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Research Article

High-Speed Train Stop-Schedule Optimization Based on Passenger Travel Convenience

Dingjun Chen,[1,2,3] Shaoquan Ni,[1,2,3] Chang'an Xu,[1,2] Hongxia Lv,[1,2,3] and Simin Wang[1]

[1] *School of Transportation and Logistics, Southwest Jiaotong University, Chengdu 610031, China*
[2] *National Railway Train Diagram Research and Training Center, Southwest Jiaotong University, Chengdu 610031, China*
[3] *National and Local Joint Engineering Laboratory of Comprehensive Intelligent Transportation, Chengdu 610031, China*

Correspondence should be addressed to Shaoquan Ni; shaoquanni@163.com

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The stop-schedules for passenger trains are important to the operation planning of high-speed trains, and they decide the quality of passenger service and the transportation efficiency. This paper analyzes the specific manifestation of passenger travel convenience and proposes the concepts of interstation accessibility and degree of accessibility. In consideration of both the economic benefits of railway corporations and the travel convenience of passengers, a multitarget optimization model is established. The model aims at minimizing stop cost and maximizing passenger travel convenience. Several constraints are applied to the model establishment, including the number of stops made by individual trains, the frequency of train service received by each station, the operation section, and the 0-1 variable. A hybrid genetic algorithm is designed to solve the model. Both the model and the algorithm are validated through case study.

1. Introduction

Train schedules program is a very important task railway transportation organization operation plan [1]. In a rail network system, the fundamental train schedule program is to determine the number of trains serving the line connecting two terminal stations in a fixed time interval (e.g., in one hour) [2]. For a rail line without branches, passenger train scheduling program is mainly concerned with the plan of stop-schedules for all train operations planned [3, 4]. A stop-schedule specifies a set or subset of stations at which the train stops in a train travel on a rail line [5].

Line planning is one of the most crucial and complex problems in transportation organization and has been explored by many researchers. However, it is essentially a multitarget combination optimization problem, which awaits an effective and universal solution algorithm. At present, the method is mainly focused on mathematical programming [2, 6, 7] and intelligent optimization [8, 9].

Most studies treat stop-schedule planning as a subproblem of line planning. Based on their objectives, those studies generally employ the following three types of models.

(1) Cost-Related Models. Cost-related models refer to line planning models that aim at minimizing the operation cost. Goossens et al. built such a passenger train operation optimization model [10–12]. With consideration of passenger flow requirements and transportation capacity, the model computes train routes, departure frequency, and marshaling. The model transfers nonlinear integer programming problems into linear integer programming problems and then solve them by using a branch and cut algorithm. The method was applied to a subnetwork of Holland's railway system, and the application demonstrated that the model could effectively reduce railway operation cost.

(2) Customer-Related Models. Customer-related models refer to line planning models that emphasize passenger benefits such as departure time and wait time. Scholl established a line planning optimization model that aims to minimize the total travel time of passengers, with constraints of passenger flow capacity, railway corporation budget, conservation of passenger flow, and sectional transportation capacity. In addition, the correlations among various solution algorithms to the model were analyzed [13]. Zhou and Zhong established

a multitarget programming model for line planning optimization, focusing on high-speed railway passenger dedicated lines. The target function minimizes the wait time for high-speed trains, as well as the total travel time on high-speed and medium-speed trains. To solve the model, a branch and bound model and a search algorithm based on efficiency evaluation were used [14]. Vansteenwegen and Van Oudheusden established a passenger train schedule optimization model that minimizes the wait time. The model consists of two phases. Phase one computes the ideal additional operation time, which is obtained based on the train delay distribution, passenger amount, and other types of additional wait time [15]. Computing this additional operation time helps ensure normal operation when branch lines are delayed. Phase two revises the train schedule by using a continuous nonlinear programming model. Simulative evaluations are performed in this phase to different train schedules for further improvements.

(3) Cost and Customer Related Models. Cost and customer related models refer to line planning models that consider the benefits of both railway transportation corporation and passengers. Chang et al. established a multitarget optimization model for nonintersected intercity high-speed train operation plans. The model aims at minimizing the total operation cost of railway corporations and travel time of passengers [5]. For multipair high-passenger flow origin-destinations (ODs) and fixed transportation capacity, fuzzy mathematical programming was adopted to decide the optimal line plan. The model generates line plans that consist of train stop-schedule, service frequency, and the number of passenger carriage pairs. Ghoseiri et al. established a multitarget line planning optimization model that solves the single-path and multipath selection problem for railway network with different capacities of train stations [16]. The model considers both railway passenger traffic department and passengers, with a target function that minimizes fuel cost and total travel time of passengers. The Pareto-frontier solution set was used for the multitarget optimization task. Borndörfer et al. studied the passenger travel time and operation cost of railway transportation corporations as a whole and explored the feasibility of applying branch and bound algorithm to the problem [17].

A few studies investigated stop-schedule planning problem. Such studies generally assume that line plans and various stop modes are already known. Goossens [12] investigated the formulation of cyclic train operation plans in the same railway network with different stop-schedule plans. The article discusses cyclic operation and organization of railway traffic and thoroughly explored the line planning models under different stop modes. In addition, a model and corresponding algorithm were proposed, which give line plans for the same path under at most three different stop modes.

China's line planning and stop-schedule planning are significantly different from those in West Europe and Japan. In China, train line planning is based on passenger traffic flow. Based on passenger flow properties, characteristics and patterns, the operation priority, origin and destination, quantity, route, marshaling, stop-schedule, passenger seat utilization, and passenger carriage utilization are reasonably arranged, with organization schemes covering from passenger flow to train flow. A high-speed railway stop-schedule plan should, after deciding train routes, train types, marshaling, and operation pairs, reasonably arrange the orders of stopping for each train based on passenger flow requirements and train collaboration. The line planning and stop-schedule planning of China are different from those of West Europe and Japan for two reasons. On the one hand, China's transportation organization mode is significantly different from that of West Europe and Japan; the former is organized transportation, and the latter is planned transportation. On the other hand, the average length of OD sections in China is much longer than those in West Europe and Japan. The much more complicated railway networks of China also disenable the train operation diagrams to be cyclic, adding difficulties to the compilation of line plans and stop-schedule plans.

In this paper, we propose two concepts, interstation accessibility and degree of accessibility. On the basis of considering the economic benefits of railway corporations and the travel convenience of passengers, a multitarget optimization model for stop-schedule planning is established, aiming at minimizing train stop costs and maximizing passenger travel convenience. A corresponding hybrid genetic algorithm is also designed.

The contribution of this paper is twofold. First, in order to better describe the number of options for passengers to travel and express the travel convenience for passengers, the concepts of accessibility and degree of accessibility are proposed. Compared with directly using travel time and wait time as indicators of passenger benefit, these two concepts are more reasonable. Meanwhile, this paper presents a hybrid genetic algorithm to solve the multitarget model. Since this paper focuses on the high-speed railway stop-schedule planning problem in China, whose railway networks are much larger and more complicated than those of West Europe and Japan, the problem cannot be effectively solved by precise algorithms such as column generation algorithm, lagrangian relaxation method, or branch and bound method. The proposed heuristic algorithm, although cannot produce the optimal solution, provides satisfying solutions, which is of practical importance.

The remainder of this paper is organized as follows. Section 2 presents the concept of passenger travel convenience, and Section 3 presents the concepts of interstation accessibility and degree of accessibility. Section 4 establishes and analyzes the model. Section 5 illustrates the algorithm design and the model solution. Section 6 validates the model and method proposed in Sections 4 and 5, with the Wuhan-Guangzhou high-speed railway as an example.

2. Passenger Travel Convenience

Passenger travel convenience is closely associated with departure time of the chosen train and degree of freedom when passengers choose trains. Through questionnaire survey, He et al. [18] found that within reasonable range of departure time, generally 6:00 to 24:00 [19], and passengers' choices of travel time show obvious bias. Passengers prefer two

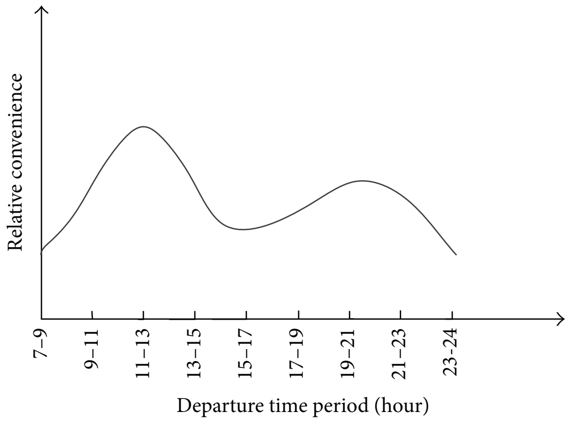

Figure 1: Passengers' travel convenience in different time periods for departure (unit: hour).

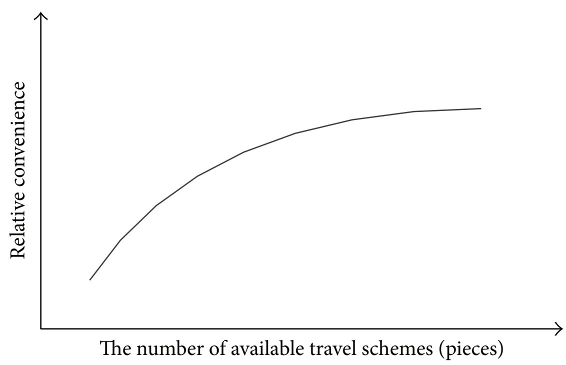

Figure 2: Variation of passenger travel convenience with the number of available travel schemes.

time periods for departure. As shown in Figure 1, the first period is 11:00 to 13:00, and the second is 19:00 to 21:00. A departure time period chosen by more passengers indicates more recognition to the period's convenience. In Figure 1, 7–9 means the period from 7:00 to 9:00, excluding 9:00.

In a reasonable range of departure time of high-speed trains, the flexibility of passengers' travel time and the number of travel schemes increase with the number of trains in the line plan that satisfies passengers' travel requirements. More travel schemes means greater flexibility, that is, higher travel convenience, as shown in Figure 2.

The number of available travel schemes can be direct accessible scheme value or transfer accessible scheme value. Direct accessible scheme value (n_d) refers to the total value of schemes where passengers travel to their destinations through direct trains, while transfer accessible scheme value (n_t) refers to the total value of schemes where passengers travel through train transfers. The transfer accessible scheme value is related to the number of trains (n_f) before the transfer and the number of trains (n_l) after the transfer that are available; generally, the product of the two numbers is used; that is, $n_t = n_f * n_l$.

Generally, when the number of available travel schemes is large, the passengers' choices on departure and arrival times

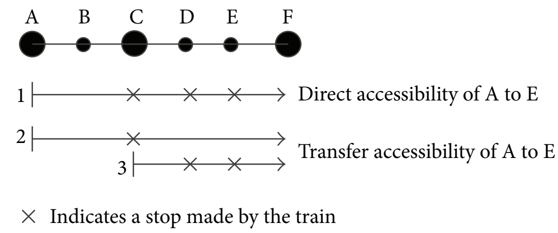

Figure 3: A line plan and its interstation accessibility.

are more dispersed (given that train operation diagrams are usually plotted in a balanced manner). Passengers tend to travel at times that are more suitable to their preferences and travel purposes. Therefore, the number of available travel schemes, compared with travel time, has greater influence on passenger's travel convenience. To a certain extent, the influence of departure time on transfer convenience can be ignored, which means passenger's travel convenience is solely decided by the number of available travel schemes.

3. Interstation Accessibility and Degree of Accessibility

In order to better describe the value of available travel schemes for passengers to choose and express the degree of passengers' travel convenience, we propose in this section the concepts of interstation accessibility and degree of accessibility.

3.1. Concepts. Interstation accessibility refers to whether the passenger flow within an OD pair can travel by direct train or through one transfer. In order to improve passengers' travel convenience and easiness, reduce their fatigue, and avoid losing passenger flow due to frequent transfers, we allow in this study at most one transfer during a passenger's travel, which means every passenger can get to their destination by at most one transfer. Accessibility is a state describing whether an OD pair is accessible. Two states, direct accessible and transfer accessible, are used based on the need for transfer. As shown in Figure 3, the passenger flow at station A can get to station E by train 1, indicating direct accessibility of A to E. Meanwhile, the passengers at station A can also get to station E by taking train 1 and then transferring to train 3 at station C, indicating transfer accessibility of A to E. Direct accessibility only means that passengers do not have to change trains to get to the destination, but not that the train does not make stops.

The degree of accessibility refers to the values of schemes to travel within any OD pair through direct trains or one transfer. Like accessibility, the degree of accessibility can be degree of direct accessibility or degree of transfer accessibility. The degree of direct accessibility means the total value of the schemes to take direct trains to reach destinations for passengers within an OD pair, whereas the degree of transfer accessibility means the total value of the schemes to reach destination by transferring once for passengers within an OD pair. For the latter, the trains taken by passengers should not

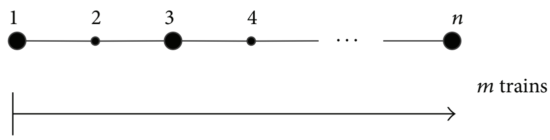

Figure 4: A high-speed railway line and the trains operating on it.

be any of the direct trains within the OD pair. If a direct train is available to reach the destination, then taking this train and transferring to another halfway to reach the destination are not counted as a transfer accessibility scheme. Assuming that in Figure 3, there are only two train operation sections, section AF and section CF. Two trains, train 1 and train 2, operate on section AF, while train 3 operates on section CF. Since only train 1 stops at both station A and station E, thus the degree of direct accessibility for A to E is 1. Other than taking train 1, passengers can only take train 2 to get to transfer station C and then take train 3 (rather than train 1) to reach station E. Thus, the degree of transfer accessibility is also 1.

The degree of accessibility not only reflects the accessibility of OD pairs in the high-speed railway network, but also describes the amount of travel options for passengers. Higher degree of accessibility indicates better accessibility of the railway network and more available travel schemes. Therefore, the degree of accessibility, to a certain extent, describes the passenger's travel convenience.

3.2. Mathematical Expression of the Degree of Accessibility. Figure 4 shows a high-speed railway line with n train stops and runs m trains. The trains only run within the shown section, all with origin and destination being stops 1 and stop n. The stop-schedules for the m trains are not given.

A variable $t_{i,j}$ with the value of 0 or 1 is defined; the value of 1 means train i stops at train station j; otherwise it does not.

The train set is $T = \{1, 2, \ldots, m\}$, and $i, i' \in T$; the train station set is $S = \{1, 2, \ldots, n\}$, and $n_1, n_2, n_k, p, q \in S$.

For an OD pair (origin and destination are n_1 and n_2, resp., where $n_1, n_2 \in N$ and $n_1 < n_2$), the degree of direct accessibility (A_d^{OD}) is denoted by

$$A_d^{\mathrm{OD}} = \sum_{i=1}^{m} t_{i,n_1} \cdot t_{i,n_2} \quad (1)$$

and the degree of transfer accessibility (A_t^{OD}) is denoted by

$$A_t^{\mathrm{OD}} = \sum_{i=1}^{m} t_{i,n_1} \cdot t_{i,n_2} \sum_{i=1}^{m} \sum_{n_k=n_1+1}^{n_2-1} t_{i,n_1} \cdot t_{i,n_k} \cdot \left(1 - t_{i,n_2}\right) \cdot \left[\sum_{i' \in \{T/i\}} t_{i',n_k} \cdot t_{i',n_2} \cdot \left(1 - t_{i',n_1}\right)\right], \quad (2)$$

where n_k is the intermediate station, $n_1 < n_k < n_2$, and $i' \in T$.

The total degree of accessibility of this OD pair (A^{OD}) is denoted by

$$A^{\mathrm{OD}} = \sum_{i=1}^{m} t_{i,n_1} \cdot t_{i,n_2} + \sum_{i=1}^{m} \sum_{n_k=n_1+1}^{n_2-1} t_{i,n_1} \cdot t_{i,n_k} \cdot \left(1 - t_{i,n_2}\right) \cdot \left[\sum_{i' \in \{T/i\}} t_{i',n_k} \cdot t_{i',n_2} \cdot \left(1 - t_{i',n_1}\right)\right]. \quad (3)$$

The total degree of OD accessibility of the line (A^L) shown in Figure 3 is denoted by

$$A^L = \sum_{p=1}^{n-1} \sum_{q=p+1}^{n} \sum_{i=1}^{m} t_{i,p} \cdot t_{i,q} + \sum_{p=1}^{n-1} \sum_{q=p+2}^{n} \sum_{n_k=p+1}^{q-1} \sum_{i=1}^{m} t_{i,p} \cdot t_{i,n_k} \cdot \left(1 - t_{i,q}\right) \cdot \left[\sum_{i'=\{T-i\}}^{m} t_{i',n_k} \cdot t_{i',q} \cdot \left(1 - t_{i,p}\right)\right]. \quad (4)$$

Equation (3) represents the total degree of accessibility of an OD pair. Equation (4) represents the total degree of OD accessibility of the line. The total degree of OD accessibility of the line equals the sum of the total degree of accessibility of every OD pair in this line.

3.3. Optimization of the Degree of Transfer Accessibility. For some OD pairs, due to some intermediate stations' inability to fulfill technical requirements of passenger transfers or other technical reasons, passengers cannot get to their destinations through transfers even though the route passes through stations that connecting trains can stop. This portion of passenger flow can only travel through direct trains. To reduce unnecessary stops at such intermediate stations so as to avoid increasing transportation cost and prolonging travel time, the degrees of transfer accessibility between such OD pairs should be regulated. Transfer accessibility schemes that do not fulfill the transfer requirements should be eliminated, thus optimizing the degree of transfer accessibility.

For the situation shown in Figure 3, assuming that the set of intermediate stations (besides n_1 and n_2) that fulfill the technical transfer requirements is S_t, where $S_t \subset S$, and that only the travel scheme of transferring at station 3 can be considered a transfer accessible scheme, that is, $S_t = \{3\}$, then the optimized total degree of OD accessibility of the line is

$$A^L = \sum_{p=1}^{n-1} \sum_{q=p+1}^{n} \sum_{i=1}^{m} t_{i,p} \cdot t_{i,q} + \sum_{p=1}^{n-2} \sum_{q=p+2}^{n} \sum_{p<n_k<q, n_k \in S_t} \sum_{i=1}^{m} t_{i,p} \cdot t_{i,n_k} \cdot \left(1 - t_{i,q}\right) \cdot \left[\sum_{i' \in T, i' \neq i} t_{i',n_k} \cdot t_{i',q} \cdot \left(1 - t_{i,p}\right)\right]. \quad (5)$$

4. Establishment of Optimization Model

While establishing a high-speed train stop-schedule optimization model, the operation benefit of railway transportation corporations should be considered, and the principle is to maximize the operation benefit. On the other hand, the passenger's travel convenience should also be considered, which means that the degree of OD accessibility in the railway network should be expressed. Therefore, this section establishes a multitarget optimization model for stop-schedule planning with the objectives of minimizing stop cost and maximizing passenger travel convenience.

4.1. Model Assumptions. In order to simplify the complexity of the model and to make the model more accurate, we make some basic assumptions before establishing the model:

(1) High-speed railways in China are usually double-track; the up direction trains and the down direction trains are independent of each other. We generally considered the same number of trains operated in the same section from opposite direction. We only study a fixed direction of the train stop schedule optimization problem in this paper.

(2) We assume that the line plan is known condition when we consider stop scheme optimization problem. Namely, passenger's flow of every OD pair, train operation section, train types, the number of trains, and train marshalling are all known conditions.

(3) We assume that the station capacity and line capacity have no restrictive effect on the train operation. That is to say, station capacity, facilities and equipment capacity, and other factors have no effect on the design of the train stop scheme.

(4) We assume that the size and nature of passenger's flow of the railway line between the departure station and arrival station do not vary from the train stop scheme changed. That is to say, the change of the stop schedule will not cause the fluctuations of the passenger flow. Besides, we do not consider the passenger flow loss due to the transfer.

(5) We assume that the frequency of the train service shown in this paper is considered on a daily basis.

4.2. Model Parameters. A train and station set $G = \{S, T\}$ is given, where $S = \{s_j \mid j = 1, 2, \ldots, n\}$ is the set of stations and n is the number of stations. $S_t \subset S$ is the set of stations that can be used as transfer stations and satisfy the technical conditions for transfer nodes. $T = \{t_i \mid i = 1, 2, \ldots, m_1, m_1 + 1, \ldots, m\}$ is the set of trains, where $i = 1, 2, \ldots, m_1, m_1 + 1, \ldots, m$ is the departure sequence of trains and m indicates the number of trains. Since only two types of trains are considered in this study, $l \in \{1, 2\}$ is used to denote type-A and type-B high-speed trains, and T_l denote the sets of different types of trains; that is, $T_1 = \{1, 2, \ldots, m_1\}$ is the set of type-A high-speed trains, and $T_2 = \{m_1 + 1, m_1 + 2, \ldots, m\}$ is the set of type-B trains, where $T_1 \cap T_2 = \varnothing$ and $T_1 \cup T_2 = T$.

In addition, x_{ij} is a 0-1 variable indicating whether train I stops at station j.

4.3. Objectives of Optimization

4.3.1. Minimizing Train Stop Cost. Different levels of trains cost differently for stops. Assuming that, on the high-speed railway line, a train costs c_l yuan each stop, and $l \in \{1, 2\}$, then the total stop cost of the line is

$$Z_1 = \sum_{i=1}^{m_1} \sum_{j=1}^{n} c_1 \cdot x_{ij} + \sum_{i=m_1+1}^{m} \sum_{j=1}^{n} c_2 \cdot x_{ij}, \tag{6}$$

where Z_1 is the total stop cost in the unit of yuan, c_1 is the cost of type-A high-speed train for each stop in the unit of yuan/stop, and c_2 is the cost of type-B high-speed train for each stop in the unit of yuan/stop.

4.3.2. Maximizing Passenger's Travel Convenience. The degree of OD accessibility expresses the accessibility within an OD pair, yet cannot accurately reflect the passenger flow's demand for accessibility. Thus, we introduce a passenger flow degree coefficient matrix and use the product of passenger flow degree coefficient and degree of accessibility to indicate the convenience provided to passengers.

The degree of OD accessibility is

$$\begin{aligned} Q = Q^Z + Q^H &= \sum_{p=1}^{n-1} \sum_{q=p+1}^{n} \sum_{i=1}^{m} \left(x_{ip} \cdot x_{iq} \right) \\ &+ \sum_{p=1}^{n-2} \sum_{q=p+2}^{n} \left[\sum_{p<k<q, k \in S_t} \sum_{i=1}^{m} \sum_{i' \in T, i' \neq i} \left(x_{ip} \cdot x_{ik} \cdot \left(1 - x_{iq}\right) \right) \right. \\ &\left. \cdot\, x_{i'k} \cdot x_{i'q} \cdot \left(1 - x_{i'p}\right) \right], \end{aligned} \tag{7}$$

where Q is the total value of all accessible schemes among all stations, that is, the degree of accessibility; Q^Z is the degree of direct accessibility among all stations; and Q^Z is the degree of transfer accessibility among all stations.

For the n train stations on the high-speed railway line, an OD passenger flow matrix N is constructed as follows:

$$N = \begin{pmatrix} - & n_{12} & n_{13} & \cdots & n_{1n} \\ & - & n_{23} & \cdots & n_{2n} \\ & & - & \cdots & n_{3n} \\ & & & \cdots & \vdots \\ & & & & - \end{pmatrix}, \tag{8}$$

where n_{pq} is the passenger flow between station p and station q. When $p = q$, there is no passenger flow; thus $n_{pq} = 0$.

Based on the passenger flow matrix, a passenger flow degree coefficient matrix $\boldsymbol{\lambda}$ is obtained as follows:

$$\boldsymbol{\lambda} = \frac{N}{\sum_{p=1}^{n-1}\sum_{q=p+1}^{n} n_{pq}} = \begin{pmatrix} - & \lambda_{12} & \lambda_{13} & \cdots & \lambda_{1n} \\ & - & \lambda_{23} & \cdots & \lambda_{2n} \\ & & - & \cdots & \lambda_{3n} \\ & & & \cdots & \vdots \\ & & & & - \end{pmatrix}, \quad (9)$$

where λ_{pq} is the passenger flow degree coefficient between station p and station q and

$$\sum_{p=1}^{n-1}\sum_{q=p+1}^{n} \lambda_{pq} = 1. \quad (10)$$

Thus, the passenger's travel convenience of the line is

$$\begin{aligned} Z_2 = \boldsymbol{\lambda} \cdot Q &= \sum_{p=1}^{n-1}\sum_{q=p+1}^{n}\sum_{i=1}^{m} \left(x_{ip} \cdot x_{iq}\right) \cdot \lambda_{pq} \\ &+ \sum_{p=1}^{n-2}\sum_{q=p+2}^{n} \left[\sum_{p<k<q,k\in S_t} \sum_{i=1}^{m} \sum_{i'\in T,i'\neq i} \left(x_{ip} \cdot x_{ik} \cdot \left(1 - x_{iq}\right)\right) \right. \quad (11) \\ &\left. \cdot x_{i'k} \cdot x_{i'q} \cdot \left(1 - x_{i'p}\right) \right] \cdot \lambda_{pq}. \end{aligned}$$

4.4. Constraints

4.4.1. "0-1" Constraint. For train i at station j, its state can only be stopped or not stopped. This state is denoted by the 0-1 variable $x_{ij} = \{0, 1\}$. $x_{ij} = 1$ indicates that train i stops at station j, and $x_{ij} = 0$ indicates that train i does not at station j.

4.4.2. Constraints on the Number of Stops Made by Each Train. On a high-speed railway line, the line plan must ensure a certain amount of stops to ensure OD accessibility, satisfy passengers' demand for train stops, and ease passengers' traveling and transferring. Meanwhile, excessive stops should be reduced in order to avoid overly long travel time and high stop cost. Therefore, certain constraints are put on the maximum number and proportion of stops. Trains of different types travel at different speeds and thus have different preferences for stops, leading to different ranges for the number of stops.

Assuming that the highest and lowest numbers of stops made by trains on a high-speed railway line are D_l^{up} and D_l^{down}, respectively, then the constraints on train i can be expressed as below:

$$\begin{aligned} &\sum_{j=1}^{n} x_{ij} \le D_i^{\text{up}}, \quad i \in T, \\ &\sum_{j=1}^{n} x_{ij} \ge D_i^{\text{down}} \quad i \in T. \end{aligned} \quad (12)$$

The number of train stops is associated with the number of stations within the train's operation section. For different railway line sections, the required numbers of stops are different.

4.4.3. Constraint on the Frequency of Service Required by Each Station. Different levels of node stations have different volumes of passenger flow. Higher-level stations often have higher social and economic status; thus their geographic locations play more important roles in the road network. This means higher volumes of passenger flow and that higher frequency of service is required. In order to meet the demands of different stations, minimum train stop times that meet passenger flow requirements are set for different levels of train stations.

This constraint means that for a train station, the number of times that a train stops at it (including departure and arrival) should not be lower than the demand A_j for train service frequency from the station's level. The train service frequency constraint is expressed as follows:

$$\sum_{i=1}^{m} x_{ij} \ge A_j \quad j = 1, 2, 3, \ldots, n. \quad (13)$$

4.4.4. Constraint on Operation Section. The set of operation sections on a railway line is denoted by $E = \{1, 2, \ldots, R\}$, where R is the number of sections. On section $r \in E$, the set of stations is $S_r = \{s_{m_r}^o, s_{m_r}^o + 1, \ldots, s_{m_r}^d - 1, s_{m_r}^d\}$, and $S_r \in S$.

The specific operation section of each train is determined and constrained. Train i never stops at a station outside its operation section but always stops at the departure and arrival stations of the section.

$S_r^{o+d} \in S_r$ is the set of departure and arrival stations on section S_r; that is, $S_r^{o+d} = \{s_m^o, s_m^d\}$. Then we have $S = S_r + S_r^{o+d}$.

T^r is the set of both type-A and type-B high-speed trains on section r, and $T^r = \sum_{l=1}^{2} T_l^r$.

The constraints on operation section are expressed as follows:

$$\begin{aligned} &x_{ij} = 0, \quad \text{where } i \in T^r, \ j \notin S_r^{o+d}, \\ &x_{ij} = 1, \quad \text{where } i \in T^r, \ j \in S_r^{o+d}. \end{aligned} \quad (14)$$

The expressions above indicate that a train never stops at a station outside its operation section but always stops at the departure and arrival stations of the section.

5. Solution Algorithm

The optimization of high-speed train stop-schedule planning is an NP-hard problem. As the number of train stations and the number of trains increase, the solution combinations increase explosively, and the difficulty of obtaining the global optimal solution increases in geometric progression. When solving large-scale practical problems, conventional optimization algorithms often fail to obtain the ideal optimal solution. Considering the fact that this study uses a nonlinear hybrid integer programming model with a 0-1 variable as a constraint, a hybrid genetic algorithm that integrates simulated annealing strategy is proposed.

The procedure of using the hybrid genetic algorithm to solve high-speed train stop-schedule optimization problems is as follows.

Step 1. Initialize algorithm parameters, including population size popsize, crossover possibility regulation parameters p_{c1} and p_{c2}, mutation possibility regulation parameters p_{m1} and p_{m2}, maximum number of iterations Maxgen, initial temperature t_s, and temperature attenuation parameter α.

Step 2. Generate initial population pop through chromosome coding, with the current generation number $n \leftarrow 1$.

Step 3. Calculate the adaptability of each chromosome in current population, select the optimum individuals for next generation, and perform roulette wheel selection to the remaining individuals.

Step 4. Calculate the crossover possibility and perform uniform crossover operations to the population.

Step 5. Calculate the mutation possibility and perform mutation operations to the population.

Step 6. Randomly choose a chromosome from the progeny population and generate its neighborhood solutions. Choose one from the two solutions and update the current generation number to $n \leftarrow n + 1$.

Step 7. If $n \leq$ Maxgen, go to Step 3; otherwise, output the optimum chromosome of the current population and decode it to the optimal train stop-schedule plan.

Figure 5 illustrates the algorithm.

In the hybrid genetic algorithm, adaptive genetic algorithm is used to control the direction of the global optimization, simulated annealing strategy is used to improve the ability of neighborhood search, and a combination of adaptive genetic algorithm and simulated annealing strategy can improve the algorithm performance.

At each iteration, a current individual chrom(i) is selected from the progeny population that executed the genetic strategy randomly, and then a neighborhood individual chrom(j) is generated in a variation way. Next, Metropolis strategy is used to replace the current individual pop(i):

$$p(i \longrightarrow j) = \begin{cases} 1, & f(j) < f(i) \\ \exp\left(\dfrac{f(i) - f(j)}{T}\right), & f(j) \geq f(i), \end{cases} \quad (15)$$

where $p(i \rightarrow j)$ is the probability that the current individual pop(i) was replaced by the neighborhood individual; $f(i)$ is the fitness of the current individual pop(i); and T is the current temperature.

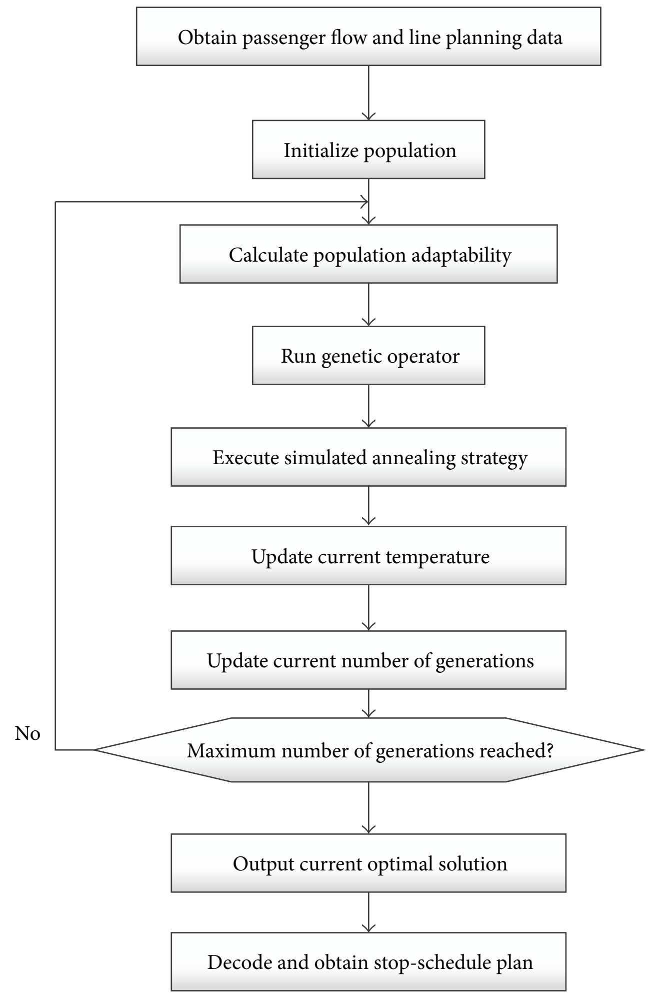

FIGURE 5: Flow diagram of the proposed algorithm.

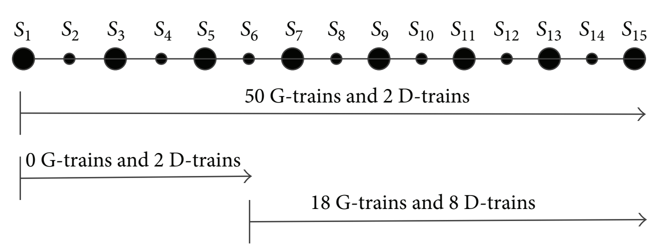

FIGURE 6: Illustration of train operation sections and operation lines.

6. Case Study

Based on the preparation to various data of the Wuhan-Guangzhou high-speed railway train stop-schedule schemes in [20], a high-speed railway section with 15 train stations was constructed. Figure 6 shows the line section, train pairs, and train types. In addition, Tables 1 and 2 give the minimum frequency of each station being served by trains, as well as the number of stops made by each type of trains on its operation section.

Assume that type-A and type-B high-speed trains operate at the speeds of 300 km/h and 200 km/h, respectively, and all

Table 1: The minimum service frequencies required by train stations.

	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9	s_{10}	s_{11}	s_{12}	s_{13}	s_{14}	s_{15}
Station level	I	IV	IV	II	IV	I	III	IV	II	IV	II	III	IV	III	I
Minimum frequency of train service (times)	40	8	8	30	8	40	20	8	30	8	30	20	8	20	40

Table 2: The number of stops by each type of trains.

Section number r	Operation section	Number of stops in the section	Number of trains		Number of stops made by the trains	
			Type-A high-speed trains	Type-B high-speed trains	Type-A high-speed trains	Type-B high-speed trains
$r = 1$	s_1–s_{15}	15	50	2	[2–7]	[9–15]
$r = 2$	s_1–s_6	6	0	2	[2-3]	[3–6]
$r = 3$	s_6–s_{15}	10	18	8	[2–5]	[6–10]

Table 3: Frequency of train service received by each station.

	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9	s_{10}	s_{11}	s_{12}	s_{13}	s_{14}	s_{15}
G-train service times	50	7	6	28	6	43	23	5	21	5	28	19	7	19	68
D-train service times	4	3	3	2	3	12	6	5	9	7	7	8	6	7	10
Total service times	54	10	9	30	9	55	29	10	30	12	35	27	13	26	78

trains are 8-car marshaled. In addition, it is assumed that each stop made by a type-A train costs c_1 yuan, each stop made by a type-B train costs c_2 yuan, and $c_1 = \tau \cdot c_2 = 2.5c_2$.

A hybrid genetic algorithm that combines simulated annealing strategy was adopted, and MATLAB7.11.0 software program was used to solve the example case. Considering the solving time and result precision, the parameters of the hybrid genetic algorithm were set to the following: population size popsize = 50, crossover possibility regulation parameters $p_{c1} = 0.7$ and $p_{c2} = 0.5$, mutation possibility regulation parameters $p_{m1} = 0.1$ and $p_{m2} = 0.01$, the maximum number of iterations Maxgen = 300, initial temperature $t_s = 999$, and temperature attenuation parameter $\alpha = 0.87$. After 107 iteration times, the algorithm converges to a constant value, and a stop-schedule plan was obtained (see Figure 7). Tables 3 and 4 present the obtained plan, which consists of the frequency of train service received by each station, and the degree of direct accessibility within each OD pair.

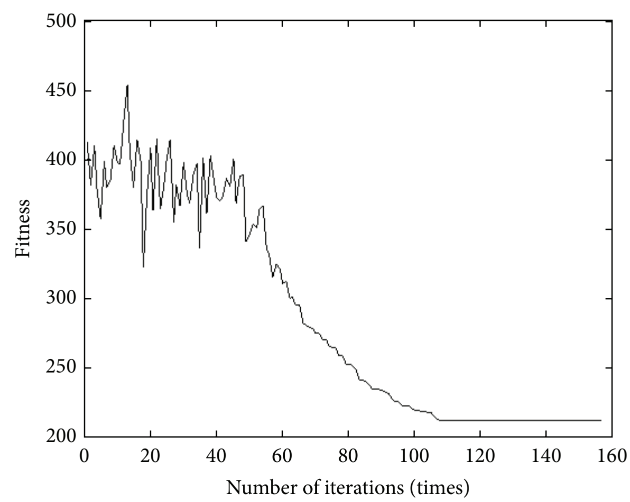

Figure 7: Iterative solution process via hybrid genetic algorithm.

Based on the passenger flow between OD pairs that have transfer stations between them, the degrees of transfer accessibility on different transfer nodes were calculated for OD pairs with relatively large passenger flow. In this study, the degree of transfer accessibility is determined by the value of transfer schemes. However, not all trains that meet the requirements of transfer accessible provide convenient travel schemes to passengers. This computation method is to a certain extent defective in practice. It is more suitable to use the minimum numbers of connecting trains fulfilling transfer accessible requirements as the chosen degrees of transfer accessibility.

In Table 5, the expression $a * b$ indicates the degree of transfer accessibility (calculated value); a is the number of trains satisfying the transfer accessible conditions before the transfer and b is that after the transfer. The expression c/d is the calculated degree of transfer accessibility divided by the chosen degree of transfer accessibility. The degree of accessibility is the sum of the degree of direct accessibility and the chosen degree of transfer accessibility.

By analyzing the degrees of direct and transfer accessibilities for OD pairs with higher volumes of passenger flow, it can be seen that, with the stop-schedule plan produced by the model, the accessibilities between all OD pairs are good. For such OD pairs, the traveling of passengers is primarily made by direct trains. Transfers are generally made at station s_6, which is equipped with sufficient abilities of receiving and sending trains. For OD pairs with smaller volumes of passenger flow, the degrees of accessibility are relatively low,

Table 4: Degree of direct accessibility within each OD pair.

OD	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9	s_{10}	s_{11}	s_{12}	s_{13}	s_{14}	s_{15}
s_1	—	10	9	30	9	29	18	4	17	6	20	16	6	16	52
s_2	—	—	2	7	3	8	1	2	3	2	5	4	2	3	10
s_3	—	—	—	4	2	7	2	1	2	3	2	6	2	4	9
s_4	—	—	—	—	5	13	11	4	8	3	7	10	4	8	30
s_5	—	—	—	—	—	5	1	1	5	1	2	4	1	3	9
s_6	—	—	—	—	—	—	7	9	20	10	24	22	9	22	55
s_7	—	—	—	—	—	—	—	3	12	8	15	9	6	12	29
s_8	—	—	—	—	—	—	—	—	4	6	7	5	4	4	10
s_9	—	—	—	—	—	—	—	—	—	6	13	13	10	12	30
s_{10}	—	—	—	—	—	—	—	—	—	—	6	6	4	7	12
s_{11}	—	—	—	—	—	—	—	—	—	—	—	9	6	10	35
s_{12}	—	—	—	—	—	—	—	—	—	—	—	—	7	15	27
s_{13}	—	—	—	—	—	—	—	—	—	—	—	—	—	6	13
s_{14}	—	—	—	—	—	—	—	—	—	—	—	—	—	—	26
s_{15}	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

Table 5: Degrees of accessibility for OD pairs with large volumes of passenger flow.

OD	Volume of passenger flow (person)	Degree of direct accessibility	Degrees of transfer accessibility with different transfer nodes					Degree of accessibility
			s_4	s_6	s_9	s_{11}	Sum	
s_1–s_6	3128	29	$16 * 0/0$	—	—	—	0/0	29
s_1–s_7	362	18	$19 * 0/0$	$22 * 11/11$	—	—	242/11	29
s_1–s_9	281	17	$23 * 0/0$	$22 * 13/13$	—	—	286/13	30
s_1–s_{14}	239	16	$22 * 0/0$	$16 * 10/10$	$12 * 6/6$	$15 * 5/5$	307/21	37
s_1–s_{15}	3239	52	$1 * 0/0$	$2 * 26/2$	$0 * 13/0$	$0 * 15/0$	52/2	54
s_4–s_{15}	776	30	—	$1 * 26/1$	$0 * 13/0$	$0 * 15/0$	26/1	31
s_6–s_{10}	645	10	—	—	$13 * 0/0$	—	0/0	10
s_6–s_{11}	2701	24	—	—	$13 * 6/6$	—	78/6	30
s_6–s_{12}	272	22	—	—	$8 * 1/1$	$15 * 0/0$	8/1	23
s_6–s_{14}	587	22	—	—	$9 * 1/1$	$15 * 0/0$	9/1	23
s_6–s_{15}	5015	55	—	—	$0 * 10/0$	$0 * 11/0$	0/0	55
s_7–s_{11}	316	15	—	—	$6 * 7/6$	—	42/6	21
s_7–s_{15}	1190	29	—	—	$0 * 17/0$	$0 * 20/0$	0/0	29
s_8–s_{15}	399	10	—	—	$0 * 26/0$	$0 * 27/0$	0/0	10
s_9–s_{14}	340	12	—	—	—	$10 * 6/6$	21/3	15
s_9–s_{15}	1638	30	—	—	—	$0 * 21/0$	0/0	30
s_{10}–s_{15}	457	12	—	—	—	$0 * 28/0$	0/0	12

thus avoiding excessive stops at stations between those OD pairs that affect travel speed and stop costs.

According to the operation sections, number of trains, and service frequency for each station (Table 3), the stop-schedule plan consists of totally 427 stop services. Besides the stops at departure and arrival stations, 267 stops are made at intermediate stations. Compared with the stop-schedule plan in [2], this plan meets the travel requirements of passengers with less stops, thus saving the operation costs of railway transportation corporations. Meanwhile, the plan ensures a certain degree of accessibility between OD pairs, thus fulfilling passengers' requirements on travel convenience.

7. Conclusions

This paper proposes a stop-schedule optimization model that aims at minimizing the train stop cost for railway transportation corporations and maximizing passenger travel convenience. The two objectives constrain each other, but also interconnect; they are integrated as a whole. The model considers both the economic benefits of railway transportation corporations and the travel convenience of passengers. Such a considerate strategy helps the transportation corporations to attract customers. When considering the travel convenience of passengers between OD pairs, instead of simply maximizing the degree of OD accessibility, the degree of accessibility is optimized based on actual volumes of passenger flow, making the model more suitable for practical use. In addition, configuring the operation section as constraints caters the multioperation section characteristic of China's high-speed railway system, making the model able to adapt to passenger flow requirements of different lines or different stages of the same line and widening the model's application.

The concept of the degree of transfer accessibility refers to the number of schemes for a passenger to travel between an OD pair through one train transfer, and its value is the product of the numbers of trains before and after the transfer. This definition, however, is not optimal. In the future, a better and quantified calculation method may be adopted in order to obtain better stop-schedule plans.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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