Price and Portcall Frequency Competition in Sea-and-Land transportation supply chain under Carbon Emission Reduction Target

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Abstract. For carbon emission reduction by ports and shipping lines under sea-and-land transportation mode, to build a two-stage transportation supply chain model consisting of two competing ports and one shipping line The profit functions of ports and shipping lines were established to analyze the impact of parameters which are port emission reduction level, port unit emission reduction cost and the proportion of emission reduction cost shared by ports to shipping lines on port handling pricing, portcalls of shipping line and respective profits. The results show that the port emission reduction level and port unit emission reduction cost have a significant impact on decision variables and profits. Conversely, there is no significant impact on the proportion of emission reduction cost shared by ports to shipping lines. Within a certain range, port handling pricing increases as the port emission reduction level and port unit emission reduction cost increase. On the contrary, portcalls of shipping line decreases and individual profits decrease as parameters increase.

Keywords: Carbon emission reduction, sea-and-land transportation, competitive port, port price, portcall.

1. Introduction

More than half of the sea cargo is transported by container ships [1]. The next step in the vertical integration of the port and shipping supply chain will be to consider extending beyond the boundaries of maritime transport to inland intermodal ports [2]. Shipping lines generally organize multimodal transport by signing contracts with waterway carriers and inland transport carriers [3]. The IMO had set a target of reducing carbon emissions by at least 50% from 2008 levels by 2050 and had encouraged policy makers to take measures such as a long-term emissions tax on ports [4]. Song et al. (2016) [5] built model of the horizontal and vertical interactions between ports and liners using a two-stage noncooperative game theory approach. Song and Lyons et al. (2016) [6] considered the competition between two ports, including the import, export and transit traffic of maritime, port, feeder and inland transport, and a static cost model is proposed to test the relative competitiveness of the ports, and a noncooperative game model is developed for two ports and one shipping line. Optimal service pricing for ports and portcall decisions for shipping lines are given. Sang Gao Feng and Meng Yan Ping (2019) [7] investigated the decisions of port and shipping enterprises in carbon emission reduction under different game models and to analyze the effects of different parameters on key variables, which showed the game models of carbon emission reduction of port and shipping lines in two scenarios what are centralized and decentralized. AU Wang J (2021) [8] considered competition and cooperation between two terminals serving partially overlapping hinterlands. Based on a three-stage game, firstly the government sets the emission tax, secondly the container terminal sets the service level, and finally the container terminal sets the emission reduction level and service pricing. The above researches show that it is significant of studying the impact of CO2 emission reduction on ports and shipping lines under the Sea-and-Land transportation.

2. Model

2.1 Competitive port game on handling pricing

In a competitive game, also known as a non-cooperative game, each player makes decisions independently. It can be formulated as a two-stage problem. In the first stage, each port makes a port handling pricing decision, and the port's handling pricing is the price charged to the shipping line. Maximize their profits by making decisions on handling prices. In the second stage, shipping line makes portcall decisions, which means the ratio of shipping lines' ocean vessels calling at two ports,
It shows that
\[ \alpha \leq 2.8a + a \cdot k \cdot t \]
and
\[ (2.8a + b) \cdot q \leq b, \]
which means that the congestion cost of the
\[ E_j = r_j \cdot f_j, \quad j = 1, 2 \quad (2-5) \]
The unit emission reduction cost factors in daily operations after the port facilities are improved are \( r_2 \). The port carbon tax levied by the government is related to the actual amount of carbon emissions from the port, and the unit carbon tax to be paid by the port is expressed as
\[ T_j = k \cdot t_j (1 - f_j) \quad (2-6) \]
The government sets a uniform unit carbon tax price for the two ports as \( k \) \( (k \geq 0) \), the initial unit carbon emissions of the two ports are \( t_1 \) and \( t_2 \). The port apportions the carbon tax to the shipping lines according to a certain percentage, which is expressed as \( \alpha_j \).

The profit function of the shipping line is,
\[ \pi = \sum_j (p^h - c^h_{q, j} - 2W_j - 2S_j) \cdot h \cdot q_j + (p^t - 4W_j - 4S_j) \cdot g \cdot q_j - c^t_{q, j} \cdot q_j - c^t_j \cdot q_j - g_j - H_j \]
s.t. \( 0 \leq q, q_2 \leq 1, q_2 = 1 - q_1 \) \( (2-8) \)

The profit function of the port is,
\[ \pi_j = (W_j - c_j - E_j - T_j) \cdot F_j - M_j \quad (2-9) \]

### 2.2 Optimal Solutions

Lemma 1 For a given port handling price \( W_1 \) and \( W_2 \), in the interval \([0,1]\), the optimal profit of the shipping line \( \pi^* \) for \( q_1 \) is concave. When \( n \geq 1, \frac{\partial^2 \pi^*}{\partial q_1^2} \leq 0 \). It shows that the profit function of the shipping line \( \pi^* \) is a strictly concave function for \( q_1 \) in the interval \([0,1]\), that is, there exists an optimal solution of Eq. \((2-8)\). Lemma 1 is proved. To facilitate the expression of the formula, let:
\[ A_1 = \frac{8a_1(h + 2g)^2}{K_1^2} + \frac{8b_1h^2}{R_1^2} \]
\[ A_2 = \frac{8a_2(h + 2g)^2}{K_2^2} + \frac{8b_2h^2}{R_2^2} \]
\[ B = 2(c_1^2 - c_2^2)h + c_1^2 - c_1^2 + c_2^2 - c_2^2 \]
\[ C = \alpha_2 \cdot t_2 \cdot (1 - f_2) - \alpha_1 \cdot t_1 (1 - f_1) \]

Lemma 2 For a given port price \( W_1 \) and \( W_2 \), the optimal portcall decision of the shipping line is
\[
q_1 = \begin{cases} 
0, D_1 < 0 \\
D_0, 0 \leq D_1 \leq 1 \\
1, D_1 > 1 
\end{cases}
\]

While the \( q_2 = 1 - q_1 \), \( D_1 = \frac{A_1 + B^2 + 2(W_2 - W_1 + k - C)(h + 2g)}{A_1 + A_2} \).

Proposition 1 The optimal decision for a shipping line and two ports is given by the following equation, where \( q_2 = 1 - q_1 \). In practice, the handling pricing at the port is bounded and expressed as \( L_i \leq W_i \leq U_i \). When \( 0 \leq D_1 \leq 1 \), \( L_1 \leq W_1 \leq U_1, L_2 \leq W_2 \leq U_2 \), \( W_1^*, W_2^* \) and \( q_1^* \) are expressed as

\[
w_1^* = \frac{A_1 + 2A_2 + B}{3(h + 2g)} + \frac{c_1 + 2c_2 + f_1 + f_2 + r_1 + r_2 + \frac{(c + 2f_1 - f_2 + r_2 - f_1)(h + 2g)}{3}}{2} (1 - q_1^*) \frac{q_1^*}{2} \]

Proposition 2 Under conditions (2-10), (2-11) and (2-12), the optimal profit expressions for shipping lines and ports are

\[
\pi_1 = 2(h + 2g)(W_1^* - c_1 - f_1 \cdot r_1 - k \cdot t_1 \cdot (1 - f_1)) \cdot q_1^* - \frac{e_1 \cdot f_1^*}{2} (2 - 13)
\]

\[
\pi_2 = 2(h + 2g)(W_2^* - c_2 - f_2 \cdot r_2 - k \cdot t_2 \cdot (1 - f_2)) \cdot (1 - q_1^*) - \frac{e_2 \cdot f_2^*}{2} (2 - 14)
\]

\[
\pi^{ii'} = 2(h + 2g)(W_2^* - W_1^* + C \cdot k) \cdot q_1^* - 2(h + 2g)(W_2^* + A_2 \cdot t_2 \cdot (1 - f_2) + k - A_1^2 \cdot q_1^* - \frac{A_2^2}{2} \cdot q_1^* - A_2 \cdot q_1^* + B \cdot q_1^* - \frac{A_2}{2} + p \cdot t \cdot g + p + h \cdot g - c_2^* - c_1^* (2 - 15)
\]

The profit-optimal solution formula is too long and is expressed succinctly in Section 2. It will be studied numerically in the case study in Section 3.

### 2.3 Analysis

Lemma 3 Under conditions (2-10), (2-11), and (2-12), the effects of the port emission reduction level \( f_2 \), port unit emission reduction costs \( r_1 \) and the proportion of emission reduction costs ascribed to shipping lines \( a_j \) on the decision variables \( W_1^*, W_2^* \) and \( q_1^* \) are expressed as:

\[
(1) \quad \frac{\partial W_1^*}{\partial f_1} > 0, \quad \frac{\partial W_1^*}{\partial f_2} > 0, \quad \frac{\partial W_1^*}{\partial r_1} > 0, \quad \frac{\partial W_1^*}{\partial r_2} > 0, \quad \frac{\partial q_1^*}{\partial f_1} < 0 \quad \text{and} \quad \frac{\partial q_1^*}{\partial f_2} < 0.
\]

\[
(2) \quad \frac{\partial W_2^*}{\partial f_1} > 0, \quad \frac{\partial W_2^*}{\partial f_2} > 0, \quad \frac{\partial W_2^*}{\partial r_1} > 0, \quad \frac{\partial W_2^*}{\partial r_2} > 0, \quad \frac{\partial q_1^*}{\partial r_1} < 0 \quad \text{and} \quad \frac{\partial q_1^*}{\partial r_2} < 0.
\]

\[
(3) \quad \frac{\partial W_1^*}{\partial a_1} < 0, \quad \frac{\partial W_1^*}{\partial a_2} < 0, \quad \frac{\partial W_2^*}{\partial a_1} < 0, \quad \frac{\partial W_2^*}{\partial a_2} < 0, \quad \frac{\partial q_1^*}{\partial a_1} < 0 \quad \text{and} \quad \frac{\partial q_1^*}{\partial a_2} < 0.
\]

The above results indicate that:

1. The unit handling pricing of a port increases with the level of carbon emission reduction of port 1 and increases with the level of carbon emission reduction of port 2; the percentage of port calls by shipping lines decreases with port emission reduction level of the port 1 and increases with the level of carbon emission reduction of port 2.

2. An increase in port unit emission reduction costs is followed by an increase in unit handling pricing at port 2, and the port’s unit handling pricing is more sensitive to an increase in unit emission reduction costs at port 2. However, the unit emission reduction cost of the port increases, and the proportion of calls to port 1 then decreases, with a corresponding increase in the proportion of calls to port 2.

(3) The proportion of emission reduction costs apportioned to shipping lines increases and the unit handling pricing for port 1 then decreases, however, the unit handling pricing for port 2 then increases. In addition, the proportion of emission reduction costs apportioned to shipping lines increases, the proportion of calls to port 1 then decreases, and the proportion of calls to port 2 increases accordingly.

### 3. Case

#### 3.1 Data

The case data is set as follows: define Port 1 as Port S and Port 2 as Port N. Assume that the average daily handling capacity of the port \( K_1 = K_2 = 121700 \) TEU, the inland transportation capacity of the port \( h = 104668 \) TEU, transshipment capacity \( g = 14802 \) TEU. According to the calculation of the tariff of the Eurasian route, the shipping line’s transportation costs, that is, the unit price of the inland container space and the unit price of the transshipment container space is \( h = g = 7250 \) per TEU. Assuming ocean port calls for maritime vessels is 2 times per day and fewer port calls for feeder transport vessels compared to the number of port calls for maritime vessels, set \( p = 1/5 \) in the paper. Due to the lack of real data, the value of the congestion cost factor in the paper is somewhat hypothetical and is set to the port congestion cost factor \( a_1 = 397000 \), which indicates the cost to shipping lines when the port is utilized to its maximum capacity (i.e., extremely long waiting times). Assume that the unit operating cost of the port \( c_1 = c_2 = 180 \) per TEU, the unit emission reduction cost of the port \( r_1 = r_2 = 360 \) per TEU. Port emission reduction level \( f_1 = f_2 = 0.2 \). Port emission reduction investment factor \( e_1 = e_2 = 36 \) million. The port’s share of emission reduction costs associated with shipping lines \( a_1 = a_2 = 0.63 \). Port initial unit carbon emissions \( t_1 = t_2 = 7.5 \) kg per TEU. Assuming hinterland transport capacity \( R_1 = R_2 = 85195 \) TEU. Inland transportation congestion factor \( b_1 = b_2 = 1598200 \). The price of fuel for ship transportation \( c_1^h = c_2^h = 3836 \) per ton and the cost of inland transportation at the port is the same \( c_1^b = c_2^b = 4640 \) per TEU.
3.2 Case Study

(1) The effect of port emission reduction level on decision variables
According to Figure 2, it can be seen that port S handling pricing increases with the level of port emission reduction, and port handling pricing grows from 439.9 per TEU to 493.9 per TEU, which verifies (1) in Lemma 3. In addition, it can be seen that the change in the level of port emission reduction has a greater impact on the handling pricing in port S than in port N. When both port emission reduction levels increase, container handling pricing at port S is generally higher than that at port N. Finally, it can be seen that the growth of the port emission reduction level decreases and the growth increases, varying in the interval of 0.452 to 0.547. This verifies (1) of Lemma 3. When the \( f_1 \) increases, the port's input increases, in order to gain profit, the port will transfer the cost of inputs to the handling pricing, and shipping lines are sensitive to handling pricing, with the increase of port S handling pricing, shipping lines consider the port call in favor of port N, and port N will increase handling pricing with the growth of the container volume of the port call, so that the handling pricing of the two ports to reach an equilibrium.

Figure 2. The effect of port emission reduction level on decision variables

(2) The effect of port unit emission reduction costs on decision variables
According to Figure 3, it can be seen that port S handling pricing increases with the increase in port unit emission reduction costs, and port handling pricing increases from 437.9 per TEU to 467.9 per TEU. This verifies (2) of Lemma 3. In addition, it can be seen that the port unit emission reduction cost has a greater impact on port handling pricing for Port S than for Port N. When both port unit emission reduction costs increase, handling pricing at Port S is generally higher than handling pricing at Port N. Finally, it can be seen that \( q_1 \) decreases if the port unit emission reduction cost grows, and \( q_1 \) increases if \( r_1 \) grows, varying in the interval of 0.473 to 0.526. This verifies (2) of Lemma 3. When the port's unit emission reduction costs increase, the port passes on the increased costs to shipping lines, in order to make a profit, creating an increase in port handling pricing. Shipping lines are sensitive to the handling pricing of the port S, which leads shipping lines to consider increasing the call rate to port N, and accordingly leads to an increase in the handling pricing of port N until the handling pricing of both ports reaches the market equilibrium.

Figure 3. The effect of port unit emission reduction costs on decision variables

(3) The effect of the proportion of emission reduction cost to shipping lines
According to Figure 4, it can be seen that as the percentage of emission reduction apportioned to shipping lines increases, the port's handling pricing increases and remains almost constant at 439 per TEU as it varies within 0.6 to 0.75. This indicates that the port's handling pricing is not sensitive to the percentage of emission reduction apportioned to shipping lines. Similarly, an increase in the percentage of emission reduction apportioned to shipping lines in port S is followed by a corresponding increase in the call rate in port N, with the call rate in port S varying between 0.49 and 0.5. This verifies (3) of Lemma 3 and can show that the decision variables are not sensitive to the parameter of the percentage of emission reductions apportioned to shipping lines.

Figure 4. The effect of the proportion of emission reduction cost to shipping lines
The effect of parameters on port profits and shipping line profit

Table 5 illustrates the effect of $f_j$ and $r_j$ on port profits and shipping line profits and $\alpha_j$ is omitted here as it is not an important parameter.

(a) The effect of $f_j$ on profits

(b) The effect of $r_j$ on profits

Figure 5. The effect of parameters on port profits and shipping line profit

It can be seen that with the growth of $f_j$, the profit of port S decreases, the profit of port N decreases, and the profit of shipping lines decreases as the same. And with the growth of $r_j$, the profit of Port S decreases, the decrease is small, and the profit of Port N increases, the increase is equally small. And the profits of shipping lines fell by a more significant amount. Combined with the data in the graph, it shows that an increase in port handling pricing or an increase in the rate of portcall by shipping lines at either of the two ports does not represent an increase in port profits. In addition, the profits of shipping lines are always higher than the profits of ports in any circumstances.

4. Conclusion

The article considers a two-stage transportation supply chain consisting of two ports and one shipping line in the context of carbon emission reduction and land-sea intermodal transport. The port provides services to shipping lines while making decisions on handling pricing. Shipping lines provide intermodal services for containers from the sender to the consignee by sea and land, and determine the rate of portcall at different ports. A profit model for ports and shipping lines was established to study the effects of port emission reduction levels, port unit emission reduction costs and the proportion of emission reduction costs shared by ports to shipping lines on port handling pricing, shipping line portcall rates, port profits and shipping line profits. The study shows that the level of port emission reduction and port unit emission reduction costs have a significant impact on port handling pricing, shipping line portcall rates, port profits, and shipping line profits, and conversely, the proportional parameters of port apportionment of emission reduction costs to shipping lines have no significant impact. Within a certain range, as the level of port emission reduction and port unit emission reduction costs increase, port handling pricing increases, portcall rates decrease, and profits decrease.

Port and shipping cooperation is common in reality, and future research can consider the cooperation between ports in the hinterland and transshipment markets before playing games with shipping lines on handling pricing and portcall rates. In addition, it is possible to study what impact and changes on the decision and profits of ports and shipping lines in the context of government issued carbon tax and carbon trading systems. Finally, container demand in the shipping industry is uncertain, and future research can be researched under the uncertainty market demand.

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References


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