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*Research Article*

# Optimization of High-Speed Railway Line Planning Considering Extra-Long Distance Transportation

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Network line planning optimal considering extra-long distance transportation can adapt to high-speed railway (HSR) network operation environment and meet the demand of extra-long distance travel. First, the distance of 1500 km or more is defined as extra-long transportation distance based on market competitiveness. The difficulties of direct or transfer transportation for extra-long distance transportation are analyzed. Direct method of extra-long distance is determined according to direct passenger volume and the number of important nodes while transfer method is represented considering transfer times, organization forms, varieties of schemes and comfort. Then, ideas of optimizing line plan based on riding scheme is put forward. Network optimizing line plan model with riding scheme is developed considering extra-long distance transportation. The model which minimizes traveling cost and train running expense optimizes train frequency and train stop plan with riding scheme. Last, the method and optimizing model is verified by the network which took Baoji–Lanzhou HSR as the core. The optimal result is benefit to improve operation efficiency and market competitiveness of HSR.

## 1. Introduction

China's HSR network is developing rapidly, with the characteristics of constantly changing network structure, providing faster and high-frequency passenger transportation, and ensuring faster transfer services. Influenced by the accelerated development of regional economy, the unbalanced development of regional economy and the ability of HSR to meet more diversified demands, the demand for extra-long distance transportation is increasing day by day.

There are a large number of OD pairs with long distance in China's HSR network. The structure of HSR network makes it impossible for OD pairs to achieve direct access. According to the statistical analysis of the timetable, only about 10% of OD pairs can be directly accessed, and most OD pairs have low service frequency. There are 2967 OD pairs over 1500 km, accounting for over 7% of the total number of OD pairs which provide transport services. The average running time of these OD pairs is about 9.9 h. In addition, the number of remaining tickets is unbalanced in the transfer scheme. Some trains have many remaining tickets while others having no optional remaining tickets in a transfer scheme. The whole travel time of transfer is longer at the same time. We can see that the accessibility of HSR networks are relatively low. HSR passenger products for extra-long distance transportation are relatively single, the matching degree between extra-long distance passenger products and passenger travel demand is low and the advantages of HSR passenger products are not fully explored.

The main directions of existing research on line planning and optimizing are as follows: (1) Research on line planning and optimizing based on mathematical methods. Chang et al. [1] established a multi-objective linear programming model for the optimization of line plan, and used the method of fuzzy mathematical programming to solve the problem. The model was applies to the Taiwan's HSR. Lee et al. [2] paid more attention to passengers' autonomous choice of transportation services. A bi-level programming model was established. The operator was the decision maker of the upper problem and the passenger was the decision maker of the lower level problem. The method was applied to Taiwan's HSR system. Yin [3] applied multi objective optimization to generate non-dominated or Pareto optimal alternatives. He proposed a solution algorithm for the multi objective bi-level models using genetic algorithms for line planning. Kaspi et al. [4] formulated an integrated line planning model with the objective of minimizing both user inconvenience and operational costs. Gallo et al. [5] proposed four different objective functions considering the costs of all transportation systems as well as the external costs. Heuristic and meta-heuristic solution algorithms were proposed to solve the model. Fu et al. [6] described an integrated hierarchical approach to determine line plans by defining the stations and trains according to two classes. Heuristics were developed for two consecutive stages corresponding to each classification based on a bi-level programming model.

(2) Solutions of the line planning based on line pool. Scholl [7] and Schöbel and Scholl [8, 9] studied the optimization method of train operation scheme with the shortest passenger travel time and the smallest passenger transfer. Based on the idea of alternative line plans, Scholl described the shortest path selection behavior of passengers in the "change and go" network, and established four integer programming models. Michaelis and Schöbel [10] summarized the classic planning process: In a first step, the lines were designed; in a second step, a timetable was calculated and finally the vehicle and crew schedules were planned. Fu [11] studied the theory of HSR line planning based on line pool in depth. The line planning procedure of HSR network was designed. Train enumeration and maximum spanning tree were developed for potential line set generating. Some reasonable criterias were established for all possible trains to be included in the set. The line planning characteristics were combined with multi-commodity flow problem to establish an integer programming model and a nonlinear mixed integer programming model. Lagrange relaxation heuristic algorithm was used to solve the model. Gattermann et al. [12] studied the effect of line pools for line planning models. An algorithm to generate 'good' line pools was proposed. The approach allowed to construct line pools with different properties and even to engineer the properties of the pools to fit to the objective function of the line planning model.

(3) Solutions of the line planning focus on stop plan. Schöbel [13, 14] constructed covering model while considering the location of stops along the edges of an already existing public transportation network. Wang et al. [15] proposed a two-layer optimization model within a simulation framework to deal with the HSR line planning problem. The top layer aimed at achieving an optimal stop-schedule set while he bottom layer focusing on weighted passenger flow assignment. Computation complexity could be reduced and an optimal set of stop-schedules could be generated with less calculation time according to this model. Qi et al. [16] put forward an optimization method of passenger train plan based on stop schedule plan under the conditions of passenger dedicated line. Train-origin/terminal-station, paths, trains grade, quantity of dispatched train, stop schedule plan were considering in the model. Objective function was the difference between operational revenue and operation cost. The model could be solved with Matlab. Yang et al. [17] formulated a multi-objective mixed integer linear programming. The model aimed at minimizing the total dwelling time and total delay between the real and expected departure time from origin station for all trains on a single-track HSR corridor. The optimization software GAMS with CPLEX solver was used to code the proposed model. Then approximate optimal solutions were generated. Luo et al. [18] put forward an integer programming model for train stop plan. The model which aimed at minimizing the total passenger travel time was solved by genetic algorithm.

Most existing studies have been done on the line planning with less consideration of the relationship of direct and transfer transportation. Relevant research on extra-long distance line planning and optimization is lacking. Lines of network is planned according to the passenger volume and characteristics of main OD pairs, which is inappropriate to the network line planning elaborately. The adaptability of the line planning method to the transportation demand of extra-long distance is still poor, and there are also some shortcomings such as less consideration of transfer and low efficiency. In this study, we make a detailed study on the direct or transfer transportation for extra-long distance passenger. Focusing on the transportation demand of extra-long distance of HSR, we put forward an optimization model of networked line plan based on the riding scheme which can obtain according to the determining methods of direct or transfer transportation.

The remainder of the paper is organized as follows. Section 1 analysis the line planning and optimizing method of HSR network. Defining of extra-long distance for HSR, explanation difference between extra-long distance and normal railway line planning, and network construction method are presented in Section 2. Section 3 presents determining methods of through train and transfer plan for extra-long distance transportation. Section 4 elaborates on ideas of optimizing line plan based on riding scheme. A network line planning optimizing model based on the riding scheme is portrayed. In Section 5, the network of Baoji–Lanzhou HSR is selected as the verification of the method. Finally, the conclusions are presented in Section 6.

## 2. Problem Description

*2.1. Analysis of Transportation Distance of HSR Based on Market Competitiveness.* (1) Passenger volume of various traffic modes before and after the opening of HSR lines.

According to the existing research, after the new high-speed railway line within 300 km is opened, airline passenger volume almost becomes zero. In the range of 300–500 km, the decrease of airline passenger volume is also significant. At the same time, the passenger volume of traditional railways decline sharply. Most of the reduced passenger volume is transferred to high-speed railways. Table 1 shows transferrable passenger volume rate after several typical HSR lines opened.

Some researchers [19–24] analyzed the longer distance lines and found that with the increase of distance, the decline of airline passenger volume gradually decreased. There is fierce competition between aviation and HSR in the range of

Table 1: Transferrable passenger volume rate after HSR lines opened.

| Lines | Distance of lines | Conventional railway | Airline | Car | Coach |
|---|---|---|---|---|---|
| Taipei-Taichung | 160 | −18 | −100 | −100 | — |
| Rome-Naples | 222 | −30 | — | −1 | — |
| Taipei-Jiayi | 246 | −21 | −100 | −17 | −31 |
| Taipei-Kaohsiung | 345 | −63 | −80 | −17 | −28 |
| Taipei-Tainan | 308 | −45 | −84 | −18 | −19 |
| Madrid-Seville | 470 | −94 | −57 | −57 | −25 |

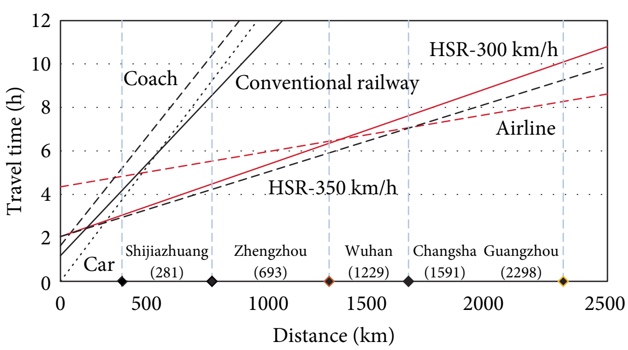


Figure 1: The relationship of distance and travel time of multiple transportation modes in Beijing-Guangzhou HSR.

500 km–800 km of transport distance. After the opening of new HSR lines, the market share of airline has decreased by about 26%. For example, the flights of Guangzhou-Changsha (621 km) and Guangzhou-Wuhan (968 km) all declined about 50% after Beiijng–Guangzhou HSR opened.

(2) Travel time of typical OD pairs in the HSR network.

Several typical OD pairs of Beijing-Guangzhou HSR are included in Figure 1. The relationship of distance and travel time of multiple transportation modes is fitted. The range of distance with shortest travel time is 200–1250 km when the operation speed is 300 km/h. When the operation speed increases to 350 km/h, the range of distance with shortest travel time will extend to 200–1500 km.

(3) Determination of the extra-long distance range of HSR.

Guiding by the market competition among various modes of transportation, the range of extra-long distance is determined under the conditions of specific competitive environment and transportation mode division of labor.

As showed in Table 2, HSR transportation distance is classified into five categories. If distance of HSR lines is in range of short distance, the major competitor is highway. Conventional railway will be the major competitor when distance of HSR lines in [300, 500). When distance of HSR lines is over 500 km, airline is the major competitor.

Extra-long distance is defined as 1500 km or more. The market competitiveness of HSR in this range is obviously reduced, and it also cannot fully guarantee the shortest travel time. However, the HSR line has strong competitiveness in large-scale HSR network when its distance is in the range of extra-long distance.

According to the transport network composed of 153 HSR stations [25] (Level I and II Stations), the shortest path is calculated by Dijsktra algorithm. The proportion of OD pairs over 1500 km is close to 40% as shown in Table 3.

*2.2. The Difference between Extra-Long Distance and Normal Railway Line Planning.* (1) Characteristic of extra-long distance transportation in different modes.

The main modes for extra-long distance transportation are direct and transfer. Direct transportation is realized by through train. Several trains which have continuation relationship also can meet the travel demand of extra-long distance passenger volume.

There are several difficulties of running extra-long distance through train. (1) The capacity of HSR is reduced. Extra-long distance trains mostly involve cross different lines. If the train with lower speed class crosses the line to the high speed class, the speed difference and the stop plan have a significant impact on the capacity. Especially cross-line trains mostly need to be on and off in busy trunk lines, which greatly affects the operation organization and ability of busy trunk lines. (2) It is difficult to satisfy the repair work of the train's bottom. The rules for operation and maintenance of railway EMUs promulgates by China Railway Corporation strictly stipulate the allocation of EMUs. In principle, the first and second level maintenance tasks assigne by each railway bureau to a railroad operation station should be carried out in the same institute. Most EMUs have a maintenance cycle of 4000 km or 48 hours. If the train runs too long, it may not be able to return to its affiliated service station within the first maintenance cycle.

There are multiple routes for extra-long distance OD pairs. There are many forms of transfer points, such as the same station and the same platform, the same station and the different platform, and the different station and the different station. There are many factors to be considered in the transfer scheme, the core factor is the transfer station or hub. And the other factors include the number of transfer, the form of transfer organization, the diversity of transfer schemes and the comfort of transfer.

(2) The particularity of optimizing networked line plan considering extra-long distance transportation.

The relationship between the direct and transfer needs to be balanced. The possible transport modes of each OD need to be defined in the ultra-long distance operation plan, and each plan needs to be evaluated. There are many transfer points which can be chosen in an extra-long distance route. Transfer schemes for extra-long distance transportation are more diversified.

Complex routes in the network with ring structure. The initial solution has a large scale. It is necessary to define the scope of study network considering the initial solution and

Table 2: Classification of HSR transportation distance.

| Items | Range of distance/km | Major competitors | Features |
|---|---|---|---|
| Short distance | [100, 300) | Highway | There is fierce market competition with highway transportation |
| Middle distance | [300, 500) | Conventional railway | Obvious annexation effect on conventional railways |
| Medium and long distance | [500, 1000) | Airline | Airline passenger volume has been reduced to a certain extent |
| Long distance | [1000, 1500) | Airline | The shortest travel time is guaranteed |
| Extra-long distance | 1500 or more | Airline | Strong competitiveness in Large-scale HSR network |

Table 3: Statistics of OD pairs in HSR network.

| The shortest distance between OD pairs/km | Number of OD pairs | Proportion |
|---|---|---|
| <300 | 1666 | 7.21% |
| 300–500 | 1660 | 7.18% |
| 500–1000 | 5257 | 22.75% |
| 1000–1500 | 5452 | 23.59% |
| More than 1500 | 9077 | 39.27% |

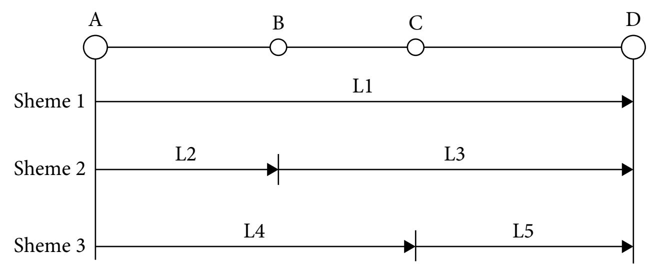


Figure 2: Several riding schemes for A to D based on the line plan.

rational utilization of important nodes and sections. In the process of line plan optimization, it is a process of optimizing the initial solution and the secondary distribution of passenger volume. It is necessary to add the transfer scheme which is composed of multiple trains into the optimization mode. The model is more difficult to describe the relationship between train and passenger volume and the relationship between train stop and passenger volume for the initial solution.

## 3. Conditions and Calculation Methods for Extra-Long Distance Riding Schemes

*3.1. Ideas of Optimizing Line Plan Based on Riding Scheme.* Line plan: Train running path, train frequency and stop plan are included in the line plan. Starting from the operator's point of view, the line plan is mainly used for the actual passenger flow and train organization.

Riding Schemes: Riding Schemes are traveling processes in the network for each OD pair in this paper, which is composed of one line or more connected lines. Riding scheme for passengers refers to the possible plan that passengers can arrive at their destination from the origin based on line plan. Riding schemes are extracted from line plan. Only by knowing which lines to operate can we determine which riding schemes are available for travel. Lines of riding schemes are included in line plan.

We already have the line plan for selected research network. Passengers have several riding schemes which can arrive at D from A in Figure 2. According to the line plan, the possible riding schemes are L1 (Scheme 1), L2 + L3 (Scheme 2) and L4 + L5 (Scheme 3). At the same time, L1–L5 are all included in the line plan.

There are two types of schemes for passenger. One type is the independent passenger scheme (Direct scheme). There is only one train in the independent passenger scheme. The cost of the passenger scheme is mainly the cost of the running time of the train. The other type refers to the transfer scheme for the extra-long distance passenger volume that needs to be transferred, which includes two or more trains. There may be many train connection schemes for the same OD pair with extra-long distance. The calculation of transfer passenger schemes includes train operation cost and transfer time cost. As Figure 1 showed, scheme 1 provides passengers with direct scheme, while Scheme 2 and Scheme 3 provide passengers with transfer schemes.

$R$ represents the set of riding scheme. In this paper, the maximum transfer times are set as two. Therefore, $R$ is made up of three parts considering transfer times, as shown in Formula (1). Formula (2) shows that $R_1$ can be obtained from the initial plan. Formula (3) indicates that the element in $R_2$ is composed of $L_i$ and $L_j$ with a close connection. The last station of $L_i$ is the same as the first station of $L_j$. Using the same principle to construct elements in $R_3$.

$$R = R_1 \cup R_2 \cup R_3, \tag{1}$$

$$R_1 = \{L_1, L_2, \ldots, L_N\}, \tag{2}$$

$$R_2 = \{r_1, r_2, \ldots, r_M\}, r_i = \{L_i, L_j\}, \tag{3}$$

$$R_3 = \{r'_1, r'_2, \ldots, r'_Q\}, r_i = \{L_i, L_j, L_k\}. \tag{4}$$

*3.2. Direct Riding Schemes: Operating Conditions of Extra-Long Distance through Trains.* Direct riding schemes for extra-long distance transportation are through trains. It is precisely because that many problems may arise from the operation of through trains. It is necessary to clarify the operating conditions of through trains of HSR network. (1) Passenger volume condition. According to the regulations

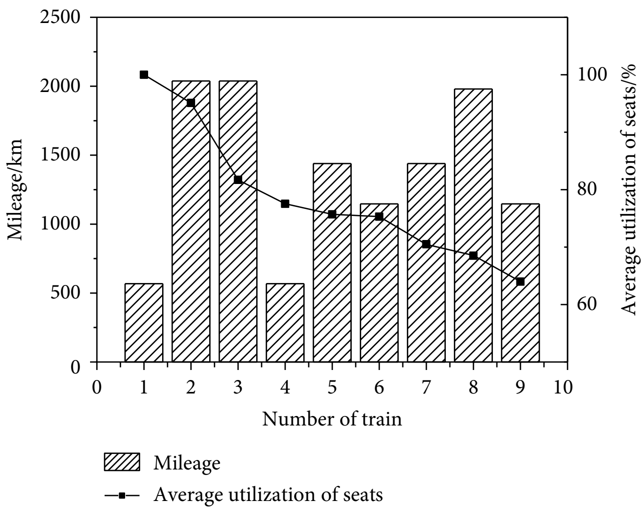


FIGURE 3: The average utilization of seats of some HSR trains (Lanzhou railway administration).

of through trains on conventional railways and the actual running conditions of cross-line trains, as shown in Figure 3. The through passenger volume of extra-long distance through trains needs to be more than 500 passengers, about 50% of the reserved passengers of re-connected trains (fixed number of passengers is about 1000). (2) Number of important nodes along the train route. The reasonable range of important nodes along the extra-long through train is 4–6, which can generally meet the distance range of 1500 km or more. If there are too many nodes, there will be too many times of cross-line and cross-bureau. And train operation will have a greater impact on the order of network operation.

*3.3. Transfer Riding Schemes: Transfer Plan for Extra-Long Distance Passenger.* For the extra-long distance passenger volume which cannot be transported by through train, it is necessary to determine a reasonable transfer plan. For the extra-long distance passenger volume $v$, at different transfer stations $ts$ may have different transfer schemes. The cost of a transfer scheme $c_{vt}^{s}$ includes the cost of running time $c_{t}^{s}$, the cost of transfer stations $c_{s}^{s}$, the cost of transfer comfort $c_{c}^{s}$ and the penalty coefficient of transfer times $t_v$.

$$c_{vt}^{s} = \left(\alpha_1 \cdot c_t^s + \alpha_2 \cdot c_s^s + \alpha_3 \cdot c_c^s\right) \cdot \left(1 + t_v\right), \quad (5)$$

$$c_s^s = SC_s = 0.65 \times \left(0.3 \times CC_s + 0.7 \times BC_s\right) \times DC_s, \quad (6)$$

$$c_c^s = \frac{T^t/2}{1 + 49\exp\left(-0.5T^t\right)}\left(1 + \rho^t\right) \cdot a_t. \quad (7)$$

Formula (5) is the method for calculating the transfer costs of transfer schemes. The main costs are expressed as standard values. Formula (6) indicates that the attribute values of transfer stations are calculated by the system centrality method. The importance of the station $s$ is calculated by the centrality of the system. The centrality of the system is calculated by degree centrality $DC_s$, adjacent centrality $CC_s$ and betweenness centrality $BC_s$ respectively. The calculation method and the determination method of related parameters can be seen in the methods proposed by Han et al. [25]. Formula (7) specifies that comfort is obtained by multiplying fatigue recovery time by time value. The fatigue recovery time is direct correlation as the travel time $T^t$. It also will increase with the travel time. When the travel time exceeds 9 hours, the fatigue aggravation factor $\rho^t$ is introduced. If the daytime HSR is less than or equal to 9 hours, the fatigue aggravation factor is 0. If the fatigue aggravation factor is more than 11 hours, the fatigue aggravation factor is taken as a linear value.

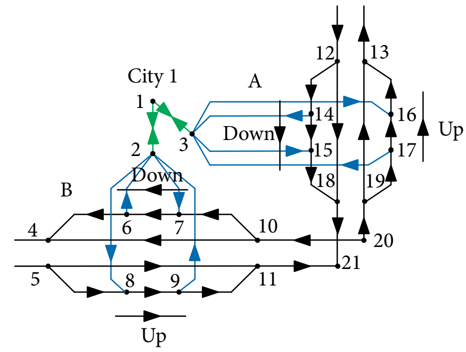


FIGURE 4: A diagram of network construction.

## 4. Network Optimizing Line Plan Model: Based on the Riding Scheme

*4.1. Network Construction Method for Optimizing Line Plan.* The construction of the network needs to depict the complete travel process of extra-long distance passengers to ensure the rationality of the network line plan. Based on the simplified station network model, virtual station nodes and city nodes are set up in the model. The simplified network model can reflect the basic travel process of passengers boarding, getting off, entering and leaving the station. Main transfer processes such as in-station transfer and transfer in different stations can also be indicated.

As Figure 4 showed, inter-station and out-station travel process can be expressed through the black arrow line. The blue arrow line are used to indicate transfer in-station. Transfer in different stations can be expressed through the blue arrow line and the green arrow line. The travel process from 20 to 13 can be indicated as 20→10→7→6→2→1→3→16→13. It means that passengers will enter station B and transfer to station A in this travel process. More detailed description of network construction can be found in the literature [26].

*4.2. Objective Function and Decision Variables of Optimization Model.* In order to solve the problem of extra-long distance passenger transportation under the condition of networked operation, a line planning optimal model of networked HSR is constructed. The main variables involved in the model and their implications are shown in the Table 4.

The process of optimizing the line plan is actually the process of adjusting riding schemes for passenger volume of each OD pair. Line plan will be optimized with adjusting the riding schemes according to the adaptability of each OD pair and its

Table 4: The meaning of symbols of line planning optimal model.

| | Symbols | The meaning of symbols |
|---|---|---|
| Variable symbols | $p$ | The train in the network (Inputs) |
| | $q$ | The riding scheme |
| | $t_{pq}$ | Required time for passenger volume of train $p$ that are transported by scheme $q$ |
| | $t^t_{pq}$ | Transfer time for passenger volume of train $p$ that are transported by scheme $q$ |
| | $L_p$ | Travel distance of train $p$ (Inputs) |
| | $D_p$ | $D_p$ is fixed number of passengers of train $p$ (Inputs) |
| | $V_p$ | All the passenger volume through the train $p$ transport (Inputs) |
| | $V^k_p$ | Passenger volume of train $p$ in the section $k$ |
| | $m_{pq}$ | The train $p$ is included in the scheme $q$ when $m_{pq} = 1$, otherwise $m_{pq} = 0$. |
| | $s^s_{pq}$ | Intermediate variable. Train $p$ which is included in scheme $q$ will stop in station $s$. |
| | $V^k_{pq}$ | Passenger volume in the section $k$ of train $p$ which is included in scheme $q$. |
| | $w^s_p$ | The origin or destination of train $p$ includes station $s$ when $w^s_p = 1$, otherwise $w^s_p = 0$. (Inputs) |
| | $l_q$ | The scheme $q$ is an independent scheme when $l_q = 1$, otherwise $l_q = 0$. (Inputs) |
| | $y_{pq}$ | The passenger volume of train $p$ can be transported by scheme $q$ when $y_{pq} = 1$, otherwise $y_{pq} = 0$. (Inputs) |
| Decision Variable symbols | $f_p$ | Frequency of train $p$ |
| | $z_p$ | Train $p$ is chosen when $z_p = 1$, otherwise $z_p = 0$ |
| | $x_{pq}$ | There are $x_{pq} \cdot D_p$ passengers are transported by scheme $q$. |
| Parameter symbols | $c_l$ | Cost per unit distance |
| | $c_{fx}$ | Fixed cost per train |
| | $c_t$ | Cost per unit time |
| | $c_{st}$ | Cost of one stop |
| | $s_p$ | Number of stops of train $p$ |

riding schemes based on initial line plan. The optimization model of networked HSR train operation scheme mainly takes into account the relationship between passenger travel convenience and operation cost. And the research objectives is the lowest travel cost of all passengers and the lowest train operation cost in the network. The cost of the independent scheme and the intermediate transfer scheme are calculated respectively. The cost of the independent scheme can be calculated by formula (8). The symbol $t_{pq}$ represents the required time for passenger volume of train $p$ through scheme $q$, $c_t$ represents the unit time cost. Formula (9) shows that the cost of transfer scheme adds transfer cost due to transfer time $t^t_{pq}$ on the basis of formula (8).

$$c^d_{pq} = t_{pq} \cdot c_t, \quad (8)$$

$$c^d_{pq} = \left(t_{pq} + t^t_{pq}\right) \cdot c_t. \quad (9)$$

As shown in Figure 5, there will be one or more riding schemes for passengers from A to B. Passengers $p$ from A to B can be transported through scheme $q_1$ and $q_2$. Scheme $q_2$ is composed of train $p_{AC}$ and train $p_{CB}$. The required time and transfer time can be expressed in Figure 5. All these are included in initial trains.

As Figure 6 showed, there are $N$ riding schemes in the model. If passengers of initial train $p$ can be transported by scheme $q$, the required time for passenger volume of train $p$ through scheme $q$ is $t_{pq}$. Otherwise, the required time and transfer time is set to a maximum value.

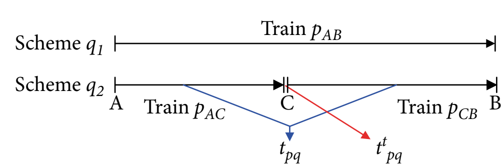


Figure 5: The relationship of initial train $p$ and scheme $q$.

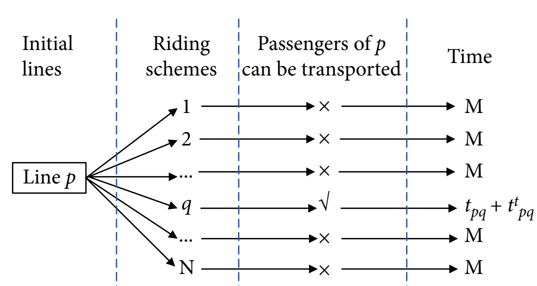


Figure 6: Representation of the required time and transfer time according to Formulas (8) and (9).

The cost of train operation includes three parts: the cost of running distance, the fixed cost and the cost of stopping. The cost of a single train is composed of the product of the running distance and the unit distance cost, the fixed cost of each train and the stopping cost, which can be expressed as follows $L_p \cdot c_l + c_{fx} + c_{st} \cdot s_p$. $L_p$ represents running distance of train $p$. $c_l$, $c_{fx}$, $c_{st}$ represent cost of unit distance, fixed cost per train and cost of one stop respectively. The total cost of trains in the network is multiplied by the number of trains and the cost of a single train.

Because the influence factors of the problem in the model can be converted into cost. The two parts of the objective function have the same dimension. In order to simplify the model, the objective function is linearized into an expression (10) considering multiple objectives. The value of $\omega$ can be determined according to the characteristics of the actual HSR network and the aim of planning, passenger-oriented or operation-oriented.

$$\min \omega \cdot \sum_p \sum_q f_p \cdot c_{pq}^d + (1-\omega) \cdot \sum_p f_p \cdot z_p \cdot \left(L_p \cdot c_l + c_{fx} + c_{st} \cdot s_p\right). \tag{10}$$

There are three kinds of decision variables in the optimization model of networked HSR line plan.

(1) $f_p$, represents the frequency of train $p$;

(2) $z_p$, $z_p$ is 0–1 variable. Train $p$ is chosen when $z_p$=1, otherwise, train $p$ isn't chosen.

(3) $x_{pq}$, $x_{pq} \in [0,1]$, there are $x_{pq} \cdot D_p$ passengers are transported by scheme $q$. Among them, $D_p$ is fixed number of passengers of train $p$.

*4.3. Major Constraints of Optimization Model.* (1) Service frequency constraints. The train service frequency of the train $f_p$ should be between the minimum frequency $f_p^{\min}$ and the maximum frequency $f_p^{\max}$.

$$f_p^{\min} \le f_p \le f_p^{\max}. \tag{11}$$

Formula (12) indicates that the frequency of a train is obtained by dividing the passenger volume of the train by the fixed number of passengers. An intermediate variable is introduced to express the passenger volume through the train $p$ in scheme $q$. In formula (13), $m_{pq}$ is 0–1 variable, indicating whether the train $p$ is included in the scheme $q$. If the train $p$ is included in the scheme $q$, $m_{pq}$ is equal to 1. All the passenger volume $V_p$ through the train $p$ can be expressed in formula (14).

$$f_p = \frac{V_p}{D_p}, \tag{12}$$

$$V'_{pq} = \begin{cases} \sum_p x_{pq} \cdot V_p, m_{pq} = 1 \\ 0, m_{pq} = 0, \end{cases} \tag{13}$$

$$V_p = \sum_q V'_{pq}. \tag{14}$$

(2) Expressions of train stops. A set of variables $w_p^s$ which are 0–1 variable are inputs to the model. $w_p^s = 1$ means the origin or destination of train $p$ includes station $s$. By introducing a class of three-dimensional variables $s_{pq}^s$, train $p$ will stop in station $s$ when $\sum_{q\in P'} s_{pq}^s \neq 0$. This process is only calculated for independent schemes because that the transfer scheme contains stops and stops cannot be included in the train, as shown in Formula (16). The 0-1 variable $l_q$ denotes whether scheme $q$ is an independent scheme, and $l_q = 1$ denotes that scheme $q$ is an independent scheme. Formula (17) which can be obtained from Formulas (15) and (16) indicates number of train $p$ stops.

$$s_{pq}^s = \begin{cases} w_p^s, x_{pq} \neq 0 \\ 0, x_{pq} = 0, \end{cases} \quad w_p^s \in \{0,1\}, \tag{15}$$

$$s_p^s = \begin{cases} 1, \sum_{q\in P'} s_{pq}^s \neq 0 \\ 0, \sum_{q\in P'} s_{pq}^s = 0, \end{cases} \quad l_q = 1, \tag{16}$$

$$s_p = \sum_{s\in N} s_p^s. \tag{17}$$

(3) Passenger volume conservation constraints. Formula (18) indicates that the passenger volume of train $p$ in the initial plan is transported by scheme $q$. As a known 0–1 variable $y_{pq}$, the passenger volume of train $p$ can be transported by scheme $q$ when $y_{pq} = 1$.

$$\sum_q x_{pq} \cdot y_{pq} = 1, \quad 0 \le x_{pq} \le 1. \tag{18}$$

(4) Transport capacity constraints. The passenger volume of a train $p$ in a section $k$ can be expressed by formula (19). And a three-dimensional intermediate variable $V_{pq}^k$ is introduced in the calculation. $V_p^k$ represents the passenger volume of train $p$ in the section $k$. The passenger volume of the section $k$ is calculated according to equation (20). Formula (21) shows that the passenger volume of a section $k$ should be less than or equal to the capacity limit of the section $k$.

$$V_p^k = \sum_q V_{pq}^k, \quad V_{pq}^k = x_{pq} \cdot V_q^k, \tag{19}$$

$$V^k = \sum_p V_p^k, \tag{20}$$

$$V^k \le B^k. \tag{21}$$

(5) The relationship between decision variables and other variable constraints. If the passenger volume of the train $p$ is 0, it means that the train $p$ isn't chosen, otherwise the train $p$ is chosen.

$$V_p = 0, z_p = 0, \tag{22}$$

$$m_{pq}, y_{pq}, l_q \in \{0,1\}, \quad x_{pq} \in [0,1]. \tag{23}$$

## 5. Application to HSR in China

In July 2017, the Baoji–Lanzhou HSR was opened. The case study selected the network composed of the Baoji–Lanzhou HSR and the lines closely connected with the Baoji–Lanzhou HSR as the research object. The network only retains the primary and secondary nodes and the main connection points.

There are 11 stations in the network, as shown in Figure 7. The passenger volume in the network includes the passenger volume between OD in the network and the cities outside the network with the nodes inside the network. These cities are Beijing, Shenzhen, Shanghai, Changsha, Tianjin, Shenzhen, Xiamen, Guangzhou, Urumqi, Xi'ning and so on.

In order to further analyze the solution effect of the combination of extra-long distance transport organization mode and network train operation scheme optimization, the above passenger volume are all related to the Baoji–Lanzhou HSR.

Line panning and line plan optimal of most existing research projects are direct-oriented. So two scenarios are set to discuss and analyze the optimization of the line plan around the combination of direct and direct oriented. Scenario 1 is consistent with the method of the paper. Line planning optimal based on determining direct or intermediate transfer for extra-long distance transportation in Scenario 1. Extra-long distance transportation is guided by direct maximization in Scenario 2. In order to balance the relationship between passenger and government, the value of $\omega$ in the objective function in this case is set to 0.5.

*Scenario 1*: According to the method of determining the organization mode of extra-long distance passenger volume, the transportation organization mode of extra-long distance passenger volume in the network is determined, and the train connection scheme is added to the set of travel plans in the optimization model of network train operation scheme. The initial train operation scheme is optimized by the network train operation scheme optimization model based on the train ride scheme.

*Scenario 2*: According to the initial operation plan, this mode is guided by maximizing the direct train arrival. Taking the lowest total train operation cost as the research objective, the corresponding operation plan will be solved.

(1) Characteristic of optimization model for networked train operation scheme.

Table 5 lists the results of scenario 1 and scenario 2, in which passenger volume of some trains is merged. Most of the passenger volume is allocated to different lines, which ensures the diversity of lines in the process of continuous optimization of the model. Based on passenger train scheme, the optimization model of networked train operation scheme can realize the integration of train route, frequency and stopping station. It is beneficial to different travel demand of OD pairs in the network and guarantees the diversity and economy of the optimized scheme.

(2) Analysis of the solution effect of the combination of extra-long distance transportation organization scheme and networked train operation scheme.

It is beneficial to providing more reasonable and diversified travel schemes for passengers combining the organizational model of extra-long distance transportation with the network train operation scheme.

By comparing and analyzing the operation schemes of the two modes in Table 6, it can be found that the number of trains running under the extra-long distance transportation organization scheme is more. The train operation cost is higher than direct-oriented while the travel cost of all passengers reducing a lot. The total cost of the networked train operation scheme is obviously reduced. At the same time, the average distance of trains running is shortened obviously. The types of trains are basically the same under the two scenarios.

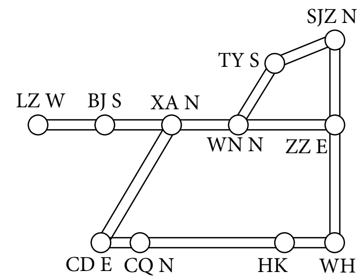


Figure 7: The network of case study. SJZ N: Shijiazhuang North; TY S: Taiyuan South; XA N: Xi'an North; BJ S: Baoji South; LZ W: Lanzhou West; WN N: Weinan North; ZZ E: Zhengzhou East; CD E: Chengdu East; CQ N: Chongqing North; HK: Hankou; WH: Wuhan.

Table 5: Partial solution results of decision variables $x_{pq}$.

| Scenario | Unselected lines | Merged Lines | Values of $x_{pq}$ |
|---|---|---|---|
| Scenario 1 | **BJ S–LZ W** | **BJ S–LZ W** | 79% |
| | | CD E–XA N–**BJ S–LZ W** | 2% |
| | | ZZ E–WN N–XA N–**BJ S–LZ W** | 18% |
| Scenario 1 | **BJ S–XA N** | **BJ S–XA N** | 96% |
| | | **BJ S–XA N**–TY S | 3% |
| Scenario 2 | **WN N–XA N–BJ S** | ZZ E–**WN N–XA N–BJ S** | 30% |
| | | SJZ N–**WN N–XA N–BJ S** | 58% |
| | | TY S–**WN N–XA N–BJ S**–LZ E | 4% |
| | | SJZ N–TY S–WN N–XA N–BJ S–LZ E | 8% |
| Scenario 2 | **XA N–BJ S** | **XA N– BJ S** | 91% |
| | | TY S–WN N–**XA N– BJ S**–LZ E | 8% |
| | | CQ N – CD E–**XA N–BJ S**–LZ E | 1% |

Note: The routes in the table represent only running paths, including information passing through nodes and arcs, but not stop information The same OD pairs are marked in bold. The passenger flow of OD pair in bold in the second column is transported by multiple lines in the third column.

Table 7 shows statistical analysis of the number of trains in different distance ranges under two scenarios. The number of trains with short distance and medium distance increased significantly, while the number of trains in long distance and extra-long distance decreased significantly in different scenarios.

As shown in Figure 8, among the plans related to the Baoji–Lanzhou HSR, Lanzhou West and Xi'an North Railway Stations have the largest passenger volume and the largest number of trains, followed by Baoji South Railway Station. The farther away from the Baoji–Lanzhou HSR, the less passenger volume there is. In scenario 1, the number of trains originating and

Table 6: Comparison of line planning in different situation.

| | Total cost of line plan | Number of trains running | Train type | Average train distance/km | Maximum travel distance/km |
|---|---|---|---|---|---|
| Scenario 1 | £ 3.17 Million | 116 | 23 | 592 | 1635 |
| Scenario 2 | £ 3.40 Million | 106 | 22 | 756 | 1692 |

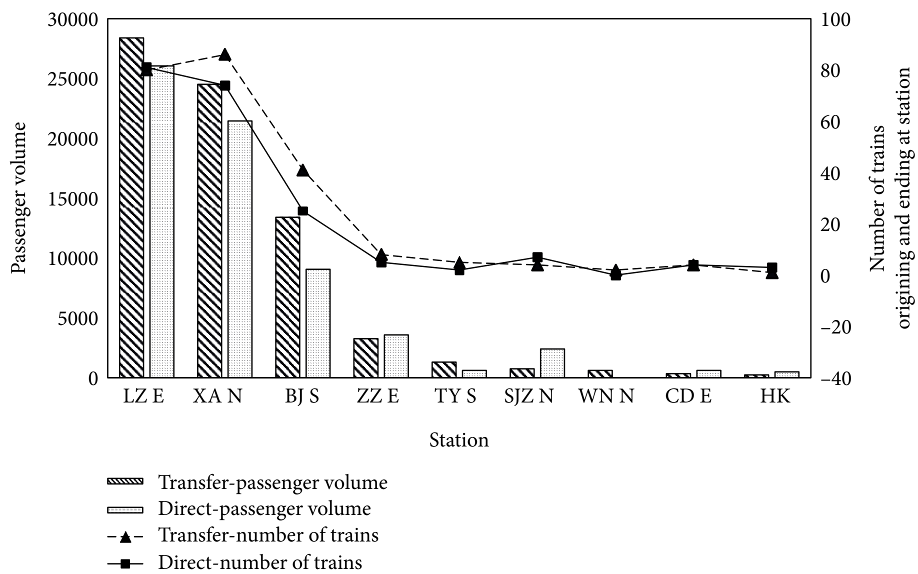


Figure 8: Stations' information of line planning that related to Baoji–Lanzhou HSR.

Table 7: The number of trains with different distance in different situation.

| Distance range of train operation/km | Scenario 1 train number | Scenario 2 train number |
|---|---|---|
| <500 | 30 | 17 |
| 500–1000 | 75 | 63 |
| 1000–1500 | 10 | 17 |
| More than 1500 | 1 | 9 |

ending at these stations are more. The number of passengers transported at these stations (referring to the total number of passengers originating at the stations) is also more.

## 6. Conclusion

In this paper, the direct and transfer transportation of HSR over 1500 km is studied. Not only the through passenger volume but also the number of important nodes in the train running path should be taken into account when extra-long distance passengers are transported by through trains. Many factors should be taken into account in the selection of transfer schemes for extra-long distance travelers. An optimization model is constructed from the perspective of passenger riding scheme. The model synthetically optimizes the service frequency of train and the stopping scheme of train.

The optimized scheme is more accord with the characteristics of HSR network operation in China. Specifically in the following areas. (1) Reduce the cost of the train operation plan, and it is conducive to further improving the efficiency of the operation department. (2) The service frequency of short-distance and medium-distance HSR trains increases, and the types of trains are more abundant, which is conducive to improving the market competitiveness of HSR under the condition of network. (3) The average transport distance of trains is obviously shortened, which is more conducive to the rapid turnover of the bottom of the networked trains and can further improve the efficiency of networked operation.

In the future, the relationship between passenger travel behavior and passenger transport products will be further studied. The sensitivity of passengers to travel time, travel time and fare should be further considered in diversified plans on the basis of subdividing passenger market. Future research needs more multi-dimensional qualitative analysis and quantitative characterization of this aspect. And the impact of passenger volume segmentation and passenger travel characteristics mining on HSR operation plan will be analyzed additionally. We can optimize and obtain more refined passenger transportation products.

## Data Availability

The data used to support the findings of this study have not been made available because that passenger volume data obtained by railway administration through investigation which can not be made public for the time being.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

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