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Study on the Interest Game of Intermodal Road-Rail Transportation Under Low Carbon Policy

Yu SHI, Hui WANG*, Shuai DI, Long CHEN

Abstract: Intermodal road-rail transportation (IRRT) integrates the advantages of railways and roads to achieve a win-win situation for all participants. However, the interest game problem of IRRT affects the enthusiasm of each sub-carrier to cooperate, which makes it difficult to show its advantages in the competition with the truck-only transport (TOT), and then retards the promotion process of the multimodal transport industry. In order to improve the competitiveness of IRRT, based on Stackelberg game and low-carbon policy, the interest coordination problem of supply chain composed of road transport enterprises (RTE), railway transport enterprises (RWTE) and multimodal transport operators (MTO) is studied under the background of the TOT's competition. The RESULTS SHOW THAT THE active intervention of the local government has a significant promotion effect on the profits of the RTE and the RWTE under the decentralized decision mode, while the profits of the MTO show a trend of decreasing first and then increasing.

Key words: carbon emissions; game theory; government intervention; interest game; IRRT supply chain

1 BACKGROUND INTRODUCTION

In recent years, the greenhouse effect and other climate problems have caused serious harm to social development. All countries in the world are trying to control the emission of carbon dioxide gas. According to the report, carbon emissions in China's transport sector accounted for about 11% of all industries in the country in 2019, among which road freight accounted for the highest proportion of about 46.85%, while railway freight's share fell to just 0.68% (Li et al. [1]), and it can save energy with low emissions, thus rail is considered to be the cleanest freight mode in land transportation (Chen et al. [2], Y. et al. [3]). At the same time, its accident rate is much lower than that of road transport (Yang et al. [4], Y. et al. [5]). Following the 14th Five-Year Plan outline that pointed out the need to build a modern comprehensive transportation system and promote the whole "one-stop" and "a single" service, in January 2022, the General Office of the State Council of the People's Republic issued the "Promote the development of multimodal transport optimization adjustment of transportation structure work plan (2021 - 2025)", again to develop the multimodal transport, create a unified market environment, promote the deep integration of various transportation modes, optimize and adjust the transportation structure, improve the comprehensive transportation efficiency, advocate further marketization of freight prices, and accelerate the promotion of green and low-carbon logistics mode. In addition, Huangshi City, Quzhou City in China and other local governments have enacted specific multimodal subsidy policies or programs in order to imply the national major policy. In the past few years, China's railway freight price has gradually changed from "government pricing" to "government guiding price", and some downward policies have been adopted. However, its approval process, especially the pricing mechanism of cross-bureau goods, is still cumbersome and cannot respond flexibly to market changes. The fundamental goal of logistics enterprises is to pursue interests, and the maximization of their own economic interests is the fundamental basis for their decision-making. Under such a background, it is an inevitable trend to build an efficient and high-quality logistics service system. The RTE and the RWTE are the implementation subjects of IRRT, and the MTO is responsible for external communication and internal coordination; thus the three are the main stakeholders and participants. Consequently, the supply chain under the participation of government subsidies and supervision policy, how to carry out the dynamic adjustment of freight market prices, and how to realize the maximization of the overall efficiency at the same time ensure that the three parties win-win in economic benefit are the key problems to be solved urgently to promote the high-speed development of IRRT.

2 LITERATURE REVIEW

2.1 Low Carbon Policy Research

Scholars have done some research on the implementation methods and effects of low-carbon policies. Studies have found that policy makers typically use subsidy incentive programs (Lebeau et al. [6]). Huang et al. [7] and Krass et al. [8] discussed the fixed-cost subsidy selection model and explored the impact of low carbon threshold subsidy policy on manufacturers' profits and carbon emissions in the automotive supply chain. Zhang et al. [9] applied Stackelberg game model to consider the selection principles of three low-carbon regulatory policies in the remanufacturing industry, namely, tax policy, subsidy policy and tax subsidy policy. Li et al. [10] analyzed the impact of different low-carbon policies, such as technology subsidy and emission reduction subsidy, on the production input and total carbon emission reduction level of enterprise supply chain. Sönke Behrends [11] discussed the relevance of local policies on the sustainable development mode of the IRRT, and found that government subsidies, supervision and evaluation and other behaviors would accelerate the evolution rate of the cooperative strategy of RTEs and RWTEs. Mohammad et al. [12] analyzed the price competition between the TOT and the IRRT under the background of government intervention (carbon tax and subsidy) from three aspects of environment, economy and social sustainability. Kundu and Sheu [13] pointed out that the government subsidy program can promote the transformation of the shipping mode to the railway mode, and obtained the optimal subsidy value for switching between the two modes based on the heterogeneity of shippers.

2.2 Freight Market Demand Research

The market demand of manufacturing industry must be predicted according to customer satisfaction, etc. Similarly, the market demand of freight service industry is also random. Meng et al. [14], Kim et al. [15]. Mills [16] and Karlin et al. [17] constructed the market demand function composed of expected demand function and random variables by adding or multiplying. Agrawal and Seshadri [18] used the demand function in the Newsvendor model, and proposed that the function is determined by the form of expected demand and random fluctuation. Wang et al. [19] discussed the impact of retailers with different risk preferences on the performance of the green supply chain under the fuzzy environment using fuzzy variables to describe the uncertainty in the distribution process of the green supply chain and considering the different attitudes of decision makers to deal with risks. Choi et al. [20] pointed out that the influence of power structure on supply chain may depend on the way demand model is formed. On this basis, Shi et al. [21] studied the influence of four types of power structure on the performance of each member of the product supply chain (composed of retailers and manufacturers) under two market demand models: additive and multiplicative. Zhang et al. [22] established a port game theory competition model based on the random market demand function. In this model, port operators consider the route selection behavior of shippers to determine the location of land ports and pricing strategies to maximize their own profits. Duan [23] took the IRRT system with the participation of railway logistics center as the research object, analyzed the pricing game model under two market demand models, and researched the influence of demand randomness on the optimal pricing strategy.

2.3 Interest Game Research

The cooperative relationship between multiple agents has a great impact on the profit of supply chain or system (Tijani et al. [24], Shahbaz et al. [25]). Stackelberg game model and Shapley value method are widely used to solve the problems of multi-agent benefit allocation and supply chain system coordination. Li et al. [26] put forward the Shapley value improvement model that comprehensively considers resource input, creation profit and risk bearing, and is used to solve the problem of benefit distribution rationalization in three-level supply chain collaborative innovation alliance. Chen et al. [27] used the improved Shapley value method to study the profit distribution and risk allocation of port logistics services, and analyzed the advantages and disadvantages of different coordination mechanisms. The selection of allocation influencing factors and the determination of corresponding weights in the above studies contain strong subjectivity, so the comprehensive factors of modified Shapley value model cannot be calculated objectively. In addition, Kang et al. [28] constructed a Stackelberg interest game model of the IRRT system with the participation of non-truck carriers, and pointed out that its participation is conducive to the significant improvement of the profits of each participant and the total profits. Ma et al. [29] explored the ideal revenue distribution method among air-rail intermodal transport participants based on the two-stage dynamic Stackelberg game model with complete information, considering the sensitivity of passengers to service level and price.

By analyzing the above existing literature, it can be seen that the interest game of the combined transport system is rarely studied from the perspective of supply chain as a whole, and the influence of local policies is mostly considered from the perspective of shippers, mainly analyzing the influence and role of government subsidies on the sharing rate of the intermodal transport. Based on the above time background and the research foundation, this paper takes the supply chain system composed of RTE, RWTE and MTO under the participation of local governments as the research object. From the perspective of carriers, carbon emission reductions, carbon emission limiting factor and the competition of TOT were added to the Stackelberg game model of supply chain profit distribution. The analysis of non-subsidy decentralized decision, centralized decision and decentralized decision with subsidies of these three kinds of mode, the system under the action of both internal and external factors of interest coordination problems was done. This paper discusses the government's optimal subsidy and supervision scheme in the early stage of the development of the IRRT, and dissects the influence of government actions on the optimal decision-making of supply chain, so as to provide new ideas for the steady advancement of modern logistics industry.

3 PROBLEM DESCRIPTION

Under the condition of market economy, the highway short barge transport enterprise (i.e. RTE above), the RWTE and the MTO among the supply chain are respectively regarded as independent subjects for analysis. This paper does not consider other income and expenditure, and assumes that the income of each mode of transport is jointly determined by the freight volume and transport rate.

The demand of cargo transportation refers to the requirements of the freight owners to realize the space displacement of cargo with the ability to pay and can be achieved due to the needs of social and economic activities in a certain period of time. Freight transportation demand is factional and partly substitutable; consequently, customers often choose one among various transportation modes according to their own conditions when they want to transport goods. Highway, railway, water and air are the four commonly used ways in the transportation of goods in China's inland. Among them, air freight is high, and its transport capacity is limited, similarly water transport time is long and severely restricted by region, while road transport in China has good accessibility and strong timeliness (Yang et al. [30]). Therefore, this paper only considers the market demand competition between TOT and IRRT.

The relationship among IRRT supply chain is as shown in Fig. 1 (including capital flows, information flow and freight service flow three aspects), and the game problem of the IRRT supply chain can be described as two stages. The first stage belongs to the market competition between the IRRT and the TOT: The total demand in the freight market is a random variable, and the IRRT and the TOT as the two sides of the game contract the transport business of customers at their respective market prices p_h and p_{r-h}. In this stage, the market price of the IRRT under the optimal market share is obtained. The second stage is the tripartite (the RTE, the RWTE and the MTO) interest game problem within the supply chain under the limit of carbon emission reduction rate: After the MTO contracts the "door-to-door" multimodal transport business at the unit price p_{r-h}, it purchases the transport services of the agreed volume from the RTE and the RWTE respectively at the agreed price v_h and v_r according to the forecast data of market demand (where the transport cost of highway short barge is c_d and the transport cost of railway is c_r. In this process, the MTO needs to consider the following problems: ① Unlike the sale of products, transport services do not have storage characteristics, so multimodal transport operators sign agreements with the RTE and the RWTE for equal volume. ② Market demand is affected by multiple factors and has randomness and uncertainty. If the actual volume of goods solicited D_{r-h} is less than the agreed volume q, it will cause empty transportation and result in capital waste. On the contrary, if D_{r-h} is greater than q, additional costs should be paid to complete the transportation task or compensate the customer accordingly. The unit cost of the excess part is expressed as penalty e (at this time, the excess demand is equivalent to the sales loss proposed by Petruzzi and Dada [31]. According to the hypothesis of Eeckhoudt et al. [32], transportation services need to be urgently procured at higher cost to meet the excess demand, therefore, $e > p_h$, $e > c_d + c_r$.

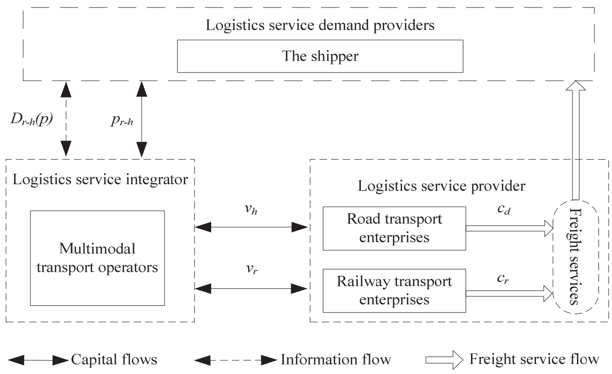


Figure 1 Schematic diagram of relationship among IRRT supply chain

4 BASIC ASSUMPTIONS AND CORRELATION FUNCTIONS

In order to further study the interest game problem of the supply chain composed of the RTE, the RWTE and the MTO under the condition of considering carbon emissions, the basic assumptions of this paper are firstly proposed, then the IRRT's market demand function and carbon emission reduction rate are defined and explained.

4.1 Basic Assumptions

Hypothesis 1: It does not consider the operational capacity limit of the transportation system, that is, it is assumed that the market demand is always smaller than the transportation capacity of the RTE and the RWTE.

Hypothesis 2: Considering only that a railway transport enterprise and a road transport enterprise cooperate under the coordination of the same multimodal transport operator and construct the transport supply chain, at the same time the game among the subjects belongs to the perfect information game.

Hypothesis 3: When local governments actively promote low-carbon policies, they will only give subsidies to the MTO that successfully contract the IRRT business.

Hypothesis 4: Only in the case of government intervention, the limiting factor of carbon emission is considered, and the carbon emission is equal to the product of the carbon emission coefficient and the amount of goods carried.

4.2 Establishment of Market Demand Function and Definition of Carbon Reduction Rate

Different from the previous classical literature on intermodal road-rail transportation, which sets freight demand as a constant, this paper sets it as a random variable affected by transport price, and there is a certain functional relationship between them. The existing literature points out that the random market demand function is composed of the expected demand and random fluctuation (Shi et al. [21]). Assuming that the expected demand is a linear function of the market freight prices of various competitive modes (the TOT and the IRRT) and the random fluctuation is additive, the market demand function of the IRRT can be expressed as follows:

$$D_{r-h} = a - bp_{r-h} + cp_h + \varepsilon \tag{1}$$

where: a denotes the basic constant term ($a > 0$), b denotes self-price sensitivity coefficient ($b > 0$), c denotes the cross-price sensitivity coefficient ($c > 0$), ε is the random fluctuation term, p_h, p_{r-h} are the market prices of the TOT and the IRRT respectively. In this paper, we assume that ε is a random variable whose distribution function is $F(x)$, density function is $f(x)$ and expectation is 0.

In order to establish the relationship between the market price and the transport order quantity namely the agreed volume, q is expressed as a function of the freight market price $p_i(i \in \{h; r-h\})$ and the volume factor y, i.e.

$$q = a - bp_{r-h} + cp_h + y \tag{2}$$

Definition 1: The carbon emission reduction rate γ represents the ratio of the carbon emission reduction value after the government intervention makes part of the goods from the TOT to the IRRT to the carbon emission generated with no government intervention, i.e.

$$\gamma = \frac{C^{(N)} - C^{(S)}}{C^{(N)}} \tag{3}$$

where $C^{(N)}$ represents the carbon emission of freight transport market with no government intervention; $C^{(S)}$ represents the carbon emission of freight transport market after government intervention.

5 MODELING

On the basis of the existing literature, this section divides the problem of interest game into two categories according to whether there is government participation or not. In the state of non-government participation, it mainly studies the construction and solution of the interest game model under the decentralized decision-making mode of IRRT supply chain. And while it is divided into two modes of centralized decision-making and decentralized decision-making for discussion in the state of government participation, the Stackelberg game models of IRRT supply chain under the two modes both consider the subsidy and carbon emission reduction given by the government under the low-carbon policy.

5.1 The Interest Game of the IRRT Supply Chain with no Government Participation

Decentralized Decision-making model of intermodal road-rail supply chain without government participation (*N-D*). In the actual freight market operation, the IRRT mostly adopts decentralized decision-making mode, and the MTO, the RTE and the RWTE operate independently, that is, the three enterprises take their own profit maximization as the ultimate goal. Based on the Stackelberg model, the non-cooperative game among the supply chain participants is also divided into two stages: in the first stage, the RTE and the RWTE consider their own costs (c_d, c_r) and expected profits, and then determine the agreed freight prices v_h and v_r with the MTO respectively. In the second stage, the MTO determines the market price p_{r-h} to trade with the shipper and the agreed volume to be purchased from the RTE and the RWTE according to the agreed freight prices and the forecast value of the freight volume to be collected.

In view of the relationship between the actual volume of orders and the agreed volume, the MTO's profit can be expressed as a piecewise function:

$$\pi_t^{(N-D)} = \begin{cases} p_{r-h} D_{r-h} - \left(v_h + v_r\right) q, \, D_{r-h} \le q \\ p_{r-h} D_{r-h} - \left(v_h + v_r\right) q - \mathrm{e}\left(x - q\right), \, D_{r-h} > q \end{cases} \tag{4}$$

Combining Eq. (1) and Eq. (2), the above equation can be rewritten as:

$$\pi_t^{(N-D)} = \begin{cases} p_{r-h}\left(a - bp_{r-h} + cp_h + \varepsilon\right) - \left(v_h + v_r\right) \cdot \\ \cdot \left(a - bp_{r-h} + cp_h + y\right), \, \varepsilon \le y \\ p_{r-h}\left(a - bp_{r-h} + cp_h + \varepsilon\right) - \left(v_h + v_r\right) \cdot \\ \cdot \left(a - bp_{r-h} + cp_h + y\right) - \mathrm{e}\left(\varepsilon - y\right), \, \varepsilon > y \end{cases} \tag{5}$$

Define $(x)^+ = \max(x, 0)$, consider the expected value of the profit function, and rewrite the above equation into integral form:

$$\begin{aligned} \pi_t^{(N-D)} &= p_{r-h}\left(a - bp_{r-h} + cp_h + E\left(\varepsilon\right)\right) - \left(v_h + v_r\right) \cdot \\ &\cdot \left(a - bp_{r-h} + cp_h + y\right) - \mathrm{e}E\left(\varepsilon - y\right)^+ = \\ &= \left(p_{r-h} - v_h - v_r\right)\left(a - bp_{r-h} + cp_h\right) - \\ &- \left(v_h + v_r\right) y - \mathrm{e}\int_y \left[1 - F\left(x\right)\right] \mathrm{d}x \end{aligned} \tag{6}$$

The profit functions of the RTE and the RWTE are:

$$\pi_h^{(N-D)} = (v_h - c_d) q = (v_h - c_d)(a - bp_{r-h} + cp_h + y) \tag{7}$$

$$\pi_r^{(N-D)} = (v_r - c_r) q = (v_r - c_r)(a - bp_{r-h} + cp_h + y) \tag{8}$$

The total profit under the decentralized decision of the supply chain is:

$$\pi^{(N-D)} = \pi_t{}^{(N-D)} + \pi_h{}^{(N-D)} + \pi_r{}^{(N-D)} \tag{9}$$

Since all participants in the supply chain are rational, the basis for the cooperation among the three parties is that both parties have profits, so $v_h \ge c_d$, $v_r \ge c_r$, that is, the agreed freight price is greater than the respective transportation costs of the RTE and the RWTE.

Proposition 1: If and only if the agreed prices v_h^* and v_r^* both meet the following conditions,

$$\begin{aligned} v_h^* &= c_d + \frac{a + cp_h}{b} + \frac{2}{b} y^* - \left[\mathrm{e} - \mathrm{e}F\left(y^*\right)\right] \\ v_r^* &= c_r + \frac{a + cp_h}{b} + \frac{2}{b} y^* - \left[\mathrm{e} - \mathrm{e}F\left(y^*\right)\right] \end{aligned} \tag{10}$$

The profit of each participant in the supply chain reaches the optimal value with no government participation, and the function expressions are as follows:

$$\begin{aligned} \pi_t^{(N-D)*} &= \frac{\left[a + cp_h - b\left[\mathrm{e} - \mathrm{e}F\left(y^*\right)\right]\right]^2}{4b} - \\ &- y^*\left[\mathrm{e} - \mathrm{e}F\left(y^*\right)\right] - \mathrm{e}\int_{y^*} \left[1 - F\left(x\right)\right] \mathrm{d}x \end{aligned} \tag{11}$$

$$\begin{aligned} \pi_h^{(N-D)*} &= \pi_r^{(N-D)*} = \left[\frac{a + cp_h}{b} + \frac{2}{b} y^* - \left(\mathrm{e} - \mathrm{e}F\left(y^*\right)\right)\right] \cdot \\ &\cdot \frac{a + cp_h - b\left[\mathrm{e} - \mathrm{e}F\left(y^*\right)\right]}{2} + y^* \end{aligned} \tag{12}$$

Proof: The backward induction method is adopted to solve the second stage: the agreed freight prices v_h and v_r are taken as known quantities to solve the IRRT market price and the agreed volume corresponding to $\max \pi_t^{(N-D)}(p_{r-h}, q)$. According to Eq. (6), $\pi_t^{(N-D)}(p_{r-h}, q)$ is a quadratic equation of one variable with respect to p_{r-h}, and $\frac{\partial \pi_t^{(N-D)}}{\partial p_{r-h}^2} = -2b < 0$, indicating that the function is convex and has a maximum in its domain. Solve $\frac{\partial \pi_t^{(N-D)}}{\partial p_{r-h}} = -2bp_{r-h} + a + cp_h + b(v_h + v_r) = 0$ and $\frac{\partial \pi_t^{(N-D)}}{\partial y} = -\left(v_h + v_r\right) + \mathrm{e}\left[1 - F\left(y\right)\right] = 0$ to obtain the optimal IRRT market price p_{r-h}^* and the optimal agreement volume q^*:

$$p_{r-h}^* = \frac{a + cp_h + b(v_h + v_r)}{2b} \tag{13}$$

$$q^* = \frac{a + cp_h - b(v_h + v_r)}{2} + y^* \tag{14}$$

where, $y^*\left(v_h, v_r\right) = F^{-1}\left(1 - \frac{v_h + v_r}{e}\right)$.

Then, the first stage of Stackelberg game was solved: the v values corresponding to $\max \pi_h(v_h)$ and $\max \pi_r(v_r)$ are obtained by combining Eq. (7) and Eq. (8) for the RTE and the RWTE. By substituting Eq. (14) into Eq. (7) and Eq. (8), we can obtain $\pi_h^{(N-D)} = (v_h - c_d)\left[\frac{a + cp_h - b(v_h + v_r)}{2} + y^*\right]$ and $\pi_r^{(N-D)} = (v_r - c_r)\left[\frac{a + cp_h - b(v_h + v_r)}{2} + y^*\right]$. By taking the second-order derivative, we can see that $\pi_h^{(N-D)}$ and $\pi_r^{(N-D)}$ are concave functions with respect to v_h and v_r, respectively $\left(\frac{\partial \pi_h}{\partial v_h^2} = \frac{\partial \pi_r}{\partial v_r^2} = -b < 0\right)$. Similarly, there are maxima in the domain. If the first-order derivative is set equal to 0, you could get that $\frac{\partial \pi_h^{(N-D)}}{\partial v_h} = -bv_h + \frac{a + cp_h - bv_r}{2} + \frac{bc_d}{2} + y^* = 0$ and $\frac{\partial \pi_r^{(N-D)}}{\partial v_r} = -bv_r + \frac{a + cp_h - bv_h}{2} + \frac{bc_r}{2} + y^* = 0$. According to $y^*\left(v_h, v_r\right) = F^{-1}\left(1 - \frac{v_h + v_r}{e}\right)$, $F(y) = \frac{e - (v_h + v_r)}{e}$ can be obtained. By substituting $v_r = e - eF(y) - v_h$ and $v_h = e - eF(y) - v_r$ into the above two first-order derivative formulas, the optimal protocol freight prices can be obtained as shown in Eq. (10), and the proof is complete.

5.2 The Interest Game of the IRRT Supply Chain Considering Carbon Emission Under Low-Carbon Policy

In recent years, countries around the world are advocating energy conservation and emission reduction with the increasing environmental problems (Yang et al. [33]). As the macro-regulator of the market economy, local governments in recent years have made corresponding requirements on the carbon emission reduction rate while implementing key support for multimodal transportation enterprises. In order to compete with the TOT to gain more market share, the MTO, as the core enterprise of the IRRT supply chain , contracts 'door-to-door' freight business at a relatively low market price (compared to the state without government participation) under the subsidy policy of local government. In this case, this section mainly researches the interest game in supply chain and a calculation method of carbon emission reduction rate.

5.2.1 Centralized Decision-Making of the IRRT Under Government Subsidy Policy(S-C)

Centralized decision-making refers to taking the service chain composed of the RTE, the RWTE and the MTO as a whole, only considering the benefits and costs of external transport, and making decisions with the goal of maximizing the total profit of the supply chain. The total profit of the supply chain with the participation of local government is the total transportation revenue plus the subsidy revenue, and then the total transportation cost and the penalty cost caused by the excess of the agreed volume are subtracted, which can be expressed as:

$$\pi^{(S-C)} = (p_{r-h} + \beta)D_{r-h} - (c_d + c_r)q - e(D - q)^+ \tag{15}$$

where, β is the coefficient of subsidy amount, and the unit is yuan/t.

Considering the expected value of the profit function and combining Eq. (1) and Eq. (2), the above equation can be rewritten into an integral form

$$\begin{aligned}\pi^{(S-C)} &= \left(p_{r-h} + \beta - c_d - c_r\right)\left(a - bp_{r-h} + cp_h\right) - \\ &-\left(c_d + c_r\right)y - \mathrm{e}\int_y \left[1 - F\left(x\right)\right]\mathrm{d}x\end{aligned} \tag{16}$$

According to the relationship between the actual contracted volume D_{r-h} and the agreed volume q (assuming that when $D_{r-h} > q$, all the remaining goods are transported by the TOT), the carbon emissions after the implementation of low-carbon policies can be written as a piecewise function:

$$C^{(S)} = \begin{cases} \theta_{r-h} * D_{r-h}, D_{r-h} < q \\ \theta_{r-h} * q + \theta_h * (D_{r-h} - q), D_{r-h} \geq q \end{cases}$$

where, θ_h and θ_{r-h} represent the carbon emission coefficient of the TOT and the IRRT respectively, in kg/t.

Similarly, according to Eq. (1) and Eq. (2), the above equation can be rewritten as an integral form:

$$C^{(S)} = \theta_{r-h}\left(a - bp_{r-h}^* + cp_h\right) + \theta_{r-h}y^* + \theta_h \int_{y^*} \left[1 - F\left(x\right)\right]]\mathrm{d}x \tag{17}$$

In this case, $C^{(N)} = \theta_h\left(bp_{r-h}^{(N)} - bp_{r-h}^*\right) + \theta_{r-h}\left(a - \right.$ $\left. -bp_{r-h}^{(N)} + cp_h\right) + \theta_{r-h}y^{(N)} + \theta_h \int_{y^{(N)}} \left[1 - F\left(x\right)\right]\mathrm{d}x$ ($p_{r-h}^{(N)}$ and $y^{(N)}$ are the freight price and volume factors of the IRRT respectively when the subsidy is 0.)

Proposition 2: If and only if the market freight price meets $p_{r-h}^{*}=\dfrac{a+cp_h+b(c_d+c_r-\beta)}{2b}$, the revenue of the IRRT supply chain under the centralized decision-making mode reaches the optimum, which is $\pi^{(S-C)*}=\dfrac{\left[a+cp_h-b\left(c_d+c_r-\beta\right)\right]^2}{4b}-\left(c_d+c_r\right)y^{*}-e\int_{y^{*}}\left[1-F\left(x\right)\right]\mathrm{d}x$.

Proof: Because the second-order derivative $\dfrac{\partial\pi^{(S-C)}}{\partial p_{r-h}^{2}}=-b<0$, we know that $\pi^{(S-C)}$ is a convex function of p_{r-h} in the domain, and there is a maximum. In the proof of Proposition 1, set the first-order derivatives $\dfrac{\partial\pi^{(S-C)}}{\partial p_{r-h}}=0$ and $\dfrac{\partial\pi^{(S-C)}}{\partial y}=0$ respectively, to obtain $p_{r-h}^{*}=\dfrac{a+cp_h+b(c_d+c_r-\beta)}{2b}$ and $y^{*}=F^{-1}(1-\dfrac{c_d+c_r}{e})$, and the proof is complete. In this case, the optimal agreed volume is $q^{*}=\dfrac{a+cp_h-b(c_d+c_r-\beta)}{2}+y^{*}$, and the actual carbon reduction rate is :

$$\gamma^{(S-C)}=\frac{C^{(N)}-C^{(S)}}{C^{(N)}}=1-\frac{\theta_{r-h}\left(a-bp_{r-h}^{*}+cp_h\right)+\theta_{r-h}y^{*}+\theta_h\int_{y^{*}}\left[1-F\left(x\right)\right]\mathrm{d}x}{\theta_h\left(bp_{r-h}^{(N)}-bp_{r-h}^{*}\right)+\theta_{r-h}\left(a-bp_{r-h}^{(N)}+cp_h\right)+\theta_{r-h}y^{(N)}+\theta_h\int_{y^{(N)}}\left[1-F\left(x\right)\right]\mathrm{d}x}\tag{18}$$

5.2.2 Decentralized Decision-Making of the IRRT Under Government Subsidy Policy (S-D)

Referring to the research content in Section 4, the profit expressions of each subject under the decentralized decision-making mode of the IRRT supply chain subsidized by the government are as follows:

$$\pi_t^{(S-D)}=\left(p_{r-h}-v_h-v_r+\beta\right)\left(a-bp_{r-h}+cp_h\right)-\\-\left(v_h+v_r\right)y-e\int_y\left[1-F\left(x\right)\right]\mathrm{d}x\tag{19}$$

$$\pi_h^{(S-D)}=(v_h-c_d)(a-bp_{r-h}+cp_h+y)\tag{20}$$

$$\pi_r^{(S-D)}=(v_r-c_r)(a-bp_{r-h}+cp_h+y)\tag{21}$$

The expression of carbon emission reduction rate is the same as the centralized decision mode. Also by backward induction, the optimal decision under the decentralized decision-making mode of the supply chain considering government subsidies can be obtained as Tab. 1.

Compared with Section 5.1 and Section 5.2.2, it is found that the agreed volume, agreed freight price and profit function all increase after the government implements subsidies, and the increased amount is directly related to the government's subsidy intensity. It can be seen that the government's subsidy policy can effectively coordinate the decentralized decision-making supply chain formed by the RTE, the RWTE and the MTO, so that the profits of all parties and the total profits of the system can be reasonably improved.

Table 1 Optimal decision under subsidy decentralized decision mode

The optimal variable	Variable meaning	expression
p_{r-h}^{*}	market price of the IRRT	$\dfrac{a+cp_1+b[e-eF(y^{*})-\beta]}{2b}$
q^{*}	agreed volume	$\dfrac{a+cp_1-b[e-eF(y^{*})-\beta]}{2}+y^{*}$
v_h^{*}	the agreed price between the MTO and the RTE	$c_h+\dfrac{a+cp_1}{b}+\beta+\dfrac{2}{b}y^{*}-[e-eF(y^{*})]$
v_r^{*}	the agreed price between the MTO and the RWTE	$c_r+\dfrac{a+cp_1}{b}+\beta+\dfrac{2}{b}y^{*}-[e-eF(y^{*})]$
π_t^{*}	MTO's profit	$\dfrac{\left(a+cp_1-b\left[e-eF\left(y^{*}\right)-\beta\right]\right)^2}{4b}-y^{*}\left[e-eF\left(y^{*}\right)\right]-e\int_{y^{*}}\left[1-F\left(x\right)\right]\mathrm{d}x$
π_h^{*}	TTE's profit	$\left[\dfrac{a+cp_1}{b}+\beta+\dfrac{2}{b}y^{*}-(e-eF(y^{*}))\right]*\dfrac{a+cp_1-b[e-eF(y^{*})-\beta]}{2}+y^{*}$
π_r^{*}	RTE's profit	$\left[\dfrac{a+cp_1}{b}+\beta+\dfrac{2}{b}y^{*}-(e-eF(y^{*}))\right]*\dfrac{a+cp_1-b[e-eF(y^{*})-\beta]}{2}+y^{*}$

6 THE EXAMPLE ANALYSIS

In order to further verify the applicability of the model and determine the influence of each parameter value on the coordination result, the above calculation formula and the optimal decision variable are numerically simulated. Taking Tianjin, China to Wuhan, China as the starting and ending point of freight transportation, and according to the measurement of the straight line distance between the two places in Google map, the railway transport distance is taken as 1150 km, while assuming that the highway barge transport distance is 10 km. Referring to the numerical and proportional relationship of the demand constant a and random fluctuation term ε in existing literature on Stochastic market demand function, it is assumed that a = 100 t and ε is the uniform distribution between (−50, 50) in this paper. Other parameters are set as follows:

Table 2 Parameters and their initial values

parameter	instructions	the numerical
b	Self-price sensitivity coefficient	1.96*
c	cross-price sensitivity coefficient	1.37*
p_h	the freight price of the TOT	220.4 yuan/t**
c_h	highway short barge transport cost	33 yuan/t***
c_r	rail transport cost	149.5 yuan/t**
β	coefficient of subsidy amount	12.76 yuan/t
e	punishment cost	450 yuan/t
θ_h	carbon emission factor of the TOT	131.78 kg/t****
θ_{r-h}	carbon emission factor of the IRRT	31.67 kg/t****
γ	a government-mandated rate of carbon reduction	20%

Note: The data with * are calculated according to the literature of Rus et al. ([34]), the data with ** are calculated according to the literature of Kang et al. ([28]), the data with *** are calculated from the official website of China 95306, and the data with **** are calculated according to the literature of Tang ([35]).

6.1 Numerical Simulation of Optimal Decisions of the IRRT Supply Chain Under Different Modes

Based on Tab. 2 and the aforementioned models, the optimal decision values of the IRRT supply chain are shown in Tab. 3 in the three modes of decentralized decision without subsidy, centralized decision and decentralized decision under government intervention.

Table 3 The calculated values of optimal decision in three modes

Optimal decision variables	Decentralized decision without subsidies	Centralized decision with government subsidy	Decentralized decision with government subsidy
p_2^*	203.115	187.408	200.430
q^*	9.141	44.073	12.762
v_h^*	42.328	—	46.022
v_r^*	158.828	—	162.522
π_t^*	70.707	—	72.384
π_h^*	85.262	—	166.189
π_r^*	85.262	—	166.189
π^*	241.232	812.508	404.761

The numerical example results in Tab. 3 show that under the influence of local government subsidy policies: (1) The market price of the IRRT has decreased, which will be conducive to seize freight market share with competition from the TOT (the agreed volume between the MTO and the RTE, and the agreed volume between the MTO and the RWTE, have all increased, also indirectly confirmed the prediction), and then the carbon emissions of the TOT is higher than the IRRT (Tang [35]), so the goods off to the IRRT will increase the rate of carbon reduction accordingly; (2) The profits of all stakeholders in the logistics supply chain and the total profits of the system have been significantly improved, indicating that the government's subsidy policy is conducive to the steady progress and long-term development of the IRRT industry; (3) The total profit of centralized decision-making supply chain is greater than that of decentralized decision-making, which verifies the Pareto improvement conclusion in supply chain management.

6.2 Influencing Factors Analysis of Dynamic Pricing and Interest Game of the IRRT Supply Chain Considering Carbon Emission

6.2.1 Government Subsidy Coefficient

Other parameters in Tab. 2 are fixed, while the government subsidy coefficient β is on the interval (0, 32.48), and the value is taken as the step of 2, and the unit is yuan/t. According to the equations of carbon reduction rate, market freight prices, the profits of the parties and the total profit under three modes (decentralized decision without subsidies, centralized decision with government subsidy and decentralized decision with government subsidy), the influences of the changes in β on carbon reduction rate, market price of the IRRT and the interest game are analyzed. The results are shown in Fig. 2 to Fig. 4 (In all figures, the units of all prices and subsidy coefficient are yuan/t, and all profit units are in yuan).

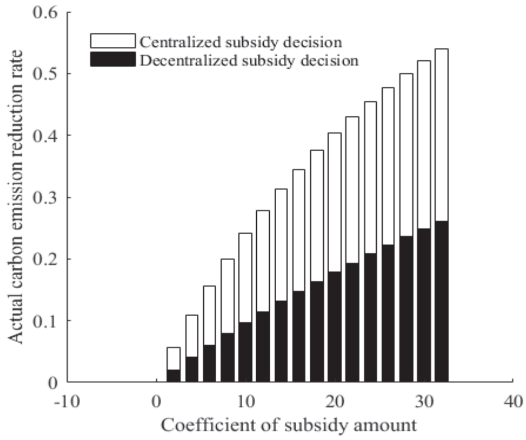


Figure 2 Influence of government subsidy amount on carbon emission reduction rate

It can be seen that when other parameters are fixed, with the increase of β: (1) In terms of carbon emission reduction rate, with the decrease of market freight price leading to the transfer of freight market from the TOT to the IRRT, the value of γ increases monotonically under the government subsidy mode (and centralized decision-making is higher than decentralized decision-making). When $\beta = 24$, γ=20.8%, which has met the government's expected carbon emission reduction rate of 20% (using γ=20% to infer $\beta \approx 23$). (2) In terms of pricing strategy, the market price variable is not affected by the decentralized decision without subsidy, which is shown by a horizontal line in the figure. After the government subsidy, the freight prices of the IRRT in centralized and decentralized decision-making modes decrease monotonically, and the rate of change of centralized decision-making is fast. (3) In terms of profit, similarly, the variables of the decentralized decision without subsidy are not affected, and they appear as horizontal lines in the figure. After government subsidies, the total profits of the supply chain under two kinds of decision mode are monotonously increasing (and centralized mode is greater than the decentralized mode), and then the profits of the

RTE and RWTE are equal and monotone increasing under decentralized decision mode, while the MTO's profit drops before rising trends: when $\beta \in [0,5.98]$, π_t monotone decreasing, and when $\beta = 5.98$ yuan/t , π_t reached its lowest point; when $\beta > 5.98$, π_t monotonically increasing, and starting from the critical point $\beta = 11.7$, the respective profits of the three parties and total profits are greater than the values in the decentralized decision-making mode without subsidies.

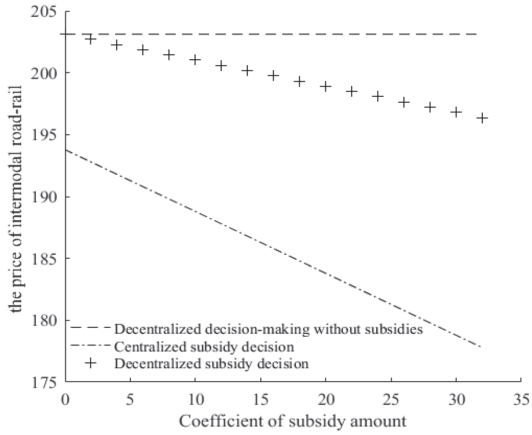
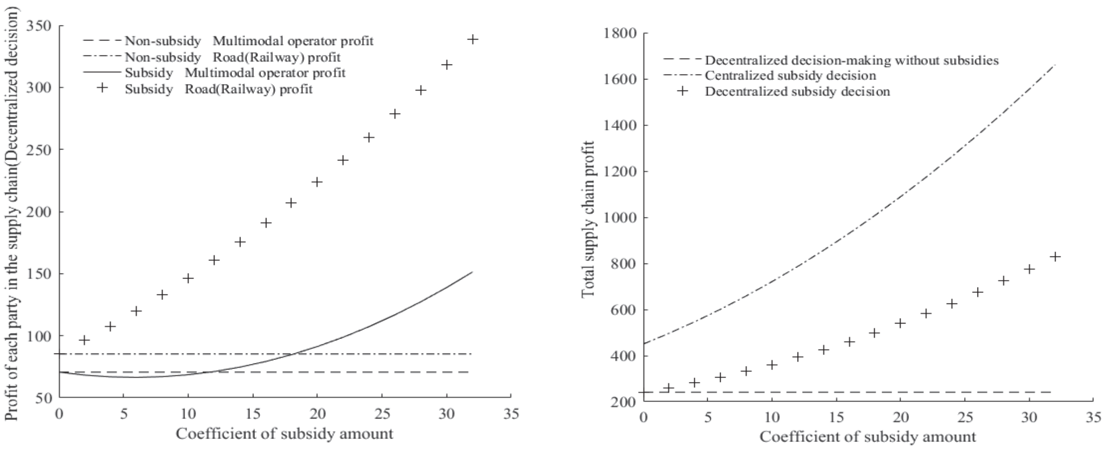


Figure 3 Influence of government subsidy amount on the price of the IRRT



(a) Influence of government subsidy amount on the profits of each participant

(b) Influence of government subsidy amount on total profit of supply chain

Figure 4 The influence of government subsidy amount on the profits of the IRRT

6.2.2 The Price of the TOT

Other parameters in Tab. 2 are fixed, while the price of the TOT p_h is on the interval (150, 300) and takes 5 as the step value, and the unit is yuan/t. According to the market price formula, the profit expressions of the parties of supply chain and total profit under three kinds of decision mode, the influence of the TOT's price changes on the pricing strategy and profits game of the supply chain constituted by the TTE, the RTE and the MTO is analyzed, and the results are shown in Fig. 5 and Fig. 6 (In the figures, all prices are in yuan/t, and all profits are in yuan).

As you can see, in the case of other parameters fixed, with the increase of the TOT's price ph: (1) The prices of the IRRT are monotone under the three kinds of decision-making mode, where the price under centralized decision with government subsidy is minimum and its agreed volume is the biggest through the derivation of the formula; (2) In terms of profits, whether local governments implement subsidy policies or not, the profits of the RTE and the RWTE are equal and monotonically increasing, while the profits of the MTO show a trend of decreasing first and then increasing.

When $p_h \in [180,\ 219.64]$, the value of π_t under the decentralized decision without subsidy is larger than that under the decentralized decision with subsidy, but its decreasing rate is relatively faster. When $p_h = 219.64$, π_t under the two decision modes is equal, which indicates that the government subsidy plays a role in making up for the profit loss of the MTO caused by the fluctuation of the TOT's price.

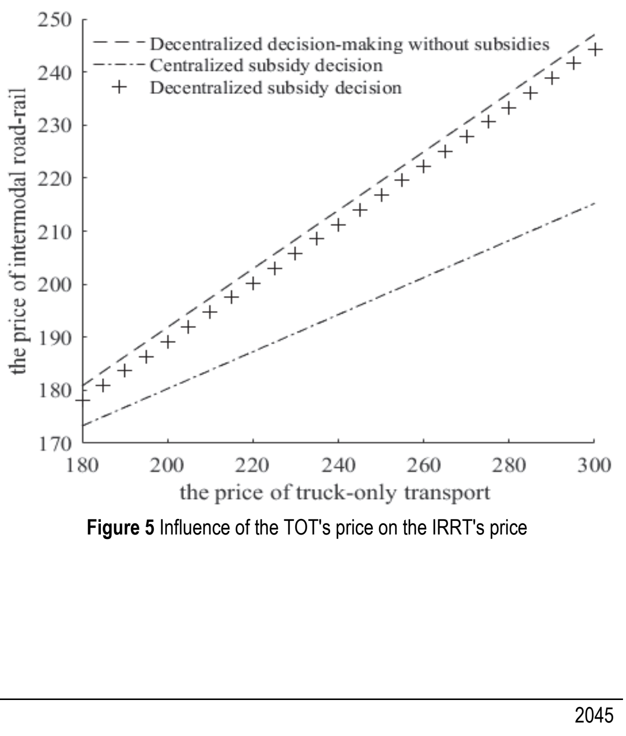
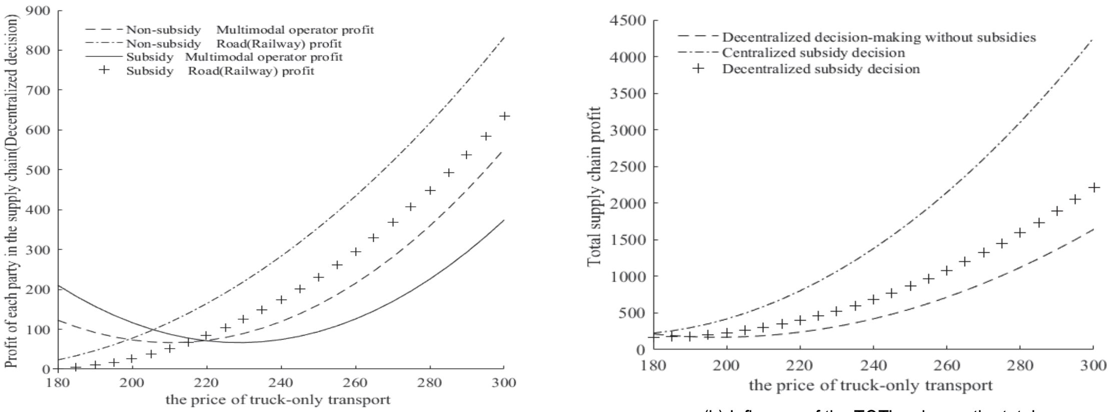


Figure 5 Influence of the TOT's price on the IRRT's price



(a) Influence of the TOT's price on the profit of each party in the supply chain

(b) Influence of the TOT's price on the total profit of the supply chain

Figure 6 Influence of the TOT's price on the IRRT's profits

7 CONCLUSION

In this paper, the interest game of the logistics service supply chain composed of the MTO, the RTE and the RWTE is studied. The main conclusions are as follows:

① By constructing a Stackelberg game model, this paper analyzes the optimal decision of the interest game of the supply chain before and after the government subsidy (including centralized decision and decentralized decision), and gets the good and bad order of the three modes: centralized decision with subsidy > decentralized decision with subsidy > decentralized decision without subsidy. Therefore, the IRRT industry should encourage all participants of the supply chain to gradually move closer to the centralized decision-making through local alliance decision-making, and finally achieve Pareto improvement.

② Higher government subsidies are not always better. With the increase of the amount of subsidy, although the total profit of supply chain and the profit of the RTE and the RWTE monotonically increase, the profit of the MTO will decline temporarily. In order to ensure a long-term and effective cooperative relationship among the IRRT supply chain, and on the premise of ensuring the growth of the profits of the three parties and the eligibility of carbon emission reduction rate, the government should reduce the financial expenditure as much as possible in the early stage of encouraging the development of multimodal transport. Therefore, the optimal range of the coefficient of government subsidy amount is (5.98, 23).

③ With the increase of the TOT's price, the market demand and freight price of the IRRT show a monotonically increasing trend. Therefore, on the basis of its own market regulation of the TOT industry, state and local government should intensify supervision, solve the problem that the market price is lower than the cost caused by malicious competition. A reasonable rise of the TOT's price will be conducive to the development of the IRRT industry, ensuring the implementation and promotion of green low carbon logistics.

Due to the limited space and energy of the author, this paper does not cover the following two aspects: First, how the shippers' choice between the two modes of transportation (mainly considering the three aspects of economy, time and environmental protection) achieves dynamic balance under the competition between TOT and IRRT. Second, further expansion of low-carbon policies, such as the in-depth study of the effective combination of green supply chain, sustainable development and IRRT. Further research on these two aspects is the next work plan of the author, and we also hope that readers of this paper can actively provide suggestions and cooperate or communicate with each other.

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Contact information:

Yu SHI
School of Management,
Shijiazhuang Tiedao University,
Shijiazhuang 050043, Hebei Province, China
E-mail: shiy@stdu.edu.cn

Hui WANG
(Corresponding Author)
School of Management,
Shijiazhuang Tiedao University,
Shijiazhuang 050043, Hebei Province, China
E-mail: wangh3368@163.com

Shuai DI
Hebei Logistics Jianlong Co., Ltd,
Shijiazhuang 050000, Hebei Province, China
E-mail: dishuai8888@126.com

Long CHEN
State Key Laboratory of Mechanical Behavior and System Safety of Traffic Engineering Structure,
Shijiazhuang Tiedao University,
Shijiazhuang 050043, Hebei Province, China
E-mail: chen0244@163.com