A model for the coordination between high-speed railway lines and conventional rail lines in a railway passenger transportation corridor

Y. Bao
School of Traffic and Transportation, Beijing Jiaotong University, China

Abstract

With the construction of high-speed railway lines in China, there are growing concerns about the rational transport cooperation between high-speed railway lines and conventional rail lines. A rational transport cooperation scheme can improve railway capacity utilization, train speed, service and the organization quality of railway transportation. The previous research mainly focused on the aspect of the management of railway or passenger organization, which ignored the interaction of them. Based on the planning of a railway transportation corridor and the structure and distribution of passenger flows, we addressed the problem of rational cooperation of the railway passenger transportation corridor, aiming at identifying the train varieties, quantities and the routes of trains on high-speed railway lines and existing conventional rail lines in a railway transportation corridor. A bi-level programming model for the division is proposed. The upper model is to minimize the total transportation cost, and the lower one is an equilibrium model determined by passengers. Then a solution algorithm based on a genetic algorithm (GA) is designed. Finally, the application of the model and the algorithm are illustrated by a numerical example.

Keywords: high-speed railway, railway passenger transportation corridor, coordination, bi-level programming, genetic algorithm.

1 Introduction

The coordination of high-speed railway (HSR) and conventional railway (CR) is the issue to identify train routes, train quantity and the distribution on the two

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lines in a railway corridor. The coordination is a mode choice problem. Meanwhile, it is a route choice problem. Therefore, the problem of coordination is to identify the routes of different trains on the two parallel lines. HSRs are developing very quickly in China, and they are built between metropolises, but there are already CRs between them, so the coordination between HSRs and CRs should be research in order to fully use resources and avoid competition.

An agreement was reached by the research of 1990s, and HSRs finished the transportation of passengers on HSR lines and most mid and long-distance passengers from CR lines, and CRs finished freight transportation and the rest of the passengers travelling by the slow trains on CRs. However, with the construction and operation of HSRs, the research background and prerequisites have changed. For example, the research in the 1990s supposed that train units on HSRs were bought from other countries, but now, China can produce train units by herself. HSRs are quite different from CRs in infrastructure, operation, and character, so the alternative is different. Therefore, the coordination between HSRs and CRs is highly desirable. The coordination is concerned with passenger transportation service quality, the revenue and the development of railway transportation.

Previous researches about the coordination of HSR and CR cover different aspects and emphases, including form the aspect of passengers by the disaggregate model [1–4], or from the aspect of the railway operator [5], or the above two aspects [6]. The research method contains the logit model [1–3], the passenger flows assessment model, based on the railway network [7], the game model about the selection of a competitive transportation corridor [8, 9], the enumeration method, the satisfaction optimization, and so on. However, most researches about the coordination of HSR and CR are from the aspect of passengers or from the aspect of the railway operator, and few researches have been done from both aspects, and most studies failed to research the feedback of the decision made by the railway operator from passengers. This paper established a bi-level programming model to describe the relationship between the decision made by the railway operator and the reaction from the passengers about the decision. The remainder of the paper is organized as follows. Section 2 explains basic assumptions about the problem. In Section 3, individual route choices and the railway operator's decision are investigated by a bi-level programming model. Section 4 introduces a genetic algorithm to solve the problem. A numerical example is provided in Section 5 to illustrate the application of the models. Section 6 presents concluding remarks.

2 Basic assumptions

The following assumptions are made in this study: (a) whether high level train units run on CR lines or whether low level train units run on HSR lines is determined by the profit of the railway operator, and is not determined by policy or other factors; (b) passengers' choices are based on the maximum travel utility; (c) the same type of trains (train units) have the same seating capacity and can be assigned to HSR lines and CR lines; (d) the operation of the two directions of a line is the same, so we only research one direction.

3 Bi-level programming model

A railway transportation corridor consists of parallel railway lines and some stations. Stations can by classified in to two types, 1) a train could run on another type of line at the station; 2) a train could not run on another type of line at the station. We establish a railway network (S, E). Tables 1 and 2 are the parameters and the decision variables used in the model, respectively.

The upper level is to maximize the profit of the railway operator, with the restriction of train limited running distance, the capacity of lines. The lower level is to maximize passengers' utility, since passengers' utility is described by passengers' cost, so the objective of the lower level is to minimize passengers travelling cost.

The upper level:

$$Max\pi = \sum_{u}\sum_{x_u=1}^{X_u} \chi_{x_u r} \times (Q_{ijx_u r} \times M_u \times \rho_{ul} \times F_{ul} - C_{ul}) \times d_{x_u}(i,j) \quad (1)$$

$$\sum_{a,b\in S} |e_{lab}| \times \chi_{x_u r e_{lab}} \le d_{x_u \max} \quad (2)$$

$$\sum_{u}\sum_{x_u=1}^{X_u} \chi_{x_u r e_{lab}} \le \phi(e_{lab}) \quad (3)$$

The lower level:

$$MinZ = \sum_{u}\sum_{x_u\in X_u}\sum_{h}^{m}\sum_{p=1}^{Q_{ijx_u rh}} \psi_{ijpx_u r} \times V_{rp} \quad (4)$$

$$Q_{ijx_u r} = Q_{ij} \times P(x_u r) \quad (5)$$

$$P(x_u r) = \frac{e^{\gamma V_{x_u r}}}{\sum_{u}\sum_{x_u=1}^{X_u} e^{\gamma V_{x_u r}}} \quad (6)$$

The lower level is the utility of passengers, and it determines passengers' travelling scheme choice. Passengers' travelling scheme choice is the basis of coordination, since it affects the load factor of a train, so it plays a vital role of the coordination in a railway transportation corridor. Passengers' travelling scheme choice is affected by passenger time value, fare, travelling distance, train frequency, train departure time, the character of HSR and CR lines, etc, and it is determined by the utility the passengers get from their travel; in addition to the utility of fare and travelling time, it also includes comfort, safety, punctuality, and so on.

Table 1: Definition of parameters and sets.

Parameter and set	Definition
S	The set of stations, station $i, j \in S$, and a, b are the adjacent stations
e_{lab}	Arc, line type l ($l = 1$, HSR line; 2, CR line)
$\lvert e_{lab} \rvert$	The length of arc e_{lab}
$\phi(e_{lab})$	The maximum capacity of arc e_{lab}
u	Train type, $u = 1$, train unit only run on HSR lines; 2, train unit on HSR lines which can run on CR lines; 3, train on CR lines which can run on HSR lines; 4, train only run on CR lines
t_u	The running time of train type u
r	Train operation scheme
R	The set of train operation schemes, $r \in R$
x_u	Train number x of train type u, $x_u = 1, 2, \cdots, X_u$
VS_{ul}	Train speed of type u on line l
ρ_{ul}	The occupation of train type u on line l
M_u	The capacity of train type u
F_{ul}	The fare of per train kilometer of train type u on line l
C_{ul}	The cost of per train kilometer of train type u on line l
C_{pa}	The fare of a passenger from his origin to his railway trip start station
C_{pe}	The fare of a passenger from his railway trip end station to his destination
t_{pa}	The time of a passenger from his origin to his railway trip start station
t_{pe}	The time of a passenger from his railway trip end station to his destination
f_u	Frequency of train type u
$d_{x_u}(i, j)$	The running distance of train x_u
T_{pi}	The transfer time of passenger p at station i
$d_{x_u \max}$	The maximum travelling distance of train x_u
Q_{ij}	The volume of passengers from i to j

Table 1: Continued.

$Q_{ijx_u r}$	The volume of passengers from i to j by train x_u of scheme r
m	The hierarchy of passengers
v_h	Time value of passengers with hierarchy h $(h = 1, 2, \cdots, m)$
$Q_{ijx_u rh}$	Passengers of hierarchy h from i to j travelling by train x_u of scheme r

Table 2: Definitions of variables.

Parameter and set	Definition
$\chi_{x_u r}$	Whether train x_u is operated on scheme r, 0, No; 1, Yes
$\chi_{x_u r e_{lab}}$	Whether train x_u of scheme r occupies arc e_{lab} ,0 , No;1, Yes
$\psi_{ijpx_u r}$	Whether passenger p chooses the train x_u of scheme r, 0, No; 1,Yes
δ_{pi}	Whether passenger p transfer at station i, 0, No; 1, Yes;
π	The profit of railway

3.1 Calculation of passengers' utility

According to random utility theory, the utility of passenger p to the choice r is U_{rp}.

$$U_{rp} = V_{rp} + \varepsilon_{rp} \tag{7}$$

U_{rp} ——the utility of passenger p for choosing travelling scheme r;

V_{rp} ——the fixed utility of passenger p for choosing travelling scheme r;

ε_{rp} ——the random error of passenger p for choosing travelling scheme r.

In this paper, passengers' travelling schemes are the travelling schemes of travelling directly by different routes or by transferring at different stations. Taking fig. 1 as example, there are 6 travelling schemes for passengers travelling from O to D, 1) passengers travel directly from O to D by the train running on HSR line; 2) passengers travel directly from O to D by the train running on CR line; 3) passengers travel directly from O to D by the train first running on HSR line, then changing to run on CR line at station A; 4) passengers travel directly from O to D by the train first running on CR line, then changing to run on HSR

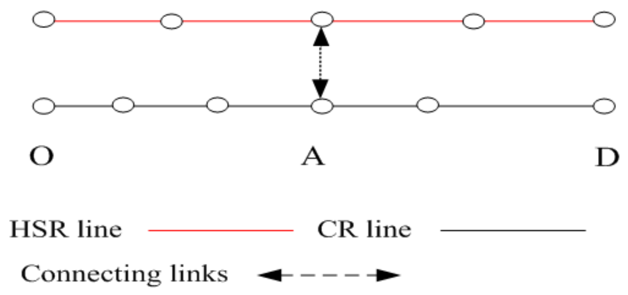

Figure 1: An illustration of passengers' travelling schemes.

line at station A; 5) passengers first travel by the train on HSR line to station A, then transfer to the train on CR line at station A; 6) passengers first travel by the train on CR line to station A, then transfer to the train on HSR line at station A.

Here we define four characters to calculate V_{rp}, economy (X_1), expeditiousness (X_2), comfort (X_3) and accessibility (X_4). Each travelling scheme has a fixed utility by the four characters. If we use V_r to replace V_{rp}, then

$$V_1 = \theta_{11}X_{11} + \theta_{12}X_{12} + \theta_{13}X_{13} + \theta_{14}X_{14} \tag{8}$$

$$V_2 = \theta_{21}X_{21} + \theta_{22}X_{22} + \theta_{23}X_{23} + \theta_{24}X_{24} \tag{9}$$

$$Vn = \theta n_1 Xn_1 + \theta n_2 Xn_2 + \theta n_3 Xn_3 + \theta n_4 Xn_4 \tag{10}$$

θ_{rq} -parameter, the preference of passenger for the character q of travelling scheme r, $q = 1,2,3,4$;

X_{rq} - the character q of travelling scheme r.

3.1.1 Calculation of travelling scheme characteristics

(1) Economy

Passengers need to pay for their travel, and the fare is used to indicate the economy of the travel. Fare consists of the access fare from origin to the start station, the riding fare on the train, and the egress fare from the end station of the travel to passenger's destination.

$$X_1 = C_{pa} + F_{ul} \times d_{x_u}(i, j) \times \psi_{ijpx_u r} + C_{pe} \tag{11}$$

(2) Expeditiousness

Expeditiousness is an importation factor affecting passengers' choice, especially to businessmen. Here, travel time is used to express the expeditiousness of a trip. Previous studies use passengers' travelling distance divides train speed. However, there are two limitations in this method, 1) the value to different type of time should be different, i.e., passengers' transfer time for waiting the connecting train is different from the time riding on the train; 2) transfer breaks the continue trip, and it may take threat to passengers in their mind. So we think we should distinguish different types of time during the trip.

Total travel time includes riding time on the train, train stop time and passengers' transfer time. However, the addition time for the late of the train is not considered.

$$X2 = d_{x_u}(i, j) / VS_{ul} + \sigma \times \delta_{pi} \times T_{pi} \qquad (12)$$

δ —parameter of the transfer time changed to riding time.

(3) Comfort

With the raise of living standard, people's consumption idea has changed. They pursue much more comfortable travelling environment. Comfort is an important character that affects passengers' choice behavior. Since travelling is a consuming of passengers' physical strength, additional time is needed to recover from the fatigue, when the travelling time is up to some hours. So passenger recovering time from fatigue reflects the comfort of a trip. The recovering time is associated with travelling time and travelling environment, and travelling environment is determined by train type. Passenger recovering time is calculated by the following equation (Peng [5]).

$$g_u(t) = M / [1 + \alpha \exp(-\beta t)] \qquad (13)$$

$$\alpha = \sum(\alpha_u t_u) / \sum t_u \qquad (14)$$

$$\beta = \sum(\beta_u t_u) / \sum t_u \qquad (15)$$

M - the limited recovering time, in general, M is 15 h;
α_u - nondimensional parameter, when train type is u, and $t = 0$, the recovering time is $M / (1 + \alpha_u)$; and
β_u - the strength coefficient of recovering time for one travelling hour, $\beta_u > 0$, the unit is h^{-1}.

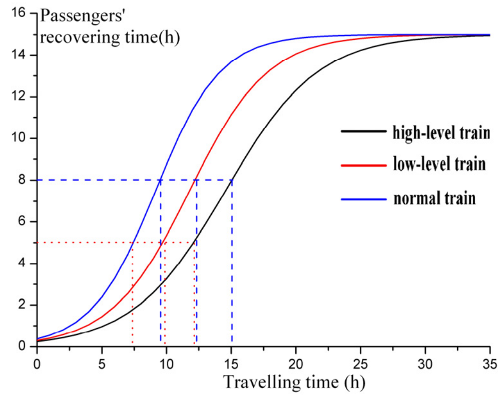

Figure 2: The illustration of passengers' travelling time and recovering time.

Table 3: Passengers' recovering time from fatigue when travelling between Beijing-Shanghai by different types of trains.

Train type	Passenger travelling time (h)	Recovering time (h)
High-level train on HSR	5	0.96
Low-level train on HSR	13	8.97
Normal train on CR	22.72	14.93

When $M = 15$ h, the recovering time travelling by different type of trains is as fig. 2.

From the comparison we can see the advantage of HSR in recovering passengers' fatigue. Taking Beijing-Shanghai HSR line for example, 1) if we assume that the travelling time of high-speed train is 5 h, the recovering time of passengers travelling by HSR is 58 min; 2) if passengers travelling by through trains (train type Z) on CR line, the travelling time is 13 h, and the recovering time will be up to 9 h; 3) if passengers travelling by normal trains on CR line, the travelling time is 22 h and 43 min, and the recovering time will be up to 14 h 56 min, nearly to the general limited recovering time M .

The above research is based on through trains, when passengers transfer, if the travelling time is t_u on train type u , in this case, parameter α_u and β_u should be calculated by weighted average method.

Therefore, passengers' comfort is calculated by eqn. (16).

$$X_3 = g_{(u)}(t) \tag{16}$$

(4) Accessibility

Most current approaches about passengers' choice behavior to different transportation modes, in the mainland of China, focus on the characters of the mode itself, rather than research from the whole trip. The usual methods to improve the market share of a mode are enlarging the network, improving the covering area of the mode, shorting the travelling time, improving the service, etc., but ignoring the accessibility of the mode. From the research of abroad and Taiwan in China, accessibility is an importation factor that affects the market share of different transportation modes [10, 11]. With the development of high-speed train units, the riding time is lower and lower. Therefore, the access time to the station and the egress time from the station occupies a large part in the whole travelling time, especially to those cities that are always in heavy traffic. In this study, station accessibility is represented by passengers' agree time, egress time, the frequency of trains and the transfer time.

$$X_4 = t_{pa} + \sigma \times T_{pi} \times \delta_{pi} + \eta / f_u + t_{pe} \tag{17}$$

η - parameter of train departure frequency.

4 Algorithm for solving the model

Genetic algorithm is introduced to solve the model, and the steps are as follows.

Step 1: Representation and initialization of chromosomes for the upper-level model

Select a feasible solution N_0 for the upper-level model, let $X^r = \{\chi_{x_u r}\}$ represent a chromosome for the upper-level model. Each code in the chromosome is the value of $\chi_{x_u r}$, generate POP_SIZE_U chromosomes, which is $\{X^r / X^r = (x_1^r, x_2^r......x_n^r), r = 1,2,......POP\_SIZE\_U\}$. The steps used to generate chromosomes could be described as below.

Select a random direction *d* from R_n;

If N_0+d is feasible, let it be a new chromosome, otherwise, generate a new *d*, until N_0+d is feasible;

Repeat steps (1) and (2) to get POP_SIZE_U chromosomes.

Step 2: Evaluation and Selection

Execute each chromosome to get each chromosome's fit value based on step6, sort the chromosomes on the basis of fit values. Select POP_SIZE_U chromosomes to execute the following steps.

Step 3: Crossover

Create a new population of POP_SIZE_U number by applying the following operations. The operations are applied to choose from the population with a probability based on fitness.

(i) Darwinian Reproduction: Reproduce an existing chromosome by copying it into the new chromosome.

(ii) Create two new chromosomes from two existing chromosomes by genetically recombining randomly chosen parts of two existing chromosome s using the crossover operation applied at a randomly (according to P_c_U) chosen crossover point within each chromosome.

Step 4: Mutation

Create a new population of POP_SIZE_U number by applying the following operations. The operations are applied to choose from the population with a probability based on fitness.

(i) Darwinian Reproduction: Reproduce an existing chromosome by copying it into the new chromosome.

(ii) Create one new chromosome from one existing chromosome by mutating a randomly (according to P_m_U) chosen part of the chromosome.

Step 5: Iterations

Iteratively perform the above steps (2) ~ (4) until the termination criterion Gen_Num_U has been satisfied.

Step 6: Solving the lower-level model based on the input from the upper-lower model

Step 6.1 Representation and initialization of chromosomes for the lower-level model

Select a feasible solution N_0 for the upper-level model, let $X_L^r = \{\psi_{ijpx_u r}\}$ represent a chromosome for the lower-level model. Each code in the chromosome is the value of $\psi_{ijpx_u r}$, generate POP_SIZE_L chromosomes, which is $\{X^r / X^r = (x_1^r, x_2^r ......x_n^r), r = 1, 2, ...POP\_SIZE\_L\}$. The steps used to generate chromosomes could be described as below.

Select a random direction d from R_n;

If N_0+d is feasible, let it be a new chromosome, otherwise, generate a new d, until N_0+d is feasible;

Repeat steps (1) and (2) to get POP_SIZE_L chromosomes.

Step 6.2: Evaluation and Selection. The same with step 2.

Step 6.3: Crossover. The same with step 3.

Step 6.4: Mutation. The same with step 4.

Step 6.5: Iterations. The same with step 5.

Step7: Return the result $Q_{ijx_u r}$ by the lower level to step 5.

5 Numerical example

The rail network topology is shown in fig. 3. Capacity of each train unit on HSR is 600 p (passenger), and 1220 p on CR. We assume that the occupation rate of each train is 90% on HSR lines, and 85% on CR lines. The fare of each passenger per train-km is 0.30 and 0.14 CNY on HSRs and on CRs of high-speed trains, and 0.12 CNY on CRs of normal trains. The cost of per train-km unit is 127.1 and 184.1 CNY of high-speed trains on HSRs and CRs, and 92.4

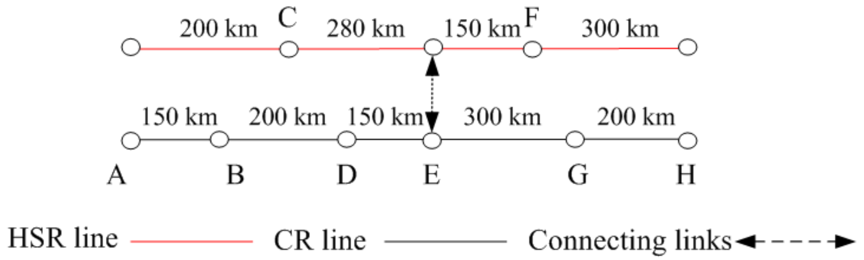

Figure 3: Illustration of the rail network used in the numerical example.

Table 4: Passengers' travelling demand.

	A	B	C	D	E	F	G	H
A		500	1000	800	3000	1500	900	5000
B			0	1200	1500	600	800	2500
C				0	2000	1500	800	3000
D					1500	1000	1200	1800
E						2000	1000	3500
F							0	3000
G								2000
H								

Table 5: The weight of services attribute for different types of passengers.

Passenger hierarchy	Passenger income level/CNY	Percentage/%	Passengers' time value/ CNY	Economy	Expeditiousness	Comfort	Accessibility
h=1	<2000	10	10	0.5	0.3	0.05	0.15
h=2	2000~3000	30	10-15	0.4	0.35	0.08	0.17
h=3	3000~5000	40	15-25	0.3	0.38	0.1	0.22
h=4	>5000	20	>25	0.2	0.4	0.15	0.25

Table 6: The number of trains of different sections.

Section	CR	HSR	Section	CR	HSR
A-C	0	2	C-H	0	4
A-D	1	0	D-E	3	0
A-E	1	4	D-G	1	0
A-F	0	2	D-H	1	0
A-H	1	7	E-F	0	6
B-D	1	0	E-G	1	0
B-E	1	0	E-H	2	7
B-H	2	0	F-H	0	5
C-E	0	6	G-H	1	0
C-F	0	3			

CNY of normal trains on CRs. The organization cost for each passenger is 0.0381 Chinese Yuan (CNY), when they transfer. Meanwhile, we assume that the volume is not a constraint for train units running on CR lines.

The genetic algorithm has been implemented by Microsoft Visual C++ 6.0 (more than 4200 code lines) and runs on a Pentium Duo, 3.4GHz PC, with 512MB RAM memory. The time cost is 56 seconds.
The results are given below.

6 Conclusions

This paper addresses the coordination issue of HSR and CR in a railway transportation corridor from the aspect of passengers and railway operator. A bi-level programming model is established to coordinate the difference of passengers' choice and the decision made by railway operator. A genetic algorithm is designed to solve the model. The model and algorithm is demonstrated by a numerical example.

The proposed model can be extended in several directions. In the upper-level level, freight transportation can be included, especially to those valuable goods. Meanwhile, in the lower level, passengers' departure time can be added as a constriction. Another possibility is to add other transportation modes in a transportation corridor, such as air transportation, and freeway.

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References

[1] Saad N Aljarad & William R Black, Modeling Saudi Arabia-Bahrain corridor mode choice, *Journal of Transport* Geography*,* 3(4), pp.257-268,1995.
[2] Bhat C.R., A Heteroscedastic Extreme Value Model of Intercity Mode Choice, *Transportation Research Part B*, 29(6), pp. 471-483, 1995.
[3] Bhat C.R., Covariance Heterogeneity in Nested Logit Models: Econometric Structure and Application to Intercity Travel, *Transportation Research Part B*, 31(1), pp. 11-21, 1997.
[4] Chaug-Ing Hsu & Wen-Ming Chung, A Model for Market Share Distribution between High-speed and Conventional Rail Services in a Transportation Corridor, *The Annals of Regional Science,* (31), pp.121-153, 1997.
[5] Qiyuan Peng, Transportation organization of passenger special line, Science Press, 2007.
[6] Jie Tang, The coordination and optimization method between high-speed railway and conventional railway, Master's Thesis, *Central South University*, 2008.
[7] IljoonC hang, A Network-based Model for Market Share Estimation among Competing Transportation Modes in a region corridor, Ph.D. thesis, *The University of Maryland*, 2001.
[8] Jianmei Zhu, Game Model of Selection of Competitive Transportation Corridors, *Journal of Southwest Jiaotong University*, 38(2), pp.336-340, 2003.
[9] Chiung-Wen Hsu, Yusin Lee & Chun-Hsiung Liao. Competition between high-speed and conventional rail systems: A game theoretical approach, *Expert Systems with Applications*, 37, pp. 3162–3170, 2010.
[10] Clever, Reinhard, Airport and station accessibility as a determinant of mode choice, Ph.D. thesis, *University of California*, Berkeley, 2006.
[11] Martijn Brons, Moshe Givoni & Piet Rietveld. Access to railway stations and its potential in increasing rail use. T*ransportation Research Part A,* (43), pp.136–149, 2009.