Research on Railway Passenger Transfer Selection Model Based on Generalized Cost

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Abstract—From the perspective of passenger demand, according to the characteristics of different types of passengers, based on the generalized cost optimization, a passenger transfer selection model is constructed. According to the actual needs of passengers during the transfer process, the definition and calculation method of the generalized cost of passenger transportation products in the model of economy, fastness, comfort, convenience and reliability are proposed, and the critical value of passenger transfer time is studied. Finally, the calculation is carried out by taking the passengers transferred from Harbin to Changsha at the Beijing as the research object. The results show that the calculation results of this model can meet the transfer needs of different types of passengers.

1. INTRODUCTION
At present, 12306 can provide passengers with transfer plans, but only complete the displacement of passenger space. With the rapid development of the national economy, service characteristics such as economy, speed, comfort, convenience, and reliability have become the focus of people's attention and have formed a huge market demand. Based on this, domestic scholars consider time, cost, and comfort to construct relevant mathematical models [1,2]. This type of model ignores some practical factors and cannot fully meet the passengers' travel needs. This paper considers the effects of transfer connection time, train arrival and departure times, train delays and service levels on passenger transfers, and establishes a mathematical model to define the critical value of the transfer time to provide passengers with good transfer program.

2. ANALYSIS OF THE TRANSFER PROCESS IN PASSENGERS
In this paper, the number of transfers on the passenger journey is 1, for the convenience of research, there are the following definitions: When a passenger chooses train to realize a full transfer, the train on the first journey is the transfer train, and the train on the second journey is the continuous train. The arrival station of the transfer train is the transfer station, and the departure station of the continuous train is the continuous station.
The passenger transfer process is shown in Fig.1. It is a decision-making process that takes into account the constraints of travel purpose, transportation service quality, and travel life needs. This paper aims at the decision-making process of railway transportation products in passenger selection, and solves the problem of passengers selecting trains in the first and the second journeys.

3. THE MODEL OF PASSENGER TRANSFER AND CHOICE BASED ON GENERALIZED COST

3.1. Influencing factors of passenger travel behavior

Passenger travel behavior is affected by subjective and objective factors. Subjective factors refer to the passenger's own characteristics, which determine the passenger's consumption characteristics and concepts. Objective factors refer to the economy, speed, comfort, convenience, reliability. According to passengers' consumption concept, passengers are classified into three categories: high, medium and low consumption. High-consumption passengers pay more attention to the speed and comfort of travel. Medium-consumption passengers have higher requirements for comfort and convenience. Low-consumption passengers are more sensitive to economy. The consumption concept of passengers and the characteristics of railway transportation products have a great influence on travel behavior.

3.2. Construction of passenger transfer selection model

According to the theory of economic management, generalized cost refer to the total outflow of all economic benefits incurred by an enterprise due to production and operation activities and other activities. The generalized cost of passenger travel refers to the monetary value that is finally expressed by economy, speed, comfort, convenience and reliability through a certain conversion relationship. The calculation formula is:

\[ C = C_1 + C_2 + C_3 + C_4 + C_5 \]  

Where 1, 2, 3, 4, 5 refer to the generalized cost of economy, speed, comfort, convenience and reliability.

Different types of passengers have different degrees of sensitivity to economy, speed, comfort, convenience and reliability. Therefore, the parameter \( \beta \) is introduced to modify the generalized cost of travel, and a passenger transfer selection model based on generalized cost is obtained:

\[ Z = \min \sum_{j=1}^{n} \sum_{i=1}^{5} \beta^k C_{ji} \]  

Where \( n \) is the number of sections of the transfer plan, which is 2 in this study. \( j \) is the \( j \) train that passengers take. \( L \) is the initial set of passenger transfer plan. \( \beta^k \) is the sensitivity of the \( k \) passenger to the \( i \) influencing factor, namely the weight. \( C_{ji} \) is the generalized cost of the \( i \) influencing factor of passengers taking the \( j \) train.

4. MODEL PARAMETER CALIBRATION AND TRANSFER TIME CRITICAL VALUE

4.1. Parameter calibration of generalized cost

(1) Economy

The generalized cost of economy refers to the fare, and the calculation formula is:
Where $E$ is fare, $\omega$ is discount factor, and when the passenger is a student and chooses to travel by high-speed rail, it is 0.75, when it is a regular-speed railway, it is 0.5, and the rest is 1.

(2) Speed

Train running time is a measure of speed, and speed is converted into speed generalized cost through time value. The opportunity cost method calculates the time value of passengers, the calculation formula is [1]:

$$V = \frac{0.5 \times Y}{50 \times 40}$$

Where $Y$ is the average annual salary of passengers, $V$ is the time value.

The formula for calculating the rapid generalized cost is:

$$C_t = t \cdot V$$

Where $t$ is the train running time.

(3) Comfort

Based on fatigue recovery time, this paper considers the effect of service level on passenger’s psychological comfort. The service level is positively related to the fare [8], and negatively related to the generalized cost of comfort. The formula for calculating the generalized cost of comfort is:

$$C_\gamma = V \cdot g(t) - \theta \cdot E$$

Where $\theta$ is the correlation coefficient between service level and fare, take 8% [8]. $g(t)$ is the fatigue recovery time of passengers, the calculation formula is [2]:

$$g(t) = \frac{T_{\text{max}}}{1 + \alpha_T \exp(-\beta_T t)}$$

Where $T_{\text{max}}$ is the maximum time required to recover from fatigue, take 14~15. $\alpha_T$ is the minimum fatigue recovery time for selecting train $T$ to travel. $\beta_T$ is the strength coefficient of fatigue recovery time per unit travel time.

When $T_{\text{max}}$ is 15, the value of $\alpha_T$ and $\beta_T$ is shown in Tab.1.

| Type                          | $\alpha_T$ | $\beta_T$ |
|-------------------------------|------------|-----------|
| high-speed railway, intercity, EMU | 59         | 0.28      |
| direct, express, fast train   | 49         | 0.33      |
| commuter, temporary train     | 39         | 0.40      |

(4) Convenience

Convenience includes the convenience of train arrival and departure and the convenience of transfer connection. The convenience of train arrival and departure time is inversely related to the time interval between the ideal and actual arrival and departure time of the train [1], and the convenience of transfer connection is indicated by the transfer time. The formula for calculating the generalized cost of convenience is:

$$C_c = (t_h + t_e + t_d) \cdot V$$

Where $t_h$ is transfer time. $t_e$ is the absolute value of the difference between the ideal and actual departure time of the train. $t_d$ is the absolute value of the difference between the ideal and actual arrival time of the train.

Literature [3] research shows that the ideal departure time for passengers is 7 o'clock, 11 o'clock, 16 o'clock, and 21 o'clock. For the convenience of research, it may be considered that the ideal arrival time is also the above four points.

(5) Reliability
Reliability refers to the impact of train delays on passenger transfers. The late arrival of the transfer train is likely to cause passengers to fail to transfer. This paper expresses the reliability by the delay time of transfer train. The formula for calculating the generalized cost of reliability is:

\[ C_s = \alpha \cdot t_w \cdot V \]  \hspace{1cm} (8)

Where \( t_w \) is the delay time of transfer train. \( \alpha \) is the influence coefficient of train delay on passenger transfer.

\( \alpha \) can be calculated by the following formula:

\[ \alpha = \frac{t_w}{t_h} \]

The delay time can be calculated with the probability density function of train delay. Normally, the probability density function of train delay follows a single parameter negative exponential distribution [4]:

\[ f_z(t) = \lambda_z e^{-\lambda_z t} \]

Suppose \( 0 \leq \alpha \leq 1 \)

Then \( 0 \leq t_w \leq t_h \)

The above formula shows that, regardless of the impact of major natural disasters, the train delay time does not exceed the transfer time. Calculating the mathematical expectation of the probability density function \( f_z(t_w) \) corresponding to the random variable \( t_w \) within this range as the reference value of the train delay time:

\[ t_{avg} = E(t_w) = \int_0^{t_h} t_w \lambda_z e^{-\lambda_z t_w} d(t_w) \]

The solution is:

\[ t_{avg} = \frac{1}{\lambda_z} (1 - e^{-\lambda_z t_h}) - t_h e^{-\lambda_z t_h} \]

Therefore, the formula for calculating the generalized cost of reliability is:

\[ C_s = \frac{t_{avg}^2 \cdot V}{t_h} \]  \hspace{1cm} (9)

4.2 Critical value of passenger transfer time

(1) The longest transfer time

The longest transfer time is related to the passenger's purpose of travel, time concept, etc. It is the subjective intention of the passengers. The longest transfer time that passengers can accept through the questionnaire survey is shown in Fig.2:

![Figure 2. Acceptance of the longest transfer time](image)

It can be seen from the figure that the longest transfer time that most passengers can accept is within 4 hours, accounting for 85.4%, and passengers with more than 4 hours account for only 14.6%. It can be seen that the maximum transfer time for passengers should not exceed 4 hours.

(2) The shortest transfer time
E-tickets are being promoted in an all-round way, so the effect of passengers’ ticket collection time on the shortest transfer time is not considered.

1）Transfer at the same station

According to the layout of the station, the same station transfer includes platform transfer, station hall transfer and transfer outside the station. Platform transfers have too high requirements for transfer facilities and transportation organizations. In China, station hall transfer and transfer outside the station are the mainstay. When there is a transfer channel in the station, the transfer time in the station hall is the shortest transfer time, otherwise it is the transfer time outside the station.

The formula for calculating the transfer time outside the station is:

\[ t_{min}^u = \varepsilon \cdot \sum_{i=1}^{\infty} t_i \]  \hspace{1cm} (10)

Where \( t_i \) is the time from the transfer station platform to the exit ticket gate. \( t_2 \) is the time from the exit ticket gate to the entry ticket gate. \( t_3 \) is the time from the entrance ticket gate to the waiting room. \( t_4 \) is the waiting time. \( t_5 \) is the ticket checking time. \( t_6 \) is the time to get on the train. \( t_{min}^u \) is the transfer time outside the station. \( \varepsilon \) is the redundant time coefficient of each link when passengers walk in and out of the station.

The formula for calculating the transfer time of station hall transfer is:

\[ t_{min}^h = \varepsilon \cdot \left( t_m + t_4 + t_5 + t_6 \right) \]  \hspace{1cm} (11)

Where \( t_m \) is the time when the passenger arrives at the waiting hall from the platform through the transfer passage, \( t_{min}^h \) is the transfer time of station hall transfer.

2）Transfer at different stations

There are buses, subways, taxis, and railway lines that can be used for transfers at different stations. The transfer time is composed of the city’s traffic running time and the travel time of entering and leaving the passenger terminal. The urban traffic environment in different railway passenger transport hubs is quite different, and the shortest transfer time at different stations should be based on the best local (short time-consuming) transfer method. The formula for calculating the shortest transfer time at different stations is:

\[ t_{min}' = \min_{M} \left( t_m + t_{i1} + t_{i2} + t_{i3} + t_4 + t_5 + t_6 \right) \]  \hspace{1cm} (12)

Where M is a collection of transportation modes in the city. \( t_{i1} \) is the running time of the \( i \) city traffic, including waiting time. \( t_{i2} \) is the time from the exit ticket gate of the transfer station to the \( i \) type of urban transportation stop. \( t_{i3} \) is the time from the \( i \) urban transportation drop-off station to the entrance station ticket gate. \( t_{min}' \) is the shortest transfer time at different station.

\( \varepsilon \) embodies the difference in the time taken by different passengers to walk in and out of the station, and is related to the age, physical fitness, luggage size and other factors of the passenger, and can be reflected by the walking speed. The walking speed of different types of passengers [5] is shown in Tab.2:

| Type       | no luggage | small luggage | large luggage | suitcase |
|------------|------------|---------------|---------------|----------|
| youth      | 1.51       | 1.46          | 1.31          | 1.39     |
| middle aged| 1.39       | 1.36          | 1.25          | 1.35     |
| elderly    | 1.14       | —             | —             | —        |
It can be seen from the table that young passengers have the fastest walking speed. Taking the ratio of the walking speed of young passengers to the walking speed of other types of passengers as the reference value of $\varepsilon$, the calculation is:

$$\varepsilon_{max} = \frac{1.51}{1.14} \approx 1.3$$

5. Examples

Take the passengers who transfer from Harbin to Changsha in Beijing as the research object. There are a total of 17 trains from Harbin to Beijing. The final stations are Beijing Railway Station and Beijing South Railway Station. There are 34 trains from Beijing to Changsha.

5.1. Weight calculation

Literature [7] research shows that the income of passengers on the Beijing-Shanghai line is mostly distributed between 5001-10000 yuan, 3001-5000 yuan and 3000 yuan, accounting for 34.67%, 35.81% and 18.29% respectively. This income range is used as the basis for dividing high, medium and low-consumption passengers. The travel preference scores of different types of passengers are obtained through questionnaire surveys and used as the original data for model weight calculation, as shown in Fig.3:

![Figure 3. The travel preference scores of different types of passengers](image)

The weight is calculated by the improved analytic hierarchy process [6], and the results are shown in Tab.3:

| Type of passenger | Speed | Economy | Comfort | Reliability | Convenience |
|------------------|-------|---------|---------|-------------|-------------|
| Low consumption  | 0.072 | 0.433   | 0.057   | 0.273       | 0.165       |
| Medium consumption| 0.050 | 0.092   | 0.446   | 0.154       | 0.258       |
| High consumption | 0.444 | 0.053   | 0.257   | 0.092       | 0.154       |

5.2. Initial plan for transfer and continuous trains

According to the survey, the shortest time by subway is from Beijing Railway Station, Beijing South Railway Station to Beijing West Railway Station. The author conducted field investigations at Beijing Railway Station, Beijing South Railway Station, and Beijing West Railway Station to obtain relevant time parameters to calculate the transfer time critical value. According to the previous study, the longest transfer time is 4 hours, and the redundant time coefficient is 1.3. For the convenience of research, it is assumed that passengers do not need to wait after entering the station.
Calculate the minimum transfer time at the same station according to formula (10): $t'_{\text{min}} = 31.2 \text{min}$
Calculate the shortest transfer time at different stations according to formula (12):
Beijing Railway Station to Beijing West Railway Station: $t'_{\text{min}} = 61.9 \text{min}$
Beijing South Railway Station to Beijing West Railway Station: $t'_{\text{min}} = 59.2 \text{min}$

Based on the critical value of the transfer time and the train schedule, there are a total of 84 passenger transfer options.

5.3. Passenger Transfer Scheme with Optimal Generalized Cost
Calculating the time value of different types of passengers according to formula (4), as shown in Tab.4:

| Type of passenger | Low consumption | Medium consumption | High consumption |
|-------------------|-----------------|--------------------|-----------------|
| mid-value income / yuan / month | 1500 | 4000.5 | 7500.5 |
| Time value / yuan / h | 4.5 | 12 | 22.5 |

Based on the time value, the initial plan for transfer, model weights, and equations (2) to (9), the optimal transfer plan for passengers is calculated as shown in Tab.5:

| Type of passenger | Transfer station | Transfer train | Continuous station | Continuous train | Generalized cost / yuan |
|-------------------|-----------------|----------------|--------------------|-----------------|------------------------|
| High consumption  | Beijing Railway Station | Z18 | Beijing West Railway Station | G79 | 237.730 |
| Medium consumption| Beijing Railway Station | Z18 | Beijing West Railway Station | G79 | 103.329 |
| Low consumption   | Beijing Railway Station | Z18 | Beijing Railway Station | K967 | 165.070 |

It is known from the calculation results that the transfer train for high and medium-consumption passengers is Z18, the continuous train is G79, the transfer train for low-consumption passengers is Z18, and the continuous train is K967. Z18 is the evening train, which has high convenience, economy and comfort, and meets the travel needs of various passengers. G79 has fast running speed, high convenience, high reliability and comfort, and is suitable for high and medium-consumption passengers. The running time of K967 is longer, but the fare is relatively low, which matches the consumption capacity and philosophy of low-consumption passengers. In summary, the passenger transfer selection model can meet the transfer needs of different types of passengers.

6. CONCLUSION
From the perspective of passenger demand, the passenger transfer selection model is constructed based on the generalized cost optimization, and the calculation method of the generalized cost of passenger transportation products in the process of passenger transfer is studied. According to different transfer modes, the critical value of transfer time is studied to solve the problem of train selection for passenger transfer. Finally, a case study of passengers who transfer from Harbin to Changsha in Beijing shows that the passenger transfer selection model considers more comprehensive factors and the research results are more reliable, which can meet the transfer needs of different types of passengers and provide technical support for the decision-making of the transportation department.
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