System Dynamics Simulation Research on Ship Emission Control Area Policy

Zheng Wang 1*, Ying Liu 2,3, Cui-hong Qin 1, Wei Zhang 1

1 China Waterborne Transport Research Institute, Beijing 100088, China,
2 China Meteorological Administration, Beijing, 100081, China
3 School of Government, Beijing Normal University, Beijing 100875, China.
*Corresponding author e-mail: wangzh@wti.ac.cn

Abstract. The ship emission control area policy involves multiple stakeholders. This paper studies the behavior selection and its influencing factors of the maritime administrative department and shipping enterprises in the policy implementation, and constructs the system dynamics model of the evolutionary game of the ship emission control area policy. The model is used to analyze the dynamic impact of different fuel costs on the strategic choices of both parties in policy implementation. The results show that the cost of low-sulfur oil has a significant impact on the behavior of shipping companies. The government management department should reasonably formulate relevant incentive policies and fuel oil supply guarantee mechanisms to ensure the smooth implementation of the ship emission control area policy.

1. Introduction

Shipping is an important part of the global transportation industry and its importance is still increasing. Although shipping is an important means of transportation, its negative impact on the atmospheric environment is also increasing. Marine engines release a variety of atmospheric pollutants into the atmosphere during combustion [1]: carbon dioxide (CO2), nitrogen oxides (NOx), sulfur dioxide (SO2), particulate matter (PM), volatile organic compounds (VOCs) and black carbon. (BC), etc.

China is a big shipping country. In the past five years, the average cargo throughput of domestic rivers and coastal transportation has reached 4.721 billion tons and 8.631 billion tons [2]. The number of international voyages carrying international trade in import and export of goods has reached more than 150,000 ships. China's inland rivers and coastal vessels have a large amount of activity, and ship emissions mainly occur within 200 kilometers from the coast [3]. The contribution to air pollution along the rivers and coastal areas in China cannot be ignored.

In order to improve the severe environmental pollution situation, the Ministry of Transport issued the "Pearl River Delta, Yangtze River Delta, Bohai Sea (Beijing-Tianjin-Hebei) Waters Ship Emission Control Area Implementation Plan" and "Ship Air Pollutant Emission Control Area Implementation Plan " in 2015 and 2018. Improve the environmental air quality of China's coastal and riverside areas, especially port cities, by controlling the discharge of pollutants such as sulfur oxides, nitrogen oxides and particulate matter in ships navigating, berthing, and operating in the emission control area. Raws and green shipping development.

As a new policy, the ship emission control area policy involves multiple stakeholders. What factors will be driven by various stakeholders in the policy implementation process, and its behavior will have an impact on policy implementation. It is worth discussing at this stage.
System Dynamics (SD, System Dynamics) focuses on the dynamic and causal effects of the system, and can solve complex problems in the case of incomplete information. It is an effective simulation method for studying information feedback behavior in complex systems. SD provides an effective aid for the dynamic evolution of systems under the condition of incomplete information [4]. At the same time, in the process of policy implementation, how to make decisions among various stakeholders can be regarded as a game problem. Therefore, this paper uses the combination of evolutionary game and system dynamics to study the simulation of ship emission control area policy, and analyzes the dynamic impact of different factors on the implementation process of ship emission control area policy.

2. Ship emission control area policy model

2.1. Problem Description and Model Hypothesis
This study regards the implementation process of the ship emission control area policy as a game process, and assumes that only the maritime administrative departments and shipping companies involved in the implementation of the ship emission control area policy. In the game of policy implementation, the strategic choices of both sides of the game are random, so the mixed strategy game model is used to describe the ship emission control area policy.

According to the requirements of relevant laws and regulations, the ship should use the low-sulfur fuel or the exhaust gas treatment device that meets the requirements after entering the ship emission control area. Due to the higher price of the higher sulfur fuel, the cost of the shipping enterprise is increased. The profit space, but the purpose of the shipping company is to maximize the benefits, driven by the interests of the shipping companies have the motive of violating the rules, their behavior decisions can be divided into two: compliance rules and violations. Suppose the company takes the violation behavior by the probability $\theta$ ($0 \leq \theta \leq 1$), the cost of the shipping company using low-sulfur fuel is $d$, and the cost saving if using the illegal fuel is $e$.

As the executive unit of the ship emission control area policy, the maritime administrative department aims to minimize the supervision cost while ensuring the effective implementation of the policy. The cost of conducting a comprehensive fuel compliance inspection for all vessels in the jurisdiction is quite high, so the maritime administration has two options for inspection and non-inspection of the fuel compliance of shipping companies. It is assumed that the maritime administrative department checks the fuel condition of the shipping enterprise with the probability $\gamma$ ($0 \leq \gamma \leq 1$), the cost of the inspection is $c$, the technical supervision fee is $a$, and the government department may add the supervision fee $b$ in the future; the maritime administrative department checks The fine for finding violations is $f$, and the policy subsidy for enterprises actively adopting exhaust gas aftertreatment and shipbuilding transformation is $g$.

| Maritime management strategy | Inspection rate ($\gamma$) | No Inspection rate ($1-\gamma$) |
|-----------------------------|---------------------------|---------------------------------|
| Shipping company strategy   | Violation ($\theta$)      | (e, -a-b)                      |
|                             | By Regulations ($1-\theta$)| (-d+g, -a-c-g)                 |

Table 1. The return matrix of the game between the maritime administration and the shipping company

2.2. Establishment of evolutionary game model
Assume that the expected and average expected benefits of "Inspection rate" and "No inspection rate" are $E_mY$, $E_mN$ and $E_m$ respectively. According to the game model hypothesis and revenue matrix in Section 1.1.

\[ E_{mY} = \theta * (f-a-b-c) + (1-\theta) * (-a-c-g) \]
\[ E_{mN} = \theta*(-a-b)+ (1-\theta) * (-a) \]
According to the principle of evolutionary game, if the fitness or payment of a strategy is higher than the average fitness of the population, the strategy will develop in the population, and the growth rate of the proportion of individuals using a strategy in the population is greater than zero. This is the replication dynamic equation. The replication dynamic equation is actually a dynamic differential equation describing the frequency or frequency at which a particular strategy is used in a population. Then, the replication dynamic equation of government strategy is constructed as follows:

\[
F(\gamma) = \frac{d\gamma}{dt} = \gamma (E_{mY} - E_m) = \gamma \star (1 - \gamma) \star (\theta f - c - g + \theta g)
\]

Assuming that the expected revenue and average expected revenue of the shipping enterprise "By Regulations" and "Violation" are respectively \(E\) and \(E_{eY}E_{eN}\) And \(E\), it can be obtained by the same logic:

\[
E_{eY} = \gamma \star (e - f) + (1 - \gamma) \star e
\]

\[
E_{eN} = \gamma \star (-d + g) + (1 - \gamma) \star (-d)
\]

\[
E_e = \theta \star E_{eY} + (1 - \theta) \star E_{eN}
\]

The replication dynamic equation of enterprise strategy is:

\[
G(\theta) = \frac{d\theta}{dt} = \theta (E_{eY} - E_e) = \theta \star (1 - \theta) \star (\gamma e - \gamma f - \gamma e - \gamma g + d)
\]

2.3. System Dynamics Evolution Model

According to the game model established in 1.2, this paper uses Vensim PLE software to establish the system dynamics model of ship emission control area policy evolution. The system dynamics model flow diagram is shown in Figure 1.

Figure 1. SD model flow diagram for ship emission control area policy evolution

The model consists of four stocks, two flow rate variables, seven external auxiliary variables and 17 intermediate variables. The four stocks represent the proportion of the "Inspection - No inspection" strategy and the "Violation - By Regulations" strategy adopted by the government and shipping companies in the ship emission control area policy; the two flow rate variables respectively indicate that the maritime administration has adopted the "Inspection - No inspection" rate of change of the strategy and the rate of change of the "Violation - By Regulations" strategy; the seven external auxiliary variables correspond to the seven variable parameters in the game income matrix of Table 1.

3. Model simulation analysis

3.1. Model settings
The initial conditions of the model are assumed as follows: Simulation start time INITIAL TIME = 0, simulation end time FINAL TIME = 100, simulation step size TIME STEP = 0.25. The model initial data sets the external auxiliary variable initial values as shown in Table 2.

| Symbol | Meaning                                                                 | The initial value |
|--------|-------------------------------------------------------------------------|-------------------|
| $a$    | Technical supervision cost                                              | 2                 |
| $b$    | Additional regulatory costs are likely in the future                    | 1                 |
| $c$    | The Cost of inspection                                                  | 2                 |
| $d$    | The cost to The shipping companies of using low sulfur fuel             | 1                 |
| $e$    | Save money when using illegal fuel                                      | 3                 |
| $f$    | Illegal fines                                                           | 6                 |
| $g$    | The government subsidies                                                | 1                 |
| $\gamma$ | The Check rate                                                        | $[0, 1]$         |
| $\theta$ | Violations rate                                                        | $[0, 1]$         |

3.2. Model Simulation and Results Discussion

The cost of fuel is the main cost of shipping companies. The cost of using low-sulfur fuel directly affects the choice of behavioral strategies of shipping companies in implementing policies. Assume that both sides of the game start the game with the initial strategy ($\gamma = 0.5, \theta = 0.5$), that is, when both the government and the shipping companies adopt a 50% summary strategy, they will examine the system by changing the size of the "low sulfur oil use cost". influences. The simulated simulation results of various strategic changes under different low-sulfur oil use costs are shown in Figure 2 and Figure 3. In the figure, $1x_{\text{cost}}$, $2x_{\text{cost}}$, and $3x_{\text{cost}}$ represent 1x, 2, and 3 times the cost of low sulfur oil, respectively.

Figure 2. Evolutionary process diagram of each party under different low sulfur oil use costs
Figure 3. Evolution of various strategies under different low sulfur oil use costs

As can be seen from Fig. 2 and Fig. 3, the game cycle increases with the increase of subsidy fees; and with the increase of the use cost of low-sulfur oil, the violation rate of shipping companies gradually increases until it stabilizes at 86%. Maritime Administration inspection rate is gradually increasing and is stable in the full inspection strategy. In summary, the use cost of low-sulfur oil is an important indicator affecting the strategic choice of shipping companies. When the cost is too high, even if the maritime management department adopts a 100% inspection rate, most shipping companies will choose a “violation strategy”.

Based on the results of the above model simulation analysis, the following recommendations are made for the maritime management department to formulate and implement the ship emission control policy:

1) Reasonable control policy incentive fees
   Through the simulation analysis of the impact of changes in policy incentive fees on the behavior of shipping companies, it can be seen that the government's appropriate increase in policy incentive fees can promote the implementation of policy behaviors by shipping companies and promote the smooth implementation of policies.

2) Improve the ship's low sulfur fuel supply guarantee mechanism
   The simulation results show that when the supply of low-sulfur fuel is insufficient, the cost of using low-sulfur fuel for shipping companies will continue to rise, and the shipping companies' demand for oil can not be met, and a countermeasure strategy will be adopted. Therefore, the government should establish a sound supply mechanism for low-sulfur oil supply to ensure the supply of low-sulfur fuels, reduce the cost of using low-sulfur fuels for shipping companies, and ensure the smooth implementation of the ship emission control area policy.

4. Conclusion
   1) Based on the combination of evolutionary game and system dynamics, the effective implementation of the policy implementation of the ship emission control area can be simulated, that is, the external dynamic factors of the policy can be analyzed, and the strategic behaviors of the parties after the policy implementation can be obtained. The ship emission control area policy provides new research ideas.

   2) The government management department should reasonably formulate relevant incentive policies and fuel oil supply guarantee mechanisms to ensure the smooth implementation of the ship emission control area policy.
Acknowledgments
This work was supported by the National Key Research and Development Program of China (No. 2016YFC0208300, No. 2016YFC0208301, No. 2016YFC0208302).

References
[1] Lloyd’s Register of Shipping (LR): Marine Exhaust Emissions Research Programme[D], Lloyd’s Register Engineering Services, UK, London, 1995.
[2] Ministry of Transport of China. Statistical Bulletin of the Development of the Transportation Industry in 2018 [R]. 2019
[3] WANG Zheng, ZHANG Wei, PENG Chuansheng. Study on Characteristics of Ship Emissions from Surrounding China Seas [J]. Energy Conservation & Environmental Protection in Transportation, 2018(14):11-15
[4] ZHU Qing-hua, WANG Yi-lei, Tian Yi-hui. Analysis of an Evolutionary Game between Local Governments and Manufacturing Enterprises under Carbon Reduction Policies Based on System Dynamics [J]. Operations Research and Management, 2014, (3) : 71-82.
[5] Friedman D. Evolutionary games in economics[J]. Econometrica, 1991, 59(3) : 637-666.