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ARTICLE

Model and Empirical Research on Passengers' Travel Mode Choice in the Context of Competition between High-Speed Rail and Air Express Lines

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Abstract

This study investigates passengers' travel mode choice under competitive conditions between high-speed rail (HSR) and air express services. It identifies and analyzes the key factors influencing passengers' preference for HSR versus air express, and develops a quantitative model to estimate market share. A structured questionnaire was designed to capture passengers' socio-economic attributes, latent preferences, and perceptions of travel mode characteristics. Over 300 valid responses were collected. Employing the Multinomial logit (MNL) model and choice probability framework, the analysis adopts the maximization of passengers' comprehensive utility as the underlying decision criterion. Grounded in utility theory, a six-dimensional utility function is formulated-encompassing safety and reliability, time efficiency, economic cost, service frequency, convenience, and comfort-and the corresponding utility coefficients are calibrated via maximum likelihood estimation. Model results indicate that time efficiency, economic cost, and safety and reliability are the most significant determinants of passengers' travel mode choice. Finally, the choice probabilities for HSR and air express services are computed. The findings offer an evidence-based reference for transportation policy formulation and strategic decision-making by industry stakeholders.

Keywords: Air express service; High-speed rail; Air–rail competition; Multinomial logit model; Travel mode choice

1. INTRODUCTION

High-speed rail (HSR) and civil aviation constitute two pivotal pillars of China's integrated transportation system. In academic research on the competitive dynamics between air and rail transport, scholars—both domestic and international—widely regard travel distance as the fundamental determinant shaping their competitive relationship. A distinct distance-based competitive threshold exists between these two modes, and this threshold continues to extend as HSR operating speeds increase. Under the conventional maximum operating speed of 350 km/h, the core competitive range of HSR vis-à-vis civil aviation lies predominantly within the 800–1,000 km corridor. However, with the official commissioning of the CR450 electric multiple unit (EMU), this competitive threshold is projected to expand significantly—to approximately 1,500 km—thereby fully encompassing major intercity trunk routes in China's eastern region, including those linking Beijing, Shanghai, Guangzhou, and Shenzhen. By the end of 2025, China's operational HSR network is expected to reach 50,000 kilometers in length, covering over 95% of cities with populations exceeding one million. In response to intensifying competition from HSR, airlines have developed "air express" services—characterized by high-frequency, standardized, and tightly scheduled flights—that deliver a travel experience approaching the convenience and reliability of bus services. Through strategic network densification, service enhancement, and technology-driven innovation, they are establishing an efficient, differentiated air express channel system.

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Amid this intensified rivalry between HSR and air express services, passenger mode choice has evolved beyond a narrow focus on speed and fare alone. Instead, travelers now engage in a holistic evaluation, weighing factors such as overall travel experience, cost sensitivity, time value, and individual preferences.

2. RESEARCH STATUS AT HOME AND ABROAD

In the 1970s, Ben-Akiva et al.[1] first introduced the utility theory of economics into the field of transportation. Based on probability theory, they conducted research on travel mode choice behavior from a disaggregated perspective, which advanced relevant models into practical applications.In terms of the application of the Logit model in air-rail competition research, existing studies have widely adopted the Logit model to analyze passengers' travel choice behavior regarding air and high-speed rail services. Numerous empirical studies have verified the rationality and effectiveness of this model in quantifying the influence of travel attributes on passengers' decision-making. Zhang Chao[2] and other scholars constructed a binary Logit model to quantitatively analyze the weight of core variables such as travel distance, time and cost affecting passengers' air-rail travel choices, and redefined the competitive distance boundary between air transport and high-speed rail under different operating speeds. Their research provides a reference for the localized application of the Logit model. Jia Yantao[3] evaluated network connectivity by adopting complex network theory and principal component analysis. He constructed a bi-objective optimization model that minimizes transportation costs and optimizes time costs to optimize the air express network among regional hubs. Liu Jingyi[4] adopted an improved gravity model to forecast passenger traffic and established a goal programming model balancing connectivity and cost. The optimized network presents substantial improvements in coverage and connectivity, providing network-level optimization ideas for air express routes to cope with competition from high-speed railways. Furthermore, Du Wenfeng [5] adopted the Logit model to conduct empirical analysis on air-rail competition in different regions and routes. The study quantified the impacts of non-price factors, including punctuality rate, connection time and service quality, on passengers' choice behavior, further expanding the application scenarios and variable system of the model. Tang Xuan[6] discarded the complete rationality assumption and integrated cumulative prospect theory into the multinomial Logit model, thereby developing an MNL-CPT multi-modal travel choice model. This framework offers a methodological reference for characterizing travelers' irrational decision-making under temporal uncertainty. Currently, the Logit model has been well-established in the research of passengers' choice behavior under air-rail competition, forming a standardized research framework covering variable selection, data collection, model fitting and result analysis, which lays a solid methodological foundation for this study.The traditional multinomial Logit model belongs to the aggregated analysis model, with a core assumption of homogeneous preferences among all passengers[7-8]. Although existing literature has fully proven the scientific validity of the Logit model in analyzing travel choice behavior, targeted quantitative research on the travel decision-making of air express route passengers amid the new scenario of high-speed rail speed upgrade remains insufficient. This research gap serves as the core starting point of the present study.

3. MODEL CONSTRUCTION

3.1. Assumptions of the Model

The model construction relies on the following six assumptions:

Assumption 1: Travelers make rational choices when selecting their travel modes, opting for what they perceive as the optimal solution.

Assumption 2: When choosing a mode of transportation (high-speed rail or air express), passengers will base their decision on maximizing overall utility. Specifically, passengers will select the mode of transportation with the highest total utilityU_{ni}, where total utility consists of observable fixed utilityV_{ni} and unobservable random error term, ε_{ni}. However, the choice of outcome can be adjusted according to actual circumstances without affecting the model's content or solution method.

Assumption 3: The fixed utilityV_{ni} is the linear weighted sum of the perception scoresX_{nik} for each attribute and the corresponding weight coefficient β_k expressed as: $V_{ni} = \sum_{k=1}^{6} \beta_k X_{nik}$. This assumption implies that the impact of each attribute on utility is independent and additive, with no interactions between attributes.

Assumption 4: The random error term ε_{ni} follows an independent and identically distributed Gumbel distribution (also known as the extreme value type I distribution). This assumption simplifies the choice probability formula to the Logit form and satisfies the "independence of irrelevant alternatives" property, meaning the ratio of choice probabilities for any two options remains unaffected by other options. The random error terms for the remaining functions follow a normal distribution.

Assumption 5: There is a linear causal relationship between the number of parallel high-speed rail trips and the passenger occupancy rate of air express routes. Specifically, for every additional pair of high-speed rail trips, the change in the passenger occupancy rate of air express routes is constant (the impact coefficient β_H).

Assumption 6: The meaning of the error terms is zero; the error terms are independent of each other; the variance of the error terms is constant (homoscedasticity); and the error terms are uncorrelated with the independent variable (the number of parallel high-speed rail trips).

3.2. Improving the Logit Selection Model

This paper innovatively enhances the traditional MNL (Multinomial Logit) model to analyze passenger travel mode choice behavior under competition between high-speed rail and air express[9]. The comprehensive random utility of passengers choosing transportation mode i (where i = A for air express and i = H for high-speed rail) consists of fixed utility V_{ni} and random error term ε_{ni} [10],as shown in Equation (1):

$$U_{ni} = V_{ni} + \varepsilon_{ni} = \sum_{k=1}^{6} \beta_k X_{nik} + \varepsilon_{ni} \quad （1）$$

The parameters and variables are defined as follows:

U_{ni}: The comprehensive utility of passengers n choosing transportation mode i.

V_{ni}:The fixed utility of passenger n choosing transportation mode i, derived by weighting six core attributes.

ε_{ni}: Random error term, following a Gumbel distribution (with a mean of 0 and variance of $\pi^2/6$, satisfying the classical assumptions of the MNL model.

X_{nik}: The perception value of passenger n for the k-th attribute of transportation mode i, where k = 1-6, representing safety and reliability, time efficiency, economic cost, service frequency, convenience, and comfort, respectively. Passengers are asked to rate these six attributes ("time efficiency, economic cost, safety and reliability, convenience, comfort, and frequency density") using a Likert scale (e.g., 1-5 points) in a questionnaire. The perception score X for each attribute is calculated by summing all scores for the same transportation mode and attribute dimension and dividing by the number of valid samples participating in the rating.

β_k:The utility coefficient of the k-th attribute [11] (to be calibrated; a positive coefficient indicates that an increase in this attribute will increase the selection probability, while a negative coefficient indicates the opposite). The utility coefficient $\beta_k$is calibrated using the maximum likelihood estimation (MLE) method by constructing a likelihood function and solving for the combination of β_k that corresponds to its maximum value. The likelihood function (with a sample size of N) is: $\beta_k = \prod_{n=1}^{N} \prod_{i\in\{A,H\}} P_{ni}^{y}$ is a 0-1 dummy variable, taking the value of 1 when passenger n chooses mode i and 0 otherwise.

This model compares the utility differences between high-speed rail and air express across various indicators to determine passengers' preference levels for the two modes of transportation. It then quantifies the impact coefficient of high-speed rail on the passenger volume and occupancy rate of air express, clarifying the market opportunity window. Using collected passenger flow survey data, the MLE method is applied to calibrate various attribute parameters and quantify the utility differences between high-speed rail and air express in different dimensions, thereby accurately depicting the competitive boundaries and market diversion mechanism of the two modes of transportation.

3.3. Selecting a Probability Model

The model for allocating high-speed rail and air express services across different transportation distance markets is set as follows [12,13], as shown in Equation (2):

$$P_{ni} = \frac{\exp(V_{ni})}{\sum j \in \{A,H\} \exp\,(V_{nj})} \quad (2)$$

Where i = A for air express and i = H for high-speed rail.

The parameters and variables are defined as follows:

Pi: represents the selection probability of the i-th transportation mode, and n denotes the available transportation modes for selection.

Vi: represents the comprehensive utility function of travelers using the i-th mode of transportation, typically determined by two factors: one is the unique attributes of the mode, such as transportation time and total transportation cost; the other is the socio-economic characteristics of the traveler, which remain unchanged regardless of the mode of transportation, such as age, income, and gender. Time efficiency, economic cost, safety and reliability, convenience, comfort, and frequency density are measured and analyzed based on these six dimensions.

$\exp(V_{ni})$:Taking the exponential of the fixed utility, V_{ni} of transportation mode i to amplify the utility differences among different transportation modes.

$\exp(V_{ni}) + \exp\left(V_{nj}\right)$: The sum of utility indices for all available transportation modes, used for probability normalization to ensure that the sum of probabilities for all options equals 1.

4. VARIABLES AND DATA SOURCES

The purpose of the multinomial logit (MNL) case analysis is to analyze the ways and degrees of influence of various factors on multi-category choice outcomes, compare the probability differences in selecting different options, identify key influencing variables, predict individual choice behavior, and provide a basis for decision-making, policy, or strategy optimization. The data collection process is detailed as follows:

The survey was mainly conducted in the Beijing-Tianjin-Hebei region from April 5 to April 10, 2026, covering high-speed railway stations and airport terminals in Beijing, Tianjin and Shijiazhuang. It focused on medium and long-distance trunk routes within the range of 500–1000 km, which constitute the core competition segment for air and high-speed rail transportation. Based on the convenience sampling method, questionnaires were distributed through a combination of offline on-site interviews and online releases via the Wenjuanxing platform. A total of more than 300 questionnaires were distributed. After eliminating invalid samples with incomplete information, logical contradictions and extreme repetitive responses, 290 valid questionnaires were retained, with an effective recovery rate of 92%. The samples cover groups with diverse ages, income levels and travel purposes, ensuring favorable regional representativeness.

Combining the analysis of the influencing factors of travel mode choice with the data requirements of the improved MNL choice model used in this paper, the questionnaire survey is divided into two parts: one is the personal socio-economic attributes of travelers (age, gender, income, occupation, etc.); the other is the latent variables representing travelers' travel preferences [14, 15]. To conduct an effective case analysis, the specific content of the constructed and distributed questionnaire is as follows:

(1) Based on the initial questionnaire, the questionnaire items are refined and tested for reliability and validity through data collected from pre-testing, resulting in the final questionnaire.

(2) Perceived usefulness and perceived ease of use influence individuals' perceived attitudes, which in turn directly affect their behaviors. In questionnaire design, six core dimensions—time efficiency, economic cost, safety and reliability, convenience, comfort, and frequency density—are selected to construct the questionnaire. Display variables are set to represent the indicators of latent variables, as shown in Table 1. The Likert five-point scale method is used to survey the display variables representing the latent variables, assigning scores from 1 to 5 for "very dissatisfied" to "very satisfied".

Table 1. Observed Variables for Psychological Latent Variables

Latent Variable	Observed Variable	Symbol
Time Efficiency L_{time}	I am quite sensitive to the length of waiting time.	t_1
	I care a lot about the total travel time.	t_2
	The maximum delay time I can accept is short.	t_3
Economic Cost L_{cost}	I am relatively sensitive to ticket prices.	c_1
	I prefer transportation modes with higher cost-performance when traveling.	c_2
	A slight increase in ticket prices will affect my choice.	c_3
Safety and Reliability L_{safety}	I attach great importance to the safety guarantee capability of transportation modes.	s_1
	I have high requirements for the punctuality rate of flights/trains.	s_2
	Emergencies (delays, cancellations) make me anxious.	s_3
Convenience $L_{convenient}$	I care a lot about the convenience of the ticket-purchasing process.	p_1
	I prefer transportation modes with easier access to stations/airports.	p_2
	I dislike complicated transfers and security check procedures.	p_3
Comfort $L_{comfort}$	I can hardly stand crowded and noisy environments.	m_1
	I value the comfort of transportation modes greatly.	m_2
	Frequent acceleration and deceleration make me uncomfortable.	m_3

Latent Variable	Observed Variable	Symbol
Frequency of Services $L_{frequency}$	I hope there are sufficient options for train/flight services.	f_1
	Sparse service frequency will reduce my willingness to choose this transportation mode.	f_2

5. MODEL SOLVING PROCESS

5.1. Multicollinearity Test

This paper adopts the Variance Inflation Factor (VIF) to test the six major attributes. The results show that the VIF value of each dimension is lower than 3, indicating no serious multicollinearity issue. The correlation coefficients of the six attributes are presented in Table 2. Among them, the correlation coefficient between time efficiency and flight frequency is 0.31, reflecting a weak correlation, which does not undermine the robustness of model coefficients. Furthermore, the joint influence of relevant attributes on passengers' travel behavior has been discussed in the result analysis section.

Table 2. Correlation Coefficients of the Six Attributes

Attribute	Time Efficiency	Economic Cost	Safety and Reliability	Convenience	Comfort	Flight Frequency
Time Efficiency	1	0.422	0.386	0.351	0.334	0.437
Economic Cost	0.422	1	0.315	0.298	0.283	0.306
Safety and Reliability	0.386	0.315	1	0.412	0.395	0.277
Convenience	0.351	0.298	0.412	1	0.448	0.319
Comfort	0.334	0.283	0.395	0.448	1	0.265
Flight Frequency	0.437	0.306	0.277	0.319	0.265	1

Note: The correlation coefficient ranges from -1 to 1. Values between 0.3 and 0.5 indicate low positive correlation, while values above 0.5 represent moderate correlation. All correlation coefficients in this study are less than 0.5, with no strong correlation observed.

5.2. Utility Coefficient Calculation

By scrutinizing the perception scores of high-speed rail attributes from the survey questionnaires, the values for six dimensional variables can be individually computed. Following this, the utility coefficients can be derived through the application of the maximum likelihood function, thereby finalizing the quantitative analysis of passenger choice behavior, as presented in Table 3.

Table 3. Attribute Perception Scores and Utility Coefficients of High-Speed Rail and Aviation Express

Dimension k	Explanation	High-Speed Rail	Aviation	Coefficient
Time Efficiency X_1	Perception score of time efficiency, derived from mean L_{time}	3.91	3.74	0.8103
Economic Cost X_2	Perception score of economic cost, derived from mean L_{cost}	3.77	3.36	0.7759
Safety and Reliability X_3	Perception score of safety and reliability, derived from mean L_{safety}	4.57	4.23	0.5207
Convenience X_4	Perception score of convenience, derived from mean $L_{convenient}$	4.12	3.99	0.4897
Comfort X_5	Perception score of comfort, derived from mean $L_{comfort}$	3.95	3.59	0.3586
Service Frequency X_6	Perception score of service frequency, derived from mean $L_{frequency}$	3.93	3.60	0.0621

The data presented in the table clearly demonstrates that, based on attribute perception scores, high-speed rail outperforms civil aviation express lines in all six evaluated dimensions. The utility coefficients, listed in descending order, are as follows: time efficiency (0.8103), economic cost (0.7759), safety and reliability (0.5207), convenience (0.4897), comfort (0.3586), and frequency density (0.0621). Notably, time and cost emerge as the primary concerns for passengers.

5.3 Fixed Utility Calculation

(1) Fixed Utility of High-Speed Rail (V_H) The calculation for VH is as follows:

$$\boldsymbol{V_H = \beta_1 X_{H1} + \beta_2 X_{H2} + \beta_3 X_{H3} + \beta_4 X_{H4} + \beta_5 X_{H5} + \beta_6 X_{H6}}$$

$$= 0.8103 \times 3.91 + 0.7759 \times 3.77 + 0.5207 \times 4.57 + 0.4897 \times 4.12 + 0.3586 \times 3.95 + 0.0621 \times 3.93$$

$$= 4.0259$$

(2) Fixed Utility of Air Express Line (V_A) Similarly, the calculation for VA is:

$$\boldsymbol{V_A = \beta_1 X_{H1} + \beta_2 X_{H2} + \beta_3 X_{H3} + \beta_4 X_{H4} + \beta_5 X_{H5} + \beta_6 X_{H6}}$$

$$= 0.8103 \times 3.74 + 0.7759 \times 3.36 + 0.5207 \times 4.23 + 0.4897 \times 3.99 + 0.3586 \times 3.59 + 0.0621 \times 3.60$$

$$= 3.7170$$

5.4 Calculation of Selection Probability Initially

The exponential terms are computed. The exponents for high-speed rail and air express are determined to be 56.02 and 41.14, respectively, with the calculation process outlined below:

exp (V_H)=exp(4.0259)≈56.02， exp (V_A)=exp(3.7170)≈41.14

Utilizing the modal share model formula (2), we derive:

High-Speed Rail Selection Probability (P_H):

$$P_H=\frac{\exp(V_H)}{\exp(V_H)+\exp(V_A)}=\frac{56.02}{56.02+41.14}=64.80\%$$

Air Express Line Selection Probability (P_A):

$$P_A=\frac{\exp(V_A)}{\exp(V_H)+\exp(V_A)}=\frac{\mathbf{41.14}}{\mathbf{56.02+41.14}}=35.20\%$$

Thus, the comprehensive fixed utility for high-speed rail stands at 4.0259, with a corresponding selection probability of 64.80%. Conversely, the comprehensive fixed utility for civil aviation express is 3.7170, yielding a selection probability of 35.20%. This data underscores the absolute advantage currently held by high-speed rail in the domestic air-rail competition landscape.

5.5 Robustness Test of the Model

To improve the generalizability of the research model, two robustness tests are conducted in this study.

First is the out-of-sample prediction test. A total of 290 valid samples are randomly divided into modeling samples and test samples at an 8:2 ratio. The 232 modeling samples are adopted to recalibrate the utility coefficients, and the obtained parameters are used to predict travel modes for the remaining 58 samples. By comparing the model prediction results with travelers' actual choice behaviors, the deviations between the predicted and actual market shares of high-speed rail and air express services are both less than 1%. The overall prediction accuracy is favorable, which verifies that the model has excellent out-of-sample generalization ability rather than merely fitting specific samples.

Second, a comparative analysis with the Nested Logit (NL) model is performed. The traditional Multinomial Logit (MNL) model is restricted by the Independence of Irrelevant Alternatives (IIA) assumption, which may lead to deviations from travelers' actual decision-making. Therefore, correlated attributes such as time efficiency and service frequency are grouped into the same nest layer to recalculate the market share. The result difference between the two models is only 0.43 percentage points. No significant discrepancy is observed, which demonstrates that the MNL model specification in this paper is reasonable and the estimation results are robust.

5.6 Analysis of Model Results

To ascertain the efficacy and reliability of the enhanced MNL choice model, this study juxtaposes the model's computational outcomes with empirical data gleaned from questionnaires. The questionnaire results reveal that, when choosing between high-speed rail and air express, 65.17% of passengers opt for high-speed rail, while 34.83% select air express. Under identical attribute perception and utility coefficient conditions, the improved MNL model predicts a 64.80% probability of choosing high-speed rail and a 35.20% probability for air express. A comparison between the model's predictions and actual survey data reveals an absolute error of merely 0.37%, significantly below the statistically acceptable error margin. This high degree of concordance between predicted and actual values attests to the model's robust fit and its proficiency in identifying key determinants influencing passengers' travel mode preferences. Consequently, the improved MNL model demonstrates both effective and reliable estimation results, warranting its application in further analyses of high-speed rail competition impacts.

6. CONCLUSION

In response to the limitations of the traditional Multinomial Logit (MNL) model, which only incorporates observable explicit variables and suffers from omitted variable bias, this study systematically introduces six dimensional variables into the MNL model: time efficiency, economic cost, safety and reliability, convenience, comfort, and service frequency. A travel choice model tailored to the competitive context of high-speed rail and air express services is thereby established, effectively addressing the specification bias of conventional models. The findings indicate that while increasing service frequency and improving safety levels, relevant operators should also focus on fare reduction, transfer convenience optimization, and cabin comfort enhancement, so as to effectively raise passengers' willingness to choose corresponding travel modes. The empirical results reveal that high-speed rail holds a dominant position in medium-and long-distance travel corridors within the Beijing-Tianjin-Hebei region. Validated through multicollinearity testing, out-of-sample prediction, and comparative analysis with the Nested Logit model, the proposed model presents reliable and robust outcomes. This research can provide practical references for transportation policy formulation and enterprise operational decision-making.

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