Model and Algorithm of Competition between High-speed Railway and Air Transport

Jia-nan ZHANG, Peng ZHAO, Yingcan LI

1 School of traffic and transportation, Beijing Jiaotong University, Shangyuancun, Beijing, China, 100044, 08114199@bju.edu.cn
2 School of traffic and transportation, Beijing Jiaotong University, Shangyuancun, Beijing, China, 100044, pzhao@bju.edu.cn
3 School of traffic and transportation, Beijing Jiaotong University, Shangyuancun, Beijing, China, 100044, 08651180@bju.edu.cn
doi: 10.4156/aiss.vol3.issue6.16

Abstract

Transport planning is usually based on models’ forecasts, but the reliability of their outputs depends much on the analysis of relationship between transportation modes. The paper considers the access and egress cost of passengers, and put forward a passenger’s total travel cost function. Firstly, we employ the concept of “linear city” to analyze the market share between high-speed rail (HSR) and airline (AIR), with the analyzing the relationship between the two competitors with the non-cooperative game theory. In addition, we take the fixed fare and variable fare rate as decision variables, and establish an optimizing model to calculate the best decision of each mode; then, a heuristic algorithm is developed to solve the model. At last, taking the Wuhan-Guangzhou transportation corridor as example, the model and algorithm are used to calculate the optimizing fares, and analyze change of solutions with different value of time. The result demonstrates that HSR can attract more passengers than AIR in the distance around 1,000km, and the best strategy of AIR is reducing price.

Keywords: High-speed Railway, Game Theory, Competition Strategies

1. Introduction

The construction and operation of high-speed rail (HSR) bring people new choice of travel, at the same time, they profound impact on passenger transport market structure. In general, transport planning is based on the forecasts of demand, and competition between transport modes will influence the demand pattern. So, the mode choice of passengers should be analyzed with consideration of relationship between transport modes. In the competition with airline (AIR), HSR attracted a considerable part of AIR flow with its own advantages. This is obviously in long-distance travel. Such as Wuhan-Guangzhou HSR, which is a recent opening line, makes a significance reduction of flights between Wuhan to Guangzhou. The HSR in China is still at the initial stage, air transport, however, as the main mode in long-distance travel, has been developed in China for more than fifty years, it has a relatively stable market share and mature operation system, additionally, the airlines have carried out a large number of research and policy adjustments face to the HSR opening and operation. Furthermore, comparing with the huge investment and operation costs in HSR, AIR has flexible transport organization, experienced management, higher pure running speed, and other advantages, if the HSRs cannot adjust their competition strategies, they will face more difficulties in future. Therefore, the study of how should HSR dealing with AIR’s competition is true important.

Studies on competition strategies of transport modes have gained considerable ground in the literature in recent decades, especially in the areas of market sharing and pricing strategy of different transport modes. In early studies, McFadden referenced the utility theory of economics and studied the issue of market share of transport modes [1]. Williams proposed the Nested Logit Model (NLM) to describe the problem of flow sharing in different transport modes [2]. Recently, Yao used a nested structure model to forecast demand of various of transport modes of inter-cities, and he got the conclusion that, the amount of inter-city travel come risen with the reduction of time and cost, and the improvement of service frequency [3]. Roman and Espino analyzed the competition of high speed rail
and air transport in Madrid-Barcelona transport corridor in Spanish, in [4], they estimated the parameters from the survey data, and found that high speed rail had been more competitive in long-distance transport. Givoni explored the issue that some air companies regard the HSR network as the extension of their route and analyzed the conditions and pattern of cooperation between air transport companies and HSR [5]. Obviously, the analysis of the competition strategies should be connected with the forecasting of the market sharing, and so far, the Logit model based on utility theory is the main way to getting passenger volume of modes.

Actually, the main competition between HSR and AIR is a game. Nicole Adler develops a methodology to assess infrastructure investments and their effects on transport equilibrium taking into account competition between multiple privatized transport operator types [6]. A combined modal split and assignment model is proposed for modeling passengers’ mode choices in a multimodal transportation network in an economic circle by [7]. The objective of this paper is to further develop the methodological framework analyzing the passenger transport market equilibrium in view of the use of game theory is rare in previous literatures. It is assumed that each transport mode in a deregulated market and maximizes profits. This paper according to the cost that passengers start from home to station or airport (access-cost) and the cost from arrival station to destination (egress-cost) to constructed a cost function. At the same time, analyze the passenger volume of HSR and AIR with the theory of “linear city” [8, 9], on this basis, established an optimization model and gave the heuristic algorithm. Finally, scenario based method are used and the results in terms of changes in passengers’ value of time analyzed. The main contribution of this study is to develop a new model of cost-benefit analysis that accounts for transport mode behavior over a corridor with heterogeneous demand based on game theory, demonstrating the change of market share with various scenarios.

2. Background

The competition strategies about passenger service include fare, service level, and so on. Obviously, ticket price is one of the most important measures to adjust competition strategy. It is also the main factor influences passenger’s choice among transport modes. Therefore, the main point of this paper is study how HSR and AIR pricing.

What the operators care most is passenger’s choice. When passengers choose mode for their travel, cost is the key factor. In this article, the costs we talk about refer to currency expenses and time expenses. Most of the early studies only draw main attention to currency expenses which passengers pay for the travel from origination station to destination station, neglecting the access and egress costs. For passengers themselves, however, they will take access-cost and egress-cost into consideration before they make choice. Usually the access-cost and egress-cost for HSR and AIR are different from each other. As a result, operators should establish pricing strategies not only according to passenger’s cost in transit, but also access (egress)-cost. Recently, researchers gradually realized the importance of access (egress)-cost, However, specific calculation methods of access (egress)-cost have not been mentioned yet. We brought access (egress)-cost into the Total Travel Cost Function (TTCF), and then found that a passenger’s expenses consist of fare, access (egress)-cost and time expenses. Since there’s lots of access (egress) modes and they show little influence on the whole travel cost, the time a passenger spend on access (egress) becomes the most effective factor for cost. In order to facilitate the calculation, we only take the access (egress) time into account, and the following is the TTCF:

\[
C_n^k = \left\{ \left( gp_n + bp_n d_k^a \right) + t_k^a v_k \right\} + \left\{ e_n^a v_k + t_n^a v_k \right\} 
\]

(1)

We summarize the notations as follow:
Table 1. Symbols of TTCF

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{km}$</td>
<td>The cost of passenger $k$ choose the transport mode $m$</td>
</tr>
<tr>
<td>$K$</td>
<td>Passengers set</td>
</tr>
<tr>
<td>$M$</td>
<td>Transport modes set, $M$={HSR, AIR}</td>
</tr>
<tr>
<td>$gp_m$</td>
<td>The fixed fare of transport mode $m$</td>
</tr>
<tr>
<td>$bp_m$</td>
<td>The variable fare rate of transport mode $m$</td>
</tr>
<tr>
<td>$d_k^m$</td>
<td>The travel distance that passenger $k$ choose transport mode $m$</td>
</tr>
<tr>
<td>$t_k^m$</td>
<td>The travel time that passenger $k$ choose transport mode $m$</td>
</tr>
<tr>
<td>$a_{km}$</td>
<td>The access time that passenger $k$ choose transport mode $m$</td>
</tr>
<tr>
<td>$e_{km}$</td>
<td>The egress time that passenger $k$ choose transport mode $m$</td>
</tr>
<tr>
<td>$v_k$</td>
<td>The value of time of passenger $k$</td>
</tr>
</tbody>
</table>

This function divides the travel cost into two parts. What is in the curly braces is the transit cost, and this part entirely depends on the mode what passengers choose, and the other part is the connection cost, which depends on access-cost and egress-cost.

3. The Model

3.1. Linear city

Under the conditions of the fixed fare and access (egress) modes, travel cost can be calculated use the TTCF. It is possible to calculate the whole amount of passengers take every transport mode when passengers want to minimize their total travel cost. This paper uses the concept of linear city to predict passenger flow volume of HSR and AIR. At first we assume that city is ribbon shape, with the ends of which are HSR station and airport [9]. To simplify the problem, we assume that the sum of access cost to the railway station and the airport are the length of the linear city, and it can be marked by $D$. Then, set the access charges of passenger $k$ from home to high speed rail station $x_k$, and set the access cost of passenger $k$ from home to airport $D - x_k$ (Figure 1).

![Figure 1. Schematic Diagram of Linear City](image)

Similarly, the assumption can be also used to the egress cost of passenger $k$, then, each line represents a linear city. Put the two lines on the same plane, we can get a two-dimensional graph of passenger $k$ from the departure city to the destination city (Figure 2).

![Figure 2. Schematic Diagram of Two-dimensional Connection Costs](image)
Each point on Figure 2 represents a combination of connection costs. $x_k$ is the abscissa of the point and it is the access cost of passenger $k$ from home to the HSR station, while $D - x_k$ represents cost of passenger $k$ from home to the airport. We can also achieve the egress charges from the ordinate of Figure 2. The two-dimensional graph can express visual difference of connection costs among passengers. We can see, when $D_x$ is equal to $D_y$, the total connection costs of HSR of passengers covered by diagonal $a$ is equal to AIR. When the general costs of HSR and AIR during operation are equal, passengers below the diagonal will prefer HSR, others will prefer AIR. At that time, diagonal of the rectangle will be the boundary of passengers choosing HSR or AIR. Assuming running times of HSR and AIR are determined, then $t_{k,i}^v + t_{s,i}^v$ in the formula (1) is a constant. When the price of mode $m$ change, the diagonal $a$ will move up or down, and determines passenger flow volume of the two transport modes. For example, HSR reduce fares, and $C_{HSR}^k / C_{AIR}^k$ represent the total cost of passenger $k$ takes HSR/AIR, then the minus of $C_{HSR}^k$ and $C_{AIR}^k$ can be expressed as:

$$\Delta C = C_{HSR}^k - C_{AIR}^k = \left(\left\{ \left(\left(\left(gp_{i,HSR} + bp_{i,HSR}d_{i,HSR}\right) + t_{i,HSR}^v + t_{i,HSR}^v\right)\right)\right.\right) - \left(\left(\left(\left(\left(gp_{i,AIR} + bp_{i,AIR}d_{i,AIR}\right) + t_{i,AIR}^v + t_{i,AIR}^v\right)\right)\right.\right)$$

(2)

For easier calculation, assuming the population of linear cities is uniformly distribution, when the cost of passengers take each mode is different, the line $a$ will shift up or down. Like Figure 3 shown, the reason is cost of passengers who covered by line $a$ should be the same whatever mode they take. So, passenger flow volume of mode $m$ can be calculated by the following formula:

$$q_m = \frac{Q}{D_x D_y} \left[ \frac{1}{2} \left( D_x - \frac{D_y}{D_x} \Delta C \right) \right]$$

(3)

Figure 3. Schematic Distribution of Passenger Flow

3.2. Model

Price is the decision variable of the split line in the two-dimensional graph, and it also determines the passenger volume of the HSR and AIR. Goal of this problem is to maximize profits of each mode, so it is a constrained extremely problem. Because the ticket price of HSR and AIR consist of two parts,
income of each mode is the product of price and the number of passengers who choose each mode, and profit for the mode is the difference between revenue and cost. Guide prices of fixed fare and variable fare in the objective function constrained by government. So the model can be expressed as:

$$
\max z_n = gp_nq_m + \sum_{k=1}^{n} bp_n d_{m}^{k} \leq \sum_{k=1}^{n} c_{k} d_{m}^{k} q_m
$$

$$
\begin{align*}
& \text{s.t.:} \\
& \quad GP^m_n \leq gp_n \leq GP^h_n \\
& \quad BP^m_n \leq bp_n \leq BP^h_n \\
& \quad \left( gp_n + bp_n d_{m}^{k} \right) + t_{n}^m v_k \leq \left( c_{n}^m v_k + t_{n}^m v_k \right) \\
& \quad \leq \left( gp_n + bp_n d_{m}^{k} \right) + t_{n}^m v_k + t_{n}^m v_k
\end{align*}$$

(4)

Table 2. Symbols of the model

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z_m$</td>
<td>Profits of mode $m$</td>
</tr>
<tr>
<td>$q_m$</td>
<td>The number of passengers that select mode $m$</td>
</tr>
<tr>
<td>$GP^m_n$</td>
<td>Lower limit of the fixed fare of mode $m$</td>
</tr>
<tr>
<td>$GP^h_n$</td>
<td>Upper limit of the fixed fare of mode $m$</td>
</tr>
<tr>
<td>$BP^m_n$</td>
<td>Lower limit of variable fare rate of mode $m$</td>
</tr>
<tr>
<td>$BP^h_n$</td>
<td>Upper limit of variable fare rate of mode $m$</td>
</tr>
</tbody>
</table>

The decision variables in the model are fixed fare and variable fare rate of mode $m$. Therefore, fixed fare and variable fare rate are strategies of HSR and AIR. Actual passenger flow volumes of the two players in this game are directly related to the two kinds of fares. By solving the above model, HSR or AIR can calculate the best pricing strategies when they face to competition from the other.

4. Heuristic algorithm

Above model shown that the competition between HSR and AIR in medium-distance passenger transport market is non-cooperative game; non-cooperative game model’s solution is Nash equilibrium. Nash equilibrium is a strategy combination, and each participant’s strategy is the most superior one in the situation of other participant’s strategy has been determined. Specific to the problem in this paper, we can use the equation below to express Nash equilibrium [8]:

$$
\Pi_m \left( gp_n, bp_n, gp_n, bp_n \right) \geq \Pi_m \left( gp_n, bp_n, gp_n, bp_n \right)
$$

(5)

That is to say, once the model achieved the Nash equilibrium under the condition of other conditions remain unchanged, and then HSR and AIR cannot get more profit however they adjust their strategies. This model includes two decision variables, namely fixed fare and variable fare rate, because what this article studies is the game of HSR and AIR, it needs to determine the strategy combination which contains four variables, so the best strategy can be expressed by:

$$
\left( gp_n, bp_n, gp_n, bp_n \right)
$$

(6)

$q_m$ is the passenger volume of transport mode $m$, whose computational method has already been given in the previous section. Because the number that passengers choose one mode may be zero, the model’s objective function cannot differential everywhere, so we cannot solve the model directly. In order to obtain the model’s Nash equilibrium, this article gives the heuristic algorithm below.
First create an initial solution according to a simple rule, and this solution will be the initial ticket price of HSR and AIR. Afterward, select one solution from the two modes as the unchanged condition, then use the (2) and (3) to calculate $q_m$, subsequently uses (4) to calculate ticket price of mode $m$ as mode $m$’s second solution and this is part of the first iteration. Similarly, we can get the second solution of mode $m$ as another part of the first iteration. After times of iterations, when the solution meets the termination condition, we obtain the solution of the whole model.

This article uses the average guide ticket price of HSR and AIR as the problem’s initial solution, namely:

$$
\left(\frac{Gp_h + Gp_m}{2} \right) \left(\frac{BP_h + BP_m}{2} \right)
$$

(7)

And set the termination condition is the two iterative difference of solution is smaller than a small positive number $\varepsilon$.

5. Validation: application to the Wuhan-Guangzhou corridor

5.1. Data

In order to validation the estimation techniques proposed so far, they were tested with data stemming from a travel demand survey on the 1,069km long Wuhan-Guangzhou corridor. The Wuhan-Guangzhou corridor represents the most important relationship in southern China. The result indicates how the operation cost and value of time will influence the strategy of HSR. In this case we only consider the direct passengers between Wuhan to Guangzhou. At present, passengers between Wuhan and Guangzhou have already be possible to choose HSR, they may also choose AIR, and the relation of two transport modes meet the above game model’s basic condition.

This case study involves the essential data of passenger demand between Wuhan and Guangzhou, such as the value of time, distance of each mode between Wuhan and Guangzhou, operation cost of HSR and AIR, and so on; we have summarized these numbers as follow:

5.1.1. Passenger transportation demand

At present, there are 29 pairs of EMUs between Wuhan and Guangzhou every day, each EMU can take 1,200 passengers, then HSR can deliver 34,800 passengers one day in each direction; In the AIR aspect, there are 10 or 11 flights every day between Wuhan and Guangzhou, the plane seat capacity varies with the aircraft type, and in this article we take the average number of one week as the capacity, which is 2,700 passengers per day. Multiplied the above two way’s delivery capacity by the average booking rate coefficient 0.7 as Wuhan and Guangzhou’s passenger flow demand reference value.

5.1.2. Value of time

Residents’ average income is 25,000 Yuan in Wuhan and 40,000 Yuan in Guangzhou, then the average value 32,500 Yuan. Considering that income of passengers who take AIR or HSR is higher than other persons, therefore we multiplied by 1.5 as the HSR and AIR passengers’ income, and it is 48,750 Yuan per year. Supposing that everyone works 365-104-14=247 days, every day we work for 8 hours, then one year everyone works 247×8=1,976 hours. Each hour’s income is 24.67 Yuan approximately is equal to 25 Yuan.

5.1.3. Operation data

The HSR running time is 3 hours, and AIR running time is 1.5 hours. Guangzhou and Wuhan’s linear city length is 2 hours. The travel distance of HSR is 1,069km; with the distance
of AIR is 1,000km. The fixed fare scope of HSR is 50 Yuan to 100 Yuan, and the Variable fare rate scope is 0.3 Yuan per passenger-kilometer to 0.5 Yuan per passenger-kilometer (Chinese Department of Railway, 2002); the fixed fare scope of AIR is 70 Yuan to 100 Yuan, and variable fare rate scope is 0.4 Yuan per passenger-kilometer to 0.8 Yuan per passenger-kilometer (Chinese Department of Traffic and Transportation). The HSR operation cost is 0.3 Yuan per passenger-kilometer, while the cost of AIR is 0.4 Yuan per passenger-kilometer [10-13].

5.2. Results analysis

After the running of computer program, we got the results of the problem shown by Table 3:

<table>
<thead>
<tr>
<th>Item</th>
<th>HSR</th>
<th>AIR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed fare(Yuan)</td>
<td>54</td>
<td>70</td>
</tr>
<tr>
<td>Variable fare rate(Yuan per kilometer)</td>
<td>0.41</td>
<td>0.5</td>
</tr>
<tr>
<td>Passenger volume(person)</td>
<td>19,258</td>
<td>6,992</td>
</tr>
<tr>
<td>Profits(Yuan)</td>
<td>3,304,480</td>
<td>1,188,640</td>
</tr>
</tbody>
</table>

It is easy to calculate the total ticket price of HSR is 492 Yuan, and the total ticket price of AIR is 570 Yuan. In practice, the price of HSR and AIR between Wuhan to Guangzhou are 490 Yuan and 740 Yuan. Obviously, according to parameter in the article, the fare of AIR is slightly high; this is also one of the reasons that after the operation of HSR, passengers who take AIR reduced rapidly. For better show of how the value of time influences the passengers’ choice, we simulate when the value of time changes between 20 Yuan per hour to 100 Yuan per hour. Result as is shown in Table 4.

<table>
<thead>
<tr>
<th>Value of time</th>
<th>20</th>
<th>40</th>
<th>60</th>
<th>80</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger volume(person)</td>
<td>22,053</td>
<td>15,286</td>
<td>12,599</td>
<td>11,193</td>
<td>10,193</td>
</tr>
<tr>
<td>Profits(Yuan)</td>
<td>3,699,381</td>
<td>2,570,327</td>
<td>2,113,980</td>
<td>1,854,550</td>
<td>1,725,674</td>
</tr>
</tbody>
</table>

Table 4 shown when the ticket price is stable and value of time increase, the passengers who choose HSR will reduce, and the profits of HSR and AIR will change. That is to say, although the travel time of each mode is short and almost equal, when passengers’ value of time higher than the threshold, travel time will be the key factor that determine which mode to choose. Therefore, HSR operators should analyze the influence of fare to the benefit, and then create more reasonable competition strategies.

6. Conclusions

In this paper we have constructed a model of optimizing transport modes’ competition strategies and gave the heuristic algorithm. Finally, through a case study, compared the changes of fares and revenue between the HSR and AIR, and then analyzed what competition strategies should HSR operators adopt. The analysis of the access and egress cost helped to calculate the total travel cost more accuracy. The Total Travel Cost Function (TTCF) can reflect the total cost of passenger travel, and it is the basis to make scientific, rational and competitive strategies. In addition, we cited the concept of “linear city” to study the connection cost generated when the urban passenger departure and arrival, and predicting the passenger volume of transport modes, experiments showed that this method is easy and with certain rationality. Parameters in the model including access and egress time, travel distance and value of time, these parameters were estimated according to the survey in Wuhan-Guangzhou.
The results of case study in Wuhan-Guangzhou corridor showed the model and algorithm is effectively and we can calculate the realistic results within a reasonable time. The result demonstrates that HSR can attract more passengers than AIR in the distance around 1000km, and the best strategy of AIR is reducing price, these can provide some reasonable reference for HSR operators. Since more factors as service frequency can also influence the choice of passengers, it would be interesting to include such variables in future studies about competition between transport modes.

7. Acknowledgement

We want to acknowledge the financial support from “the Fundamental Research Funds for the Central Universities” (2009YJS048).

8. References