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Optimization Strategy of Ship Speed and Fuel Supply based on SECA and Carbon Tax

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Abstract

At present, due to the unreasonable allocation of resources in waterway transportation, problems such as emissions amplification and serious pollution are caused. This paper considers the impact of carbon tax and SECA on the speed of navigation, and considers the operating costs such as inventory cost, fuel replenishment cost, carbon tax, ship time delay cost, etc., to minimize the total operating costs with the limitation of time window.

Keywords

SECA Rules; Water Transportation Economy; Speed Optimization; Fuel Replenishment; Carbon Tax.

1. Introduction

Among all modes of transportation, waterway transportation has the longest history of development, but its development momentum in the new era has decreased. Since 2017, the national waterway passenger volume has decreased year by year, and the passenger volume in 2019 has decreased by 2.6% year on year. The reason is that waterway transportation has obvious disadvantages in environmental protection, energy conservation and economic applicability. Waterway transportation is a long-distance transportation operation, so the cost is high, the energy consumption is high, and the tail gas emitted by it is more destructive to the atmosphere. In addition, the extensive growth mode and non-standard transportation phenomenon also aggravate the difficulty of water transportation governance. Although in recent years, through the relevant policies of green water transportation and smart water transportation, coupled with the continuous development of energy technology, in the environmental protection department With the coordination and cooperation of the customs supervision department and the financial department, many links such as ferry, ferry and route setting have been regulated and standardized. However, due to the failure to fundamentally solve the problems of tail gas emissions and energy consumption, fuel use and sulfur emissions are still two prominent technical issues, and the road of water transport governance is still long.

However, it is obvious that it is necessary to solve relevant problems and vigorously develop water transport. For example, water transport travel is similar to shared travel to a certain extent, which not only meets people's travel needs, but also reduces the waste of resources that cannot be effectively used by public travel, which also plays a certain role in promoting economic development. Therefore, it is also the starting point of this research to solve the problem of fuel selection and sulfur oxide exhaust emissions, and promote the integration and

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development of waterway transportation and "Internet plus", "Internet of Things" and other technologies on the basis of the original transportation.

2. Model Establishment

2.1. Design Principle

The design principle of the optimal supply strategy is shown in Figure 1 and Figure 2.

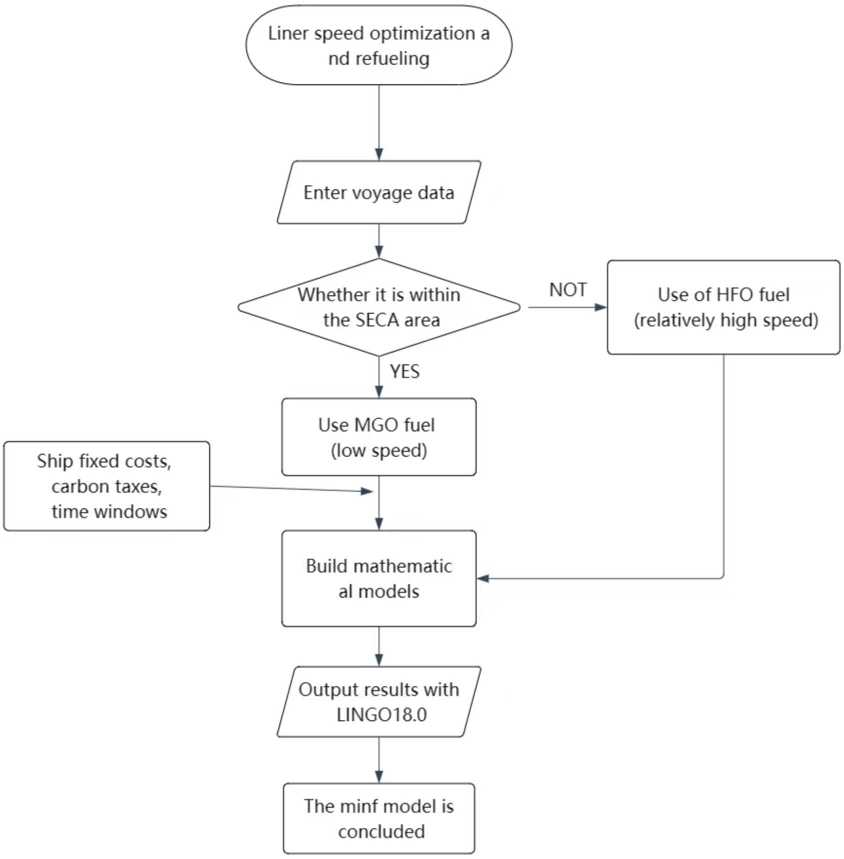

Figure 1. Model flow chart

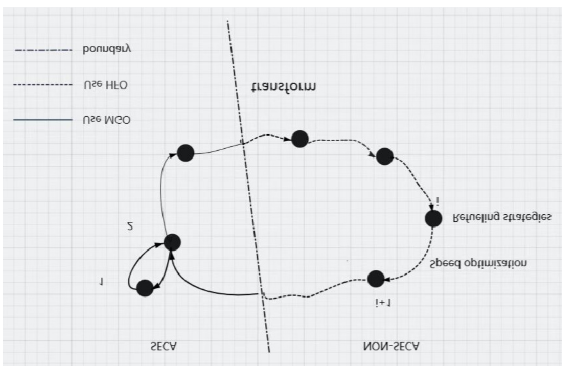

Figure 2. Liner transportation route of route r

2.2. Model Assumptions

The mixed integer nonlinear programming model with 0-1 variables is assumed as follows:

The ship's navigation route is known. MGO is used in SECA and HFO is used outside SECA. The ship route and port sequence are determined, and the liner will eventually return to the starting point, that is, the route will form a closed loop. Each port of call has a soft time window limit.

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Ships on the same route belong to the same type. The service frequency of the ship is once a week. Only the fuel consumption of the main engine is considered.

2.3. Variables and Parameters

Symbols and decision variables are shown in Table 1 and Table 2.

Table 1. Symbol definition

Symbols	Definition	Symbols	Definition
R	Route assembly $r \in R = \{1,2,\cdots,m\}$	P_r	Port assembly of route r $i \in P_r = \{1,2,\cdots,n_r\}$
$P_{r,i}^M$,$P_{r,i}^H$	The price of MGO/HFO at the ith port of route r (USD/ton)	φ	Unit fuel storage cost (USD/ton)
v_{min} ,v_{max}	Minimum/maximum sailing speed of the ship (nautical miles/hour)	θ	Delay cost per unit time (USD/hour)
λ_M ,λ_H	MGO/HFO Carbon emission factor	e	Carbon tax rate (USD/ton)
W_M ,W_H	MGO/HFO Maximum capacity of fuel tank (ton)	c_r^{fix}	Fixed cost of a single voyage of a ship on route r (USD)
$y_{r,i,1}^M$,$y_{r,i,2}^M$	MGO inventory of the ith port of ship arrival/departure route r (ton)	L	Upper limit of carbon emission (ton)
$y_{r,i,1}^H$,$y_{r,i,2}^H$	HFO inventory at the ith port of ship arrival/departure route r (ton)	$t_{r,i}$	The berthing time of the ship at the ith port of route r (hours)
$d_{r,i}^M$,$d_{r,i}^H$	The ship's navigation distance inside/outside SECA in the ith leg of route r (nautical miles)	$[\alpha_{r,i}, \beta_{r,i}]$	Time window of the ith port in route r

Table 2. Definition of decision variables

Variables	Definition	Variables	Definition
$S_{r,i}^M$,$S_{r,i}^H$	The replenishment volume of MGO/HFO at the ith port of route r (ton)	$A_{r,i}$	Time of ship arriving at the ith port of route r
$v_{r,i}^M$,$v_{r,i}^H$	SECA of the ship in the ith leg of route r, Internal/external speed (knots)	m_r	Number of vessels on route r
$B_{r,i}^M$,$B_{,r,i}^H$	0-1 variable, 1 when supplying MGO/HFO, otherwise 0.		

2.4. Model Establishment

(1) Fixed cost of the ship.

$$\sum_{r=1}^{m} c_r^{fix}\, m_r \tag{1}$$

(2) Fuel supply cost.

$$\sum_{r=1}^{m}\sum_{i=1}^{n_r} m_r\left(P_{r,i}^M S_{r,i}^M + P_{r,i}^H S_{r,i}^H\right) \tag{2}$$

(3) Fuel inventory cost (assuming inventory cost is φ).

$$\frac{1}{2}\sum_{r=1}^{m}\sum_{i=1}^{n_r} m_r\, \varphi\left(S_{r,i}^M + S_{r,i}^H\right) \tag{3}$$

(4) Time delay cost.

$$\sum_{r=1}^{m}\sum_{i=1}^{n_r} m_r \theta max\left\{A_{r,i} - \beta_{r,i}, 0\right\} \tag{4}$$

(5) Carbon tax.

$$\sum_{r=1}^{m}\sum_{i=1}^{n_r} m_r\, \mathrm{e}\left[\lambda_M F_0^K\left(\frac{v_{r,i}^M}{v_d}\right)^3 \frac{d_{r,i}^M}{24 v_{r,i}^M} + \lambda_H F_0^K\left(\frac{v_{r,i}^H}{v_d}\right)^3 \frac{d_{r,i}^H}{24 v_{r,i}^H}\right] \tag{5}$$

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Where, F_0^K is the fuel consumption constant of the ship, v_d is the design speed of the ship.

The minimum total operating cost model is as follows:

$$minf\left(v_{r,i}^M, v_{r,i}^H, S_{r,i}^M, S_{r,i}^H, A_{r,i}, m_r, B_{r,i}^M, B_{,r,i}^H\right)$$

$$=\sum_{r=1}^m c_r^{fix} m_r + \sum_{r=1}^m \sum_{i=1}^{n_r} m_r\left(P_{r,i}^M S_{r,i}^M + P_{r,i}^H S_{r,i}^H\right)+\frac{1}{2}\sum_{r=1}^m \sum_{i=1}^{n_r} m_r\,\varphi\left(S_{r,i}^M + S_{r,i}^H\right) + \sum_{r=1}^m \sum_{i=1}^{n_r} m_r \theta max\left\{A_{r,i} - \beta_{r,i}, 0\right\} + \sum_{r=1}^m \sum_{i=1}^{n_r} m_r\, e\left[\lambda_M F_0^K \left(\frac{v_{r,i}^M}{v_d}\right)^3 \frac{d_{r,i}^M}{24 v_{r,i}^M} + \lambda_H F_0^K \left(\frac{v_{r,i}^H}{v_d}\right)^3 \frac{d_{r,i}^H}{24 v_{r,i}^H}\right] \quad (6)$$

Model constraints.

$$\sum_{i=1}^{n_r}\left(t_{r,i} + \frac{d_{r,i}^M}{v_{r,i}^M} + \frac{d_{r,i}^H}{v_{r,i}^H}\right) \le 168 m_r \quad \forall r \in R \quad (7)$$

$$20\% B_{r,i}^M W_M \le S_{r,i}^M \le B_{r,i}^M W_M, 20\% B_{r,i}^H W_H \le S_{r,i}^H \le B_{r,i}^H W_H \quad \forall r \in R, \forall i \in P_r \quad (8)$$

$$y_{r,1,1}^M = y_{r,1,1}^H = 1000 \quad \forall r \in R, \forall i \in P_r \quad (9)$$

$$y_{r,i,1}^M \ge 10\% W_M, y_{r,i,1}^H \ge 10\% W_H \quad \forall r \in R, \forall i \in P_r \quad (10)$$

Constraint (7): ship deployment constraint to ensure the weekly service frequency of the ship.

Constraint (8): fuel quantity constraint, which limits the range of fuel quantity.

Constraint (9): inventory constraint, which fixes the initial inventory of two fuels.

Constraint (10): the inventory range of two fuels when the ship arrives at the port.

2.5. Model Analysis

The model is a mixed integer nonlinear programming model with 0-1, and its objective function and some constraints contain $u_{r,i}^M$, $u_{r,i}^H$ and ship arrival time $A_{r,i}$. Because the model is complex, it can be simplified by mathematics.

Define a new variable. $u_{r,i}^M = 1/v_{r,i}^M$, $u_{r,i}^H = 1/v_{r,i}^H$.

Introduce auxiliary variables. $l_{r,i} = max\{A_{r,i} - \beta_{r,i}, 0\}$.

The above model can be transformed into:

$$minf\left(u_{r,i}^M, u_{r,i}^H, S_{r,i}^M, S_{r,i}^H, A_{r,i}, l_{r,i}, m_r, B_{r,i}^M, B_{,r,i}^H\right)$$

$$= \sum_{r=1}^m c_r^{fix} m_r + \sum_{r=1}^m \sum_{i=1}^{n_r} m_r\left(P_{r,i}^M S_{r,i}^M + P_{r,i}^H S_{r,i}^H\right)\frac{1}{2}\sum_{r=1}^m \sum_{i=1}^{n_r} m_r\,\varphi\left(S_{r,i}^M + S_{r,i}^H\right) + \sum_{r=1}^m \sum_{i=1}^{n_r} m_r \theta l_{r,i} + \sum_{r=1}^m \sum_{i=1}^{n_r} m_r\, e\left[\frac{1}{24}\lambda_M F_0^K v_d^{-3} d_{r,i}^M \left(u_{r,i}^M\right)^{-2} + \frac{1}{24}\lambda_H F_0^K v_d^{-3} d_{r,i}^H \left(u_{r,i}^H\right)^{-2}\right] \quad (11)$$

It can be proved that the transformed model is a convex optimization model, which can be solved using LINGO18.0.

3. Case Analysis

This paper selects AUS1, an Australian airline, as the research object.

After the data and parameters such as the distance between ports, port berthing time, time window and fuel price are taken into the above convex optimization model, LINGO18.0 is used for calculation. The results are shown in Table 3:

The data in this table is the result of the optimization model in this example. Considering the port distance factor, the optimal replenishment strategy is selected. At the same time, the speed will change appropriately according to fuel and SECA restrictions. From the result of selecting the refueling port, under the consideration of the distance between different ports, the optimal fuel replenishment strategy should try to select the lowest fuel port, and the refueling volume in the port with low fuel price is higher than that in the port with high fuel price. Therefore, this model can ensure that ships arrive at the port on time and reduce the total cost.

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Table 3. Results of model calculation

Serial number	Port	Speed		arrival time	Whether to refuel		Fuel quantity	
		SECA	Non-SECA		$B^M_{r,i}$	$B^H_{r,i}$	MGO	HFO
1	Shanghai	16.92	21.69	0	0	0	0	0
2	Chiwan	16.88	19.65	67.51	0	0	1245.21	0
3	Hong Kong	16.86	19.45	73.26	1	0	0	0
4	Sydney	16.82	19.41	219.32	0	1	0	1623.74
5	Melbourne	16.80	24.86	310.25	0	0	0	0
6	Brisbane	16.80	19.67	437.81	0	0	0	0
7	Kaohsiung	16.76	19.05	639.54	0	1	0	2049.12
8	Hong Kong	16.76	20.23	802.18	0	0	0	0
9	Shanghai			876.94				

4. Innovative Features and Application Prospects

4.1. Innovative Features

Different from the traditional liner speed optimization and fuel replenishment scheme, this paper, from the perspective of energy conservation and emission reduction, innovatively considers the background of carbon emissions and SKCA, and introduces the situation of multi-cycle and multi-port liner transportation, making the model closer to the reality of life. In addition, when establishing the objective function, in addition to the above five basic costs, the time window is also considered to find a balance between low speed and high service level, which is closer to the concept of energy conservation and emission reduction. According to the model test results, in addition to the appropriate solutions for the speed of the ship on the route and the time of docking at the port, a flexible fuel replenishment strategy is also proposed, which can maximize the adaptation of people's traffic and further improve the economic benefits of shipping.

In addition, based on the concept of energy conservation and emission reduction, this topic not only seeks technical improvement, but also focuses on solving the contradiction between water transportation and actual needs. For the contradiction between environmental carrying capacity and pollution, consider the pollution caused by multiple links in the actual operation process, measure the environmental carrying capacity, and calculate the optimal route solution. For the contradiction between current interests and future interests, follow the strategic principle of sustainable development, and calculate the optimal emissions of tail gas, in order to maximize the compatibility with the concept of green development, and also improve the research value of this topic.

4.2. Application Prospect

The optimization and analysis of waterway travel routes is the basic work of transportation construction. In combination with the development of the sharing society and economy, the economic benefits of waterway transportation can be improved. The waterway transportation industry is an important link of foreign trade and international competitiveness. In the era of sharing economy, the sharing concept and waterway transportation industry will be combined to produce the effect of "1+1>2".

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5. Conclusion

Under the background of carbon tax and SECA, this paper studies the fuel replenishment strategy of multi-port ship transportation. Taking the sum of fixed cost, fuel cost, inventory cost, ship delay time cost and carbon tax as the objective function, considering the port fuel replenishment strategy and speed optimization in the constraints, a mixed integer nonlinear programming model with 0-1 variables is established, and the model is converted into a convex programming model other than integer variables by introducing auxiliary variables. Further, LINGO software is used to solve the model, and the speed optimization and refueling strategy of each port on each route are obtained. From the optimization results of numerical experiments, it can be seen that the fuel replenishment strategy will change with the change of fuel price and other costs when considering the factors of different port distances. This paper provides a reference basis for how to select the lowest price fuel port and improve the fuel volume.

References

[1] Li Dechang, Yang Hualong, Zhao Shuaiqi, Zheng Jianfeng. Joint optimization of container liner shipping schedule design and fuel supply under emission control area [J]. Transportation System Engineering and Information, 2022,22 (01): 273-281+310.

[2] Li Haoqiang. Thoughts on the ship emission control area and the implementation of sulfur limitation regulation [J]. China Maritime, 2022, (01): 43-45.

[3] Sun Shuhai, He Jinping. Comparison of common fuel replenishment methods for LNG fuel-powered ships [J]. Tianjin Science and Technology, 2022,49 (03): 43-46.

[4] Sun Shuhai, He Jinping. Fuel supply mode for LNG fuel-powered ships [J]. Marine Engineering, 2022, 51 (02): 70-72+76.

[5] Liu Yiming, Zhang Yan, Yuan Yupeng, Wang Shanshan, Guo Jundong, Wang Lei, Zhou Bin. Research on the identification method of fuel sulfur content based on real-time emission of ships and online monitoring of smoke plume [J]. Journal of Environmental Science, 2021,41 (07): 2624-2632.

[6] Lin Guihua, Li Meng, Li Yuwei, Xu Weina. Liner speed optimization and fuel replenishment strategy considering sulfur emission control area and carbon tax [J]. Systems Engineering, 2020,38 (02): 98-108.

[7] Cai Yiji. Marine route optimization and emission reduction technology selection under sulfur emission control zone [D]. South China University of Technology, 2019.

[8] Cheng Wentao, Zhang Huachun. Sulfur emission control zone and carbon emission reduction constraint next round route optimization [J]. Journal of Central China Normal University (Natural Science Edition), 2017,51 (05): 663-670.