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Analyzing the Competitiveness of Intermodal Road-Rail Transport through the Lens of Cumulative Prospect Theory

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Abstract: Due to the long-standing government pricing system implemented by the railway, the market-oriented reform mechanism for freight transportation pricing remains imperfect. As a result, Intermodal Road-rail Transport (IRRT) has not fully utilized its advantages in the market competition against the Truck-Only Transport (TOT) mode. This paper addresses the limited rationality of decision makers and considers the interests of shippers and carriers in order to enhance the competitiveness of IRRT. To tackle the uncertainty associated with transportation costs, including economic and time costs, a two-layer programming model is employed. The upper layer model focuses on maximizing the operator's profit, while the lower layer model captures the equilibrium freight volume resulting from the shippers' choice behavior when competing modes reach equilibrium. In order to construct the competitiveness model accurately of IRRT, the study integrates the principles of cumulative prospect theory (CPT). Finally, the model is solved using a heuristic algorithm based on sensitivity analysis, presenting a fresh perspective for the steady development of IRRT.

Keywords: competitiveness research; CPT; IRRT; sensitivity analysis; two-layer programming model

1 INTRODUCTION

With the continuous development of economy, it is difficult for a single mode of transportation to meet the growing demand of logistics. According to "Terminology of intermodal freight transport" published by the Ministry of Transport, PRC, IRRT refers to the mode of combined transport in which goods are loaded by one and the same carrier unit and transported successively by road and railway, and the goods themselves are not operated in the process of transfer. As shown in Fig. 1, the multimodal transport operator (MTO), who is fully responsible for the transport process, signs a transport contract with the shipper and organizes the actual carrier (road and rail enterprise) to transport the goods from the place where they are taken over to the designated place of delivery. Compared with the traditional transportation, the one-unit multimodal transport system not only realizes the complementary advantages, but also has significant advantages in reducing transport costs, improving transport efficiency, decreasing cargo damage and cargo defects, simplifying procedures and so on. In September 2019, the Central Committee of the Communist Party of China and The State Council issued the "Outline of Building China into a powerful Country in Transport", which proposed to promote the development of multimodal transport, optimize the transport structure, speed up the construction of key projects of "Road to Rail" such as port collection and distribution railways, logistics parks and special railway lines for large industrial and mining enterprises, promote the orderly transfer of bulk and medium and long distance cargo transport to railways, and adapt to modern logistics high-quality development of railway requirements. The report of the 20 National Congress once again stressed the importance of accelerating the building of China into a transportation powerhouse and promoting the deep integration of various modes of transport. For the government, multimodal transport will help stimulate regional development by providing cheaper inland transport services (Monios et al. [1]).

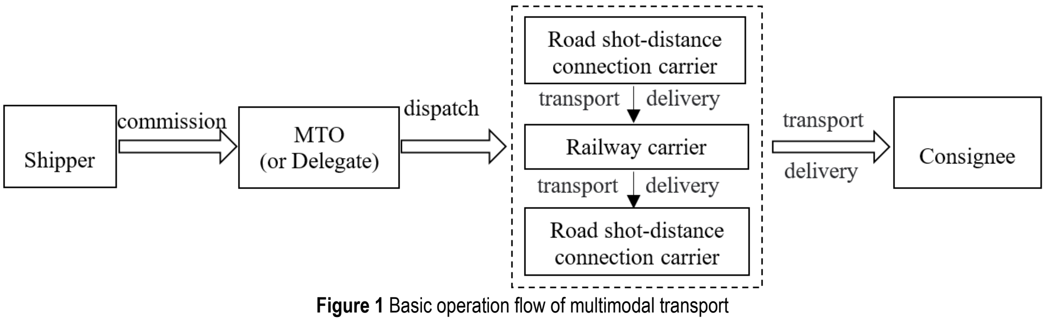


Figure 1 Basic operation flow of multimodal transport

With the rapid development of Chinese logistics industry, the problem of social logistics cost is widely concerned by the government and society from all walks of life (Li [2]). At present, in air, railway, road, water of four transportation modes, railway is the cheapest way of relative freight besides water transport. Thanks to several years of efforts, remarkable progress has been made in the "Road to Rail" and "Road to Water" projects. China's railway freight volume accounted for 9.2% of the total freight volume in 2021, up from 7.8% in 2017. However, China's railway freight has long adhered to the government pricing system, while road freight is relatively flexible (Tang et al. [3], Yuan et al. [4]), so the road freight volume always accounts for more than 80% of the total freight volume in China. The research on the competitiveness of IRRT with the participation of railway is closely related to its pricing mechanism and the transport decision of shippers. The pricing mechanism of railway transportation has not yet been perfected, and the pricing strategy of IRRT fails to follow the common practice. Factors affecting decision making include both objective factors and subjective factors such as personal preference. In addition, there are also some uncertain random factors (Fan [5], Chang et al. [6], Khoa et al. [7]). Therefore, shipping customers in the choice of transportation mode, it is difficult to do completely rational. Therefore, based on the cumulative prospect theory, this paper constructs a comprehensive perceived utility function for shippers based on economy and timeliness, uses a two-layer programming model to calculate the transport cost when different transport schemes reach the equilibrium state, and studies how to improve the competitiveness of IRRT from two perspectives: the decision-making behavior of shippers and the pricing mechanism of freight operators. It has a certain practical significance for the healthy and rapid development of China's logistics industry.

2 LITERATURE REVIEW

According to the research objectives, this part mainly introduces and summarizes the literature on the existing research on the competitiveness of multimodal transport and the application of the cumulative prospect theory in the field of transportation.

2.1 Competitiveness Analysis of Multimodal Transport

As a transport service product, the competitiveness of multimodal transport is ultimately reflected in the freight market share, that is, the probability of being selected by shippers. Zhang et al. [8] classified and sorted out nearly 50 literature studies after 2000 according to the research theme of freight disaggregated behavior model, and analyzed the theoretical basis, modeling ideas and data sources of shipper's freight service selection behavior; Tang [9] based on the random utility maximization theory, constructed the competitiveness Model between TOT and IRRT using MNL (Multinominal Logit Model). Based on RP/SP survey data in Yiwu city, Zhang et al. [10] used Nested-Logit disaggregated model to study the behavior of international container shippers from the perspective of port selection and inland transport mode selection. The analysis results showed that the important factors affecting transport chain selection were transport cost, transport time and reliability. And since the unit value of Yiwu's export commodities is low, the transportation cost is the main factor that Yiwu shippers consider when choosing the transportation chain.

After No. 33 Document in 2013 of the State Council proposed to continuously improve the railway tariff mechanism and adhere to the market-oriented orientation, the research on railway-related multimodal transport competitiveness research has also attracted wide attention. Throughout the existing literature, the studies of experts and scholars are mainly divided into two directions: ① External pricing problem, namely the study of market rates between MTO and shippers: Labbe et al. [11] studied the network pricing problem (NPP) with linear relationship between objective function and constraint by using the theory of two-layer programming and combinatorial optimization in virtue of the shortest path idea, which regards transportation cost as the impedance of the section. According to the Logit separation model and the utility value of each travel mode, Jiang et al. [12] built a double-layer programming model and obtained the optimal ticket price by taking the minimum travel cost of passengers and the maximum profit of air and rail combined transport operators as the objective function. Zhang et al. [13] established a competitive game model for transportation hubs in view of the route selection and pricing strategy of multimodal transportation, and realized the profit maximization of operators based on Nash equilibrium solution. ② Internal pricing problem, that is, the study of the agreed rates between various actual carriers and MTO: Duan et al. [14], based on the non-cooperative game theory, respectively constructed the game models under centralized and decentralized decision-making of IRRT, and solved the optimal rates under different situations. On this basis, Kang et al. [15], Shi et al. [16] and Tang et al. [17] respectively studied the optimal pricing of IRRT with the participation of non-truck carriers and the government. Zhang et al. [18], taking the profit of each carrier as the objective function, constructed the game model of pricing strategy of TOT and IRRT, and adopted the double-matrix game Nash equilibrium crossing method to solve it.

2.2 Cumulative Prospect Theory

Kahneman and Tversky [19, 20] successively put forward the prospect theory and the improved prospect theory, namely CPT, to describe the decision-making behavior under uncertain environment. Compared with prospect theory, CPT has the following advances: it is more applicable, allows income and loss to have different weights, and satisfies first-order random dominance. In recent years, CPT has been widely applied to travel selection (Avineri [21], Xing [22], Jhala et al. [23], Hu et al. [24], Yang et al. [25]), pricing of different transportation modes (Li et al. [26], Jing et al. [27], Li et al. [28], Yang et al. [29]) and other transportation researches. An et al. [30] compared the differences between CPT and expected utility theory in examples of travel mode choice behavior, and better explained the decision-making process of car owners' travel mode under uncertain and risky conditions. Yang et al. [31] took passengers' variability and bounded rationality into consideration, selected appropriate influencing factors, and built a two-layer programming model about time-sharing pricing based on CPT, which maximizes railway enterprise's revenue and minimizes passengers' generalized travel cost. According to CPT, Ma et al. [32] proposed the profit maximization model and social welfare maximization model of flexible bus operators. Ulteriorly the results show that heterogeneous fares can help flexible bus companies gain higher profits.

Throughout the literature above, no matter Logit model, two-layer programming model or Stackelberg game theory, decision-makers are regarded as completely rational decision-making subjects, which cannot accurately describe the heterogeneous individual behaviors in reality, resulting in a discrepancy with the actual situation. The cumulative prospect theory can better describe the finite rationality and difference of the decision-making subject's choice behavior, which makes up for the above deficiencies.

However, it is often used in the discussion of passenger transport pricing. This study can not only expand the application scope of CPT, but also provide new ideas for the research of multimodal transport competitiveness. Based on the above summary, this paper fully considers the heterogeneity and bounded rationality of decision makers, and constructs a two-layer programming model that considers the dual interests of shippers and IRRT operators (the upper layer programming describes the MTO to achieve the goal of maximizing their own interests by formulating the optimal tariff strategy, while the lower layer programming describes the shipper based on the cumulative prospect theory to achieve the goal of minimum generalized travel cost under the competition conditions of TOT and IRRT), then calculate the market share of each transport mode according to the basic freight rate and the obtained optimal freight rate, analyze the competitiveness problem of IRRT, and then solve it based on the heuristic algorithm of sensitivity analysis, and finally conduct numerical experiments.

3 IRRT COMPETITIVENESS BASED ON CPT

Among the four common modes of freight transport, water transport is slow in speed, poor in flexibility and continuity, and greatly affected by natural conditions such as hydrologic and meteorological environments. Then air transport has a small volume, high energy consumption and high freight rate. It can be seen, road and railway have obvious competition in terms of economy and timeliness in medium and long distance transport. Therefore, this paper only considers TOT and IRRT.

3.1 Comprehensive Perceived Utility Based on CPT

As the decision maker of transportation scheme, the shipper is bounded rationality in real life, which has the characteristics of personal preference and heterogeneity. Cumulative prospect theory holds that decision makers will show different risk preferences when facing returns and losses. Therefore, between the two modes of IRRT and TOT, the shipper calculates the benefits (or losses) of different transportation schemes according to his own perception, and finally chooses the scheme with the greatest comprehensive utility.

3.1.1 Shipper's Transportation Cost Function

There are many factors affecting the shipper's decision, most of which are based on transportation freight rate and transportation time. Therefore, this paper selects economic cost and time cost to calculate the shipper's transportation cost S_i, as shown in Eq. (1) to Eq. (3).

$$S_i = E_i + T_i \tag{1}$$

$$E_i = p_i \times L_i \tag{2}$$

$$T_i = VOG \times d_i \tag{3}$$

i - The index number of transport schemes.
E_i - Economic cost: the economic cost paid directly by the shipper of transport scheme i.
p_i - Freight rate, namely the price per unit corresponding to transport scheme i, unit: yuan/unit volume·km.
L_i - Freight distance corresponding to transport scheme i, unit: km.
T_i - Time cost: The cost of the in-transit value of the consignment of transport scheme i.
VOG - The monetary value of the goods consigned by the unit within the unit time, unit: yuan/unit volume·h.
d_i - The total transportation time of the consignment process in transport scheme i (from the time when the goods leave the specified place to the time when they arrive at the receipt place), unit: h.

3.1.2 Calculation of Shipper's Cumulative Prospect Value

CPT uses the sum of value function and cumulative weight function times each other to represent the prospect value of an event, fully considers the heterogeneity and bounded rationality of decision-makers, and gives an explanation for the situation that violates the expected utility theory. Therefore, the determination of value function and cumulative weight function is the key.

First, the value carrier in CPT is the gain or loss of a factor relative to the "reference point" (Tversky et al. [20]), so the calculated value function is subjective and used to represent the psychological impact of the actual utility level on decision-makers. In this paper, the value function of different factors for different types of shippers is described by Eq. (4).

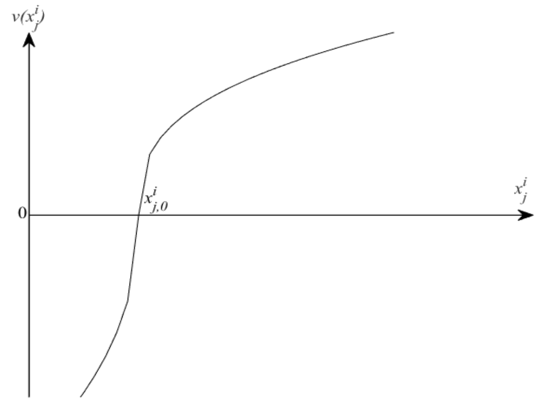
$$v\left(\Delta x_j^i\right) = \begin{cases} \left(\Delta x_j^i\right)^a, & \Delta x_j^i \geq 0 \\ -\lambda\left(-\Delta x_j^i\right)^\beta, & \Delta x_j^i < 0 \end{cases} \tag{4}$$

Where: Δx_j^i represents the gain or loss perceived by the decision-maker of type i regarding factor j relative to the reference point $\Delta x_{j,0}^i$, $\Delta x_j^i \geq 0$ represents the gain, $\Delta x_j^i < 0$ represents the loss), $\alpha\left(0 < \alpha < 1\right)$ and $\beta\left(0 < \beta < 1\right)$ are risk preference coefficients, and the larger the value is, the more sensitive the decision-maker is to the risk. For convenience of calculation, it is assumed that the convexity of the gain region and the loss region are equal, i.e., $\alpha = \beta$; $\lambda\left(\lambda > 1\right)$ is risk aversion factor. As shown in Fig. 3a, compared with income, the widespread loss aversion makes decision makers more sensitive to loss, which is specifically manifested by a higher slope of value function curve.

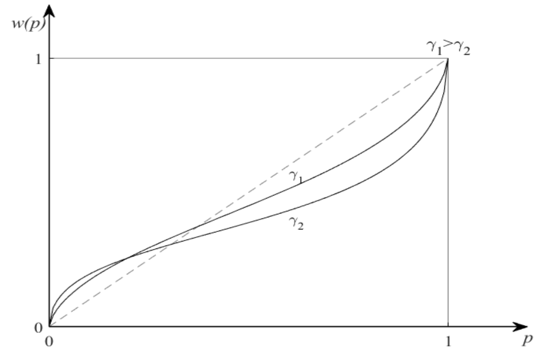
Secondly, the weight function of CPT is subjective probability, which represents the subjective effect of decision makers on objective probability. Taking probability P_j^i as the objective probability or ideal probability of the type j shipper choosing transport scheme i, the weight function expression can be obtained as Eq. (5).

$$w\left(P_j^i\right)=\frac{\left(P_j^i\right)^{\gamma}}{\left[\left(P_j^i\right)^{\gamma}+\left(1-P_j^i\right)^{\gamma}\right]^{1/\gamma}} \tag{5}$$

Where: $w\left(P_j^i\right)$ is the subjective perceived probability when facing the risk of gain or loss; γ is the corresponding sensitivity coefficient. As shown in Fig. 3b. γ is intuitively represented as the bending degree of the decision weight function. The smaller the value, the greater the bending degree of the function. Kahneman et al. [19] obtained after test calibration: when facing income, $\gamma = 0.61$, when facing loss, $\gamma = 0.69$.



(a) Relationship between subjective value and actual value



(b) Relationship between subjective probability and ideal probability

Figure 2 Schematic diagram of the relationship between the hypothesis of bounded rationality and that of complete rationality

Finally, the cumulative prospects of different factors for different types of shippers are calculated. According to the operating conditions of CPT, the hypothesis is $\Delta x_j^i\left(-m \le j \le n\right)$ arranged in the order from small to large, which is satisfied $\Delta x_{-m}^i < \Delta x_{-m+1}^i < \cdots \Delta x_0^i < \cdots \Delta x_{n-1}^i < \Delta x_n^i$.

Then the corresponding objective probability is $P_j^i=\left\{P_{-m}^i, P_{-m+1}^i, ..., P_0^i, ..., P_{n-1}^i, P_n^i\right\}$, and the subjective probability at this time can be expressed as $w\left(P_j^i\right)=\left\{w\left(P_{-m}^i\right), w\left(P_{-m+1}^i\right), ..., w\left(P_0^i\right), ..., w\left(P_{n-1}^i\right), w\left(P_n^i\right)\right\}$.

Similarly, corresponding to income and loss, cumulative prospect value can also be divided into positive prospect value (namely, cumulative value of income, represented by CPV+) and negative prospect value (namely, cumulative value of loss, represented by CPV−), which are respectively composed of corresponding subjective utility and subjective probability, as shown in Eq. (6).

$$\begin{cases} CPV^{+}=\sum_{i=0}^{n} w^{+}(P_j^i)v(\Delta x_j^i) & n>0 \\ CPV^{-}=\sum_{i=-m}^{0} w^{-}(P_j^i)v(\Delta x_j^i) & m>0 \end{cases} \tag{6}$$

The "capacity" concept proposed by Tversky and Kahneman [20] is introduced to define the weight function of an event. The decision weight π_i^+ of a positive prospect is the difference between the volume of the event "whose outcome is at least as good as x_i" and that of the event "whose outcome is strictly better than x_i". The decision weight π_i^- of the negative prospect is the difference between the volume of the event "whose outcome is at least as bad as x_i" and the event "whose outcome is strictly worse than x_i". According to the definition, the decision weight at this time is the cumulative weight, and there is Eq. (7).

$$\begin{cases} \pi_n^{+}=w^{+}\left(P_n\right), \quad \pi_{-m}^{m}=w^{-}\left(P_{-m}\right) \\ \pi_i^{+}=w^{+}\left(P_i+\cdots+P_n\right)-w+\left(P_{i+1}+\cdots+P_n\right), 0\le i\le n-1 \\ \pi_i^{-}=w^{-}\left(P_{-m}+\cdots+P_i\right)-w-\ \left(P_{-m}+\cdots+P_{i-1}\right), 1-m\le i\le 0 \end{cases} \tag{7}$$

π_i^+ and π_i^- are the cumulative weight functions when decision-makers face gains and losses, respectively; P_i is the ideal probability of the event x_i occurring.

By substituting Eq. (7) into Eq. (6), the cumulative prospect value of the influencing factor j for the shipper of Class i is $CPV\left(x\right) = CPV + CPV = \sum \pi\, v\left(\Delta x\right) + \sum \pi\, v\left(\Delta x\right)$, $n > 0$, $m > 0$.

3.1.3 Shipper's Comprehensive Perceived Utility

By combining CPT and shippers' transportation cost function, the comprehensive perceived utility of scheme i for the type j shipper can be expressed as Eq. (8).

$$\begin{cases} U_{j,i}=\alpha_{1,i} * CPV\left(E_{j,i}\right)+\alpha_{2,i} * CPV\left(T_{j,i}\right)+\varepsilon_{j,i} \\ CPV\left(E_{j,i}\right)=\sum_{r=0}^{n}\pi_{j,r}^{i+}v\left(p_j^i L_j\right)+ \\ +\sum_{r=-m}^{0}\pi_{j,r}^{i-}v\left(p_j^i L_j-p_{j,0}^i L_j\right), n>0, m>0 \\ CPV\left(T_{j,i}\right)=\sum_{r=0}^{n}\pi_{j,r}^{i+}v\left(VOG * I *\left(d_j^i-d_{j,0}^i\right)\right)+ \\ +\sum_{r=-m}^{0}\pi_{j,r}^{i-}v\left(VOG * I *\left(d_j^i-d_{j,0}^i\right)\right), n>0, m> \end{cases} \tag{8}$$

$V_{j,i}$ is the observable utility, that is, the determined utility of economic cost and time cost; $\varepsilon_{j,i}$ stands for unobserved utility, independent of each other and subject to Gumbel distribution; $a_{j,1}$ and $a_{j,2}$ are undetermined parameters, which represent the sensitivity coefficients of Class j

shippers to economic cost and time cost respectively, values are shown in Tab. 1.

3.2 Two-Layer Programming Model for IRRT Competitiveness

Although multi-stakeholders (road enterprises, railway enterprises and multimodal transport operators) participate in IRRT, "one ticket system" is implemented in the process of freight pricing. Therefore, this paper regards IRRT as a service product in the same position as TOT. The multimodal transport operators, as the decision maker, are responsible for the "door to door" freight business. Road enterprises and railway enterprises, as sub-carriers, perform specific transportation tasks. Many decision-making problems are composed of multiple decision-makers with hierarchy, and these decision-makers are relatively independent. That is to say, the decision-makers at the top guide the decision-makers at the bottom through their own decisions without direct interference, and then the lower decision-makers take the upper decision as parameters or constraints and make decisions freely within their own possible range. Therefore, the research on the pricing strategy of IRRT can be regarded as a question of the leader and the follower, in which MTO is the leader and shippers are the follower. MTO changes the perceived utility value of the shippers for IRRT through the adjustment of transport charges and transport time, so as to improve the competitiveness of IRRT, and ultimately affect the choice of the shippers and increase their own profits.

Since the factors affecting freight prices and the competitive environment of freight market are targeted, the assumptions of the model are set before building the two-layer programming model.

3.2.1 Model Assumptions

In order to study the advancement and applicability of CPT, the following conditional assumptions are made in this paper due to the numerous factors involved in the competitiveness of IRRT.

Hypothesis 1: Only the competition between TOT and IRRT is considered.

Hypothesis 2: The decision maker is bounded rationality and always chooses the consignment scheme with the minimum perceived generalized cost.

Hypothesis 3: The shipper is mainly concerned about the economic cost and time cost.

Hypothesis 4: Both road and rail transport capacity can meet the needs of shippers, and there is no overload problem.

Hypothesis 5: During a given period of time, the total freight volume (measured in TEUs) of a given origin and destination is known and remains fixed.

Hypothesis 6: Road transport and rail transport in the consignment process are uniform speed, and do not consider the storage and transfer time issues.

3.2.2 Model Construction

As the leader of the two-layer programming model, MTO takes the maximization of the benefits of IRRT supply chain as the objective function when making decisions. The upper layer model is shown in Eq. (9).

$$\begin{cases} \max F\left(p,q\right)=\sum\limits_{i\in M}\sum\limits_{j\in N}\left[q_{j,rr}^{i}\left(p_{j,rr}^{i}\right)\cdot\left(p_{j,rr}^{i}\cdot L_{rr}^{i}-C_{rr}^{i}\right)\right] \\ s.t. C_{rr}^{i}\Big/L_{rr}^{i}\le p_{j,rr}^{i}\le p_{rr}^{(\max)} \end{cases} \tag{9}$$

$p_{j,rr}^{i}$ - Freight rates for IRRT Scheme i signed between MTO and the Class j shipper, unit: yuan/TEU·km.

L_{rr}^{i} - Transportation distance of IRRT scheme i, unit: km.

C_{rr}^{i} -The MTO's transport cost regarding IRRT Scheme i, unit: Yuan /TEU, $\left(C_{rr}^{i}=\sum\limits_{j=1}^{3}c_{j}^{i}+2c_{h}\right)$ (where, c_{j}^{i} is the transportation cost in transportation distance j of IRRT scheme i, unit: yuan/TEU; c_h is the packing/stripping cost, unit: yuan/TEU).

M, N - Total numbers of IRRT schemes and shipper types respectively.

$q_{j,rr}^{i}\left(p_{j,rr}^{i}\right)$ - The freight volume entrusted by the category j shipper to IRRT Scheme i at the rate of $p_{j,rr}^{i}$, unit: TEU.

$p_{rr}^{i(\max)}$ - Maximum price of IRRT Scheme i, unit: yuan/TEU·km.

The shipper, as a follower of the two-layer programming model, takes the minimum generalized cost perceived by himself as the objective function when making decisions, and constructs the lower layer model as Eq. (10).

$$\begin{cases} \min Z\left(q\right)=\sum\limits_{j}\sum\limits_{i}\int_{0}^{q_{j,i}}f\left(x\right)\mathrm{d}x \\ s.t. \sum\limits_{j\in N}\sum\limits_{i\in\{rz,rr_1,rr_2\}}q_{j,i}=Q \\ q_{j,i}\ge 0 \end{cases} \tag{10}$$

$f(x)$ - Generalized perceived cost function of economic cost and time cost, and the independent variable is freight volume. According to relevant research, the shipper's generalized cost function is often expressed by logarithmic function and power function, and we select the first one.

The specific form is: $f\left(q\right)=a\,ln\,q-U$, a is the undetermined parameter, $U_{j,i}$ is the comprehensive perceived utility based on CPT, and the specific form is shown in Eq. (8). The condition constraint shows that the total consignment demand is a known number Q and the freight volume of different types of shippers choosing a certain transportation scheme is non-negative. rz is the index of TOT scheme; rr_1, ..., rr_n indicates the index of different IRRT schemes.

In order to reflect the characteristics of freight volume changing with the change of generalized travel cost, $f\left(q\right)=a\,ln\,q-U$ is substituted into Eq. (10) to obtain the following freight volume distribution model (Yang et al. [31], Si et al. [33]):

$$\begin{cases} \min Z(q) = \sum_j \sum_i \int_0^{q_{j,i}} \left(a \ln q_{j,i} - U_{j,i} \right) \mathrm{d}x \\ s.t. \sum_{j \in N} \sum_{i \in \{rz, rr_1, rr_2\}} q_{j,i} = Q \end{cases} \tag{11}$$

3.3 IRRT's Competitiveness

According to stochastic utility theory, shippers tend to choose the transportation scheme with the most comprehensive perceived utility. Therefore, the competitiveness of IRRT can be expressed by the probability that shippers choose it as the mode of transport, as shown in Eq. (12).

$$\begin{aligned} P_{rr} = \sum_{n \in \{rr_1, \dots, rr_n\}} P_n = \frac{\exp(\tau V_{rr_1})}{\sum_{m \in \{rz, rr_1, \dots, rr_n\}} \exp(\tau U_m)} + \\ + \frac{\exp(\tau V_{rr_2})}{\sum_{m \in \{rz, rr_1, \dots, rr_n\}} \exp(\tau U_m)} + \ldots + \frac{\exp(\tau V_{rr_n})}{\sum_{m \in \{rz, rr_1, \dots, rr_n\}} \exp(\tau U_m)} \end{aligned} \tag{12}$$

V_m - The determined utility of transport scheme m based on CPT is shown in Eq. (8).
τ - The undetermined coefficient which indicates the shipper's perception of the entire transportation network.

4 HEURISTIC ALGORITHM DESIGN

It is assumed that the disturbance parameter of sensitivity analysis is IRRT's freight rate, and other factors affecting the change of freight volume (cargo transit time, TOT's freight rate, etc.) remain unchanged. Determining the expression form of the response function is the key to solving the two-layer programming model. The heuristic algorithm based on sensitivity analysis can obtain the derivative relationship between volume and rate in the lower layer programming, and approximate the response function by combining the Taylor expansion to simplify the programming model and solve the problem. The specific steps are as follows:

Step 1: It is assumed that there are two IRRT schemes and one TOT scheme between the beginning and the end of a certain freight, and the scheme index number is i $\left(i \in \{rr_1, rz, rr_2\}\right)$.

Step 2: The freight rates $p_{j,i}^{(n)}$ of three freight schemes are initialized, where n is the number of iterations, i is the index of transportation schemes, j is the shipper type number, and iteration precision ε is set. At this time, $n = 0$.

Step 3: Under the condition that the freight rate is $p_{j,i}^{(n)}$, combined with the cumulative prospect value of the three transportation schemes, and solved the lower programming model Eq. (11) by referring to references [33] and [34], the solution $q_{j,i}^{(n)*}$ of the freight volume distribution problem under the equilibrium state was obtained.

Step 4: Use sensitivity analysis method to find out the derivative relation between freight volume and freight rate in IRRT Scheme rr_1, and obtain linear approximate response function:

$$q_{j,rr_1}^{(n+1)} \approx q_{j,rr_1}^{(n)*} + \left.\frac{\partial q_{j,i}}{\partial p_{j,i}}\right|_{p_{j,rr_1} = p_{j,rr_1}^{(n)}} \left(p_{j,rr_1}^{(n+1)} - p_{j,rr_1}^{(n)} \right).$$

Step 5: The above response function is substituted into the objective function of the corresponding upper-level programming Eq. (9), and a new rate $p_{rr_1}^{(n+1)}$ is obtained;

Step 6: Convergence judgment: if $\left| p_{j,rr_1}^{(n+1)} - p_{j,rr_1}^{(n)} \right| \le \varepsilon$, that is, meet the requirement of iteration accuracy, then set $p_{j,rr_1}^{*} = p_{j,rr_1}^{(n+1)}$; Otherwise, set $n = n + 1$ and go back to Step 3 to continue.

Step 7: p_{j,rr_1}^{*} was used to replace the corresponding value in the initial freight rate, and the lower layer programming model was solved again to calculate the solution $q_{j,i}^{(n)*}$ of the freight volume distribution problem under the equilibrium state.

Step 8: Use sensitivity analysis method to find out the derivative relation between freight volume and freight rate in IRRT scheme rr_2, and obtain linear approximate response function:

$$q_{j,rr_2}^{(n+1)} \approx q_{j,rr_2}^{(n)*} + \left.\frac{\partial q_{j,i}}{\partial p_{j,i}}\right|_{p_{j,rr_2} = p_{j,rr_2}^{(n)}} \left(p_{j,rr_2}^{(n+1)} - p_{j,rr_2}^{(n)} \right).$$

Step 9: The above reaction function is substituted into the objective function of the corresponding upper programming Eq. (9), and the new freight rate $p_{rr_2}^{(n+1)}$ is obtained.

Step 10: Convergence judgment: if $\left| p_{j,rr_2}^{(n+1)} - p_{j,rr_2}^{(n)} \right|$, that is, meet the requirement of iteration accuracy, then set $p_{j,rr_2}^{*} = p_{j,rr_2}^{(n+1)}$. Otherwise, set $n = n + 1$ and go back to Step 7 to continue the iteration.

Step 11: If the convergence judgment in Step 6 and Step 10 is established, then the calculation is terminated and the optimal freight rate $p_{j,rr}^{*} = \left\{ p_{j,rr_1}^{*}, p_{j,rr_2}^{*} \right\}$ of IRRT is output.

5 SIMULATION ANALYSIS

5.1 Example Description and Parameter Setting

In this paper, taking the shipping service (container) between a certain terminal and starting point as an example, we solve the pricing problem of IRRT based on CPT. According to the assumed conditions, the shipper has only two transport modes to choose: IRRT and TOT.

As shown in Fig. 2, this paper takes the shipping service (container) between a specific starting point S and ending point F as an example to study the competitiveness of IRRT in the situation where three transport schemes (①Route S-CS1-CS2-F, $i = rr_1$; ② Route S-F, $i = rz$; ③ Route S-CS3-CS4-F, $i = rr_2$) coexist. Among them, CS_1 and CS_3 are the transfer stations of road short barge to rail transport, similarly, CS_2 and CS_4 are the transfer stations of rail to road short barge. The content in ( ) on each road section represents the transportation distance, and the values are shown in Tab. 1.

Different from passenger transport, container cargo transport is mostly business behavior of enterprises, most of which involve industry or enterprise secrets, so it is inconvenient to carry out RP or SP investigation. Assuming that the road transport speed is 70 km/h and the railway transport speed is 100 km/h, the goods' transit time di is calculated according to the subsection distance of the three modes of transport in Fig. 2. The heterogeneity of shippers determines their different requirements for the attributes of goods transportation services. For example, shippers transporting low-value products are more concerned about economy, while shippers transporting fresh products may prefer timeliness. In this paper, they are classified into two groups: economic-sensitive and time-sensitive, with index numbers 1 and 2, respectively. With reference to the data on the official website of China 95306 and literature [35], the values of other parameters involved in model solving and example analysis in this paper are shown in Tab. 1.

Due to the short distance between the two places, most shippers choose TOT. Assuming that the proportion of container transport by IRRT in this scenario is 10%, τ in Eq. (12) is 0.17 combined with Tab. 1. The benchmark freight rates of TOT and IRRT respectively are {10.3, 9.0, 8.0} yuan/TEU·km. With the average cargo value per container of a freight station being 300000 yuan and the interest rate taking the current demand deposit interest rate, namely, I = 0.25%, the VOG in Eq. (3) is 33.56 yuan/TEU·h.

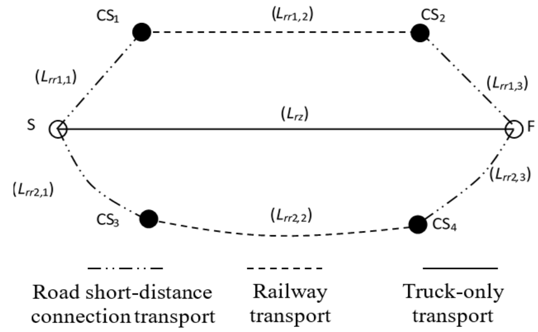


Figure 3 Schematic diagram of transportation scheme between the place of dispatch and the place of receipt

Table 1 Parameter values

Parameter	Value	Unit	Parameter	Value	Unit
β	0.75	-	c_h	375	yuan/TEU
λ	2.25	-	Q	100000	TEU
$L_{rr1,1}$	30	km	L_{rr}^{i}	$L_{i,1}+L_{i,2}+L_{i,3}$	km
$L_{rr1,2}$	374	km	$p_{rr}^{i(\max)}$	$1.2C_{rr}^{i} / L_{rr}^{i}$	yuan/TEU·km
$L_{rr1,3}$	30	km	$\alpha_{1,1}$	0.6	-
L_{rz}	400	km	$\alpha_{1,2}$	0.3	-
$L_{rr2,1}$	20	km	$\alpha_{2,1}$	0.5	-
$L_{rr2,2}$	432	km	$\alpha_{2,2}$	0.4	-
$L_{rr2,3}$	20	km	d_i	$\{4.6,\ 5.71,\ 4.9\},\ i\in\{rr_1,\ rz,\ rr_2\}$	h
C_{rr}^{i}	$[250+15\cdot\max(0,L_{i,1}-10)]+[440+3.185\cdot L_{i,2}]+[250+15\cdot\max(0,L_{i,3}-10)]+2c_h$				yuan/TEU

Note: c_{rr}^{i} is divided into four parts: the first part and the third part represent the cost of short-distance connection at both ends of the road, which is 250 yuan/TEU within 10 km, and 15 yuan/TEU is increased for each exceeding 1 km. If less than 1 km, it is calculated as 1 km. The second part represents the railway transportation cost, which is the sum of fixed cost (440 yuan/TEU) and variable cost (3.185 yuan/TEU·km times railway distance $L_{i,2}$). The fourth part represents the loading/emptying charges at both ends.

In cumulative prospect theory, the selection of reference points directly affects the decision maker's evaluation of the results of gain and loss. According to Eq. (13), the utility value of the transportation scheme is calculated according to the weighted average of the ideal probability, and multiple reference points of the shipper are obtained, as shown in Tab. 2.

$$X_{j,i}=\frac{\sum_{i\in\{rz,\,rr_1,\,rr_2\}}\left(P_{j,i}\left(V_{j,i}\right)\right)}{\sum_{i\in\{rz,\,rr_1,\,rr_2\}}P_{j,i}} \tag{13}$$

Where, $X_{j,i}$ is the psychological reference point of the type j shipper for scheme i; $P_{j,i}$ is the ideal probability of the type j shipper choosing scheme i, and $V_{j,i}$ is the determination utility of the type j shipper for scheme i (same as Eq. (8)).

Table 2 Shipper type and corresponding psychological reference points

Shipper type	Transport scheme	Rate / yuan/TEU·km	Time / h
Economic-sensitive type	rz	9.5	5.8
	rr_1	8.9	4.8
	rr_2	8.2	5.2
Time-sensitive type	rz	9.8	5.5
	rr_1	9.2	4.3
	rr_2	8.4	4.6

5.2 Result Analysis

Combined with the data in Tab. 1, $L_{rr}^{i} = \{434;\ 472\}$ km and $C_{rr}^{i} = \{3.481;\ 3.366\}$ yuan/TEU are obtained. $p^{(n)} = \{p_{rz}, p_{rr}\} = \{10.3,\ 9.5\}$ is taken as the initial value, and the cumulative prospect value of different shipping schemes for the two types of shippers is calculated according to CPT. The results are shown in Tab. 3.

Table 3 Shippers' cumulative prospects for the three transport options

Shipper	Transportation scheme	Value function		Cumulative weight		Synthetic perceptual utility
		$v(\Delta E)$	$v(\Delta T)$	π_E	π_T	U
Economic-sensitive type	rz	−170.23	5.51	0.373	0.311	−37.59
	rr_1	−145.85	4.17	0.370	0.429	−31.87
	rr_2	−192.73	5.65	0.257	0.260	−29.23
Time-sensitive type	rz	−119.66	−42.73	0.373	0.488	−30.63
	rr_1	−86.72	−12.71	0.364	0.364	−17.62
	rr_2	−155.33	−12.71	0.264	0.149	−21.24

As can be seen from Tab. 3, the comprehensive perceived utility ranking of the three transportation schemes is different for different types of shippers. Under the set initial freight rate, the preference degree of economic sensitive shippers for different schemes is: IRRT Scheme rr_2 > IRRT Scheme rr_1 > TOT. The preference degree of time-sensitive shippers for different schemes is as follows: IRRT Scheme rr_1 > IRRT Scheme rr_2 > TOT.

In Eq. (11), $a = 1$ is taken and combined with the data in Tab. 3, the initial value of corresponding cargo flow under the equilibrium state in this situation is {5.4894, 2.981, 3.265, 23.927, 9.861, 5.072}. By combining Eq. (11) and literature [32], the corresponding Jacobian matrix form can be obtained as follows:

$$J_y(p) = \begin{bmatrix} \frac{1}{q_{1,1}} & 0 & 0 & 0 & 0 & 0 & -1 \\ 0 & \frac{1}{q_{1,2}} & 0 & 0 & 0 & 0 & -1 \\ 0 & 0 & \frac{1}{q_{1,3}} & 0 & 0 & 0 & -1 \\ 0 & 0 & 0 & \frac{1}{q_{2,1}} & 0 & 0 & -1 \\ 0 & 0 & 0 & 0 & \frac{1}{q_{2,2}} & 0 & -1 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{q_{2,3}} & -1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 0 \end{bmatrix},$$

$$J_p(p) = \begin{bmatrix} \alpha_1 \frac{\partial CPV(E_{1,1})}{\partial p_{1,1}} & 0 & 0 & 0 & 0 & 0 \\ 0 & \alpha_1 \frac{\partial CPV(E_{1,2})}{\partial p_{1,2}} & 0 & 0 & 0 & 0 \\ 0 & 0 & \alpha_1 \frac{\partial CPV(E_{1,3})}{\partial p_{1,3}} & 0 & 0 & 0 \\ 0 & 0 & 0 & \alpha_1 \frac{\partial CPV(E_{2,1})}{\partial p_{2,1}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \alpha_1 \frac{\partial CPV(E_{2,2})}{\partial p_{2,2}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \alpha_1 \frac{\partial CPV(E_{2,3})}{\partial p_{2,3}} \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}.$$

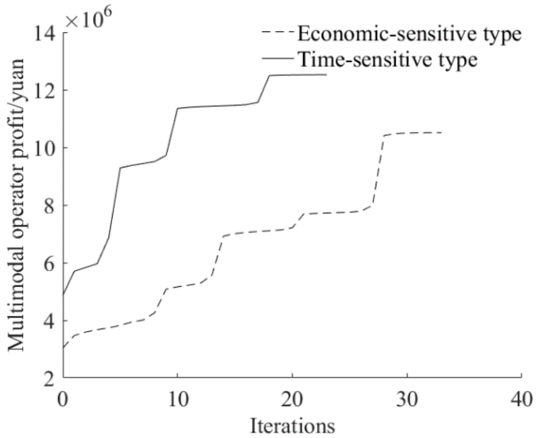
According to the heuristic algorithm of sensitivity analysis, MATLAB software was used to solve the two-layer programming model, and the convergence accuracy ε was set to 0.02, and the convergence result as shown in Fig. 4 was obtained.

As can be seen from Fig. 4a, with the increase of the number of iterations, the MTO's profits gradually rise from the initial value and eventually tend to be flat. After 31 iterations, the calculation results meet the convergence condition. At this time, the optimal freight rate and profit of IRRT schemes are {[8.81 yuan/TEU·km, 7.78 yuan/TEU·km]; [8.96 yuan/TEU·km, 7.85 yuan/TEU·km]} and {1.31×10^7 yuan, 1.07×10^7 yuan} respectively. Taking economically sensitive shippers as an example, the relationship between freight rate and traffic volume of public railway combined transport is shown in Fig. 4b. It can be seen from this that, with the addition of cumulative prospect theory, with the increase of freight rate, traffic volume does not decline strictly, but the general trend still conforms to the conclusion that freight rate and traffic volume are negatively correlated.

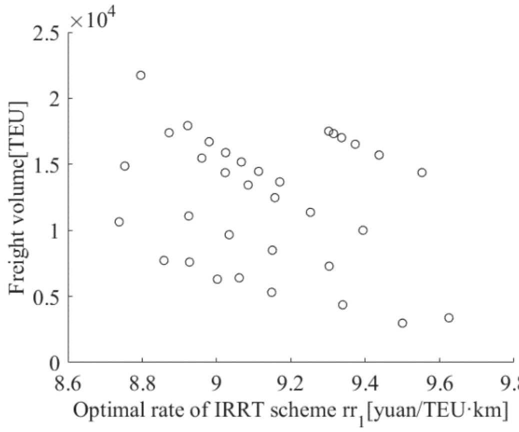
Similarly, taking economically sensitive shippers as the research object, the corresponding market share of IRRT in the process of solving the optimal freight rate is formed in a bar chart, as shown in Fig. 4c. The ninth bar chart in the figure has the highest market share, reaching 76.8%, which corresponds to the optimal freight rate of the IRRT scheme mentioned above. It is also confirmed that the research has practical significance: Optimizing the freight rate of IRRT based on the cumulative prospect theory can greatly improve its competitiveness.

The comparison results of the freight volume and revenue of the three freight modes (TOT, IRRT Scheme rr_1, IRRT Scheme rr_2) under the two scenarios of the standard freight rate and the optimal freight rate solved based on CPT are shown in Tab. 4.

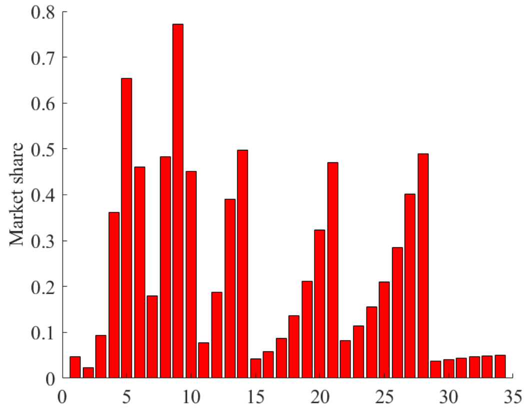
It can be seen from Tab. 4 that: First, when other conditions are fixed, the freight volume of IRRT increases with the decrease of freight rate, which confirms the conclusion in Fig. 4b; Second, after the pricing strategy is optimized by the cumulative prospect theory, the profit value of the IRRT schemes is improved compared with the current one. In scheme rr_1, the traffic volume is increased by 1.98 times and the profit is increased by 1.4 times. In scheme rr_2, the volume increases by 2.75 times and the profit increases by 2.1 times, while Scheme rz reduces the volume and the profit by 61%. Therefore, through the optimization of freight rates, IRRT has increased its competitiveness about twice as much in the competition with TOT.



a) The relationship between MTO's profit and iterations



b) The relationship between Optimal rate and Freight volume (Economic-sensitive)



c) The relationship between Optimal rate and Market share (Economic-sensitive)

Figure 4 Convergence results based on CPT

Table 4 Optimal freight rate and income results

Transport scheme	Base rate / yuan/TEU	Freight volume / TEU	Profit / yuan	Optimal rate / yuan/TEU	Freight volume / TEU	Profit / yuan
rz	4120.00	7.88×10^4	1.49×10^7	-	3.03×10^4	5.76×10^6
rr_1	3906.00	1.28×10^4	5.44×10^6	{3823.54, 3888.65}	3.82×10^4	1.31×10^7
rr_2	3823.20	0.84×10^4	3.45×10^6	{3672.16, 3705.20}	3.15×10^4	1.07×10^7

6 CONCLUSION

With the further market-oriented reform policy of railway freight rate proposed, on the basis of considering the competition of two modes (TOT and IRRT) and taking into account the interests of carrier and shipper, a two-layer programming model based on CPT is established to study the competitiveness of IRRT. The results show that:

1. The way for multimodal transport operators to increase profits is not simply to increase freight rates, but to reverse operations to improve their competitiveness and maximize profits. In this process, the shipper's broad perception of comprehensive transportation costs to achieve the lowest, the win-win situation makes the future development of IRRT more sustainable and healthy.

2. Multimodal transport operators can formulate appropriate transport plans and conduct differential pricing according to the heterogeneity of shippers, so as to increase the probability of being selected by customers in market competition, occupy more market shares, and ultimately achieve the purpose of increasing profits.

3. In actual transportation, because of the different value and attributes of goods, shippers have different concerns when choosing transportation schemes. Therefore, it is of practical significance to describe the generalized cost function of shippers for different modes of transport based on cumulative prospect theory, breaking the assumption of complete rationality of decision makers in previous studies.

Compared with previous studies, this paper pays more attention to the heterogeneity and subjectivity of shippers (personal preference, understanding degree of market information, etc.), so the results are more consistent with the actual situation. In order to facilitate calculation, some parameters are set directly. In practical application, calibration should be carried out according to the actual data collected. In addition, due to the size of the paper, this paper assumes that other factors (TOT's freight rate and time factor) except IRRT schemes' freight rate are fixed values. Instead of this assumption, the author's next research plan is that TOT's price is also regarded as a variable factor, and the competitive two-layer programming model (including IRRT's freight rate and TOT's freight rate) is solved when the equilibrium state is finally reached.

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