Hindawi
Journal of Advanced Transportation
Volume 2019, Article ID 4213095, 9 pages
https://doi.org/10.1155/2019/4213095

Research Article

Optimal High-Speed Railway Timetable by Stop Schedule Adjustment for Energy-Saving

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Received 22 May 2019; Revised 12 August 2019; Accepted 4 September 2019; Published 8 December 2019

Guest Editor: Morris Brenna

Timetable optimization techniques offer opportunity for saving energy and hence reducing operational costs for high-speed rail services. The existing energy-saving timetable optimization is mainly concentrated on the train running state adjustment and the running time redistribution between two stations. Not only the adjustment space of timetables is limited, but also it is hard for the train to reach the optimized running state in reality, and it is difficult to get feasible timetable with running time redistribution between two stations for energy-saving. This paper presents a high-speed railway energy-saving timetable based on stop schedule optimization. Under the constraints of safety interval and stop rate, with the objective of minimizing the increasing energy consumption of train stops and the shortest travel time of trains, the high-speed railway energy-saving timetable optimization model is established. The fuzzy mathematics programming method is used to design an efficient algorithm. The proposed model and algorithm are demonstrated in the actual operation data of Beijing-Shanghai high-speed railway. The results show that the total operating energy consumption of the train is reduced by 3.7%, and the total travel time of the train is reduced by 11 minutes.

1. Introduction

By the end of 2018, China high-speed railway operating mileage reached 29,000 km, accounting for about 69% of the world's total amount. With the gradual formation of China high-speed railway network, the energy consumption brought by the high-speed trains is increasing. In 2018, the energy consumption of the railways in China, as expressed in terms of standard coal, reached 16.2411 million tons, decreasing 25700 tons (0.2%) compared with last year. The problem of huge energy consumption in railway transportation is still severe. Reducing the energy consumption generated by railways has become a topic of great research for many scholars.

The train operation strategy is the main influencing factor of railway energy consumption. The train operation strategy includes train timetable and train control mode. Chevrier et al. [1], Shoichiro and Koseki [2], Yang et al. [3, 4], Wang and Goverde [5], Ning et al. [6], Zhang et al. [7] and Yang et al. [8] optimized the train timetable by adjusting the train running path, the arrival and departure time or the passing time of the train, and realized energy-saving operation. Albrecht et al. [9–11], Scheepmaker and Goverde [12], Yan et al. [13], Ye and Liu [14], Luan et al. [15], Yang et al. [16], Fernández-Rodríguez et al. [17] under the constraints of train characteristics, ramps, curves and speed limits, achieved optimal operating conditions and reduced energy consumption by adjusting the acceleration, cruising, coasting and braking phase.

Taking into account the convenience of railway managers and passengers, the train timetable should remain relatively stable and only allow adjustment within a certain range. Zhang et al. [7] used particle swarm optimization to optimize the arrival and departure time of trains at intermediate stations and minimized the energy consumption of each train. Shoichiro and Koseki [2] kept the total running time constant, optimized the running time allocation (reducing the stop and turnaround time, increasing the running time) and improved the energy-saving efficiency according to the saving energy between the stations. Yang et al. [3] considered the dynamic rescheduling problem to reduce or eliminate the delay with the minimum net energy consumption during the train running phase. Wang et al. [5] determined optimal meeting stations and time of multiple trains on a single-track railway to save energy while reducing delays. An effective train timetable should consider the balance between the operating costs of the company and the travel time of the passengers. Li (2013) used a fuzzy multi-objective optimization algorithm to minimize carbon emissions costs and total travel time in order to achieve a solution that is balanced with both goals. Chevrier et al. [1] simultaneously minimized train energy consumption and running time based on a multi-objective evolutionary algorithm for speed analysis. In the subway system, compared with all-stop patterns, stop-skipping patterns during off-peak hours can not only improve the service level of passenger travel time, but also reduce energy consumption [3].

The train running time between two stations directly affects the traction energy consumption. Yang et al. [16] calculated the energy-saving operation of multiple trains in different sections and different working conditions, and used Taylor approximation to rephrase the problem as a strict quadratic programming model, and developed an efficient algorithm combined with ASM. Albrecht et al. [10] first determined the only optimal switching point of the running state on each steep slope segment, and then used local optimization to find the switching point of the global optimal strategy. Based on this study, Albrecht et al. [11] found that the optimal strategy for each train is determined entirely by the total travel time allowed and the specified train interval, which can be used for the study of optimal driving strategies for multiple trains. The optimal train control problem is mainly to find the optimal speed curve. Fernández-Rodríguez et al. [17] used detailed train simulation models to find energy-saving speed curves. Yan et al. [13] used the ant colony algorithm to obtain energy-saving operation modes of each train under different conditions by exchanging the trajectories of multi high-speed trains. Albrecht et al. [9] looked for optimal operating conditions for leading and following trains on flat railway by existing train intervals. Luan et al. [15] simultaneously reduced energy consumption and delays by controlling train speed.

However, considering energy-saving issues from a single view of train timetables or train control methods, it may be difficult to find a suitable energysaving strategy. Therefore, the energy-saving schemes that combine these two angles are gradually becoming research focus Ye and Liu [14] established the multiphase optimal control problem to make the train's optimal strategy change with line conditions, and got the optimal train arrival and departure time under the condition of ensuring the safety interval. Ning et al. [6] optimized the distribution of running time on the section and appropriately adopted a coasting state to reduce the energy consumption of the train during the specified total running time. Scheepmaker and Goverde [12] determined the energy-saving driving strategy by finding the optimal cruising speed and the optimal coasting point. In addition, the study had shown that redistributing running time can additionally reduce energy consumption and improve train punctuality. Yang et al. [4] reviewed energy-efficient operation strategy and timetable optimization, and considered that the integrated method of jointly optimizing the timetable and the speed profile can maximize the utilization of regenerative energy and minimize traction energy consumption.

The method of saving the operating energy consumption by adjusting the train timetable is mainly to adjust the running time of the train. However, under the condition of satisfying the safety interval, there is almost no adjustment interval of the running time for the high-speed train, or the optimized timetable has a great influence on the line carrying capacity and time costs of the passengers. By finding the best operating conditions of the train to reduce energy consumption, most studies assume that the train runs on a straight track, partly taking into account the single factor of the train characteristics, ramps, curves, etc., which are significantly different from the actual line standards. Based on the above considerations, this paper designs a high-speed railway energy-saving timetable based on stop schedule optimization. Since there are many high-speed trains with the same original and terminal stations and running path in the same direction on the high-speed railway, the total numbers of the train stopping at each station can satisfy the passenger flow demand. In the case that the train running path is the same, the total numbers of the train stopping meets the passenger flow demand and the train operation is standard, the total operating energy consumption of the train depends mainly on the stop schedule. Due to different line conditions such as ramps, curves, signal lamps, electric phase separation and speed limits, the increasing energy consumption of trains that stop at the intermediate station is different. By optimizing the stop schedule, the energy consumption of train stops is reduced, thus saving the total operating energy consumption. Optimizing the stop schedule not only reduces the energy consumption of railway transportation, but also is an important way to improve the line carrying capacity. The optimized stop schedule does not change the running time of the train on the section, and it will try to avoid overtaking between the trains. At the same time, the train travel time is compressed under the constraint of the stop time, and finally the total travel time of the train is minimized, which can effectively improve the passenger's travel comfort. In this paper, with the objective of minimizing the increasing energy consumption of train stops and the shortest travel time of trains, the high-speed railway energy-saving timetable optimization model is established. In order to solve the optimization problem effectively, this paper uses the fuzzy mathematics programming method to design an efficient algorithm, which can obtain the optimal solution in a short time, and implements the model through a case study in China.

2. High-Speed Railway Energy-Saving Timetable Optimization Model

2.1. Nomenclature List

Sets

J: Set of trains

L: Set of lines

S: Set of stations

Parameters

I: Tracking interval time of the train
I_a: Arrival and passing interval time of the train
I_d: Passing and departure interval time of the train
t_s: Additional starting time of the train
t_b: Additional braking time of the train
$t_{s,s+1}$: Running time of the train on section$[s, s+1]$,
$t_{\min}$: Minimum stop time of the train
$t_{\max}$: Maximum stop time of the train
T^d: Earliest reasonable departure time of the first train at the original station
T^a: Latest reasonable arrival time of the last train at the terminal station
γ_s: Minimum stop rate of stations,
e_s: Increasing energy consumption of train stops at stations,
$E_{s,s+n}$: Operating energy consumption of the train without stops on section $[s, s+n]$
E_j: Operating energy consumption of train j

Decision variables

$T^d_{j,s}$: Departure time of train j at station s
$T^a_{j,s}$: Arrival time of train j at station s
$x_{j,s}$: $= \begin{cases} 1, & \text{if train } j \text{ stops at station } s \\ 0, & \text{otherwise.} \end{cases}$

2.2. Objective Function. An efficient train timetable should consider both the travel time and the energy consumption, which respectively represents the benefits of passengers and the railway company. In this paper, we formulate the following multi-objective optimization model, which minimizes the total travel time and the energy consumption.

Train travel time is an important indicator reflecting the quality of passenger travel, which can be expressed by the difference between the arrival time at the terminal station and the departure time at the original station. The model with the shortest total travel time of trains is as shown in Equation (1).

$$\min T = \sum_{j=1}^{J} \left(T^a_{j,S} - T^d_{j,1}\right). \tag{1}$$

Trains stopping at the station generate more energy consumption than passing the station. This paper defines that in the adjacent interval, the difference between the energy consumption generated by the train stopping at the intermediate station and the energy consumption generated by the train passing through the intermediate station is the increasing energy consumption of train stops. The model with the minimum increasing energy consumption of train stops is shown in Equation (2).

$$\min E = \sum_{j=1}^{J} \sum_{s=1}^{S} x_{j,s} e_s. \tag{2}$$

2.3. Constraints. The optimization model is subject to the following constraints.

(1) Train running time on the section constraint: the train running time on the section refers to the running time when the train passed through two adjacent stations without stopping. If the train stops at the intermediate station, then additional starting and braking time need to be added. The additional starting time refers to the extra part of the section running time caused by the train departure, and the additional braking time refers to the extra part of the section running time caused by the train arrival.

$$T^a_{j,s+1} - T^d_{j,s} = t_{s,s+1} + t_s \cdot x_{j,s} + t_b \cdot x_{j,s+1}. \tag{3}$$

(2) Train stop time constraint: For high-speed railway, the train stop time mainly includes the passenger's travel time and the locomotive crew shift time. In order to meet the passenger's travel time requirement and technical operation time standard, the train stop time must be guaranteed in the current time.

$$x_{j,s} t_{\min} \leq T^d_{j,s} - T^a_{j,s} \leq x_{j,s} t_{\max}. \tag{4}$$

(3) Arrival and departure interval constraint: The train arrival and departure interval should meet the safety interval requirement. If train j and train $j+1$ pass through station s or stop at station s, the minimum interval time should be met.

$$\begin{aligned} T^d_{j+1,s} - T^d_{j,s} &\geq I \\ T^a_{j+1,s} - T^a_{j,s} &\geq I. \end{aligned} \tag{5}$$

If train j stops at station s and train $j+1$passes through station s, the minimum interval time should be met. I_d is the interval between the departure of the following train and the passing of the leading train, and I_a is the interval between the passing of the following train and the arrival of the leading train.

$$\begin{aligned} T^d_{j,s} - T^d_{j+1,s} &\geq I_d \\ T^a_{j+1,s} - T^a_{j,s} &\geq I_a. \end{aligned} \tag{6}$$

(4) Train stop constraint of the original and terminal stations: Since stop services of the original and terminal stations are intrinsic, the train must stop at the origin and destination station.

$$\begin{cases} x_{j,1} = 1 \\ x_{j,S} = 1. \end{cases} \tag{7}$$

(5) Overtaking constraints: The train can only overtake other trains at the station. Overtaking is forbidden to happen on the section.

$$\left(T^d_{j,s} - T^d_{j+1,s}\right)\left(T^a_{j,s+1} - T^a_{j+1,s+1}\right) > 0. \tag{8}$$

(6) Reasonable departure and arrival time constraint: The energy-saving timetable must meet the reasonable departure and arrival time range. The departure time of the first train is not earlier than the earliest reasonable departure time at the original station. The arrival time of the last train is not later than the latest reasonable arrival time at the terminal station.

$$\begin{aligned} T^d_{1,1} &\geq T^d \\ T^a_{j,s} &\leq T^a. \end{aligned} \tag{9}$$

(7) Stop rate constraint: The stop rate is divided into train stop rate and station stop rate.

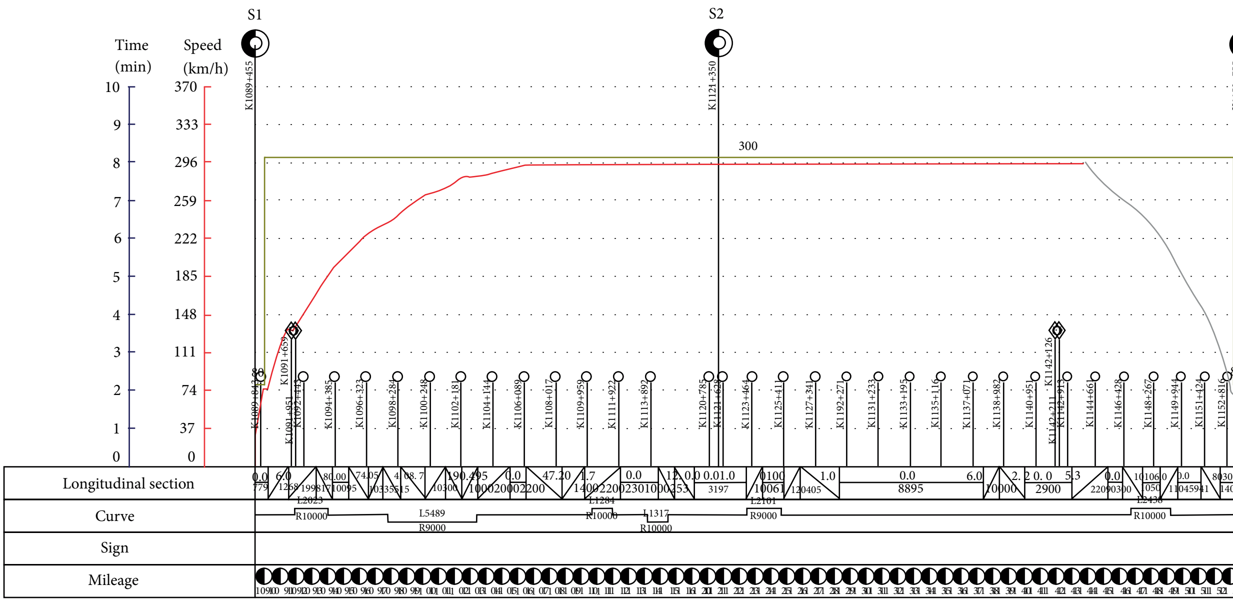

FIGURE 1: The running state of train J_1.

①Train stop rate is the ratio of the stop number of train j to the total number of stations.

$$\alpha_j = \frac{\sum_{j=1}^{J} x_{j,s}}{S}. \quad (10)$$

In order to ensure that the train stop rate remains unchanged, this paper stipulates that the number of stops per train is the same as the number of stops in the existing timetable, namely:

$$\alpha_j = \frac{M}{N}. \quad (11)$$

In the existing timetable, M is the stop number of train j and N is the total number of stations.

②Station stop rate is the ratio of the number of trains stopping at station s to the total number of trains.

$$\beta_s = \frac{\sum_{j=1}^{J} x_{j,s}}{J}. \quad (12)$$

According to the passenger flow demand, the minimum stop rate of the station can be obtained. In order to meet the passenger flow demand, this paper stipulates that the stop rate of each station must be greater than or equal to the minimum stop rate, namely:

$$\beta_s \geq \gamma_s. \quad (13)$$

3. Algorithm

3.1. Model Setting. The train traction calculation software developed by Southwest Jiaotong University Ni et al. [18] is used to simulate the running state of the train on the actual line. By inputting the line data such as ramps, curves, signal lamp position, electric phase separation position and speed limits, and train data such as train type and group length into the software, the train's speed curve and energy consumption can be output.

Assume that there are three stations S_1, S_2 and S_3 on line L_1, station S_1 is the original station, station S_3 is the terminal station and station S_2 is the intermediate station. Train J_1 departs from station S_1 to station S_3, and doesn't stop at station S_2 (Figure 1), while train J_2 departs from station S_1 to station S_3, and stops at station S_2 (Figure 2). Then the extra energy consumption generated by train J_2 compared with train J_1 between station S_1 to station S_3 is the increasing energy consumption caused by the stop of train J_2 at station S_2, i.e., $e_2 = E_{1,2} + E_{2,3} - E_{1,3}$. The total operating energy consumption of train j is $E_j = E_{1,S} + \sum_{s=1}^{S} x_{j,s} e_s$. While in the case of train standardization operation, $E_{1,S}$ is constant, so E_j only depends on $\sum_{j=1}^{J}\sum_{s=1}^{S} x_{j,s} e_s$, i.e., the total increasing energy consumption of train stops. If the stop rate of the train is constant and the station stop rate is not lower than the minimum limit, the train stop schedule can be optimized to minimize the energy consumption generated by the train stop, that is, the total operating energy consumption of the train is minimal.

3.2. Solution Method. The model established in this paper is a multiobjective linear programming problem. In general, multiple objective functions cannot reach their optimal values at the same time. Therefore, people can only find fuzzy optimal solutions that make each target relatively satisfied. The fuzzy mathematics programming method can effectively obtain the best compromise solution in multi-objective linear programming problems. With fuzzy linear programming, multi-objective linear programming problems can be solved as easily as single-objective linear programming problems. The specific steps are as follows.

Step 1. Construct the payoff table of the positive-ideal solution by solving the objective function T and E of the single-objective programming problem. A positive-ideal solution is a solution that optimizes two single objective functions simultaneously. In Table 1, z is the best compromise solution to be

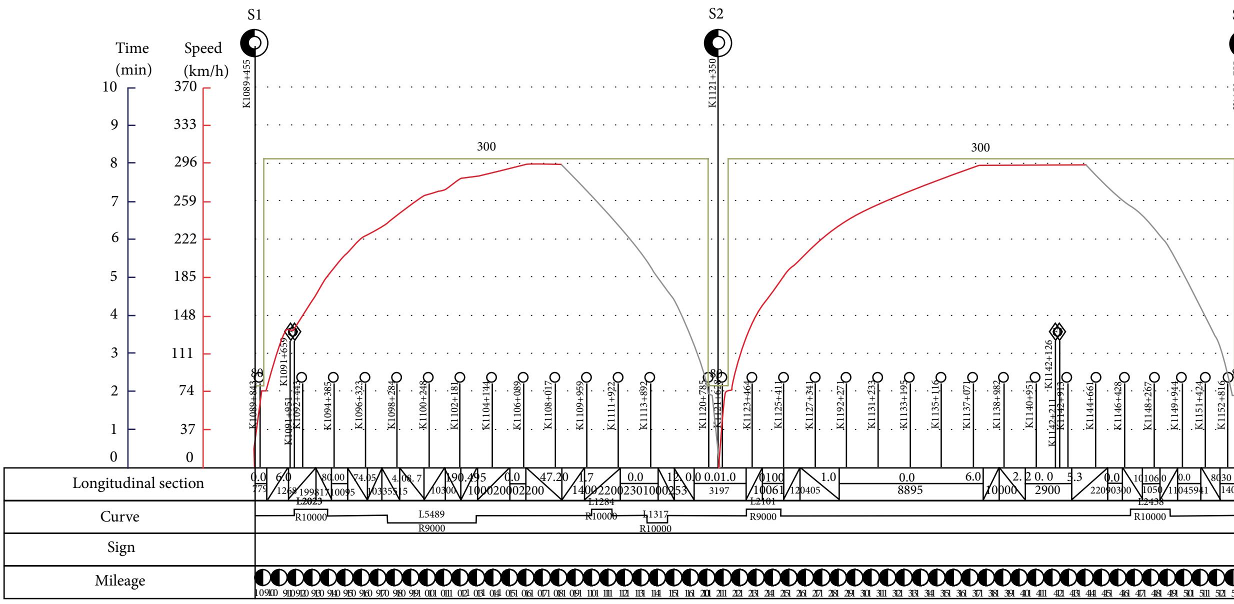

Figure 2: The running state of train J_2.

Table 1: Payoff table of positive-ideal solution.

	$T(z)$	$E(z)$	z
Min T	$T(z_1^*)$ $T(z_2^*)$	$E(z_1^*)$ $E(z_2^*)$	z_1^*
Min E	$T_1 = \min T(z_1^*), T(z_2^*)$ $T_2 = \max T(z_1^*), T(z_2^*)$	$E_1 = \min E(z_1^*), E(z_2^*)$ $E_2 = \max E(z_1^*), E(z_2^*)$	z_2^*

found. For the objective function T, z_1^* is the optimal solution that satisfies the constraints of Equations (3)~(13). T_1 and T_2 are the lower and upper bounds of the solution set. For the objective function E, z_2^* is the optimal solution that satisfies the constraints of Equations (10)~(13). E_1 and E_2 are the lower and upper bounds of the solution set.

Step 2. Construct the membership functions $\mu_1(z)$ and $\mu_2(z)$ for the two objective functions T and E, respectively by

$$\mu_1(z) = \begin{cases} 1 & \text{if } T \le T_1, \\ \dfrac{T_2 - T}{T_2 - T_1} & \text{if } T_1 < T < T_2, \\ 0 & \text{if } T \ge T_2, \end{cases} \quad (14)$$

$$\mu_2(z) = \begin{cases} 1 & \text{if } E \le E_1, \\ \dfrac{E_2 - E}{E_2 - E_1} & \text{if } E_1 < E < E_2, \\ 0 & \text{if } E \ge E_2. \end{cases} \quad (15)$$

Step 3. Transform multi-target problems into single-target problems.

$$\max F = \zeta + \frac{\varepsilon(\mu_1(z) + \mu_2(z))}{2}, \quad (16)$$

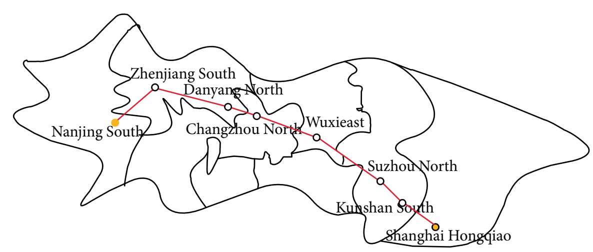

Figure 3: Railway network structure of the Nanjing South-Shanghai Hongqiao section.

Table 2: The parameter values.

Parameter	Value	Parameter	Value	Parameter	Value
$t_{\min}$	2 min	I_a	3 min	γ_3	0.1
$t_{\max}$	10 min	I_d	2 min	γ_4	0.25
t_s	2 min	T^d	11:22	γ_5	0.4
t_b	3 min	T^a	14:55	γ_6	0.45
I	4 min	γ_2	0.25	γ_7	0.1

$$s.t. \begin{cases} \zeta \le \mu_1(z) \\ \zeta \le \mu_2(z), \end{cases} \quad (17)$$

where F is the single objective problem objective function; ζ is the optimal satisfaction; ε is a sufficiently small positive number.

Step 4. Take $\varepsilon = 1.0 \times 10^{-7}$ to solve the single-objective programming problem in CPLEX software.

4. Case Study

4.1. Data and Parameters. This paper selects 20 high-speed trains with a top speed of 300 km/h in the downward

Table 3: Comparisons on the train stop schedule.

Train number	*G103*	*G101*	*G1735*	*G1805*	*G105*	*G143*	*G1911*	*G1715*	*G1809*	*G107*
Existing result	1-3-6-8	1-2-5-8	1-5-6-7-8	1-2-5-6-7-8	1-5-8	1-4-8	1-4-6-7-8	1-6-8	1-2-3-4-5-6-8	1-2-6-8
Optimized result	1-5-6-8	1-5-6-8	1-3-4-5-8	1-2-4-5-6-8	1-4-8	1-5-8	1-2-4-5-8	1-5-8	1-3-4-5-6-7-8	1-5-6-8
Train number	*G221*	*G1775*	*G109*	*G111*	*G113*	*G1767*	*G211*	*G41*	*G359*	*G115*
Existing result	1-4-5-8	1-2-4-5-6-7-8	1-4-6-8	1-3-5-8	1-4-6-8	1-2-6-8	1-5-6-8	1-4-8	1-3-8	1-2-5-8
Optimized result	1-2-6-8	1-2-4-5-6-7-8	1-2-6-8	1-2-6-8	1-5-6-8	1-5-6-8	1-5-6-8	1-6-8	1-5-8	1-5-6-8

Table 4: Comparisons on the energy consumption of each station.

Station		Zhenjiang South	Danyang North	Changzhou North	Wuxi East	Suzhou North	Kunshan South	Sum
e_s(kw h)		527.8	547.29	532.83	422.46	421.67	531.94	2983.99
Stop number	Existing result	7	4	8	10	12	4	45
	Optimized result	6	2	6	14	15	2	45
	Difference	−1	−2	−2	4	3	−2	0
Increasing energy consumption of train stops (kw h)	Existing result	3694.6	2189.16	4262.64	4224.6	5060.04	2127.76	21558.8
	Optimized result	3166.8	1094.58	3196.98	5914.44	6325.05	1063.88	20761.73
	Difference	−527.8	−1094.58	−1065.66	1689.84	1265.01	−1063.88	−797.07

direction on the Nanjing South-Shanghai Hongqiao section of the Beijing-Shanghai high-speed railway (Figure 3) as a case study. The selected trains all stop at Nanjing South and Shanghai Hongqiao, so this paper can use Nanjing South as the original station and Shanghai Hongqiao as the terminal station, i.e., $\beta_1 = 1, \beta_8 = 1$. In this paper, according to the safety interval standard in the existing timetable and the passenger flow demand, the research case parameter value is selected (Table 2).

4.2. Analysis of Results. This paper calculated the specific stop plan of each train (Table 3). The train traction calculation software is used to calculate the increasing energy consumption of train stops in Zhenjiang South, Danyang North, Changzhou North, Wuxi East, Suzhou North, and Kunshan South (Table 4). This paper guarantees that the stop number of each train on the Nanjing South-Shanghai Hongqiao section is constant and each station meets the minimum station stop rate, and uses CPLEX software to iterate 160,000 times. The energy-saving timetable with the minimum energy consumption and travel time is calculated within 1 minutes and 7 seconds.

In Table 4, the trains in the stop schedule of the energy-saving timetable are more likely to stopping at stations with less increasing energy consumption of train stops, and e_s in Wuxi East and Suzhou North is more than 100 kw hless than the remaining four stations, the stop number increased by 4 times and 3 times, respectively, and 4 stations with more increasing energy consumption of train stops, Zhenjiang South, Danyang North, Changzhou North and Kunshan South, the stop number is reduced by 1 time, 2 times, 2 times, 2 times respectively. The total increasing energy consumption of train stops in the energy-saving timetable is 20761.73 kw h, which is 797.07 kw h lower than the existing timetable, which is reduced by 3.7%. In Figure 4, the energy consumption of each train has also changed. The energy consumption of 13 trains has been reduced to varying degrees, accounting for 65% of the total trains. This indicates that the method of this paper also reduces the energy consumption of single trains.

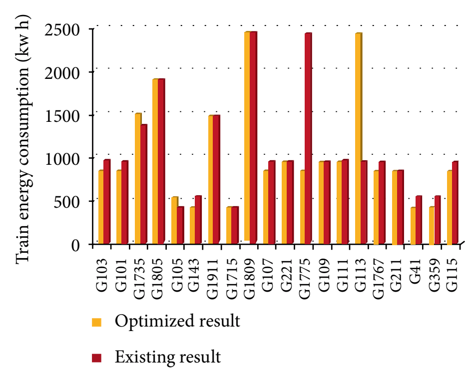

Figure 4: Comparisons on the energy consumption of each train.

By comparing the train travel time (Table 5), it can be found that the G1805, G1911, and G211 trains have reduced

Table 5: Comparisons on the train travel time (unit:min).

Train number	*G103*	*G101*	*G1735*	*G1805*	*G105*	*G143*	*G1911*	*G1715*	*G1809*	*G107*
Existing result	80	80	87	104	73	73	90	73	108	80
Optimized result	80	80	87	94	73	73	87	73	112	80
Difference	0	0	0	−10	0	0	−3	0	4	0
Train number	*G221*	*G1775*	*G109*	*G111*	*G113*	*G1767*	*G211*	*G41*	*G359*	*G115*
Existing result	80	107	80	80	80	80	87	73	73	80
Optimized result	80	112	80	80	80	80	80	73	73	80
Difference	0	5	0	0	0	0	−7	0	0	0

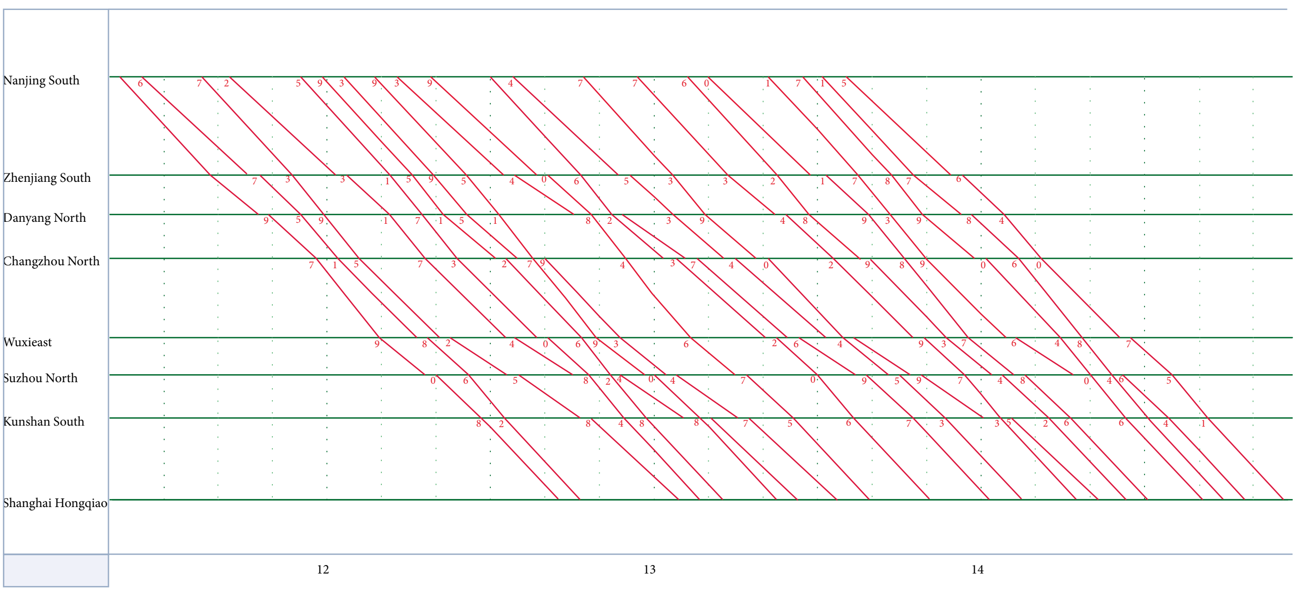

Figure 5: Existing timetable.

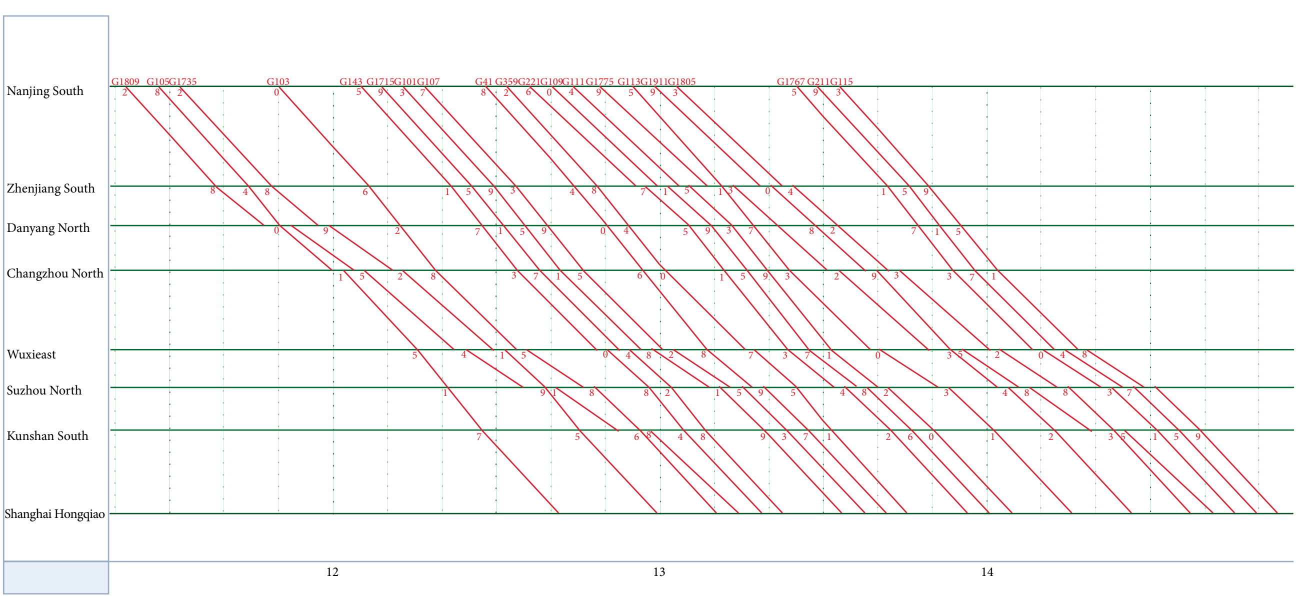

Figure 6: Energy-saving timetable.

travel time, trains with reduced or constant train travel time account for 90% of the total trains, and the total train travel time is 1657 min, which is reduced 11 min.

By comparing the existing timetable (Figure 5) and the energy-saving timetable (Figure 6), the overtaking of three trains with reduced running time has changed. Before optimization, G1805 is overtaken by two trains in Suzhou North, and one train in Kunshan South, G1911 is overtaken by a train in Changzhou and G211 is overtaken by two trains in Suzhou North. The overtaking of three trains does not happen after optimization. The overtaking of two trains with increased running time also has changed. Before optimization, G1809 is overtaken by two trains in Danyang North. It is once overtaken in Danyang North, Suzhou North and Kunshan South after optimization. Before optimization, G1775 is once overtaken in Wuxi East and Kunshan South. It is overtaken by a train in Zhenjiang South, Wuxi East and Kunshan South after optimization. It can be seen that the change of train travel time is mainly caused by overtaking, which provides an idea for the preparation of reasonable and efficient timetables. In order to make full use of the line carrying capacity, the train should follow the tracking operation as much as possible. The stop schedule can be used in a far-reaching or strictly consistent manner to reduce the overtaking number. If a train overtakes another train, the train that is overtaken will wait at least 5 minutes ($I_a + I_d$). If a train is overtaken by other two trains, then the train will wait at least 9 minutes ($I_a + I + I_d$). So if overtaking happens, this paper recommends that the train is better overtaken by a train at a certain station to avoid being overtaken by multiple trains. In the energy-saving timetable, the train schedule excessively adopts a strictly consistent manner. And the stop number is too many in Suzhou North and Wuxi East, where the increasing energy consumption of train stop is low. To a certain extent, it violates the rules of train operation and cannot meet the demand of some passengers. Intensive arrival of trains at certain times may result in tight service capacity of passenger equipment at the station.

5. Conclusion

This paper presents a high-speed railway energy-saving timetable based on stop schedule optimization. Under the constraints of safety interval and stop rate, with the objective of minimizing the increasing energy consumption of train stops and the shortest travel time of trains, the high-speed railway energy-saving timetable optimization model is established. In order to solve the optimization problem effectively, this paper uses the fuzzy mathematics programming method to design an efficient algorithm, which can obtain the optimal solution in a short time. The 20 trains of Nanjing South-Shanghai Hongqiao section of Beijing-Shanghai high-speed railway are optimized by this energy-saving method. The results show that the total operating energy consumption of the train is reduced by 3.7%, and the total travel time of the train is reduced by 11 minutes. Future research can consider the timetable design method that minimizes energy consumption and travel time by optimizing the stop schedule based on the rules of train travel under the conditions of satisfying passenger flow demand.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interests regarding the publication of this paper.

Acknowledgments

This research was supported by the National Key R&D Program of China (2017YFB1200702), National Natural Science Foundation of China (Project No. 61703351) , Sichuan Science and Technology Program (Project NO. 2018RZ0078, 2019JDR0211,2018123), Science and Technology Plan of China Railway Corporation (Project No.: P2018T001), Chengdu Soft Science Research Project (2017-RK00-00028-ZF, 2017-RK00-00378-ZF) and the Fundamental Research Funds for the Central Universities(2682017CX022, 2682017CX018). The authors' special thanks go to Dr.Chow, A.H.F. for help on professional English writing and useful suggestions(University College London and City University of Hong Kong).

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