Study on cruise speed optimization and refueling strategy considering emission control areas

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Abstract. In order to alleviate the cost pressure caused by navigation restrictions and rising fuel prices faced by cruise companies, on the basis of considering the constraints of emission control areas and the arrival time constraints of each port, according to the relationship between the speed and fuel consumption of ships during navigation, a mixed integer nonlinear programming model with the minimum sum of the sum of ship fuel replenishment cost, arrival delay penalty cost and carbon tax cost is established to optimize the speed and refueling strategy of cruise ships. The results show that with the change of fuel price and time constraints, the fuel replenishment strategy will also change.

1. Introduction
In recent years, with the increasing development and maturity of cruise tourism, its economic benefits are accompanied by various environmental problems. In order to comply with the relevant regulations of the ECA, the emission control area is a product of the development of green shipping, and the use of low-sulfur fuel oil in the ECA can be changed to meet the emission requirements, but the price of low-sulfur fuel is high, and the fuel cost accounts for about 2/3 of the total operating costs, so the use of low-sulfur fuel oil has caused certain economic pressure on cruise companies. Ref.[1] allows for an effective compromise between the cost and time of navigation by optimizing the speed inside and outside the ECA. Ref.[2] studied the impact of ship speed changes on total SO2 emissions and fuel costs under the premise of constant voyage time and shipping schedule, and concluded that speed optimization inside and outside the ECA can save a lot of costs.

Among the means to reduce CO2 emissions, the carbon tax policy is widely adopted in various countries, and reducing the speed of ships is the most direct and effective way to reduce carbon emissions. Ref.[3] pointed out that slowing down can reduce fuel consumption and carbon dioxide emissions. Considering the changes in fuel prices and CO2 emissions, Ref.[4] optimizes the solution of the fuel replenishment strategy and speed of ships, and suggests that liner companies should reasonably set the ambiguity of fuel prices and carbon tax rates.

Most of the research on routes is liners, and there are relatively few studies on cruise ships. Zhen Lu et al.[5] considered emission control areas, but they ignored the impact of carbon tax costs on shipping speed, especially in the current era of vigorously reducing greenhouse gas emissions.

When taking into account ECA, carbon tax costs, fuel costs, and arrival time constraints at each port, there are few studies on cruise ship speed. In view of this, this paper proposes a mixed integer nonlinear programming model with arrival time constraint, consideration of ECA navigation restriction and refueling strategy, with speed as the decision variable, and the minimum sum of fuel replenishment cost, arrival delay penalty cost and carbon tax cost as the objective function, and optimizes the solution by MATLAB software, so as to enrich and improve the cruise speed optimization theory.

2. Problem description and modeling
2.1. Problem description

On the premise of predicting the distance between ports in the order of arrival inside and outside the emission control area, the time window of each port, the oil price of each port and other relevant data of the ship during the planning period, this paper proposes a speed optimization model for N fixed routes with arrival time limits, and uses the model optimization to determine the refueling volume of the port of call and the sailing speed inside and outside the emission control area, with the overall goal of minimizing the operating cost of cruise ships in the whole voyage. Among them, the influence of tank capacity on the refueling volume in Hong Kong is considered. The effect of speed on fuel consumption; restrictions on arrival time windows; Fuel consumption limits and other constraints for the sector.
2.2. Model assumptions

The assumptions in this paper are as follows:
1) Ignore the time of fuel switching.
2) Ignore the impact of cruise weight on fuel consumption, and take the weight at the time of departure.
3) The port call sequence has been determined.
4) The average entry and exit and waiting time of different ports are the same, and the average value is 9h.

2.3. Symbol definition

\[ M \] \text{: Sufficiently large positive number; } \quad \text{A: Port collection } \{1, 2, \ldots, n, n+1\}, \text{ and } n+1 \text{ are both departure ports; } \quad F_{i,i+1}^E \text{: The amount of MGO fuel consumed by the host when the cruise ship travels from port } i \text{ to port } i+1 \text{ within the ECA area, } t; \quad F_{i,i+1}^N \text{: The amount of HFO fuel consumed by the main engine of the cruise ship from port } i \text{ to port } i+1 \text{ outside the ECA area, } t; \quad F_{i,i+1}^M \text{: MGO fuel consumption of auxiliary aircraft when the cruise ship travels from port } i \text{ to port } i+1, t; \quad c_p \text{: MGO price, USD/t; } \quad c_v \text{: HFO price, USD/t; } \quad T_{i,i+1}^E \text{: The time of the cruise ship sailing from port } i \text{ to port } i+1 \text{ within the ECA area, } h; \quad T_{i,i+1}^N \text{: The time the cruise ship sail to from port } i \text{ to port } i+1 \text{ outside the ECA area, } h; \quad T_{i,i+1}^M \text{: The time it takes for the cruise ship to sail from port } i \text{ to port } i+1, h; \quad T_i \text{: The length of stay of the cruise ship at port } i, h; \quad D_{i,i+1}^N \text{: The distance traveled by the cruise ship from port } i \text{ to port } i+1 \text{ in the ECA area, n mile; } \quad D_{i,i+1}^N \text{: The distance traveled by the auxiliary aircraft from port } i \text{ to port } i+1 \text{ outside the ECA area, the distance traveled by the cruise ship from port } i \text{ to port } i+1, n mile; \quad v_{min} \text{: The minimum value of the speed on the route, km/h; } \quad v_{max} \text{: The maximum value of the speed on the route, km/h; } \quad \lambda_{E} \text{: Carbon emission factor of MGO; } \lambda_{X} \text{: Carbon emission factor of HFO; } \epsilon \text{: Carbon tax rate, USD/t; } \quad EM_{E} \text{: Carbon emission cost of cruise ships, USD/d; } \quad P_{E} \text{: The time when the cruise ship arrives at port } i, h; \quad P_{L} \text{: The lower limit of the time window for the cruise ship to arrive at the port } k, h; \quad Q_{K} \text{: The upper limit of the time window for the cruise ship to arrive at the port } k, h; \quad v_{min} \text{: The speed of the cruise ship from port } i \text{ to port } i+1 \text{ within the ECA area, kn; } \quad v_{max} \text{: The speed of the cruise ship from port } i \text{ to port } i+1, kn; \quad s_{i} \text{: Whether the cruise ship is port } i \text{ at the kth port of call, yes is equal to 1, no is equal to 0; } \quad D_{E}^F \text{: MGO remaining at port } i, t; \quad D_{H}^N \text{: HFO remaining at the time of arrival and departure of the cruise ship, t; } \quad W_{E} \text{: Cruise MGO tank capacity, t; } \quad W_{N} \text{: Cruise HFO tank capacity, t; } \quad \alpha \text{: Whether the cruise ship adds MGO at the port } i, \text{ is equal to 1, or is equal to 0; } \quad \beta \text{: Whether the cruise ship adds HFO at the port } i, \text{ yes is equal to 1, no is equal to 0; } \quad x_{i} \text{: The refueling volume of the MGO corresponding to the cruise ship at port } i, t; \quad y_{i} \text{: The amount of HFO refueling corresponding to the cruise ship at port } i, t. \]

2.4. Parameter relationships

The total operating costs of a round-trip cruise considered in this article include the cost of refueling the cruise, the cost of arrival delay penalty, and the cost of carbon tax.

2.4.1 Cruise fuel replenishment costs

The fuel cost of the voyage includes two parts: the fuel cost of the main engine and the fuel cost of the auxiliary engine. When the cruise ship is sailing in the ECA, the main engine uses HFO (heavy fuel oil) for the cruise outside the sulphur emission control area, and MGO (light diesel oil) is used as fuel in the sulfur emission control area. Auxiliary aircraft are all operated on the route using MGO (light diesel oil).

1) Main engine fuel cost

The daily fuel consumption of the main engine of the ship is proportional to the cubic of the sailing speed, then the fuel consumption of the main engine of the cruise ship is:

\[
F_{i,i+1}^E = P_{M}^E \cdot \left( \frac{v_{i,i+1}^E}{V_d} \right)^3 \cdot T_{i,i+1}^E
\]

2) Auxiliary fuel costs

The fuel consumption of the auxiliary engine is independent of the cruise speed, and is only composed of the consumption of the fixed components of the ship, then the daily MGO consumption of the auxiliary engine is:

\[
F_{i,i+1}^A = SFOC^A \cdot EL^A \cdot P^A \cdot \left( T_{i,i+1}^E + T_{i,i+1}^N + T_i \right) \cdot 10^{-6}
\]

Among them, \( P^A \) is the auxiliary horsepower of the cruise ship (KW); \( SFOC^A \) is the fuel consumption rate of the auxiliary engine, which is 221g/KW∙h; \( EL^A = 0.8 \) is the auxiliary load. \( C^A \) is the fuel cost when the cruise auxiliary engine consumes fuel.

2.4.2 Late arrival penalty costs

To improve service levels, this article considers ports with
time windows, and late arrival penalties for cruise ships will incur a late arrival penalty. Assuming that the time window of the kth port of the cruise voyage is \( [P_k, Q_k] \), the delay cost per unit time is \( \beta_i \), and the cruise ship arrives at port \( i \) for \( d_i \), then the arrival delay penalty cost is:

\[
\sum_{i=1}^{n} \beta_i [d_i - Q_i]
\]  

Among them, \([d_i - Q_i] = \max \{d_i - Q_i, 0\}\).

### 2.4.3 Cost of carbon tax

This article takes the cost of carbon tax into account in the total cost of operation. The cost of carbon emissions is the product of the tax rate \( e \), the carbon emission factor and the fuel emissions. Then the total carbon tax cost is:

\[
EM_e = e \lambda_k \cdot \sum_{i=1}^{n} \left( F_i^{E} + F_i^{A} \right) + e \lambda_N \cdot \sum_{i=1}^{n} F_i^{N}
\]  

### 2.5. Model Building

\[
\text{Min} C = (c_k + e \lambda_k) \cdot \sum_{i=1}^{n} \left( F_i^{E} + F_i^{A} \right) + (c_N + e \lambda_N) \cdot \sum_{i=1}^{n} F_i^{N} + \sum_{i=1}^{n} \beta_i [d_i - Q_i]
\]  

\[
T_{i+1}^{E} = \frac{D_i^{E}}{v_{i+1}^{E}}
\]  

\[
T_{i+1}^{N} = \frac{D_i^{N}}{v_{i+1}^{N}}
\]  

\[
T_{i+1} = T_{i+1}^{E} + T_{i+1}^{N}
\]  

\[
d_i = 0
\]  

\[
d_i + T_i + P_{i+1} = d_{i+1}, i \in A
\]  

\[
d_i - M (1 - s_a) \leq Q_i, i \in A, k \in K
\]  

\[
d_i + M (1 - s_a) \geq P_k, i \in A, k \in K
\]  

\[
\sum_{i=1}^{n} s_a = 1, i \in A
\]  

\[
x_i \leq W_e, i \in A
\]  

\[
y_i \leq W_N, i \in A
\]  

\[
D_{i+1}^{E} + x_i - T_i \cdot SFOC^E \cdot \text{EL} \cdot P^A \cdot 10^{-6} \geq F_{i+1}^{E}
\]  

\[
D_{i+1}^{N} + y_i \geq F_{i+1}^{N}, i \in A
\]  

\[
v_{\text{min}} \leq v_{i+1}^{E} \leq v_{i+1}^{N} \leq v_{\text{max}}, i \in A
\]  

\[
20\%a_iW_e \leq x_i \leq a_iW_e
\]

The objective function is the sum of minimized bunkering costs, arrival delay penalty costs, and carbon tax costs. Among them, equation (10) ~ equation (12) indicates the sailing time of the cruise ship. The total voyage time of the cruise ship is equal to the sum of the time spent sailing within the ECA and the time spent sailing outside the ECA. Equation (13) ~ Equation (14) is the time constraint of the cruise ship arriving at the port. Equation (15) ~ Equation (17) indicates that the time for the cruise ship to arrive at each port must meet the time window constraints of that port. Equation (18) indicates that the refueling volume of a single MGO must not exceed the maximum tank capacity of the MGO. Equation (19) indicates that the amount of HFO refueling in a single pass must not exceed the maximum tank capacity of the HFO. Equation (20) indicates that the cruise ship's MGO reserves at the time of departure from the port must meet the consumption of the next leg of the voyage. Equation (21) indicates that the cruise ship's HFO reserves at the time of departure from the port must meet the consumption of the next leg of the voyage. Equation (22) is the speed constraint of the cruise ship. Formula (23) ~ Formula (24) is the range of refueling volume. Equation (25) ~ Equation (26) indicates that \( s_a, a_i, \) and \( \beta_i \) are all 0-1 decision variables.

### 3. Instance verification and analysis

#### 3.1. Data Collection

Taking the cruise route in New England as an example, the cruise ship departs from New York, USA, passes through Halifax, Canada, Sydney, Canada, Nuuk, Greenland, Nanortalik, Greenland, St. John's, Canada, and finally returns to New York. See Table 1 for route information. The total length of the route is 5849 n mile and the total length of the ECA segments is 1606 n mile, which is a percentage of 27.5 ECA segments. Based on the corresponding model parameter values in the Forth IMO GHG Study 2020 report, Table 2 lists the selected values for the parameters when solving the model.

<table>
<thead>
<tr>
<th>Table 1. Data for ship navigation</th>
<th>Port</th>
<th>Distance</th>
<th>Time window</th>
</tr>
</thead>
<tbody>
<tr>
<td>New York</td>
<td>545</td>
<td>438</td>
<td>892</td>
</tr>
<tr>
<td>Halifax</td>
<td>235</td>
<td>0</td>
<td>235</td>
</tr>
<tr>
<td>Sydney</td>
<td>286</td>
<td>1471</td>
<td>1757</td>
</tr>
<tr>
<td>Nuuk</td>
<td>0</td>
<td>326</td>
<td>326</td>
</tr>
<tr>
<td>Nanortalik</td>
<td>199</td>
<td>741</td>
<td>940</td>
</tr>
<tr>
<td>St. John</td>
<td>432</td>
<td>1267</td>
<td>1699</td>
</tr>
<tr>
<td>New York</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>
### 3.2. Model results

#### 3.2.1 Analysis of optimization results

Based on the data presented in Table 1 and Table 2, this paper uses the self-written code of MATLAB software to obtain the optimal decision scheme to satisfy the objective function, and the results are shown in Table 3. According to the calculation results, the total operating cost is 841,627.39 US dollars, the total fuel consumption cost is 688,251.17 US dollars, the total carbon tax cost is 153,376.22 US dollars, and the total CO₂ emission is 4511.06 tons. Due to the high price of low-sulphur fuel used in the ECA, cruise lines generally use the lowest possible speed during the ECA segment and then increase the speed of the outer ECA segment to meet the port's time window. According to the results of bunkering port selection, considering the distance between different ports, the optimal bunkering strategy selects the bunkering port with the lowest fuel price as much as possible, and the bunkering volume in the port with low fuel price is higher than that at the port with high fuel price, so the model can not only ensure that the ship arrives at the port according to the predetermined time range, but also minimize the total cost.

#### 3.2.2 Sensitivity analysis of ECA scope and fuel cost

As shown in Figure 1, when the distance traveled by a cruise ship in the ECA increases, that is, the proportion of the cruise ship travels in the ECA increases in the total voyage, the fuel cost of the cruise operator increases as the speed in the ECA continues to decrease.

### 4. Conclusion

From the perspective of energy conservation and emission reduction, this paper studies the speed and fuel replenishment strategy of cruise ships in the context of carbon emissions and ECA. Taking the summing of the sum of the fuel replenishment cost, the arrival delay penalty cost and the carbon tax cost as the objective function, a mixed integer nonlinear programming model with 0-1 variables is established by considering the port refueling strategy and speed optimization in the constraints. On this basis, a simulation experiment was carried out on the cruise route in New England as an example, and the model was solved by MATLAB software to obtain the speed optimization and refueling strategy of each port on each flight segment, and the sensitivity analysis of the ECA range was carried out to test the influence of the parameter change range on the numerical results. According to the results of numerical experiments, it is more economical and reasonable for cruise ships to adopt different sailing speeds in each leg than single speeds. It is necessary for cruise operators to reduce operating costs by adopting different refueling strategies according to different prices.

With the gradual deepening of the attention of countries to marine environmental issues, the ECA area will become larger and larger, so the function of reducing the speed in the ECA and increasing the speed outside the ECA is becoming weaker and weaker, which requires scientific researchers in the shipping industry to actively explore other solutions, such as the use of smoke cleaners as future research directions. In addition, other uncertainties such as ship breakdowns and port congestion are also topics that need to be studied.

### References


