/	11.5		
8	16.59	19	55.22	246.24	301.46		
Total			295.17	344.16	639.33		

Table 3: Route selection under the influence of emission control area

Leg	option	speed		Fuel consumption			Fuel cost	So2 emissions
		Within ECA	Outside ECA	Within ECA	Outside ECA	Total fuel consumptiom		
1	3	15	15	15.48	17.67	33.15	335150	29.49
2	1	20	21	13.82	29.17	42.99		
3	3	20	21	12.1	52.43	64.53		
4	1	21	/	58.14	/	58.14		
5	3	20.6	21	22.51	44.06	66.57		
6	1	21	21	34.07	25.30	59.37		
7	1	15.42	/	11.50	/	11.5		

8	1	16.59	19	55.22	246.24	301.46		
Total				222.84	414.87	637.71		

5.2. Change the effect of the weight on the result

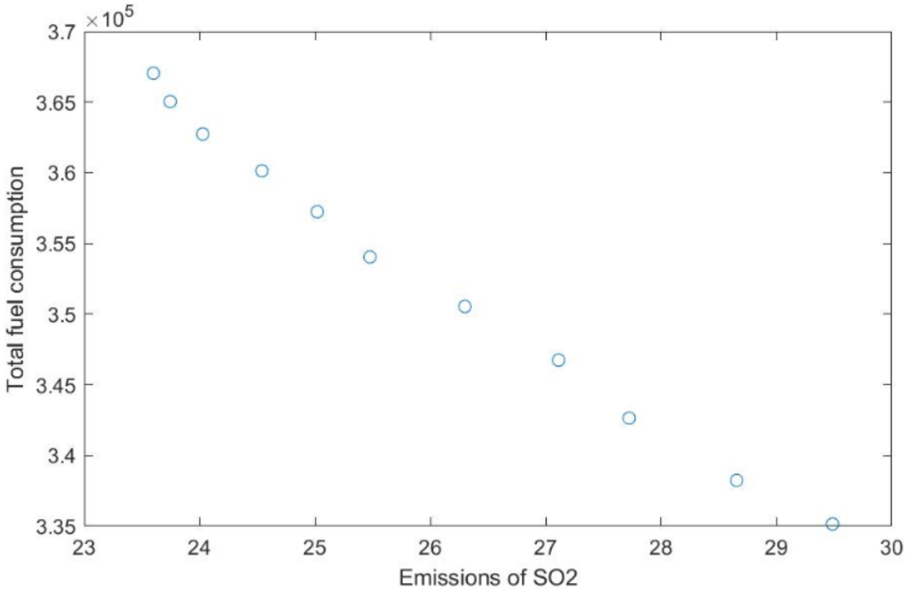

Figure3: Solution set of Pareto with dual targets

Table 4 Navigation path selection between each two ports under different weights

	Leg1	Leg2	Leg3	Leg4	Leg5	Leg6	Leg7	Leg8
1.0/0	3	1	3	1	3	1	1	1
0.9/0.1	3	1	3	1	3	1	1	1
0.8/0.2	1	1	3	1	3	1	1	1
0.7/0.3	3	1	3	1	1	1	1	1
0.6/0.4	3	1	3	1	1	1	1	1
0.5/0.5	1	1	3	1	1	1	1	1
0.4/0.6	1	1	3	1	1	1	1	1
0.3/0.7	2	1	1	1	1	1	1	1
0.2/0.8	1	1	1	1	1	1	1	1
0.1/0.9	1	1	1	1	1	1	1	1
0/1.0	1	1	1	1	1	1	1	1

6. Conclusion

Fuel cost has become an important cost item in shipping, sometimes accounting for more than 50% of the total operating cost. The Marine Pollution Control Organization has recently placed strict limits on the maximum sulphur content of fuel used by ships in some emission control areas. To comply with these requirements, many ship operators will need to switch to low-sulphur fuels (e.g., Marine gas and oil (MGO)) when sailing within the ECAs. Low-sulphur fuels are more expensive than ordinary heavy fuel oil, which can be used outside the emission control zone, so rising or falling fuel prices will affect international shipping

In this paper, we propose an optimization model in which ship operators consider emission control zones to determine sailing paths and speeds to minimize ships' operating costs over a given port sequence. In order to study the socio-economic impact of environment-related policies, we have carried out a computational study of some realistic shipping routes. Studies have shown that the likely impact of these provisions is that, in many cases, ship operators will choose to sail longer distances in order to avoid or reduce navigation within the ECA. Another effect is that they will sail at lower speeds inside the ECA and at higher speeds outside, to reduce the use of expensive fuel. On some routes, this could significantly increase the total amount of fuel used, thereby increasing carbon dioxide emissions. In some rare cases, the consequence of ECA rules may even be an increase in Sox emissions, since it may be advantageous to take longer sailing routes to avoid ECAs. This effect will depend on the price difference between MGO and HFO and will become stronger if MGO is more expensive than HFO.

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