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Evaluating Line Capacity with an Analytical UIC Code 406 Compression Method and Blocking Time Stairway

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Abstract: Railways around the world are experiencing growth in traffic flow, but the problem concerning how to optimize the utilization of capacity is still demands significant research. To accommodate the increasing traffic demand, the high-speed railway operator in China is interested in understanding the potential benefit of adopting reasonable headway to balance the safety and efficiency of train operations. In this study, a compress timetable scheduling model based on the UIC Code 406 method is presented to evaluate the line capacity. In this model, train headway is not pre-fixed as in the existing research, but considers the actual operating conditions and is calculated using actual running data. The results of the case study show that refined headway calculations generally have positive capacity effects.

Keywords: high-speed railway capacity; train headway; blocking time theory; UIC Code 406

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1. Introduction

The China high-speed railway has made remarkable achievements after operations. However, with the rapid development of economy and society, the China high-speed railway is facing a big problem of capacity shortage. The railway operator in China, the National Railway Administration of People's Republic of China (CR), has found good ways to increase its system capacity. Since the first high-speed railway in China was open to traffic in 2008, the CR upgraded its infrastructure, such as building new rail lines and stations and purchasing rolling stocks, to provide high-quantity and high-quality services. In recent years, improving the signaling systems has also been regarded as a potential solution to increase the railway system capacity [1]. However, the above projects need a great amount of capital investment. Therefore, exploring other different kinds of methods to increase the China high-speed railway capacity seems especially important.

Train timetables play an important role in daily actual railway transportation operation. There are many elements in making railway timetables, such as the train journey time, train dwell time and the train headway, which can greatly affect the utilization of the railway system capacity. Based on timetables, the UIC Code 406 method compresses the gap between two adjacent trains under the condition of meeting the standard interval time required for safe railway operation. In this manner, we can get a closely scheduled timetable and the capacity consumption, which we can use to represent the line capacity utilization.

In this paper, we want to use the UIC Code 406 method to calculate the consumption time, in order to measure line capacity. The structure of the manuscript is as follows: the next section of this paper describes the literature review. Then, we present a linear programming model for railway capacity evaluation and some formulas of blocking time in Section 3 and then a solution based on Python is proposed in Section 4. In Section 5, we analyze the Beijing–Tianjin Intercity Railway as a research case. In Section 6, the outcomes and the significance of the paper are summarized.

2. Literature Review

In general, a railway line capacity is defined as the maximum number of trains that would be able to operate on a given railway infrastructure and operation conditions during a specific time interval. Moreover, Heydar [2] and Petering [3] proposed a different definition for railway capacity in a cyclic train timetable, i.e., the capacity is the minimum cycle length that can feasibly accommodate a given number of trains over a given section of track in each cycle. Inspired by them, we define capacity in this paper as the minimum occupation time of a railway line under the conditions of a given infrastructure and the number of trains within one day, i.e., a makespan of the timetable.

Numerous approaches and tools have been developed to evaluate railway capacity; Abril et al. [4] categorized the capacity computation methods in three types: analytical methods, optimization methods and simulation methods. Among these three types of methods, although analytical methods and simulation methods present a good estimate, they cannot give an exact amount. Optimization methods are based on obtaining optimally saturated timetables; therefore, one can acquire a more accurate amount of capacity.

The International Union of Railways (UIC) put forward a method of capacity estimation, namely the UIC Code 406, which is based on a timetable compression method and calculates the consumption time and capacity consumption [5]. Table 1 presents some studies on the UIC Code 406 method and other evaluation methods based on timetables and compares them with our research within the key dimensions of the model structure: objective, headway and problem size.

From Table 1, we can find that there have been many researchers using capacity consumption, cycle time or train travel time as a measure to evaluate railway line capacity. Therefore, in this paper, we apply the UIC Code 406 compression method to calculate the consumption time, which is also the minimum makespan of a timetable.

In addition, some researchers have studied the calculation method of station capacity, such as Corriere [14], Armstrong [15] and Chen [16]. However, the evaluation approach of station capacity is very different from the estimation of line capacity. Lindner [17] analyzed the applicability of the UIC Code 406 method for evaluating the line and station capacity. He showed an example where the node capacity determines the maximum capacity of the whole infrastructure. Using this example, he explained that the UIC Code 406 method cannot be applied for node capacity research. In our study, we regard the station as two block sections and the train operations in the station are analyzed in detail, which can be found in Section 3. In this manner, the station capacity is transformed into line capacity which we can use our method to evaluate.

Moreover, we can find in Table 1 that many researchers set "headway" to a certain value. Headway is the time interval between two following trains and the minimum line headway is the minimum time interval in which two successive trains of either direction may enter a section of line without any overlapping of the blocking time stairways [18]. Additionally, the headway is not a certain or fixed value, but related to the actual condition of the railway line, train speed, signaling system and the operation schedule [19] and it is one of the most important elements of the timetable because it can ensure running efficiency and safety. If the headway is too small, knock-on delays would occur due to occasional disruptions on the lines. However, if the headway is too long, it will cause a problem of capacity shortage. Therefore, finding a good method to calculate reasonable train headway in a more refined way is a very important issue related to railway capacity.

In China, the calculation method of train headway I is taking the maximum of four types of headways based on the train control system, which are section headway I_s, departure headway I_d, arrival headway I_a, passing headway I_p, that is to say, $I = max\{I_s, I_d, I_a, I_p\}$. In addition, there are four formulas of four types of headways in China, which give full consideration to the issue of the safety. Figure 1 is a diagram of the train headways in China and Table 2 gives definitions of the parameters in Figure 1.

Table 1. Studies about the railway capacity evaluation and timetabling.

Publication	Model Structure	Objective	Headway	Problem Size
A. Jamili [6]	UIC Code 406 compression method	Minimize consumption time	Minimum required headway applied by the signaling system	6 stations, 9 trains, 7 sections
Rob M.P. Goverde [7]	UIC Code 406 compression method	Minimize cycle time	The minimum headway time depends on the critical block section	6 stations, 10 trains in one cycle
Friederike Chu [8]	UIC Code 406 compression method	Higher occupancy rate in one cycle	The minimum headway time is 2.5 minutes	20 trains per hour
Mojtaba Heydar [2]	Mixed-integer linear programming model	Minimize the cycle lengthand the total dwell time of trains at all stations	The minimum headway time is a certain value varying from 1 to 5 minutes	10–70 stations, 3–64 trains
Matthew E. H. Petering [3]	Mixed-integer linear programming model	Minimize the cycle length and the total journey time of all trains	Headways are different certain values in different examples	5–35 intermediate stations, 3–11 train types
Xin Zhang [9]	Integer programming model	Minimize the cycle time	7 types of headways with certain values	23 stations, 18 trains in one cycle
Feng Li et al. [10]	Mixed-integer programming model	Maximize the number of train-pairs and Minimize the total travel times of all trains	Consist of 4 types of headways with certain values	5 stations, 4 train-pairs, 4 segments
A. Dicembre et al. [11]	A methodology for capacity quantification	Maximize the number of trains	The adopted headway depending upon the adopted signaling system, such as minimum headway of 3 min during rush hours in Milan	10 stations
Yung-Cheng Lai et al. [12]	A comprehensive evaluation framework of capacity	Maximize capacity utilization and minimize expected recovery time	Headway is a certain value, such as 2.5 min on 07:00–09:00 weekday and 5 min on 06:00–23:00 weekend	24 stations
Fei Yan [13]	Mixed-integer linear programming model	Minimize travel time, empty-seat-hour and the number of lines	The minimum headway time is 3 minutes	14 stations, 25 trains in one cycle
Ruxin Wang et al. (this paper)	Linear programming model	Minimize makespan of timetable	Based on a large number of real train operations data, the minimum headway is calculated by using blocking time stairway	5 stations, 131 trains, 56 sections

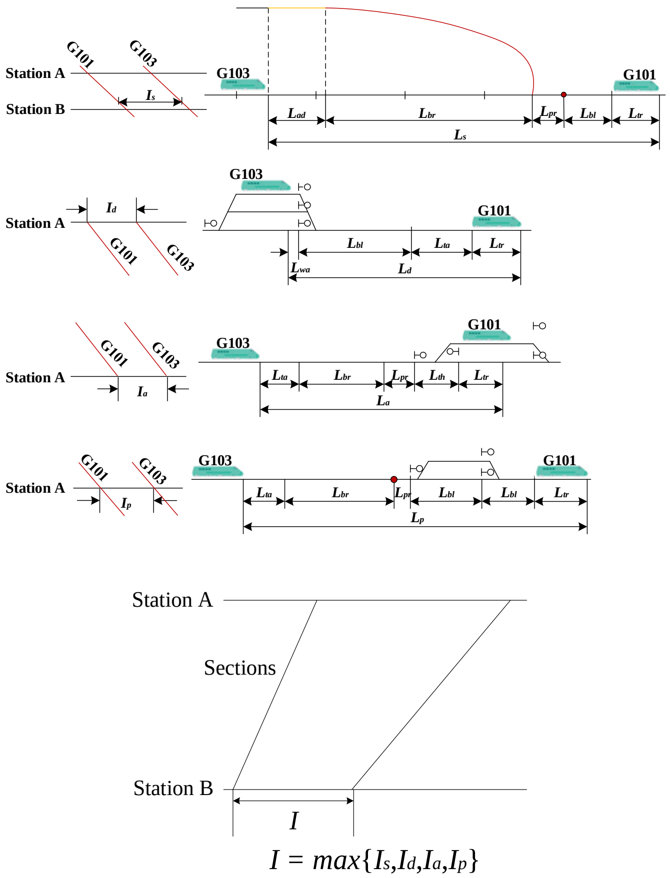


Figure 1. Diagram of the train headways in China.

Table 2. Definitions of the parameters in Figure 1.

Notation	Description
L_{ad}	Distance traveled by a train during additional time of interval tracking operation
L_{br}	Braking distance
L_{pr}	Safety protection distance
L_{bl}	Length of the block section
L_{tr}	Length of the train
L_s	Train interval tracking distance between sections
L_{wa}	Distance between train stop sign and departure signal
L_{ta}	Distance traveled by a train during station operation time
L_d	Train interval tracking distance when departing from a station
L_{th}	Length of throat area of station
L_a	Train interval tracking distance when arriving in a station
L_p	Train interval tracking distance when passing a station

Based on the Chinese Train Control System (CTCS-2/CTCS-3) and the technical characteristics of Centralized Traffic Control System (CTC) in high-speed railway, Tian [20] proposed the calculation method of train headway with the automatic block sections of a high-speed railway, discussed the choices of the values of every parameter in formulas and then calculated the realizable train headway on automatic block sections based on the characteristics and operation status of the China high-speed railway. In his research, the train headway of the China high-speed railway was mainly limited by I_d, which can basically be 4.5–5 minutes. Wang [21] optimized the arrival headway, calculated the arrival headway and the section headway by using CRH EMU traction calculation system (Version 1.0, National Railway Train Diagram Research and Training Center, Chengdu, China) and then used cellular automata to simulate it. Wu Gao and Mu [22] analyzed some types of train headways and optimized the high-speed railway interval tracking and arrival tracking models under the signaling system by the research of the train tracking model. Chen [23] studied the calculation method of train headways under the CTCS-3 Train Operation Control System. By presetting the condition of the train tracking interval, he analyzed the influence of the rear train on the front train in different tracking circumstances.

The scheduled headway between two trains must consist of the minimum line headway plus the required buffer time to compensate small delays. Many scholars in other countries considered to compress train headways or buffer times in order to improve high-speed railway capacity. The computation of minimum headway on a line is based on the blocking time stairway [16]. This means that not only one block section but the whole blocking time stairways of a line should be considered to calculate the line headway. However, the blocking times depend not only on the signal spacing and train length, but also from the actual train speed, deceleration rate and the conditions of the block sections, which we present in the next section. For a given timetable, we can push the blocking time stairways together as closely as possible without any buffer times left, which is shown in Figure 2.

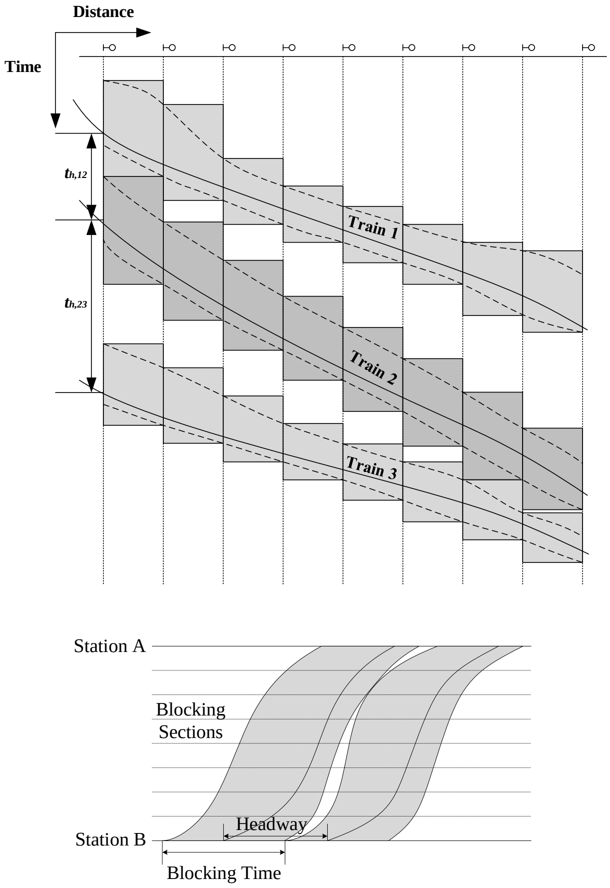


Figure 2. Diagram of the train headway proposed by Pachl.

Sangphong et al. [24] presented a primary model to maximize rail line capacity by minimizing the train headway and the influence of the length of the block sections and the train headway on capacity is analyzed. Medeossi et al. [25] presented a method for introducing stochastic blocking times to support timetable planning. Liu and Han [19] analyzed the influencing factors of the train headway, established an integer linear programming model to solve the problem of a high-speed railway train schedule under large capacity and considered the utilization of capacity under different train headways. Lai, Liu and Lin [26] developed headway-based models and computational processes for the standard rail capacity unit, which would be instrumental in the assessment of the impact of heterogeneous trains. Xu [27] proposed an optimization method to minimize the headway of the mainline in the moving block and the case study showed that this method could effectively reduce the train headway and there would be a negligible increase in train running time. In addition, there were some Chinese scholars researching this aspect. Based on the blocking time under the moving block system, Liu and Miao [28] designed a new headway calculation method and made a quantitative analysis of different influencing factors on the law of time headways. Lu [29] calculated the minimum train headway with reference to the UIC Code 406 capacity analysis method and analyzed the influence of the maximum running speed and approach speed of trains on the minimum train headway.

From the different calculation methods of train headway, it can be found that the calculation of train headways in China is mostly based on the characteristics of the train operation control system, which can only take the maximum values or the published empirical values and these values are mostly based on the premise of the full consideration of safety and therefore, there will be more safety separations and buffer times in these headways, which cannot truly reflect the train headways under different infrastructure and transportation conditions, but instead would reduce the capacity of the whole lines to some extent. However, the calculation method of train headway proposed by Pachl is mostly based on the blocking time theory, which is based on the train timetable and can greatly reduce buffer times between two train lines, in order to get the maximum utilization of railway capacity. This method is also a vacancy in the field of train headways and capacity calculation in China.

The main innovation of this paper is that a large number of actual train operation control data was analyzed to calculate the headway. These data came from the Beijing–Tianjin Intercity Railway, containing the real operation of different types of trains on this line. Giorgio Medeossi et al. [25] collected the GPS data of trains and proposed a method to introduce stochastic blocking times to improve timetable planning. Inspired by them, we processed these data and obtained the minimum headway between two adjacent trains based on the blocking time stairway. The data processing and our innovation is shown in Section 4. Therefore, the blocking times and headways we used are based on real data and could reflect all kinds of situations encountered in the process of train operations.

This paper can be divided into three parts. Firstly, we combined the calculation method of the minimum headway proposed by Pachl and established a compress timetable scheduling model based on the UIC Code 406 method. The input of this model is the actual timetable and blocking time parameters. Secondly, we presented the solution process. Finally, capacity was evaluated based on this method and real data. In this part, we also focused on the impact of the distance interval between trains on train speed and we reached useful conclusions.

3. Mathematical Formulas

3.1. Model

The notations involved in our model are listed in Tables 3 and 4.

As we mentioned in Section 2, railway line capacity can be defined as the minimum occupation time of a railway line under the condition of a given infrastructure and the number of trains within one day, i.e., a makespan of the timetable. Therefore, we proposed a model with the objective function of minimizing the total time of trains occupying high-speed railway sections under the given number of trains and train sequence. This is formally stated in Equation (1):

$$min\ Z = max\{x_{in}^{d}, i \in M\} - min\{x_{j1}^{a}, j \in M\} \tag{1}$$

Table 3. Definition of the sets, indices and the parameters.

Notation	Description
m	Number of trains
n	Number of block sections
M	Set of trains, M
M_s	Set of stopped trains, $M_s \in M$
N	Set of block sections, N
N_s	Set of block sections of stations, $N_s \in N$
i, j	Train index, $i, j \in M$
k	Block section index, $k \in N$
t_{ik}	Journey time for train i in block section k
t_{ik}^s	Dwell time for train i in block section k
$t_{s,ik}$	The time when train i passes the blocking signal of block section k (the arrival time of the train at the block section is set to 0)
$t_{bb,ik}$	The beginning time when block section k begins to lock for the occupation of train i (the arrival time of the train at the block section is set to 0)
$t_{be,ik}$	The ending time when block section k ends to lock for the occupation of train i (the arrival time of the train at the block section is set to 0)
T_s	The beginning time of maintenance
T_e	The ending time of maintenance

Table 4. List of variables.

Variable	Description
x_{ik}^a	The arrival time for train i arriving at block section k
x_{ik}^d	The departure time for train i leaving block section k

The objective of the model is to minimize the occupation time of the timetable, by using the time when the last train leaves the last block section minus the time when the first train enters the first block section.

However, there are some constrains that must be considered, such as the train headway, journey time, commercial stop and maintenance, which ensure the safety of trains and compress the train diagram as much as possible:

$$x_{ik}^d - x_{ik}^a = t_{ik},\ i \in M, k \in N \tag{2}$$

$$x_{ik}^d = x_{i(k+1)}^a,\ i \in M, k \in \{1, 2, \ldots, n-1\} \text{ and } k \notin N_s \tag{3}$$

$$x_{ik}^a - x_{jk}^a \geq t_{be,jk} - t_{bb,ik},\ i, j \in M,\ i > j, k \in N \text{ and } k \notin N_s \tag{4}$$

$$x_{ik}^d - x_{i(k+1)}^a \geq t_{ik}^s,\ i \in M_s, k \in N_s \tag{5}$$

$$x_{ik}^d \neq x_{i(k+1)}^a,\ i \in M, k \in \{1, 2, \ldots, n-1\} \text{ and } k \in N_s \tag{6}$$

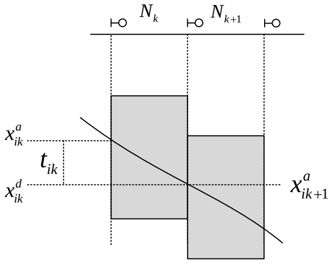
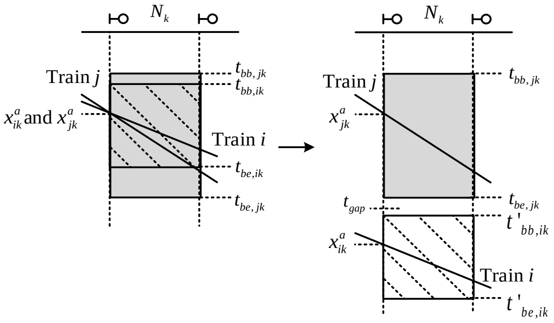
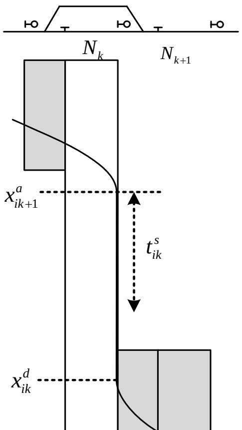
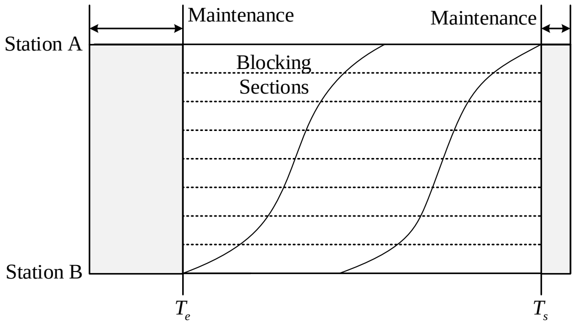
$$x_{ik}^a \geq T_e,\ i \in M, k \in N \tag{7}$$

$$x_{ik}^d \leq T_s,\ i \in M, k \in N \tag{8}$$

We now introduce each of these in turn. Constraints (2) and (3) are journey time constraints and the arrival time or departure time of each train in each block section should satisfy these two constraints. Constraint (4) is a headway constraint in each block section, which refers to that if a train is running on a line, the blocking time block of each block section formed by this train cannot be overlapped with the other blocking time blocks of a certain block section formed by other trains. Constraints (5) and (6) are commercial stop constraints and the dwell time of a stopped train at a station must satisfy this constraint. Constraints (7) and (8) are maintenance constraints, where T_s and T_e are the beginning and end of two maintenance periods surrounding one operation period and the arrival and departure times of trains shall be within this operation period.

Table 5 shows a graphical representation of each constraint.

Table 5. Constraints of the capacity evaluation model.

Constraint	Graphical Representation
Journey time constraint	
Headway constraint	 where $t'_{bb,ik} = t_{bb,ik} + \left(x^a_{ik} - x^a_{jk}\right) = t_{bb,ik} + \left(t_{be,jk} - t_{bb,ik}\right) + t_{gap}$ $t'_{be,ik} = t_{be,ik} + \left(x^a_{ik} - x^a_{jk}\right) = t_{be,ik} + \left(t_{be,jk} - t_{bb,ik}\right) + t_{gap}$ t_{gap} is the time interval between the two blocking time blocks after the delay of the latter train line and the value of t_{gap} should be greater than or equal to 0
Commercial stop constraint	
Maintenance constrain	

3.2. Blocking Time Parameters

In order to obtain the minimum high-speed railway capacity, we should determine the train headways. As mentioned before, the minimum headway on a line with a fixed block system depends on the blocking time, so we should analyze the composition of the blocking time and calculate three parameters of the blocking time, $t_{s,ik}$, $t_{bb,ik}$ and $t_{be,ik}$, which are: the time when the train i passes the blocking signal of the block section k, the beginning time when the block section begins to lock and the ending time when the block section ends to lock, respectively.

There are many running states for a train running on a high-speed railway line, such as running, arriving and departing and the composition of the block time is different under different conditions. We analyzed the blocking time and gave some formulas to calculate the blocking time variables.

Pachl proposed that the blocking time of a block section is usually much longer than the time for which the train occupies that block section and therefore, for a train without a scheduled stop, he divided the blocking time of a block section into six parts, which are: the time for clearing the signal, the signal watching time, approach time, the time between blocking signals, clearing time and release time [18], as shown in Figure 3.

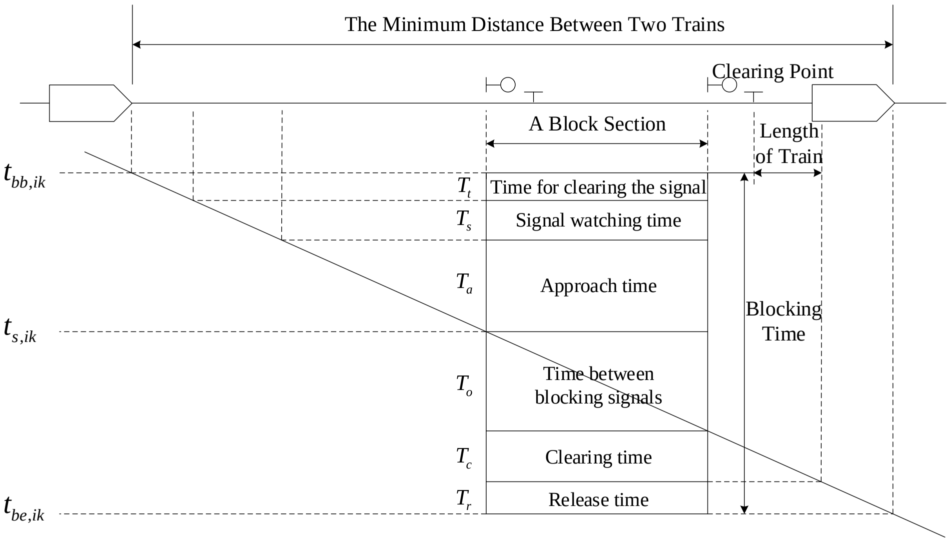


Figure 3. Diagram of the composition of the blocking time for a train without a scheduled stop.

When a train has a scheduled stop at a station, the blocking time of a block section at the station would be changed. We used the clearing point to divide the block section at the station into two parts: one is the throat points and the other is the arrival–departure tracks. After a train with a stop at a station passes through the first part of the block section, the blocking time of this part goes directly to the clearing time. Figure 4 shows this situation.

After a commercial stop, a train should leave that station. At this time, the approach time does not apply. Moreover, we used a clearing point to divide the block section behind the station into two parts. Figure 5 shows this situation.

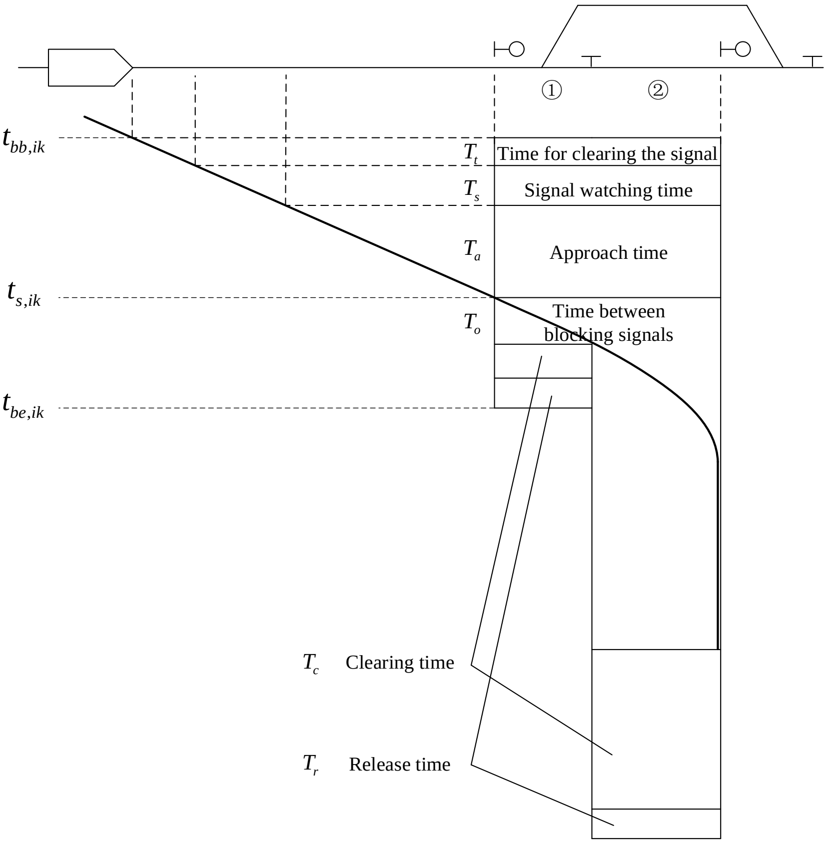


Figure 4. Diagram of the composition of the blocking time when a train has a scheduled stop.

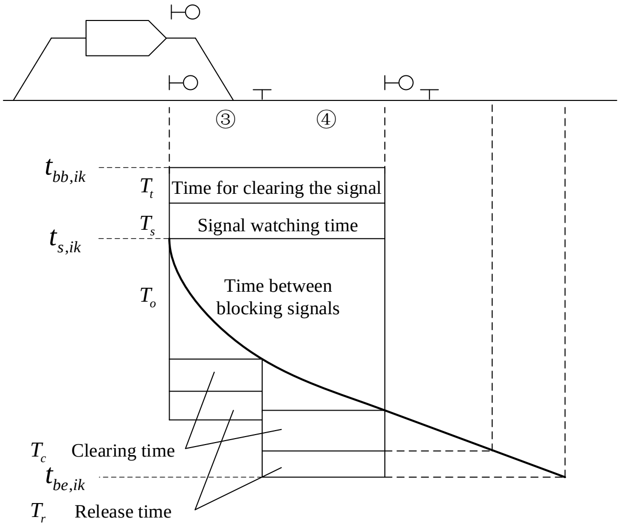


Figure 5. Diagram of the composition of the blocking time when a train leaves a station.

Based on these three situations, the calculation formulas of $t_{bb,ik}$ and $t_{be,ik}$ are as follows:

$$t_{bb,ik} = t_{s,ik} - (T_{t,ik} + T_{s,ik} + T_{a,ik}) \tag{9}$$

$$t_{be,ik} = t_{s,ik} + (T_{o,ik} + T_{c,ik} + T_{r,ik}) \tag{10}$$

In principle, the six parts of the blocking time should be determined based on the actual conditions of the trains and the fundamental infrastructures and the values of each parts are given in this paper, as shown in Table 6.

Table 6. Values of the six parts of the blocking time.

Each Part of the Blocking Time	Values (in Seconds)
Time for clearing the signal $T_{t,ik}$	5
Signal watching time $T_{t,ik}$	3
Approach time $T_{a,ik}$	L^a_{ik}/v^a_{ik}
Time between blocking signals $T_{o,ik}$	L_k/v_{ik}
Clearing time $T_{c,ik}$	$L^c_k/v_{i(k+1)}$
Release time $T_{r,ik}$	5

In Table 6, L^a_{nk} is the distance from the location of the train i to the block section k, v^a_{ik} is the average speed of the train i when the train is located in the approach intervals, L_k is the length of the block section k, v_{ik} is the average speed of the train i in block section k, L^c_k is the distance from the length of a train after the clearing point to the block section k.

4. Solution

Based on the JetBrains Pycharm Community Edition 2018.1.2, we used the Python 3.6 to process the data and program the model and the programming language was Python. The solution flow chart is shown in Figure 6.

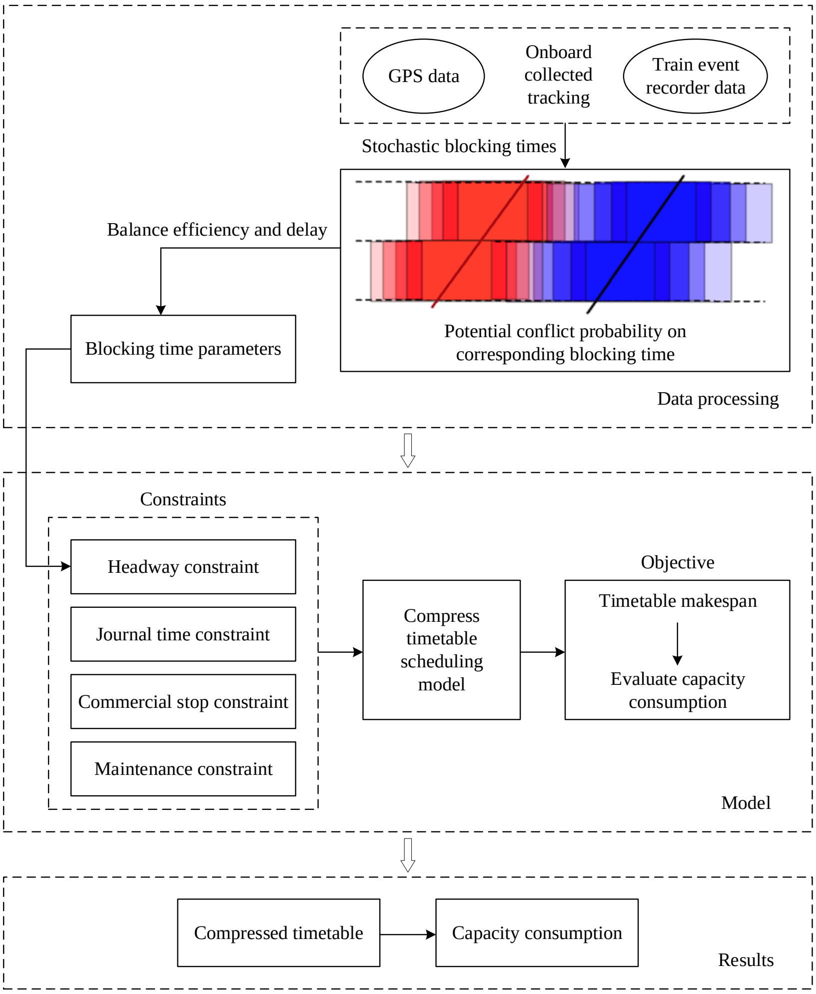


Figure 6. The flow chart of the solution.

5. Case Study

We obtained a large number of data of actual train operations on the Beijing–Tianjin Intercity Railway and therefore, the Beijing–Tianjin Intercity Railway was selected as the research case and the railway capacity evaluation model proposed above was used to make a quantitative analysis of the case.

5.1. Background

The Beijing–Tianjin Intercity Railway is an intercity railway connecting Beijing and Tianjin, it was the first high-standard and high-speed railway and it has a 350 km/h design speed in mainland China. The Beijing–Tianjin Intercity Railway has been in operation since August 1, 2008 and the total length of whole line is 120 kilometers. There are five stations in total, namely Beijing South Railway Station, Yizhuang Railway Station, Yongle Railway Station, Wuqing Railway Station and Tianjin Railway Station, as shown in Figure 7, among which Yizhuang Railway Station and Yongle Railway Station are not handling passenger transport business temporarily. In addition, there is a Nancang Block Post on the Beijing–Tianjin Intercity Railway line. On January 5, 2019, the national railways adjusted the train timetables and the stop stations of 26 pairs of Beijing–Tianjin intercity trains changed from Tianjin Railway Station to Tianjin West Railway Station.

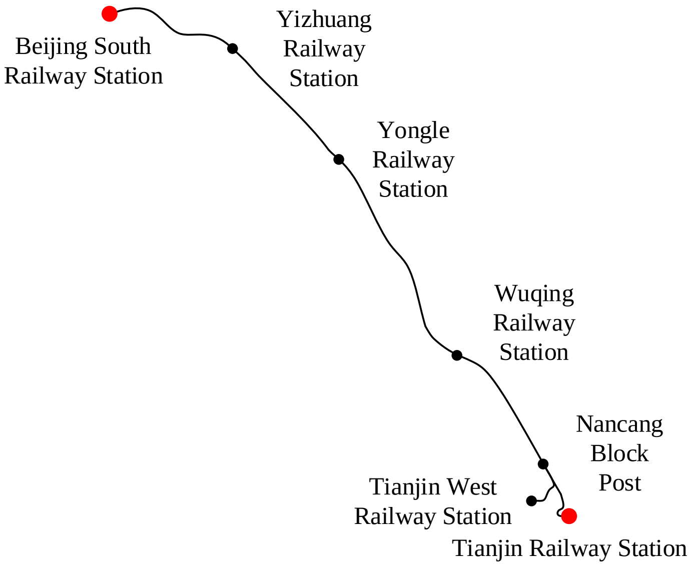


Figure 7. Diagram of the Beijing–Tianjin Intercity Railway line.

Based on the blocking time theory, we only needed to calculate the minimum occupation time of the trains in the critical sections with the largest number of trains. According to the model above, we chose the down direction of the Beijing–Tianjin Intercity Railway from Beijing South Railway Station to Nancang Block Post, which contains 56 block sections, as the critical sections for our research.

Using the actual data of the Beijing–Tianjin Intercity Railway to produce the train paths in one day, only considering the down direction and sorting out the data of all the trains (131 trains in total) running on the critical sections, we obtained some relevant data of the original timetable, as shown in Table 7 and drew the original timetable as shown in Figure 8.

Table 7. Statistical table of some of the relevant data of the original timetable.

Data Name	Value
The earliest departure time	6:02:00
The latest arrival time	0:29:15
Occupation time on sections	1107.25 min
The average train headway	8.34 min
The average journey time	25.46 min

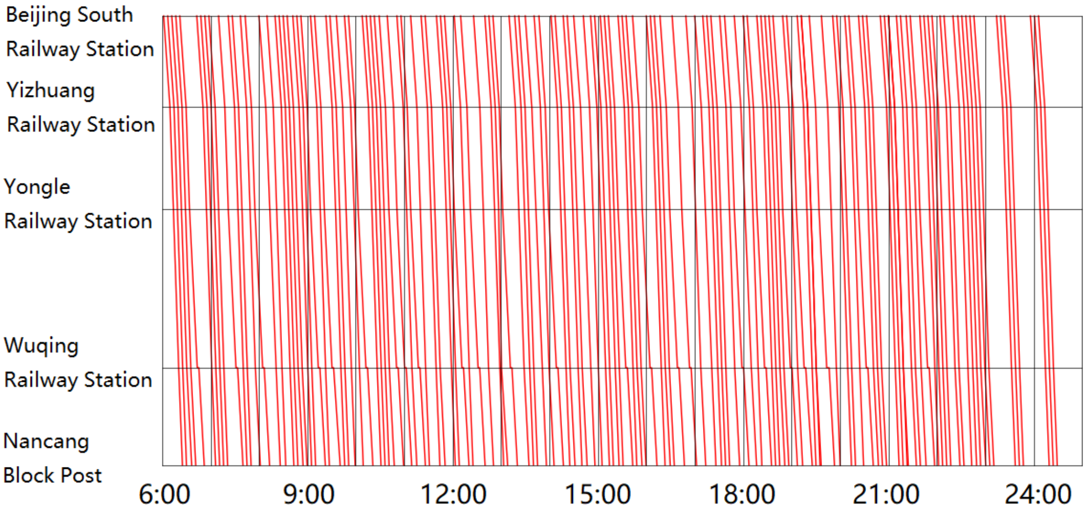


Figure 8. An original timetable of the Beijing–Tianjin Intercity Railway.

5.2. Results

We performed several computational cases using the train operations data.

With the allowable time window of the journey from 6:00 a.m. to 0:00 a.m., a total of 18 hours, we obtained the result which showed that the minimum occupation time of the trains on the high-speed railway line is 777.33 minutes and the corresponding timetable is drawn as shown in Figure 9.

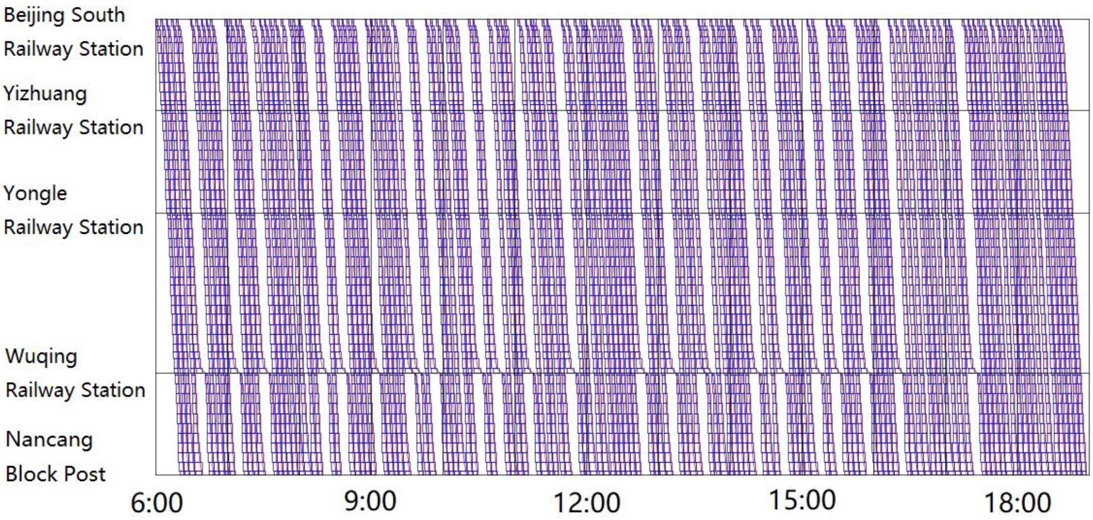


Figure 9. Timetable of the Beijing–Tianjin Intercity Railway during the minimum occupation time.

We also calculated the corresponding occupation time of trains based on the train control system. According to the block system of the high-speed railway and the characteristics of the train operation control system in China, we took $I_s = 2.5$ min, $I_p = 3$ min, $I_d = 3$ min and $I_a = 5$ min to calculate the time. The occupation time we obtained for the journey was 842.75 min.

Compared with the occupation time calculated based on the characteristics of the train control system, there are 65.42 minutes less when using blocking time and train headway theories and obviously, the average train headway also decreases, as shown in Table 8. It can be seen that the calculation method of the high-speed railway capacity based on the blocking time and train headway theories is better than the calculation method based on the characteristics of the train control system, in terms of capacity improvement.

Table 8. Comparison of the relevant indicators.

Indicator	Result of the Refined Model	Result of the Existing Method
The earliest departure time	6:00:00	6:00:00
The latest arrival time	18:57:20	20:02:45
Occupation time on sections	777.33 min	842.75 min
The average train headway	5.78 min	6.29 min

In order to show to what degree the different factors have an effect on high-speed railway capacity, we considered two more cases with different factors, one with less interval distance and the other with higher speed.

In the actual operation of the China high-speed railway at present, the minimum train headway is 4 minutes and the interval distance between two adjacent trains is about seven block sections. In the three-aspect automatic block system, when the signal shows green, it means that there are at least three block sections free in front of it, that is, when there are at least three block sections free in front of the block section where a train is running at normal speed. Then, we simulated the case that the interval distance is three block sections and compared it with seven block sections. The relevant indicators are arranged as shown in Table 9.

Table 9. Comparison of relevant indicators when different interval distance.

Indicator	Result of Seven Block Sections	Result of Three Block Sections
The earliest departure time	6:00:00	6:00:00
The latest arrival time	18:57:20	15:12:51
Occupation time on sections	777.33 min	552.85 min
The average train headway	5.78 min	4.06 min

From the data above, we can see that with the decrease of the interval distance between two adjacent trains, the occupation time and average train headways also decrease, which shows the positive correlation. Meanwhile, the maximum capacity of the Beijing–Tianjin Intercity Railway can be significantly improved.

Speed determines the journey time of a train in line sections and plays a decisive role in capacity. Due to the different trains and line plans, the maximum speed of high-speed railway trains in China is different, such as 350 km/h or 300 km/h. We simulated two cases in which the maximum speed of trains was 350 km/h and 300 km/h. The relevant indicators are arranged as shown in Table 10.

Table 10. Comparison of relevant indicators when different train speed.

Indicator	Result of 350 km/h	Result of 300 km/h
The earliest departure time	6:00:00	6:00:00
The latest arrival time	18:57:25	20:54:50
Occupation time on sections	775.41 min	894.83 min
The average train headway	5.77 min	6.66 min

From the data above, it can be seen that with the decrease of the maximum speed of trains, the occupation time and average train headway will increase, which shows a negative correlation. Meanwhile, the maximum capacity of Beijing–Tianjin Intercity Railway will decrease.

6. Conclusions

The evaluation method of high-speed railway capacity was discussed in this paper. In our research, a compress timetable scheduling model was established to evaluate line capacity and the blocking time was not pre-fixed but considered the state of actual operations. A case study on the Beijing–Tianjin Intercity Railway line showed that this method can improve the capacity to a certain extent and that if the interval distance between two adjacent trains can be decreased or the speed of trains can be increased, the capacity can be improved effectively. Moreover, we can also get the corresponding highly accurate train timetable with the minimum occupation time.

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References

1. Lai, Y.C.; Wang, S.H.; Jong, J.C. Development of Analytical Capacity Models for Conventional Railways with Advanced Signaling Systems. *J. Transp. Eng.* **2012**, *138*, 961–974. [CrossRef]
2. Heydar, M.; Petering, M.E.H.; Bergmann, D.R. Mixed integer programming for minimizing the period of a cyclic railway timetable for a single track with two train types. *Comput. Ind. Eng.* **2013**, *66*, 171–185. [CrossRef]
3. Petering, M.E.H.; Heydar, M.; Bergmann, D.R. Mixed-integer programming for railway capacity analysis and cyclic, combined train timetabling and platforming. *Transp. Sci.* **2016**, *50*, 892–909. [CrossRef]
4. Abril, M.; Barber, F.; Ingolotti, L.; Salido, M.A.; Tormos, P.; Lova, A. An assessment of railway capacity. *Transp. Res. Part E Logist. Transp. Rev.* **2008**, *44*, 774–806. [CrossRef]
5. UIC. *UIC Code 406: Capacity*; International Union of Railways: Paris, France, 2004.
6. Jamili, A. Computation of practical capacity in single-track railway lines based on computing the minimum buffer times. *J. Rail Transp. Plan. Manag.* **2018**, *8*, 91–102. [CrossRef]
7. Goverde, R.M.P.; Corman, F.; D'Ariano, A. Railway line capacity consumption of different railway signalling systems under scheduled and disturbed conditions. *J. Rail Transp. Plan. Manag.* **2013**, *3*, 78–94. [CrossRef]
8. Chu, F.; Oetting, A. Modeling capacity consumption considering disruption program characteristics and the transition phase to steady operations during disruptions. *J. Rail Transp. Plan. Manag.* **2013**, *3*, 54–67. [CrossRef]
9. Zhang, X.; Nie, L. Integrating capacity analysis with high-speed railway timetabling: A minimum cycle time calculation model with flexible overtaking constraints and intelligent enumeration. *Transp. Res. Part C Emerg. Technol.* **2016**, *68*, 509–531. [CrossRef]

10. Li, F.; Gao, Z.; Wang, D.Z.W.; Liu, R.; Tang, T.; Wu, J.; Yang, L. A subjective capacity evaluation model for single-track railway system with δ-balanced traffic and λ-tolerance level. *Transp. Res. Part B Methodol.* **2017**, *105*, 43–66. [CrossRef]
11. Dicembre, A.; Ricci, S. Railway traffic on high density urban corridors: Capacity, signalling and timetable. *J. Rail Transp. Plan. Manag.* **2011**, *1*, 59–68. [CrossRef]
12. Lai, Y.C.; Ip, C.S. An integrated framework for assessing service efficiency and stability of rail transit systems. *Transp. Res. Part C Emerg. Technol.* **2017**, *79*, 18–41. [CrossRef]
13. Yan, F.; Goverde, R.M.P. Combined line planning and train timetabling for strongly heterogeneous railway lines with direct connections. *Transp. Res. Part B Methodol.* **2019**, *127*, 20–46. [CrossRef]
14. Corriere, F.; Di Vincenzo, D.; Guerrieri, M. A logic fuzzy model for evaluation of the railway station's practice capacity in safety operating conditions. *Arch. Civ. Eng.* **2013**, *59*, 3–19. [CrossRef]
15. Armstrong, J.; Preston, J. Capacity utilisation and performance at railway stations. *J. Rail Transp. Plan. Manag.* **2017**, *7*, 187–205. [CrossRef]
16. Chen, L.; Li, X.; Liu, G. Analysis of the capacity of the turning-back station in the railway system. In Proceedings of the ICTE 2013, Chengdu, China, 19–20 October 2013; pp. 2761–2765.
17. Lindner, T. Applicability of the analytical UIC Code 406 compression method for evaluating line and station capacity. *J. Rail Transp. Plan. Manag.* **2011**, *1*, 49–57. [CrossRef]
18. Pachl, J. *Railway Operation and Control*; VTD Rail Publishing: Mountlake Terrace, DC, USA, 2018.
19. Liu, P.; Han, B. Optimizing the train timetable with consideration of different kinds of headway time. *J. Algorithms Comput. Technol.* **2017**, *11*, 148–162. [CrossRef]
20. Tian, C.H.; Zhang, S.S.; Zhang, Y.S.; Jiang, X.L. Study on the Train Headway on Automatic Block Sections of High Speed Railway. *J. China Railw. Soc.* **2015**, *37*, 1–6.
21. Wang, D.T. Optimization and Simulation Research of High-Speed Railway Train Tracking Interval. Ph.D. Thesis, Southwest Jiaotong University, Chengdu, China, 2016.
22. Wu, L.; Gao, J.Q.; Mu, J.C. Model and calculation for tracking interval control of high-speed passenger trains. Jisuanji Yingyong. *J. Comput. Appl.* **2007**, *27*, 2643–2645.
23. Chen, C. Study on train headways under CTCS-3 Train Operation Control System. *Sci. Tech. Inf. Gansu.* **2012**, *41*, 23–24.
24. Sangphong, O.; Siridhara, S.; Ratanavaraha, V. Determining critical rail line blocks and minimum train headways for equal and unequal block lengths and various train speed scenarios. *Eng. J.* **2017**, *21*, 281–293. [CrossRef]
25. Medeossi, G.; Longo, G.; de Fabris, S. A method for using stochastic blocking times to improve timetable planning. *J. Rail Transp. Plan. Manag.* **2011**, *1*, 1–13. [CrossRef]
26. Lai, Y.C.; Liu, Y.H.; Lin, Y.J. Standardization of capacity unit for headway-based rail capacity analysis. *Transp. Res. Part C Emerg. Technol.* **2015**, *57*, 68–84. [CrossRef]
27. Xu, L.; Zhao, X.; Tao, Y.; Zhang, Q.; Liu, X. Optimization of train headway in moving block based on a particle swarm optimization algorithm. In Proceedings of the 2014 13th International Conference on Control Automation Robotics & Vision (ICARCV), Singapore, 10–12 December 2014; pp. 931–935.
28. Liu, M.; Miao, J.R. Study on tracking headway of moving block based on blocking time. *Shandong Sci.* **2018**, *31*, 55–61.
29. Lu, Q.Z. Investigation of Trains in Moving Block System Crossing a River Based on UIC406. *Urban Rapid Rail Transit.* **2018**, *31*, 140–144.