Analysis of the impact of differentiated carbon tax policies on shore power technology selection by port and shipping enterprise

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Abstract. Reducing carbon emissions has become a common goal in today's world for the protection of the environment, and the shipping industry, as an important force in the development of global trade, will be unavoidable involved in this conversion. This research paper develops an evolutionary game model between port and shipping enterprise under the differentiated carbon tax policy, analyses the evolutionary stabilization strategies between port and shipping enterprise, and explores the influence of relevant influencing factors on the evolutionary path. The results show that the differentiated carbon tax policy can effectively incentive port and shipping enterprise to adopt shore power technology, and the greater the difference between carbon taxes the more obvious the promotion effect of shore power. In addition, lowering the construction and operation costs for port and shipping enterprise to use shore power technology, and increasing other costs of not using shore power technology can contribute effectively to the willingness of shipping companies to utilize shore power.

1. Introduction

With shipping accounting for about 80% of global trade transportation and 2.89% of global greenhouse gas emissions, there is an urgent need to reduce carbon emissions from the shipping industry[1]. Lately, the International Maritime Organization (IMO) has been considering the possibility of introducing a global shipping carbon tax, which would be levied based on a ship's carbon emissions, with the proceeds supporting the development of low-carbon technologies[2]. But a harmonized carbon tax policy could have a negative impact on smaller shipping enterprises that are less resilient to external risks, meanwhile potentially reducing the overall capacity of the global shipping market[3].

In contrast, a differentiated carbon tax policy could target different ports and shipping enterprises, thereby reducing greenhouse gas emissions more effectively, meanwhile taking into account economic efficiency, fairness and industry competitiveness[4], [5]. In practice, some countries and regions have begun to explore and implement differentiated carbon tax policies. For example, the use of low-carbon or carbon-free fuels is encouraged through the imposition of carbon taxes at different rates on ships using different types of fuels; or tax incentives or subsidies are provided for ships and ports adopting energy-efficient technologies and operational optimization to reward their efforts to reduce emissions[6].

For the purpose of reducing the pollution to the environment caused by power generation from moored ships, more and more experts and scholars have begun to advocate shutting down the auxiliary engines of the ships and connecting the ships with the shore power grid to get power while moored, i.e., utilizing the shore power to generate electricity[7], [8]. However, some ports and shipping enterprises are reluctant to adopt shore power due to its high construction and operating costs. Therefore, how to promote the use of shore power in ports and shipping enterprises has become a hot topic of concern today.

This paper focuses on the decision behavior of port and shipping enterprise on whether to utilize shore power and its interaction under the guidance of differentiated carbon tax policy, and analyses the dynamic evolution process and steady state of the two parties under different combinations of strategies through the perspective of evolutionary game theory.

2. Evolutionary game model construction and solving

2.1. Specimens results

The participants of the game are ports and ship enterprises, both of which are finite rational beings and will pursue the maximization of their own utility. Among them, the probability that the port "uses shore power" in the strategy of using shore power is \(x\) (\(0 \leq x \leq 1\)), then \(1 - x\) is the probability of "not using shore power". Meanwhile, assuming that the probability of ship enterprises "using shore power" is \(y\) (\(0 \leq y \leq 1\)), then \(1 - y\) is the probability of "not using shore power".

When the port chooses to carry out the "use of shore power" strategy, it needs to pay the corresponding...
construction costs $C_{p1}$, in addition, the construction of shore power, after the adoption of shore power technology, the use of shore power for the port of the incremental revenue for the port of $I_1$, but the port needs to bear a certain degree of shore power operation and maintenance costs $C_{p2}$.

Similarly, when the port chooses to carry out the "use of shore power" strategy, meanwhile, the ship enterprise chooses the "use of shore power equipment" strategy, at this time, the ship enterprise needs to bear the cost of transforming the shore power system as $C_{s2}$, the incremental revenue of the ship after adopting the shore power technology as $I_2$. When ports or ship enterprises use shore power technology, they need to pay carbon tax as $T_1$; when they do not use shore power technology, they need to pay carbon tax as $T_2, T_1 > T_2$.

### 2.2. Construction of the model and its solution

According to the previous hypotheses, the payoff matrix of game between port and shipping enterprise is established (see Table 1).

<table>
<thead>
<tr>
<th>Implementation of shore power</th>
<th>Accepting shore power</th>
<th>No shore power accepted</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{p0} - T_1Q_2 - C_{p1} - C_{p2}$</td>
<td>$R_{p0} - T_1Q_2 - C_{p1} - C_{p2}$</td>
<td></td>
</tr>
<tr>
<td>$I_1, R_{s0} - T_1Q_4 - C_{s0} - C_{s1} - C_{s2}$</td>
<td>$R_{s0} - T_1Q_4 - C_{s0} - C_{s1} - C_{s2}$</td>
<td></td>
</tr>
<tr>
<td>No implementation of shore power</td>
<td>$R_{p0} - T_2Q_1$</td>
<td>$R_{p0} - T_2Q_1$</td>
</tr>
<tr>
<td>$R_{s0} - T_2Q_3 - C_{s3}$</td>
<td>$R_{s0} - T_2Q_3 - C_{s3}$</td>
<td></td>
</tr>
</tbody>
</table>

The expected benefit of "not accepting shore power" is:

$$U_{22} = x(R_{s0} - T_2Q_3 - C_{s3}) + (1 - x)(R_{s0} - T_2Q_3 - C_{s3})$$

Then the average return is:

$$U_2 = yU_{21} + (1 - y)U_{22}$$

The replicated dynamic equation for the shipping enterprises is:

$$F(y) = y(y - 1)(C_{s0} + C_{s1} + C_{s2} - C_{s3} - T_2Q_3 + T_1Q_4 - I_2x)$$

### 2.3. Equilibrium strategy analysis for evolutionary game models

Setting the dynamic equations for replication equalized to zero results in four pure strategy equilibrium points, obtain the 5 equilibrium points of this game matrix: $O(0, 0), A(1, 0), B(0, 1), C(1, 1), D[ (C_{s0} + C_{s1} + C_{s2} - C_{s3} - T_2Q_3 + T_1Q_4)/I_2 , (C_{p1} + C_{p2} - T_2Q_1 + T_1Q_2)/I_1 ]$The Jacobi matrices calculated from the dynamic equations for the replication of harbour and shipping companies are as follows:

$$J = \begin{bmatrix} (2x - 1)(C_{p1} + C_{p2} - T_2Q_1 + T_1Q_2 - I_2y) & -I_1x(y - 1) \\ -I_2y(y - 1) & \frac{dF(y)}{dy} \end{bmatrix}$$

$$dF(y)/dy = c_{22} = (2y - 1)(C_{s0} + C_{s1} + C_{s2} - C_{s3} - T_2Q_3 + T_1Q_4 - I_2x)$$

Taking the equilibrium points, and bringing them into and , respectively, results are obtained about the system equilibrium points corresponding to the following table 2.

<table>
<thead>
<tr>
<th>Equilibrium points</th>
<th>Det(J)</th>
<th>Tr(J)</th>
<th>Stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>O (0, 0)</td>
<td>+</td>
<td>-</td>
<td>ESS</td>
</tr>
<tr>
<td>A (1, 0)</td>
<td>+</td>
<td>+</td>
<td>Unstable</td>
</tr>
<tr>
<td>B (0, 1)</td>
<td>+</td>
<td>+</td>
<td>Unstable</td>
</tr>
</tbody>
</table>
Based on local stability analysis, the equilibrium point is an ESS stable point when $>0$ and $<0$. In this paper, O(0,0) and C(1,1) are analyzed:

(1) O(0,0)

When $Q_2T_2 - C_{p1} - C_{p2} - Q_2T_1 < 0$, $C_{s2} - C_{s0} - C_{s1} - C_{s2} + Q_3T_2 - Q_4T_1 < 0$, the evolutionary stabilization strategy for port and shipping enterprise is (not implemented, not used). If $Q_2T_2 - C_{p1} - C_{p2} - Q_2T_1 < 0$, the port enterprise to implement shore power investment costs (construction costs, technology costs, labour costs, etc.) and the cost of operation and maintenance is large, the port enterprise tends not to implement; if $C_{s2} - C_{s0} - C_{s1} - C_{s2} + Q_3T_2 - Q_4T_1 < 0$, the cost of using shore power for the shipping enterprise is greater than the cost of not using shore power, and the final stabilization point falls at (no implementation, no use), and the evolution path diagram is shown in Figure 1(a).

(2) C(1,1)

When $C_{p1} + C_{p2} - I_1 - Q_1T_2 + Q_2T_1 < 0$, $C_{s0} + C_{s1} + C_{s2} - C_{s0} - C_{s1} - C_{s2} + Q_3T_2 - Q_4T_1 < 0$, the evolutionary stabilization strategy for port and shipping enterprises is (implement, use). If $C_{p1} + C_{p2} - I_1 - Q_1T_2 + Q_2T_1 < 0$, the port implementation of shore power investment costs (construction costs, technology costs, operation and maintenance costs) and the use of shore power by the shipping enterprise is lower than the cost of not using shore power, the incremental benefits for the ship after the adoption of shore power technology is higher, and ultimately stabilized. point falls on (implementation, use), and the evolution path diagram is shown in Figure 1(b).

According to the evolutionary stability point O(0,0) in Table 2, i.e., the port does not put the shore power system into operation, the shipping enterprise does not receive shore power and the port puts the shore power system into operation and the shipping enterprise receives shore power C(1,1), the gaming behaviour reaches stability. A(1,0) and B(0,1), meanwhile, exhibit evolutionary instability, and D($C_{s0} + C_{s1} + C_{s2} - C_{s0} - Q_3T_2 + Q_4T_1)/I_2$, $(C_{p1} + C_{p2} - Q_1T_2 + Q_2T_1)/I_1$) is a saddle point. The evolution process of port and shipping enterprise’s implementation of shore power is shown in Figure 2. Combining this figure with the above analysis, it can be seen that O(0,0) and C(1,1) are the evolutionary stable strategies in the evolutionary game system of port and shipping enterprise. And point D is used as the saddle point, although the specific strategy choice of both parties’ decision-making cannot be determined, the dynamic evolution process of the game between port and shipping enterprise can be obtained through the movement of the saddle point.

![Figure 1. Evolutionary path diagram](image)

![Figure 2. Dynamic evolutionary processes](image)

O(0,0) and C(1,1) are the evolutionary stabilization strategies in the evolutionary gaming system of ports and shipping enterprises. The final evolutionary outcome depends on the magnitude of the probabilities represented by the area of $S_{ADBC}$ and $S_{AOBD}$. If $S_{ADBC} > S_{AOBD}$, the probability that the system converges to (0,0) is less than the probability that (1,1); if $S_{ADBC} < S_{AOBD}$, the probability that the system converges to (1,1) is less than the probability that (0,0). In order for both ports and shipping enterprises to implement shore power, measures should be taken to increase the area of $S_{AOBD}$. Further analysis of the factors affecting the area of $S_{ADBC}$ and $S_{AOBD}$ gives the main factors affecting the evolution path of both sides.

\[
S_{ADBC} = S_{AD} + S_{BDC} = 1 - \frac{1}{2}((C_{s0} + C_{s1} + C_{s2} - C_{s3} - Q_3T_2 + Q_4T_1)/I_2 + (C_{p1} + C_{p2} - Q_1T_2 + Q_2T_1)/I_1) \tag{10}
\]
3. Impact of different influences on evolutionary pathways

3.1. The effect of construction cost $C_{s0}$ on the evolutionary path to shore power use by shipping companies:

Proposition 1. Holding the rest of the factors constant, the larger the construction cost of a shipping enterprise using shore power, the smaller the probability of cooperation between the two parties.

Proof: the more $S_{ADBC}$ is a partial derivative of $C_{s0}$, $\frac{\partial S_{ADBC}}{\partial C_{s0}} = -(2I_2)^{-1} < 0$, and $S_{ADBC}$ is a decreasing function of $C_{s0}$, the greater the probability that the system converges to $(0,0)$.

3.2. Shipping enterprises are required to bear the cost of shore power usage during berthing $C_{s1}$ on the evolutionary path:

Proposition 2. Holding the rest of the factors constant, the greater the cost of shore power usage in the berthing process that the shipping enterprise has to bear, the lower the probability of co-operation between the two parties.

Proof: the more $S_{ADBC}$ is a partial derivative of $C_{s1}$, $\frac{\partial S_{ADBC}}{\partial C_{s1}} = -(2I_2)^{-1} < 0$, and $S_{ADBC}$ is a decreasing function of $C_{s1}$, the greater the probability that the system converges to $(0,0)$.

3.3. The shipping enterprise has to bear the cost of modifying the shore power system $C_{s2}$ on the evolutionary path:

Proposition 3: The greater the cost that the shipping enterprise has to bear to modify the shore power system, the lower the probability of co-operation between the two parties, when the rest of the factors are constant.

Proof: the more $S_{ADBC}$ is a partial derivative of $C_{s2}$, $\frac{\partial S_{ADBC}}{\partial C_{s2}} = -(2I_2)^{-1} < 0$, and $S_{ADBC}$ is a decreasing function of $C_{s2}$, the greater the probability that the system converges to $(0,0)$.

3.4. The effect of cost $C_{s3}$ of not using shore power in shipping enterprises on the evolutionary path:

Proposition 4: The greater the cost to the shipping enterprise of not using shore power, the greater the probability of co-operation between the two parties, holding the rest of the factors constant.

Proof: the more $S_{ADBC}$ is a partial derivative of $C_{s3}$, $\frac{\partial S_{ADBC}}{\partial C_{s3}} = (2I_2)^{-1} > 0$, and $S_{ADBC}$ is an increasing function of $C_{s3}$, the greater the probability that the system converges to $(1,1)$.

3.5. The impact on the evolutionary path of the carbon tax $T_1$ to be paid by port or shipping enterprises adopting shore power:

Proposition 5: Holding the rest of the factors constant, the smaller the carbon tax to be paid by the port or shipping enterprise that adopts shore power technology, the higher the probability of cooperation between the two parties.

Proof: the more $S_{ADBC}$ is a partial derivative of $T_1$, $\frac{\partial S_{ADBC}}{\partial T_1} = -2^{-1}(Q_1I_3^{-1} + Q_2I_1^{-1}) < 0$, and $S_{ADBC}$ is an increasing function of $T_1$, the higher the probability that the system converges to $(0,0)$.

3.6. The impact on the evolutionary path of the carbon tax $T_2$ to be paid by port or shipping enterprises that do not adopt shore power:

Proposition 6: Holding the rest of the factors constant, the larger the carbon tax to be paid by the port or shipping enterprise that has not adopted shore power technology, the higher the probability of cooperation between the two parties.

Proof: the more $S_{ADBC}$ is a partial derivative of $T_2$, $\frac{\partial S_{ADBC}}{\partial T_2} = 2^{-1}(Q_3I_2^{-1} + Q_1I_3^{-1}) > 0$, and $S_{ADBC}$ is an increasing function of $T_2$, the higher the probability that the system converges to $(1,1)$.

3.7. Impact of construction cost $C_{p1}$ on the evolutionary path of inputs for the use of shore power in ports:

Proposition 7: Holding the rest of the factors constant, the greater the construction cost invested in the use of shore power in the port, the lower the probability of co-operation between the two parties.

Proof: the more $S_{ADBC}$ is a partial derivative of $C_{p1}$, $\frac{\partial S_{ADBC}}{\partial C_{p1}} = -(2I_1)^{-1} < 0$, and $S_{ADBC}$ is a decreasing function of $C_{p1}$, the greater the probability that the system converges to $(0,0)$.

3.8. Impact of operating costs $C_{p2}$ on evolutionary pathways for the use of shore power in ports:

Proposition 8: The greater the operating cost of using shore power in the port, the lower the probability of cooperation between the two parties, holding the rest of the factors constant.

Proof: the more $S_{ADBC}$ is a partial derivative of $C_{p2}$, $\frac{\partial S_{ADBC}}{\partial C_{p2}} = -(2I_1)^{-1} < 0$, and $S_{ADBC}$ is a decreasing function of $C_{p2}$, the greater the probability that the system converges to $(0,0)$.

4. Discussion

This study has two theoretical significance. On the basis of domestic and international literature on differentiated carbon tax and port and shipping shore power emission reduction research, this paper reveals the decision-making logic and behavioral motivation of all parties between...
economic interests and environmental protection under the influence of the differentiated carbon tax policy, which can effectively incentive port and shipping enterprise to take emission reduction measures. Secondly, this study provides an in-depth analysis of the economic effects of the differentiated carbon tax policy, and explores the specific manifestations of the policy's incentive effects on ports and shipping enterprises and its impact on the competitiveness of the shipping industry as a whole. The results of the study show that through the enforcement of differentiated carbon tax policies, not only can we enhance the environmental performance of the port and shipping industry and promote the green transformation of the industry, but we can also strengthen the competitiveness of the port and shipping industry in the international arena and promote sustainable development.

The paper has also provided the government with practical policy insights. This paper proposes an innovative strategy to incentive port and shipping enterprises to reduce emissions through the policy of differentiated carbon tax. Firstly, the results of the study can provide guidance for the government to optimize the design of carbon emission reduction policies. By understanding the gaming behaviors of ports and shipping enterprises, the government can adjust the carbon tax rate in a targeted manner to achieve optimal emission reduction. Meanwhile, through the introduction of shore power technology for emission reduction, port and shipping enterprises can reduce carbon emissions and environmental risks, and based on the results of the study, the government can also formulate corresponding motivational policies that encourage port and shipping enterprise to use shore power more often to reduce emissions.

5. Conclusion

This paper analyses whether port and shipping enterprise make use of shore power or not under the consideration of differentiated carbon tax policy, constructs a two-party evolutionary game model of port-shipping enterprise under the consideration of differentiated carbon tax policy, and analyses the influencing factors of the strategy choices of each participant subject in the promotional process of port and shipping enterprise regarding the use of shore power for emission reduction under the differentiated carbon tax policy. The following conclusions are drawn:

(1) The construction and operation cost of shore power technology is negatively correlated with the willingness of port and shipping enterprise to use shore power, i.e., the higher the cost invested in shore power technology, the lower the probability of port and shipping enterprise to use shore power, and vice versa. China's port shore power technology is negatively correlated with the willingness of port and shipping enterprise to use shore power. Therefore, the state should increase the research and extension of technology for shore power, reduce the cost of using shore power technology, and give certain subsidies to incentive port and shipping enterprise to use shore power technology.

(2) The higher the cost to the shipping enterprise of not using shore power, the higher the probability that the shipping enterprise will use shore power. The use of shore power can be promoted by adjusting the costs to shipping enterprise of not using shore power. For example, measures such as increasing the cost of bunker fuel for ships and increasing the environmental costs of using bunker fuel after entering a port could be used to induce shipping enterprise to use shore power.

(3) Differentiated carbon tax policy can effectively promote the use of shore power in ports and shipping enterprise, and the greater the difference between carbon taxes the more obvious the effect of the promotion of shore power. It is found that the higher the carbon tax for port and shipping enterprise not using shore power and the lower the carbon tax for using shore power will finally tend to both sides meanwhile using shore power. Therefore, the differentiated carbon tax policy can effectively promote the use of shore power and enhance the emission reduction effect of port and shipping enterprise. The implementation of this policy will create positive incentives for port and shipping enterprise to promote sustainable development and mitigate climate change.

References