Evaluation of the Impact of High-Speed Train Service Level on Passenger Flow

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Abstract—Quantitative analysis of the relationship between high-speed train service level and passenger flow is the cornerstone of the scientific and reasonable formulation and optimization of train operation plan. The two most critical elements of train service level are travel speed and train service frequency. Based on the city level, the number of departure trains per day, and the number of departure passengers per day, the stations are divided into three classes: large stations, medium stations and small stations. Aiming at large stations OD (Origin-Destination), a Logit model was constructed to quantitatively analyze the impact of travel speed on passenger flow. Aiming at medium and small stations OD, the gravity model is constructed to quantitatively analyze the impact of train service frequency on passenger flow. Taking China’s Beijing-Shanghai high-speed rail line as an example, the results show: Large stations OD should reduce train stops and increase travel speed overall to attract more transferring passengers; Medium and small stations OD should increase train stops and increase service frequency to induce more potential passengers.

1.INTRODUCTION

Passenger train operation plan is the plan of train operation section, route, armistice plan, train type and operation logarithm. Its formulation is an important content in the process of high-speed railway transportation. Train service level is the manifestation of various service elements provided by high-speed railways for passengers in the operation plan, including train service frequency, travel speed, arrival time, time density deviation, direct access and transfer convenience, etc. The core factors are travel speed and train service frequency. Train service level will determine the quality of service obtained by passengers between OD (Origin-Destination) who choose high-speed rail to travel, which will have a huge impact on travel mode choice and passenger flow. Based on the quantitative relationship between train service level and passenger flow, scientifically and reasonably formulating and optimizing the train plan can increase the market share rate and passenger flow of high-speed railways while ensuring the rational use of transportation resources.

At present, the research on the train service level mostly focuses on constructing utility models and evaluation index systems to evaluate the service level of train plans. Meng[1] established a passenger train service level evaluation model and algorithm that considers travel time, transfer time, comfort, and station density based on complex network theory. Ning Jilong et al.[2] have established a comprehensive evaluation system for the supply and service level of high-speed railways based on the principles of convenience, economy, rapidity and reliability of passenger travel.

The research on the relationship between service level and passenger flow mainly focuses on the analysis of share rate and passenger flow forecast based on passenger flow factors such as service level...
factors. However, there is little research on the quantitative relationship between travel speed, service frequency and passenger flow for the characteristics of each type of OD. Román[3] used the disaggregated model to analyze the competitive relationship and sharing rate between high-speed railways and aviation by correlating RP and SP, and found the difference in willingness to pay for tickets for various passenger flow types under different service levels. Maria[4] aimed at the problem of inaccurate demand forecasts in the standard logit model under the condition of drastically reduced travel time. By studying the literature on the time elasticity of long-distance railway travel, looking for a model that can accurately predict the passenger demand of high-speed railway under the changing travel time in long-distance transportation. Xu Ruoxi[5] selected five factors of economy, rapidity, convenience, comfort, and safety, and constructed a logit model based on the generalized passenger travel expenses, and analyzed the changes in the share rate of high-speed railway passenger flow under different operating parameter adjustment schemes.

This paper selects two factors that have the most significant impact on passenger flow in the service level of train operation: travel speed and train service frequency, taking China's Beijing-Shanghai high-speed rail as an example. First, use the station importance index to classify the stations, and then construct models to calculate the quantitative relationship between the service level factors and the passenger flow for the OD of different station types, and analyze the impact of the service level improvement on the passenger flow.

2. CLASSIFICATION OF STATIONS
The passenger flow demand of different types of OD will have obvious differences. Therefore, it is necessary to classify the level of the station first, and distinguish the OD according to the type of the station, in order to perform quantitative calculations for each type of OD.

2.1. Classification evaluation index
The level of the station will be affected by the level of city where the station is located, as well as the supply and demand of the station itself. This paper selects the following three factors as the evaluation indicators for station classification: the level of city where the station is located, the average number of departure trains, and the average number of departure passengers every day. The level of city where the station is located is determined according to the city's administrative level, economic level, status and function in the railway network[6].

2.2. Classification method
The station importance method is used to construct a model to classify the stations. The station importance is a quantitative index to study the station's collection and distribution capacity in the railway network, and it is the main basis for measuring the importance of the station. In the high-speed railway network, the importance index of station can be calculated according to (1)[7].

\[ D_i = \sum_{j=1}^{w_j} \frac{x_{ij}}{\max_{1 \leq j \leq m} \{x_{ij}\}} \]

(1)

\( w_j \) is the weight of the j-th evaluation index. \( x_{ij} \) is the value of the j-th evaluation index of the i-th station. \( m \) is the number of evaluation indicators. \( n \) is the number of stations participating in the classification. \( \max_{1 \leq j \leq n} \{x_{ij}\} \) is the maximum value of the j-th evaluation index in all stations.

After the station importance is calculated, the results are systematically clustered, and the stations are divided into three classes: large stations, medium stations, and small stations.
2.3. Index value
This paper studies the Beijing-Shanghai high-speed railway line in China as an example. The level of city where the station is located is evaluated according to the research results of literature [6]. The results are shown in Table 1.

Table 1. The level of city where the Beijing-Shanghai high-speed rail stations are located

| City Level | Stations                                                                 |
|------------|--------------------------------------------------------------------------|
| Level 1    | Shanghai Hongqiao, Beijing South, Nanjing South, Jinan West, Xuzhou East, Tianjin South (West) |
| Level 2    | Kunshan South, Suzhou North, Bengbu South, Wuxi East, Changzhou North, Dezhou East, Cangzhou West, Zhenjiang South, Danyang North |
| Level 3    | Qufu East, Tai’an, Langfang, Zaozhuang, Suzhou East, Chuzhou, Tengzhou East |
| Level 4    | Dingyuan                                                                |

The daily average number of departure trains and departure passengers choose the actual value, and finally all indicators are normalized.

The weight of each evaluation index $w$ are determined by the expert scoring method. The weight of city level is 0.1429, the weight of train service frequency is 0.4286, and the weight of passenger flow is 0.4286.

2.4. Classification results
After calculation and clustering, the final station level is shown in Table 2.

Table 2. The final classification results of Beijing-Shanghai high-speed railway station

| City Level | Stations                                                                 |
|------------|--------------------------------------------------------------------------|
| Large Station | Shanghai Hongqiao, Nanjing South, Beijing South, Xuzhou East, Xinan West, Tianjin South (West) |
| Medium Station | Kunshan South, Suzhou North, Bengbu South, Dezhou East, Wuxi East, Changzhou West, Zhenjiang South, Qufu East, Tai’an |
| Small Station | Zaozhuang, Suzhou East, Chuzhou, Tengzhou East, Langfang, Danyang North, Dingyuan |

3. Evaluation of the Impact of Travel Speed on Passenger Flow
We call the OD from large station to large station as the “large station OD”. Currently, large station OD has a high frequency of train services and sufficient ticket supply. Other transportation modes such as expressways and air transportation are also relatively developed. Passenger travel demands can basically be met. Under this circumstance, there is an obvious competitive relationship between high-speed railways and other transportation modes. If the travel speed of high-speed railways increases, it will bring about changes in passenger choice behavior and adjustments in the sharing rate of various transportation modes. The increased passenger flow on high speed rail is transferring passenger flow. Therefore, it is the train travel speed that has the greatest impact on the OD passenger flow of major stations, and it is necessary to build a sharing rate model for research.

3.1. Logit model construction
The influencing factors of passenger choice behavior include economy, rapidity, convenience, comfort, and safety. These factors are fully considered to construct a Logit model to study the competitive relationship between OD high-speed railway, expressway and air transportation. The equation of the Logit model is as follows:

$$P_i = \frac{\exp(-V_i)}{\sum_{j=1}^{n}\exp(-V_j)}$$  \hspace{1cm} (2)
$P_i$ represents the sharing rate of the i-th transportation mode, and $V_i$ is the generalized cost of passengers who choose the i-th transportation mode to travel. The generalized cost calculation model is:

$$V_i = \frac{\alpha (\lambda_i E_i + \lambda_j F_i + U_i + \lambda_k C_i - U_i) - \lambda_s D_i}{S_i}$$ (3)

$E_i$ is economy, $F_i$ is rapidity, $C_i$ is convenience, $D_i$ is comfort, and $S_i$ is safety. $\lambda$ represents the weight of each factor, satisfies two conditions: $0 \leq \lambda_i \leq 1$ and $\sum \lambda_i = 1$. $\alpha$ is the model adjustment coefficient, adjusting the weight of factors according to actual situation of each OD. $U$ is the passenger time value, the calculation formula is:

$$U = \frac{GDP}{t \times N}$$ (4)

$GDP$ is the gross national product of the study area, $t$ is the average working hours of travelers each year, $N$ is the total population of the study area.

3.2. Parameter value

This article takes China's Beijing-Shanghai high-speed rail line as an example for research. The values of the factors affecting the OD sharing rate such as economy and rapidity are shown in Table 3:

| Factors | Transportation Mode | Way to Assume Value |
|---------|---------------------|---------------------|
| $E_i$   | High-speed railway  | Weighted average of first-class and second-class fares |
|         | air transportation  | 30% off on full-price economy class tickets |
|         | expressway          | Average value of car fare between OD |
| $F_i$   | High-speed railway  | Average travel time between OD trains plus traffic time from station to city center |
|         | air transportation  | Average flight time of direct flights between OD plus transportation time from airport to city center |
|         | expressway          | Divide the mileage between OD bus stations by the travel speed, then plus the traffic time from the station to the city center, the travel speed is 70km/h |
| $C_i$   | Conveniece is mainly reflected in the length of passenger waiting time. High-speed railway waiting time is 0.3h; air waiting time is 1h; expressway waiting time is 0.3h[5]. |
| $D_i$   | The comfort level can be reflected in the fare to a certain extent, so 5%-10% of the fare is taken[8]. |
| $S_i$   | Safety can be determined according to the number of casualties in various modes of transportation, 0.99 for high-speed railways and air, and 0.9 for expressway[9]. |

The parameter $U$ of the passenger time value is calculated using the average $GDP$ and population data of each city on the Beijing-Shanghai line. The annual working time $t$ is 2000 hours, $U$ is 57.88 yuan/hour after calculation.

The weight $\lambda$ of each factor is calibrated using the analytic hierarchy process[10], and the calibration results of the corresponding weight of each influencing factor are shown in Table 4:

| Factor | Economy | Rapidity | Conveniece | Comfort |
|--------|---------|----------|------------|---------|
| Weight | 0.26    | 0.36     | 0.23       | 0.15    |
3.3. Result analysis
Substituting the values and weights of the influencing factors, and the current OD sharing rate data of the Beijing-Shanghai high-speed railway line into (1) and (2). Calculating the adjustment factor $\alpha$. The results are shown in Table 5:

| OD                  | $\alpha$ | OD                  | $\alpha$ |
|---------------------|----------|---------------------|----------|
| Xuzhou East-Jinan West | 0.0477   | Xuzhou East-Beijing South | 0.0169   |
| Shanghai Hongqiao-Nanjing South | 0.0604 | Shanghai Hongqiao-Jinan West | 0.0688 |
| Nanjing South-Xuzhou East | 0.0375 | Nanjing South-Beijing South | 0.0536 |
| Jinan West-Beijing South | 0.0663 | Shanghai Hongqiao-Tianjin South (West) | 0.0555 |
| Nanjing South-Jinan West | 0.0125 | Shanghai Hongqiao-Beijing South | 0.0807 |
| Shanghai Hongqiao- Xuzhou East | 0.0131 |

Each OD has different trains. Due to the different number of stops, the travel speed between trains will also be different. We will set the difference between the travel speed and the maximum travel speed between ODs to be less than or equal to 10% of the maximum called “fast train”. On the contrary, trains with a speed difference greater than 10% of the maximum are called “slow train”. By reducing train stops and increasing the speed of “slow train” to the level of “fast train”, the calculation of the change in the share rate of the high-speed railway between OD and the increase in passenger flow is shown in Table 6:

| OD                  | Mileage(km) | Share Rate Increase | Passenger Flow Increase | Income Increase (yuan/day) |
|---------------------|-------------|---------------------|-------------------------|----------------------------|
| Xuzhou East-Jinan West | 286        | 0.68%               | 9.08                    | 1249                       |
| Shanghai Hongqiao- Nanjing South | 295 | 1.30%               | 275.26                  | 39356                     |
| Nanjing South-Xuzhou East | 331        | 0.11%               | 10.44                   | 1658                      |
| Jinan West-Beijing South | 406        | 0.22%               | 29.03                   | 5692                      |
| Nanjing South-Jinan West | 617        | 0.32%               | 8.23                    | 2437                      |
| Shanghai Hongqiao- Xuzhou East | 626 | 0.33%               | 15.29                   | 4532                      |
| Xuzhou East-Beijing South | 692        | 0.07%               | 3.41                    | 1117                      |
| Shanghai Hongqiao- Jinan West | 912        | 4.90%               | 221.62                  | 93755                     |
| Nanjing South-Beijing South | 1023       | 3.26%               | 441.72                  | 207924                    |
| Shanghai Hongqiao- Tianjin South (West) | 1204 | 13.13%              | 726.53                  | 393945                    |
| Shanghai Hongqiao- Beijing South | 1318     | 14.03%              | 5483.01                 | 3218006                   |
| Total               | -          | -                   | 7223.62                 | 3969671                   |

It can be seen from Table 6 that for the large station OD, the increase in the travel speed of high-speed railway trains will bring about a significant increase in passenger flow, and with the increase of mileage, the impact of travel speed on passenger flow is also greater. For all large station OD on the
Beijing-Shanghai line, after the slow train travel speed increases, the average daily passenger flow will increase by 7,223.62 people, and the average daily ticket revenue will increase by 3,969,700 yuan. Therefore, in the design process of the train operation plan, for the large station OD, it is necessary to minimize train stops, increase the frequency of “fast train”, and comprehensively increase the travel speed of the large station OD train, so as to increase the passenger flow sharing rate of the high-speed railway and attract more passengers.

4. EVALUATION OF THE IMPACT OF TRAIN SERVICE FREQUENCY ON PASSENGER FLOW

We call the OD of medium station-small station, small station-medium station, and small station-small station as “medium and small station OD”. The service frequency of high-speed railway trains between small and medium station OD is relatively low, and other transportation modes are not very convenient. In this case, some passengers cannot meet their travel demands because they cannot buy tickets. At this time, if the service frequency between the small and medium stations OD is increased, this part of the potential travel demand can be met, and the induced passenger flow will increase. Therefore, it is the train service frequency that has the greatest impact on the passenger flow of medium and small station OD. An improved gravity model needs to be constructed to quantitatively calculate how much increased passenger flow will be induced by the increase in service frequency.

4.1. Gravity model construction

The influencing factors of induce passenger flow include OD population, GDP, and generalized cost. In order to study the influence of train service frequency on passenger flow, this paper treats train service frequency as an influencing factor of passenger flow alone. Construct a gravity model considering the influence of service frequency on passenger flow as follows:

\[ q_{ij} = k \left( \frac{G_i \cdot N_i}{V_y^i} \right)^{\gamma} \left( \frac{G_j \cdot N_j}{V_y^j} \right)^{\gamma} \cdot F(\tilde{f}_{ij}) \]  

Where \( q_{ij} \) is the passenger flow between ODs. \( G_i \) and \( G_j \) are GDP of node i and node j. \( N_i \) and \( N_j \) are the population of node i and node j. \( f_{ij} \) is the train service frequency between ODs. \( V_y \) is the generalized cost of passengers between ODs. \( F(\tilde{f}_{ij}) \) is a function with \( \tilde{f}_{ij} \) as the independent variable. \( k, \eta, \mu, \gamma \) are coefficients to be solved.

Since only the high-speed railway transportation mode is considered to attract passenger flow, and the competition between transportation modes is not considered, the generalized cost here only considers economy, rapidity and convenience. The calculation formula is:

\[ V_y = E_y + F_y + C_y \]  

In the non-bus operation mode, when the frequency of train service increases, the time points available for passengers to travel will increase, and the waiting time will decrease accordingly. The service frequency and waiting time have the following relationship[10]:

\[ T_w = \frac{18(f_y + 1)}{4f_y} \]  

After integration, the final gravity model is:

\[ q_{ij} = k \left( \frac{G_i \cdot N_i}{V_y^i} \right)^{\gamma} \left( \frac{G_j \cdot N_j}{V_y^j} \right)^{\gamma} \cdot F(\tilde{f}_{ij}) \left[ E_y + F_y + \frac{18(f_y + 1)}{4f_y} U \right] \]
4.2. Model solving
For different types of OD, the relationship between service frequency and passenger flow is different, and the function form of \( F(f_q) \) is also different. Therefore, the function form and the coefficient values of (8) need to be calculated separately for different types of OD. The following calculation process still uses China's Beijing-Shanghai high-speed rail line as example.

4.2.1. Medium station - small station
For the passenger flow data of medium station to small station, the least square method is used to fit the (8), and the function form of \( F(f_q) \) with the highest goodness of fit is selected. The solution results are shown in figure 1 and formula (9). In the figure 1, the abscissa is the OD daily average train service frequency, and the ordinate is the OD daily average passenger flow.

![Diagram of relationship between train service frequency and passenger flow of medium station-small station](image)

\[
q = 6.941 \left( G_{ij} \cdot N_{ij} \right)^{0.251} \left( G_{ij} \cdot N_{ij} \right)^{0.084} \ln(0.088 + 0.44f_q + 1.182)
\]

\[
q = \left[ E_q + F_q + 57.88 \cdot \frac{18(f_q + 1)}{4f_q} \right]^{1.084}
\]

Equation (9) contains the function form of \( F(f_q) \) and the values of each parameter. The model fitting accuracy \( R^2 \) is 0.729, and the parameter fitting degree can meet the requirements.

4.2.2. Small station - small station
For the passenger flow data of small station to small station, the least square method is used to fit the (8), and the function form of \( F(f_q) \) with the highest goodness of fit is selected. The solution results are shown in figure 2 and formula (10). In the figure 2, the abscissa is the OD daily average train service frequency, and the ordinate is the OD daily average passenger flow.
Figure 2. Diagram of relationship between train service frequency and passenger flow of small station-small station

\[ q_v = 1.018 (G_i \cdot N_j)^{0.112} (G_j \cdot N_i)^{0.123} \left[ \ln(f_{ij} + 15.069) \right]^{0.056} \left[ \frac{E + F_v + 57.88}{4f_v} \right]^{0.99} \] (10)

Equation (10) contains the function form of \( F(f_v) \) and the values of each parameter. The model fitting accuracy \( R^2 \) is 0.812, and the parameter fitting degree can meet the requirements.

4.2.3 Small station- medium station

For the passenger flow data of medium station to small station, the least square method is used to fit the (8), and the function form of \( F(f_v) \) with the highest goodness of fit is selected. The solution results are shown in figure 3 and formula (11). In the figure 3, the abscissa is the OD daily average train service frequency, and the ordinate is the OD daily average passenger flow.
Figure 3. Diagram of relationship between train service frequency and passenger flow of small station-medium station

\[
q_{ij} = 0.061 (G_i \cdot N_j)^{0.149} (G_j \cdot N_i)^{0.188} \left[ \ln(f_{ij} + 4.879) \right]^{-0.065} \left( F_{ij} + 57.88 \right)^{0.189} \left( 18f_{ij} + 1 \right) \cdot 4f_{ij} \quad (11)
\]

Equation (11) contains the function form of \(F(f_{ij})\) and the values of each parameter. The model fitting accuracy \(R^2\) is 0.725, and the parameter fitting degree can meet the requirements.

4.2.4. Result analysis

According to the gravity models calibration results of three OD types, the increase in passenger flow and ticket revenue brought by service frequency increase is shown in Table 7.

| Train Frequency Increment of Each OD | Passenger Flow Increase | Passenger Flow Increase Rate | Income Increase (yuan/day) |
|-------------------------------------|-------------------------|------------------------------|---------------------------|
| 1                                   | 1088.69                 | 12.05%                       | 211459.5                  |
| 2                                   | 2184.94                 | 24.18%                       | 423194.3                  |
| 3                                   | 3291.20                 | 36.43%                       | 635780.7                  |

From the above formula and quantitative calculation, it can be seen that for the medium and small station OD, the service frequency is the main influencing factor of passenger flow, and the increase of service frequency will bring about a significant increase in passenger flow. The larger GDP and population of the OD node, the greater the passenger flow between ODs, and the growth of passenger flow will be faster when the service frequency increases. The longer the mileage and the more travel time of the OD, the less passenger flow, and the slower the passenger flow growth when the service frequency increases.

During the formulation of the train operation plan, medium and small station OD should increase train stops, so as to increase the service frequency and attracting more passenger flows. The shorter mileage, the larger GDP and population of OD, train service frequency have a more significant impact
on passenger flow, and the service frequency of this type of OD should be increased when the development plan is formulated.

5. CONCLUSIONS
Mastering the quantitative relationship between travel speed, train service frequency, the two high-speed railway train service levels and passenger flow, is of great significance to the formulation and optimization of train plans. This paper selects two factors that have the most significant impact on passenger flow in the service level of train operation: travel speed and train service frequency. Firstly, the importance of the station is calculated by comprehensively considering the level of city where the station is located, the average number of departure trains, and the average number of departure passengers, then the station classes are divided. Secondly build a Logit model to analyze the quantitative relationship between travel speed and share rate of large stations OD, and then calculate the impact of travel speed increase on passenger flow. Finally, a gravity model is constructed to analyze the quantitative relationship between train service frequency and passenger flow at medium and small station OD, and to calculate the impact of train service frequency increase on passenger flow.

The results show that for large stations OD, the increase in high-speed railway train travel speed will increase the high-speed railway share rate and attracts more diversion passenger flows. And with the increase of mileage, the influence of travel speed on passenger flow is also increasing. For the medium and small station OD, the increase in train service frequency will bring about a significant increase in passenger flow, and the larger GDP and population, the more significant the impact of train service frequency on passenger flow. During the making of the train operation plan, large station OD should minimize train stops and increase train travel speed. Medium and small station OD should increase train stops and increase train service frequency.

Based on the research in this paper, the next research can be carried out in the following aspects: a) Consider the case of passenger transfer. b) Consider the impact of seats allotment on passenger flow.

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