Research on the Choice of Multimodal Transportation Emission Reduction Schemes Based on Different Carbon Tax Models

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Abstract. Different carbon tax collection methods have an important impact on the emission reduction effect of multimodal transportation. In the entire transportation process of containerized cargo multimodal transportation, the generalized external cost is considered to establish the total utility model of multimodal transportation. Based on the optimal carbon tax rate, we studied the impact of single tax rate and progressive tax rate on carbon emissions of multimodal transportation schemes. Also, the Tianjin-Weihai section of the Bohai Rim Economic Circle is used for example analysis. The results of the study found that under different carbon tax starting points, the cost of electronic goods can be reduced by 80-200 yuan per ton, and the carbon emissions can be reduced by 350-600 tons. The effect of reducing emissions is also different for different cargo values. By adjusting the structure of cargo transportation, an optimal multimodal transportation plan considering carbon tax is proposed to provide a basis for carbon tax policy formulation and implementation.

1. INTRODUCTION
In terms of multimodal transportation, Chun-XinZhai et al. minimized the total transportation cost by establishing a multimodal transportation system [1]. Hao et al. proposed an optimization model based on dynamic programming to obtain the optimal transportation mode combination strategy [2]. In terms of carbon tax rate, Cui set up a supply chain network to verify and analyze different carbon tax models, and constructed an optimal tax rate model [3].

2. BROAD EXTERNAL COST OF MULTIMODAL TRANSPORT
The broad external cost of multimodal transport includes water transport cost $C_1^{\text{tran}}$, road transport cost $C_2^{\text{tran}}$, rail transport cost $C_3^{\text{tran}}$, port area service fee $C_{\text{handle}}$, carbon emission cost $C^Z$, freight safety cost $C_{\text{sa,fe}}$, and time cost $P(T_{\text{total}})$.

The cost of waterway container transportation is calculated using FAK packing rate, and the packing rate is $P_1$; Highway freight is composed of basic freight rate $P_2$, freight rate $P_2^{\text{box}}$, and other charges. Railway freight is calculated by the sending base price $P_3^{\text{bp}}$ and the running base price $P_3^{\text{bo}}$.

$$C_1^{\text{tran}} = P_1 \times N_1 + \sum VC_1$$
$$C_2^{\text{tran}} = P_2 \times N_2 \times D_2 + P_2^{\text{box}} \times N_2 + \sum VC_2$$
$$C_3^{\text{tran}} = (P_3 + P_3^{\text{PC}}) \times N_3 + \sum VC_3$$

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International Conference on Internet of Things and Smart City (IoTSC 2021)  
Journal of Physics: Conference Series  
1972 (2021) 012111  
doi:10.1088/1742-6596/1972/1/012111

\[ P_3 = P_3^{bp} + P_3^{bo} \times D_3 \]  
where \( P_3^{EC} \) refers to railway freight and miscellaneous expenses; \( N_i, D_i \) and \( \sum VC_i \) are the number of boxes, distance, and other expenses for various types of transportation, respectively. The service fee of the port area includes loading and unloading fees \( C_{\text{charge}} \), stockpiling \( C_{\text{yard}} \), and other miscellaneous charges \( C_{\text{charge}} \). \( T_{\text{save}} \) represents the stockpiling time.

\[ C_{\text{charge}} = (C_{\text{carry}} + C_{\text{yard}} \times T_{\text{save}}) \times N + C_{\text{charge}} \]  
The research object of this paper is multimodal transport of goods. When calculating the freight safety cost \( C_{\text{saf}} \), only the cost of goods loss \( r_n \) is considered. The loss rate \( \bar{p}_n \) is the unit price of \( N \) kinds of goods. \( n_n \) is the number of boxes of \( N \) kinds of goods.

\[ C_{\text{saf}} = \bar{p}_n \times r_n \times n_n \]  
The transportation time of goods \( T_{nTotal} \) consists of in-transit travel time \( T_{nTravel} \), loading and unloading time \( T_{nLoad} \), and waiting time \( T_{nWait} \).

\[ T_{nTotal} = T_{nTravel} + T_{nLoad} + T_{nWait} \]  
Tax \( C^2 \) is levied according to the carbon emission produced by energy, \( \beta \) is the carbon tax rate, \( EC \) is the carbon emission rate

\[ C^2 = \beta \cdot EC \]  
where \( \beta \) - carbon tax rate; \( EC \) -- Carbon emissions.

It is composed of consumption, production, and environment modules \(^4\). The optimal carbon tax rate is solved based on the maximum utility of residents.

\[ \text{tax}^* = \frac{\theta_1 \cdot \theta_2 \cdot (1 - \beta \cdot x) \cdot e_x}{N \cdot e_x \cdot (1 - \frac{\theta_3 \cdot e_x}{P})} - 1 \]  
The determination of optimal carbon tax rate gives a range of value of carbon tax rate, which can reduce the workload of scheme selection and ensure the reliability of scheme selection results to a certain extent.

### 3. MULTIMODAL TRANSPORT EMISSION REDUCTION UTILITY MODEL UNDER DIFFERENT CARBON TAX MODES

The utility model of multimodal transport based on single tax rate and progressive tax rate is established. The choice of multimodal transport scheme is based on the minimum utility. The model of single tax rate \(^5\) is as follows:

\[ C = \sum_{i \in E} \sum_{j \in P} \sum_{n \in N} C_{\text{tran}} X_{ij}^n + \sum_{i \in E} \sum_{j \in P} \sum_{n \in N} C_{\text{handle}} Y_{ij} + \sum_{i \in E} \sum_{j \in P} \sum_{n \in N} r_{n}^{\text{saf}} + \sum_{i \in E} \sum_{j \in P} P(T_{nTotal}) + \beta \left( \sum_{i \in E} \sum_{j \in P} \sum_{m \in M} E_{ij} X_{ij}^m + \sum_{i \in E} \sum_{j \in P} \sum_{m \in M} \sum_{n \in N} E_{mn} Y_{mn} Y_{mn}^i \right), \quad E(0, +\infty) \]  
\[ \text{s.t.} \]

\[ \sum_{n \in N} X_{ij}^m \leq 1, i, j = 1, 2, \ldots, P; n \in N \]  
\[ \sum_{n \in N} \sum_{m \in M} Y_{mn} \leq 1, i, j = 1, 2, \ldots, P; m \in N \]  
\[ X_{ij}^m \in [0, 1], Y_{mn} \in [0, 1] \]  
\[ q_{ij} \leq Q \]  
\[ X_{ij} \cdot X_{jk} = Y_{nm} \]  
\[ X_{ij}^m = 1 \text{ if the goods can be transported in the mode } m \text{ at node } i \text{ and node } j \text{ and } 0 \text{ otherwise. } \]

\( Y_{mn} \) is the decision variable, \( X_{ij}^m = 1 \) if the goods can be transported in the mode \( m \) at node \( i \) and node \( j \) and \( 0 \) otherwise.

According to the gradient of different carbon emissions, the final carbon emission cost is graded and progressive corresponding to different carbon tax rates. In the piecewise progressive mode, the constraints of the emission reduction utility model include the constraints of different levels of carbon tax rates corresponding to the tax interval in Equation (10) to (15).
4. CASE ANALYSIS
As shown in Figure 1, the Bohai Economic Rim from Tianjin to Weihai is selected as the starting and ending points of the multimodal transport network, and six major port cities are selected as the nodes of multimodal transport. It is assumed that the transshipment and reloading occur only once during the transshipment and reloading. Take 2000 20-foot standard railway containers as the object of goods to conduct research. And the transportation time of each section should not exceed 30 days. Among these 2000 boxes, 1000 boxes are general industrial containers with low timeliness and low value. The price is 60,000 yuan/box, and the weight is 20 tons. The monthly depreciating rate is 2%; 1000 boxes are product with high timelines and high value. The price is 150,000 yuan/box. The weight is 10 tons. The monthly depreciating rate is 6%.

Figure 1 Multimodal transport network

4.1. Basic data setting
The average of the transport speed of various modes of transport is utilized in this paper, i.e. road transport of 70 km/h, railway transport of 100 km/h, and water transport of 40 km/h. The transport distances of the three modes of transport between nodes are shown in Table 1.

| Table 1: nodes (km) |
|---------------------|
| Route | 1-2 | 1-3 | 2-4 | 3-4 | 4-5 | 5-6 |
|--------|-----|-----|-----|-----|-----|-----|
| highway | 280 | 225 | 130 | 182 | 107 | 240 |
| railway | 460 | 220 | 195 | 237 | 120 | 280 |
| waterway | 165 | 123 | 117 | 151 | 93 | 268 |

This article respectively makes assumptions about the calculation standard of freight rate, loading and unloading cost, loading and unloading time, transfer cost of different modes and the time of replacement of the three modes of transportation[5].

4.2. Impact analysis under a single optimal tax rate model
Figure 2 and Figure 3 show the transport scheme with the minimum total cost and carbon emissions at a single optimal tax rate.

Figure 2 Total cost and carbon footprint of ordinary goods
As can be seen from Fig.2 and Fig.3, with the increase of the cost, ordinary cargos will be transformed into waterway-railway combined transportation with low carbon emissions, while the carbon tax rate interval of electronic cargo changes relatively lags behind. Also, electronic cargo shows a stronger ability to accept the cost fluctuation. Under the mode with a single tax rate, the low tax rate has a better emission reduction effect on low-value ordinary goods, while the high tax rate has a more significant emission reduction effect on high-value electronic goods.

4.3. Influence analysis under the progressive tax rate model

The carbon emission increases with the increase of the carbon tax rate by 10 yuan/ton per step. For ordinary goods, the minimum carbon tax rate is set as 10 yuan/ton, and carbon emission increases 500 tons and 1500 tons, respectively. Figure 4 and Figure 5 present the effects of the different tax rate on total cost and carbon emission.

As can be seen in Fig.4 and Fig.5, the transportation scheme of ordinary goods in the low carbon tax interval is almost not affected. Possible reason for that is the initial carbon tax rate of 10 yuan/ton has exceeded the optimal interval and ordinary goods tend to choose the low-cost intermodal transportation scheme.

The effects of different carbon emission gradients on intermodal transport scheme, cost, and carbon emission for the same carbon tax starting point are studied below. After calculation, when the minimum carbon tax rate rises to the critical value of 30 yuan/ton, the multimodal transport network transportation scheme will not be changed.
As can be seen from Fig 6 and Fig 7, at the same starting point of carbon tax rate, the optimization of electronic cargo transportation mode needs to be within a smaller carbon emission gradient range. It is because that the electronic cargo has a higher bearing capacity for transportation cost, while the carbon emission gradient is small and the carbon tax rate shared is relatively higher.

As shown in Fig 8 and Fig 9, the optimized carbon emission gradient from a high carbon tax starting point is larger than that from a low carbon tax starting point. This is because when the initial carbon tax rate is higher, the cost of increasing the carbon emission within the bearing range of electronic goods is relatively less, and the corresponding carbon emission gradient is higher.

5. CONCLUSION

(1) Carbon tax rates should be set with full consideration of the differences of goods types. According to
the optimal carbon tax rate, relatively high carbon tax rates should be set for goods with high average value.

(2) The stepped carbon tax rate can be further studied to determine the optimal carbon tax rate and carbon emission gradient according to the actual situation. Meanwhile, this paper obtains the best emission reduction effect on the premise of economic cost.

(3) The optimal multimodal transport scheme considering carbon tax can be obtained by adjusting the structure of cargo transportations.

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