Dynamic pricing analysis of railway freight transport under different carbon emission penalties

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Abstract: In order to better promote the transportation industry to reduce carbon emissions and improve the competitiveness of railway freight in the whole freight market, to achieve the "double carbon" strategy and promote the "transit rail". In this paper, considering the dynamic pricing of freight volume and freight price, a two-layer programming model is established under the minimum social total cost of railway and road. The upper level considers the income of railway freight, and the lower level considers the total social cost of freight transportation, so as to realize the increase of railway freight revenue and the decrease of the general total expenditure paid by freight owners. Considering the transportation of bulk commodity freight from Shandong to Sichuan, it is concluded that the railway freight market has a good development prospect under the consideration of the total social expenditure such as carbon emission. Under the carbon emission charge, the appropriate increase of railway freight rate will not lead to the reduction of railway freight volume. As rail freight becomes more competitive under increasingly stringent carbon emissions penalties, the volume of rail freight will continue to rise even after appropriate increases in rail freight fees. At this point, rail freight companies can transport more goods and gain higher returns, slightly increasing the overall cost borne by shippers in a broad sense, and helping to reduce carbon emissions in the process of freight transport.

1. Introduction

According to data released by the Ministry of Transport, the freight volume of roads, railways, waterways (excluding ocean transportation), aviation and pipelines reached 46.302 million tons and 14.53 trillion ton-km in 2019, of which 9.48 percent and 20.77 percent were railways, 74.2 percent and 41.03 percent were roads. According to estimates, the total carbon emissions from China's transport sector in 2019 were about 1.1 billion tons, accounting for about 10% of the country's total carbon emissions, with road transport accounting for 74% and railway transport accounting for 8%. China's railways account for 20.77% of the country's freight turnover and only account for 8% of the transport industry's carbon emissions [1]. The adjustment of freight transportation structure and the implementation of "transit rail" is an important measure to reduce the comprehensive transportation cost of the whole society and achieve "carbon neutrality" and "carbon peak"[2]. However, the current pricing power of railway freight was controlled by the state before 2014, and the pricing of railway freight is inconsistent with the market price, which reduces the market competitiveness of railway freight. In 2018, the State Administration for Market Regulation of the National Development and Reform Commission issued a notice on further sorting out and standardizing charges related to railway freight transport, which included that relevant localities should scientifically determine freight rates and charge standards in accordance with the principle of compensating reasonable costs and making appropriate profits. In the process of road transport, it produces a large number of greenhouse gases such as carbon dioxide, which has a broad cost to the society is often ignored by freight companies, with the strict requirements of countries on carbon emissions, road transport than rail transport produces more carbon emissions can not be ignored as before. Therefore, we will consider carbon emissions in the broad social cost of transport. With the continuous promotion of the national "double carbon" strategy, the importance of railway freight is increasing. Therefore, the implementation of railway freight dynamic pricing, and consider the carbon emission factors in the process of freight transportation, and traditional road market competition, improve the competitiveness of railway freight and market share.

From the existing literature at home and abroad, the existing research on railway transport price mainly includes the change of freight system mechanism and the research on the pricing of railway freight enterprises. Based on the improved RFM model, Shuai Bin, DENG Shaowei and Huang Lixia [3] studied the freight needs of different customers and made targeted prices and services according to customer types. YANG H,
YAGAR S [4] proposed a sensitivity analysis method and a two-layer programming model to solve the traffic flow allocation problem. Zhang Xiaoqiang, Liu Dan and Wang Bin [5] studied the dynamic pricing of railway fast freight transportation under the competition between road and railway, established the generalized user cost minimization model and the two-layer programming model, and made a comparative analysis. Li et al [6] used pricing strategies to improve operational structure and efficiency. Sangpil Ko et al [7] studied the railway timber transportation in the United States and improved the competitiveness of railway freight transportation by reducing the freight rate of railway freight and increasing the number of railway transportation routes. Luce Brotcorne [8] established a two-layer programming model based on the pricing problem and expounded a series of solutions. However, the dynamic pricing in the field of railway transport pricing mainly focuses on railway passenger transport. There are still few studies on railway freight transport, and the papers that directly consider the cost of carbon emissions in freight transport pricing are even rarer. In this paper, the dynamic pricing method is adopted, the generalized transportation cost of freight is considered, various direct costs and social costs generated in the transportation process are analyzed, and the carbon emission penalty coefficient of highway is introduced under the premise of considering the carbon emission cost of road and railway transportation. In addition, the discount of long-distance railway freight income is considered. A two-layer programming model based on the maximum comprehensive income of railway freight and the minimum generalized cost of freight owners is established to improve the income of railway freight and reduce the carbon emissions of freight terminal.

2. A two-layer programming model for dynamic pricing

2.1. Freight revenue maximization model

The mode of freight transport is defined as i = 1 for rail transport and i = 2 for road transport. According to the traditional rail freight pricing rules:

\[ Z = \left( p_{11} + p_{12} q_i \right) q_i \]  \hspace{1cm} (1)

\( p_{11} \) is the delivery base price of freight per ton of truckload, \( p_{12} \) is the operating base price of freight per ton of truckload, \( q_i \) is the freight flow of railway freight, \( l_i \) is the mileage of railway freight, and \( Z \) is the income of railway freight. Based on dynamic pricing theory, this paper considers the income model of freight railway transportation enterprises:

\[ \text{Max } Z(p_i) = (p_{11} + p_{12} q_i) q_i = p_i q_i \]  \hspace{1cm} (2)

\( Z(p_i) \) represents the total freight profit of the railway sector, \( p_i \) represents the transportation income per ton of goods of the railway freight enterprise.

\[ s.t. p_{\text{min}} \leq p_i \leq p_{\text{max}} \]  \hspace{1cm} (3)

\( p_{\text{min}} \) represents the lower limit of freight price per ton, which is an acceptable cost after comprehensive consideration, because the pricing of railway freight market is gradually liberalized and the lower limit of railway freight price is gradually reduced. \( p_{\text{max}} \) represents the upper limit of freight price per ton. Currently, the price of railway transportation per ton cannot exceed a certain upper limit. The lower model is the socially generalized total cost of goods transportation, which includes the sum of the generalized cost of goods transportation in railway and road:

\[ \min G(x) = \sum_{i=1}^{n} f(x) dx \]  \hspace{1cm} (4)

\[ \text{s.t. } \sum_{i=1}^{n} q_i = Q, \forall j \in B \]  \hspace{1cm} (5)

\( q_i \) represents the freight volume transported by mode \( i \) in the process of freight transportation, \( f(x) \) represents the socially generalized total cost function of mode \( i \) in the process of freight transportation, and \( Q \) is the sum of the freight volume of this kind of goods in the process of transportation. The generalized total cost function required by the owner of goods, which includes two parts: the generalized cost of goods transportation and the social cost. The generalized cost includes two parts, namely, the freight cost paid by the owner in the process of transportation \( F^1_{ij} \) and the time cost of cargo transportation \( K_{ij} \). The social cost also includes two parts, namely, the cost of goods security \( P^1_{ij} \) and the social cost (the cost of carbon emission) \( P^2_{ij} \).

\[ f_i(q_i) = \sum_{i=1}^{2} f_{ij}(q_i) + \sum_{i=1}^{2} K_{ij} + \sum_{i=1}^{2} P^1_{ij} + \sum_{i=1}^{2} P^2_{ij} \]  \hspace{1cm} (6)

Based on the relationship between traffic and cost, this paper selects unit transportation cost as a power function of demand. Considering the price coefficient \( \omega \) of freight and miscellaneous charges such as vehicle use fee, railway construction fund, etc. to the base price in the transportation process of \( t \) in this time period, the railway freight pricing cost model is as follows:

\[ f_i(q_i) = (p_{11} + p_{12} q_i) q_i = a(q_i)^{\gamma} l_i + \omega p_i \]  \hspace{1cm} (7)

\[ F^3_{ij} = R^1_{ij} + R^2_{ij} = p_i F_{ij}^1 + p_i \delta l_{ij} \]  \hspace{1cm} (8)
\( F_i \) is the sum of the time value cost of goods \( R_i \) caused by the occupation of goods in the process of transportation and the cost of goods \( R_i^2 \) caused by the depreciation in the process of freight transportation. The time cost generated by transportation is correlated with the value \( p_i \) of the goods themselves, the derogation rate \( \delta_i \) of the goods in the transportation process, the transportation time \( t_{i\text{sp}} \), and the annual return rate \( \gamma_i \) of the owners of class \( j \) goods. The linear function of the time cost \( \theta_i \) is established as follows:

\[
P_i^1 = p_i \theta_i \tag{9}
\]

Safety cost is the loss rate of this kind of goods, that is, the loss cost of goods after the completion of the transportation process, that is, the linear relationship between the value of goods itself and the loss rate of goods transportation, the formula is as follows:

\[
P_i^3 = h H_i \tag{10}
\]

2.2. The cost of carbon emissions during transportation

Social cost \( P_{i}^3 \) is the carbon emission cost, which is the linear function of the carbon emission \( H_i \) transportation mode \( i \) and the average price \( h \) of carbon emission trading in China in 2022:

\[
P_i^3 = h H_i \tag{10}
\]

According to data released in the 2023 China Carbon Market Annual Report, the average price of carbon emission trading in China in February 2023 was about 63 yuan/ton. For the calculation of carbon emission \( H_{ij} \) in railway transportation, this paper adopts the energy consumption calculation method based on train weight [9]:

\[
H_{ij} = 1200GWT^{-0.19} t_{i\text{sp}} U_i D_i \tag{11}
\]

\( GWT \) is the total weight of the freight train; \( U_i \) is the conversion coefficient of railway energy consumption, calculated in standard coal, unit: kg; \( D_i \) is the carbon emission coefficient, calculated according to the recommended value of 0.68 by China Energy Research Institute; \( GW \) is the net weight of the truck that throws the goods, unit: t.

\[
GWT = GW + q_i^0 \tag{12}
\]

In this paper, Gambhir [10] is used to calculate the carbon emissions of road transportation in China's transportation industry from 2010 to 2050, and some improvements are made to make the freight volume and carbon emission cost directly linked:

\[
H_{2} = \sum_{m} \sum_{n} q_{i}^{0.3} h_{2m}^{2} h_{2nn}^{4} \tag{13}
\]

\( q_i^0 \) is to judge the number of freight cars according to the highway freight volume. \( h_{2m}^2 \) is the traveling distance of \( m \) type vehicle, unit: km; \( h_{2nn}^4 \) is the fuel consumption of \( N \) type engine of \( m \) type vehicle 100 km, unit: L; \( h_{2m}^2 \) is the carbon emission coefficient of fuel consumed by \( N \) type engine of \( m \) type vehicle, unit: kg/L. To sum up, the multi-transport mode game model based on the two-layer programming model is established as follows:

\[
\text{Max } Z(p_i) = (p_{i1} + p_{i2} \gamma_i) q_i = p_1 q_1
\]

\[
s.t. p_{\text{min}} \leq p_i \leq p_{\text{max}}
\]

\[
\min G(x) = \sum_{i \in A} \int_{x_i}^{\infty} f(x) dx
\]

\[
s.t. \sum_{i} q_i = Q, \quad \forall j \in B
\]

\[
f(x_i) = \sum_{i=1}^{2} f_i(x_i) + \sum_{i=1}^{2} K_i + \sum_{i=1}^{2} P_i + \sum_{i=1}^{2} P_i^2 = a_i (q_i) l_i + \omega p_i + a_2 (q_2)^{l_2} l_2 + a_1 l_i (q_1 + \delta_i) t_{1\text{sp}} + a_2 l_i (q_1 + \delta_i) t_{2\text{sp}}
\]

\[
+ \epsilon_2^{1} (p_1 \theta_1 + p_2 \theta_2) + \epsilon_1^{1} 1200GWT^{-0.19} t_{1\text{sp}} U_i D_i + \sum_{m} \sum_{n} q_{i}^{0.3} h_{2m}^{2} h_{2nn}^{4} h_{2nn}^{5}
\]

\[
(14)
\]

\[
\gamma_i \geq 0 \tag{15}
\]
3. Panalysis of solution methods and examples

3.1. Solution design of two-layer programming model algorithm

In the competitive analysis of railway freight market considering dynamic pricing, the solution algorithm and efficiency are considered. Because of the gradient information between the upper and lower models, the method based on sensitivity analysis is adopted to solve the two-layer programming.

According to the selection of Shandong Jining to Longgong Port station Fashuicheng 20-foot railway universal box strip project. In order to implement the strategic deployment of "transit railway", combined with the actual situation of our section, the depot and the station have negotiated with the enterprise for many times. The enterprise said that if the cost of railway transportation is basically equal to the price of highway transportation, they agreed to transfer part of the goods to Yunguichuan and other areas to railway transportation, with an estimated total volume of 3,000 tons.

3.2. Dynamic pricing and price analysis based on carbon emission penalty

Based on spss data analysis of specific transit rail freight in 2023, the functional relationship between freight volume and freight price is established according to literature, and the basic dynamic function of freight volume and price of railway transportation and fixed price of road transportation are obtained. Because of the upper limit of road transport capacity, so as the volume of road transport increases, its price is constantly getting higher and the result is shown in Figure 1.

![Fig. 1 Chart of freight price per unit of railway and highway along with freight volume](image)

The data parameters of highway and railway transportation are shown in Table 1.

<table>
<thead>
<tr>
<th>Transport mode</th>
<th>transport time Day</th>
<th>Yield %</th>
<th>depreciation rate %</th>
<th>Security %</th>
<th>Number of vehicles</th>
<th>carbon emission index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rail</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>99</td>
<td>1</td>
<td>0.68</td>
</tr>
<tr>
<td>Road</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>98</td>
<td>Max(60)</td>
<td>1.47</td>
</tr>
</tbody>
</table>

At present, China's carbon emission price is lower than that of developed countries. In the road transport process, it is still mainly burning gasoline, diesel and other fossil fuels, producing a lot of carbon dioxide and other greenhouse gases, and Europe and other countries are committed to 2050 to achieve "carbon neutrality", one of the ways is to reduce road freight emissions, therefore, by increasing carbon emissions penalties to show the disadvantage of road transport, and reduce the competitiveness of freight. Therefore, a carbon emission penalty coefficient based on roads is established to replace subsidies such as "transit rail" with increasing carbon emission cost. According to the prediction analysis, set O is established, and different carbon emission penalty costs are selected for price selection and the penalty costs are shown in Table 2.

<table>
<thead>
<tr>
<th>Different carbon emission penalty cost parameters</th>
<th>$\rho$ is the specific gravity parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho_1$</td>
<td>$\rho_2$</td>
</tr>
<tr>
<td>1</td>
<td>1.2</td>
</tr>
</tbody>
</table>

According to the above information, the sensitivity analysis is solved, and the result is shown in the Table 3:
Table 3 Rail freight revenue stack represents

<table>
<thead>
<tr>
<th>Iterations (k)</th>
<th>Railway freight rate $p_1^{(k)}$</th>
<th>volume of railway freight $q_1^{(k)}$</th>
<th>volume of road freight $q_2^{(k)}$</th>
<th>Railway freight revenue $Z^{(k)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>501.84</td>
<td>1612</td>
<td>1388</td>
<td>809068</td>
</tr>
<tr>
<td>1</td>
<td>529.9</td>
<td>1658</td>
<td>1342</td>
<td>878605</td>
</tr>
<tr>
<td>2</td>
<td>537</td>
<td>1668</td>
<td>1332</td>
<td>895797</td>
</tr>
<tr>
<td>3</td>
<td>538</td>
<td>1670</td>
<td>1330</td>
<td>899576</td>
</tr>
</tbody>
</table>

According to the above iterative process, a local optimal solution of railway freight revenue can be obtained when the time cost parameter $\delta=10$ and the penalty coefficient $\rho=1$. When $p_1 = 538$, the freight owners in consideration of time, safety, carbon emissions and other comprehensive costs, although the price of railway freight float 20%, but the railway freight volume still increased by 250 tons, the total income of railway freight still increased by 286,130 yuan. After considering carbon emission cost and based on dynamic pricing situation, the competitiveness of railway freight transportation becomes stronger in the transportation.

According to the above calculation process, matlab is used to solve the data of freight cost and freight volume under different carbon emission penalty coefficients, as shown in the following table 4:

Table 4 Revenue of rail freight under different carbon emission costs

<table>
<thead>
<tr>
<th>No</th>
<th>Carbon emission penalty factor $\mu$</th>
<th>volume of railway freight tons</th>
<th>volume of road freight tons</th>
<th>Railway freight unit rate Yuan/ton</th>
<th>Total railway freight revenue Yuan</th>
<th>Generalized total cost Yuan</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1670</td>
<td>1330</td>
<td>538</td>
<td>899576</td>
<td>2806637.09</td>
</tr>
<tr>
<td>2</td>
<td>1.2</td>
<td>1730</td>
<td>1270</td>
<td>563</td>
<td>960415</td>
<td>2838478.34</td>
</tr>
<tr>
<td>3</td>
<td>1.4</td>
<td>1743</td>
<td>1257</td>
<td>600</td>
<td>1045800</td>
<td>2872754.25</td>
</tr>
<tr>
<td>4</td>
<td>1.5</td>
<td>1760</td>
<td>1240</td>
<td>617</td>
<td>1087475</td>
<td>2887719.73</td>
</tr>
<tr>
<td>5</td>
<td>1.8</td>
<td>1793</td>
<td>1207</td>
<td>658</td>
<td>1180493</td>
<td>2941524.23</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>1811</td>
<td>1189</td>
<td>683</td>
<td>1237602</td>
<td>2978124.33</td>
</tr>
</tbody>
</table>

Fig. 2 Curve of railway freight revenue with carbon emission penalty coefficient

Figure 2 reflects that with the increasing cost of carbon emissions, the competitiveness of railway freight is enhanced, the freight volume is increased, and the freight revenue is increased.

Fig. 3 Changes of freight volume of railway and road under different carbon emission costs

As shown in Figure 3, with the increasing cost of carbon penalties, freight transport gradually shifted from road to rail, when carbon penalties are double the current, in this period, rail freight volume increased by 8.4%.

4. Conclusions

In this paper, we study the dynamic pricing of railway freight. Based on the competition between railway and road, we establish a two-tier programming model considering the carbon emission penalty, and conclude that as the carbon emission penalty increases, the mode of freight transport will gradually shift from road to railway. The stronger the carbon emission penalty, the more competitive rail freight will be. At the same time, as the cost of carbon emissions increases, rail freight companies can appropriately raise prices without reducing freight volume, thus obtaining higher freight revenue. When China's carbon emission requirements become more stringent in the future, China's rail freight will become more competitive.

Acknowledgment

Key project of China National Railway Group Co., LTD. "Research on Dynamic Adjustment Mechanism of Railway Freight Rate Driven by Data" (N2023X035)
References


