A Method for Enhancing Global Safety of Regional Rail Transit Based on Coordinative Optimization of Passenger Flow Assignment and Train Scheduling

Mengyu Zhang\textsuperscript{1,2}, Wei Dong\textsuperscript{1,*}, Xinya Sun\textsuperscript{1,2} and Yindong Ji\textsuperscript{1,2}

\textsuperscript{1}Beijing National Research Center for Information Science and Technology (BNRist), Tsinghua University, Beijing, China
\textsuperscript{2}Department of Automation, Tsinghua University, Beijing, China

*Corresponding author email: weidong@mail.tsinghua.edu.cn

Abstract. Regional rail transit is a kind of comprehensive railway transportation system, which originates from the demand of economic integration of city groups and contains various kinds of sub-transportation systems such as high speed railway, inter-city railway, subway and monorail. Due to the deficiency of coordination between different kinds of transportation systems, the global risk of regional rail transit network greatly increases. Therefore, it is urgent to evaluate the rail transit network safety from a global perspective and enhance the safety through coordinative optimization. To address this problem, a method to evaluate the global safety of regional rail transit system based on passenger flow demand load is proposed, a mathematical model to minimize the global risk of rail transit network is constructed, and the global safety is enhanced by coordinative optimization of passenger flow assignment and train scheduling. An example on the regional rail system in Chengdu-Chongqing district validates the effectiveness of the proposed method. Compared with the method in the literature where only passenger flow assignment is considered, the example shows that the proposed approach can bring a further 10\% decrease of the global risk of rail transit network.

Keywords: Regional rail transit; Global safety; Passenger flow assignment; Train scheduling; Coordinative optimization.

1. Introduction
Regional rail transit is a kind of comprehensive railway transportation system, which originates from the demand of economic integration of city groups and contains various kinds of sub-transportation systems such as high speed railway, inter-city railway, subway and monorail. A regional rail transit system is heterogeneous, integral, interactive and coordinative. The existence of various kinds of sub-transportation systems diversifies the risk sources, and greatly increases the uncertainty, coupling and global impact of the risk. The lack of effective coordination between different sub-transportation systems can easily lead to a reduction in the safety of the entire rail transit network. Therefore, it is of paramount importance to evaluate the global safety of rail transit network in regional rail transit system and then enhance the global safety by coordinative optimization based on the evaluation. While the composite of different sub-transportation systems increases the complexity of rail transit network, the path redundancy and fault tolerance capability are also increased. Therefore, by appropriate passenger flow assignment and train scheduling, different sub-transportation systems can effectively operate in a coordinative way. Thus transport capability of rail transit network can be exploited and the global risk of the whole system can be attenuated. This paper takes the passenger
flow demand load of stations and sections as the core to evaluate the global safety of the regional rail transit network. And the global safety is enhanced by coordinative optimization between train scheduling and passenger flow assignment. The main contribution of this paper are as follows.  
1) A global safety evaluation method for regional rail transit is proposed which focuses on the passenger flow demand load risk (namely, transport capacity risk).  
2) To enhance the safety of regional rail transit, a global safety optimization model with coordination of passenger flow assignment and train scheduling is established.  

2. Related Works  
Related researches about the safety evaluation of the rail transit network safety mainly focus on the index fusion method to establish a safety index system for urban rail transit operation from the aspects of equipment safety, rail transit network structure and rail transit network load. The risk level of the rail transit network was given according to the result of the index fusion [1-3]. However, this method is greatly affected by subjective factors and did not take the transport capacity risk as the core to evaluate the global risk of the rail transit network. Furthermore, such method hasn't established the inclusion relationship between transport capacity risk and single-point risk. Many literatures tried to enhance the rail transit network safety by reducing the failure rate of specific equipment or systems. In terms of research on enhancing the safety through the method of decreasing the transport capacity risk, most have used the method of passenger flow control to lower the load of rail transit. Xu X [4] studied the passenger flow organization model in three different scenarios for the passenger flow control under uncertain demand and developed a simulation-based algorithm to solve these models. Wang L [5] established an integer programming model for multi-station cooperative control under sudden large passenger flow, and distributed the pressure of supersaturated stations to other stations. Xu X [6] proposed a multi-station coordinated passenger flow control model for passenger flow control in multi-line subway networks during peak periods. Although many researches have used multi-station coordination to reduce the risk caused by excessive load on the rail transit network, most of them only took the passenger flow into consideration and didn't aim at improving the rail transit network safety directly. To solve above problems, HUANG [7] proposed a method for assessing the safety of urban rail transit based on the load rate of stations and sections and established a mathematical optimization model to minimize rail transit network risk through passenger flow assignment. The method makes use of redundant paths in the rail transit network to reduce the risk of urban rail transit systems. Based on the method in [7], this paper further considers the coordinative optimization of passenger flow assignment and train scheduling to improve the safety of regional rail transit.  
At present, there is almost no research on coordinative optimization of passenger flow assignment and train scheduling. Most of the literature concentrates on adjusting train schedules according to the rules of passenger flow, but does not consider the guidance and assignment of passenger flow. Canca D [8] proposed a mixed integer non-linear programming model to determine the optimal departure frequency and vehicle capacity of each line in a dense rapid rail transit network, which took into account factors such as the average travel time, the convenience and the cost of the operating department under a certain Origin-Destination (OD) demand. Cadarso L [9] studied the disruption management problem of rapid transit rail networks. They proposed a two-step approach which first calculated the passenger flow demand and then optimized the timetable and the rolling stock schedules in an integrated way. Based on the characteristics of dynamic passenger flow in urban rail transit, Qi [10] used the spatio-temporal network representation to model the actual rail transit network and constructed a schedule optimization model with the minimum passenger waiting time as the goal. Zhou [11] established optimization models to optimize the number of trains and train departure intervals for the two situations of daily peak operating hours and sudden large passenger flow. In terms of cooperation between railway and urban rail transit, some studies have optimized subway timetables based on the characteristics of railway passenger flow, but failed to combine the method of passenger flow assignment. From the station level, Hu [12] analysed the passenger flow rule of railway passengers transferring to the subway, and established an optimization model for the departure time of subway trains at the hub station with the goal of minimizing the total waiting time of
passengers in the station. Further, Cai [13] considered the passenger flow arrival characteristics of the hub station and the time-varying passenger flow distribution of the entire line, and proposed a train departure time adjustment model to minimize passenger's waiting time on the line. Zhang [14] studied train timetabling problem for additional trains on an urban rail network considering the high-speed railway train delay in the evening, and established a bi-objective model to maximize the number of passengers that can reach the destination and minimize the number of additional trains.

In summary, there are few studies on the global safety evaluation and enhancement of regional rail transit based on the transport capacity risk of the rail transit network. Most of the literature on passenger flow optimization focused on the local optimization, and did not take the improvement of rail transit global safety as the optimization goal. For optimization strategies, many literature have studied how to schedule rail transit trains based on passenger flow demand. On the cooperation between railway and urban rail transit, some studies have analysed the characteristics of passenger flow that transfer from high-speed railway to subway, and improved the coordination between the two by adjusting the train timetable of urban rail transit. But few researches focus on coordinative optimization of passenger flow assignment and train scheduling. So this paper proposes a method for evaluating and enhancing global safety of regional rail transit to solve these problems.

3. Global Safety Evaluation Method of Regional Railway System

Safety is defined as “freedom from unacceptable risk of harm” in the international standard IEC62278-2002. For a regional rail transit system, the global safety evaluation should focus on the overall function of the rail transit network (i.e., transporting passengers). At the same time, the evaluation method should include two aspects: the rail transit network's overall functional satisfaction risk (i.e., transport capacity risk) and the risk of loss of personnel and equipment (i.e., single-point risk), and the interaction between the two aspects should be taken into consideration. The evaluation idea is shown in figure 1.

![Figure 1. Global safety evaluation system of regional rail transit.](image)

The main points of figure 1 are as follows:
1) The global risk of regional rail transit is embodied in two aspects: transport capacity risk and loss risk of personnel and equipment.
2) Transport capacity risk is determined by OD demand (external conditions), capacity of rail transit network (inherent capability), and coordinative scheduling strategy (dynamic optimization factors). Under the constraint of passenger flow capacity of the rail transit network, the passenger flow load distribution of the stations and sections is formed by OD demand with coordinative assignment (i.e., the assignment of passenger flow and trains), and then the transport capacity risk of the whole rail transit network is determined.
The single-point risk is determined by factors such as people, equipment, environment and management in stations and sections, and ultimately leads to the loss risk of personnel and equipment in the rail transit network.

There are interactions between the transport capacity risk and the single-point risk. The single-point risk will affect the transport capacity risk of the rail transit network by reducing capacity of the station or section. Correspondingly, higher transport capacity risk (i.e., high passenger flow load) may cause new single-point risks.

The focus of this paper is to reduce the global transport capacity risk of the regional rail transit network through coordinative optimization strategies, so the related narratives below mainly concentrate on the transport capacity risk in figure 1, and the concepts related to the calculation of transport capacity risk are explained as follows:

1) OD demand: the passenger's travel demand from the departure station to the destination station. It can be expressed by OD matrix $Q$, and each $q_{ij} \in Q$ represents the passenger flow demand from station $i$ to station $j$, and its unit is “passenger number/hour”. The passenger flow at time $t$ should be expressed by the number of passengers who entered station $i$ and destined for station $j$ in unit time at time $t$.

2) Station or section capacity: the maximum number of passengers that can safely pass through a station or section within a unit of time, and its unit is “passenger number/hour”.

3) Passenger flow demand load of station or section: the ratio of the passenger flow that needs to pass through the station or section (the passenger flow can be obtained from the OD demand through the passenger flow assignment) to the capacity of the station or section. This ratio reflects the relationship between the passenger flow demand and the capacity at the station or section, and is the determinant of the risk probability of transport capacity at the station or section.

The calculation method of passenger flow demand load risk (i.e., transport capacity risk) is given below. According to the method widely used in risk assessment, the quantitative risk calculation is the product of the probability of risk occurrence and the consequences (i.e., loss) caused by it. Risk calculation is essentially an estimate of possible risk losses and is additive. Therefore, the total transport capacity risk of the rail transit network can be obtained by adding the transport capacity risks of all stations and sections in the rail transit network and the formula is shown in (1). $x_i(t)$ denotes the passenger flow demand of station or section $i$ at time $t$. $c_i(t)$ represents the traffic capacity of station or section $i$ at time $t$. $x_i(t)/c_i(t)$ represents the passenger flow demand load of station or section $i$ at time $t$. $f(x)$ is the transport capacity risk probability function, which can map the passenger flow demand load to the possibility of transport capacity risk occurrence. $w_i(t)$ denotes the transport capacity risk consequences in the station or section $i$ at time $t$.

$$s(t) = \sum_{i=1}^{N} w_i(t) f\left(\frac{x_i(t)}{c_i(t)}\right)$$ (1)

Transport capacity risk probability function (TCRPF) is determined by its function structure and function parameters. For the function structure, TCRPF should grow with the increase of passenger flow demand load. Furthermore, since the tendency of TCRPF approximating 1 should increase as the passenger flow demand load increases, $(1 - f(x))^{-1}$ should exponentially increase with the increase of $x$. Aside from this, TCRPF should only be sensitive to the input of certain range, under relatively low or high passenger flow demand load, the absolute variation of TCRPF caused by the change of passenger flow demand load should be small. Based on the aforementioned consideration, TCRPF is chosen as $f(x) = \left(1 + e^{-ax+bx}\right)^{-1}, a > 0$. For the function parameters, according to the experts’ experience, a risk event is unlikely to happen under zero passenger flow demand load, this is, the probability is less than 0.001 in that case; when the passenger flow demand load is greater than 1.5, the probability is greater than 0.8, therefore, the parameters are chosen as $a = 6, b = 7$. If a risk event
happened in a regional rail transit system, the severity of the consequence grows with the number of the actual aggregated people, therefore, the smaller one of passenger flow demand and capacity is chosen as the measure for the risk consequence, i.e., \( w_i(t) = \min(x_i(t), c_i(t)) \). In practical applications, the initial parameters and structure of \( f(x) \) and \( w_j(t) \) should be determined based on expert experience first, and then be perfected based on accumulated data to make up for the lack of expert experience. Here the initial calculation formula is given based on expert experience just as an example.

| Parameters and symbols | Meanings |
|------------------------|----------|
| \( w_k \)             | Consequence of passenger flow demand load risk in section \( k \) |
| \( y_k \)             | Passenger flow demand of section \( k \) after passenger assignment (Unit: passenger number/hour) |
| \( b_k \)             | Capacity of section \( k \) (Unit: passenger number/hour) |
| \( w_p \)             | Consequence of passenger flow demand load risk in station \( p \) |
| \( C_p \)             | Throughput of station \( p \) (Unit: passenger number/hour) |
| \( z_p \)             | Passenger flow demand of station \( p \) after passenger assignment (Unit: passenger number/hour) |
| \( x_{ij}^m \)         | Passenger flow demand assigned to path \( r_{ij}^m \) (Unit: passenger number/hour) |
| \( \delta_{ik} \)     | \( \delta_{ik} \) is 1 if section \( k \) is on path \( r_{ij}^m \), otherwise 0 |
| \( \lambda_l \)       | Capacity of trains on line \( l \) |
| \( t_l \)             | Train departure interval of line \( l \) (Unit: minute) |
| \( \xi_{ik} \)         | \( \xi_{ik} \) is 1 if the section \( k \) belongs to line \( l \), otherwise 0 |
| \( n_l \)             | The number of trains in line \( l \) |
| \( T_l \)             | One-way running time of line \( l \) (Unit: minute) |
| \( t_{l\text{min}} \) | Minimum departure interval of trains in line \( l \) |
| \( t_{l\text{max}} \) | Maximum departure interval of trains in line \( l \) |
| \( n \)               | Total number of trains in the rail transit network |
| \( q_{ij} \)          | The passenger flow demand of OD pair with station \( i \) as origin station and station \( j \) as destination station |
| \( \theta_{ip} \)      | \( \theta_{ip} \) is 1 if station \( p \) is the starting station, ending station or transfer station of the path \( r_{ij}^m \) |
| \( d_{ij}^m \)        | Length of path \( r_{ij}^m \) |
| \( d_{ij\text{min}} \) | Length of the shortest path in \( r_{ij} \) |
| \( \beta \)           | Limiting factor for passenger satisfaction. As shown in (11), this parameter indicates the extent to which the longest path length tolerated by passengers exceeds the shortest path length |

4. Method for Enhancing Global Safety of Regional Rail Transit Based on Coordinative Optimization

In this section, we establish a global safety enhancement model for regional rail transit based on coordinative optimization. With the objective of minimizing the global risk of rail transit network, this
model optimizes the passenger flow demand assignment strategy, train departure intervals and the number of trains assigned to each line. Let $G = G(\mathcal{N},\mathcal{E})$ be an undirected graph representing the regional rail transit network, where $\mathcal{N}$ is the set of stations and $\mathcal{E}$ the set of sections. Let $\mathcal{L}$ be the set of lines and each line $l \in \mathcal{L}$ correspond to actual operating lines in the rail transit system such as high-speed railway and subway. Let $i, j, p = 1, 2, 3, \ldots, S$ be indices of the stations, where $S$ is the total number of stations. Let $k = 1, 2, 3, \ldots, K$ represent indices of the sections where $K$ is the total number of sections. Set $l = 1, 2, 3, \ldots, W$ as indices of the lines with $W$ the total number of lines. Let $r_{ij}$ be the path sets of OD pair from station $i$ to station $j$ and $r_{ij}^m$ the $m$-th path. The parameters and symbols used in the model are listed in Table 1. The global risk of the regional rail transit can be obtained by formula (1). Here we choose $f(x) = \left(1 + e^{-6x+7}\right)^{-1}$ as the risk probability function. According to the previous analysis, the consequence of risk is related to actual passenger flow at the station or section, so we define that $w_k = \min(y_k, b_k)$, $w_p = \min(z_p, C_p)$. The optimization goal is to minimize the global risk function of the regional rail transit as follows.

$$\min \left\{ \sum_k w_k f\left(\frac{y_k}{b_k}\right) + \sum_p w_p f\left(\frac{z_p}{C_p}\right) \right\}$$

(2)

The constraints are as follows:

$$y_k = \sum_{i} \sum_{j} \sum_{m} x_{ij}^m q_{ik}^m, i, j = 1, 2, \ldots, S \quad k = 1, 2, \ldots, K \quad (3)$$

$$b_k = \sum_{l} \frac{10 \lambda_l z_{lk}}{t_l} \quad l = 1, 2, \ldots, W \quad (4)$$

$$t_l \geq \frac{2T_r}{n_l} \quad (5)$$

$$t_{l_{\text{max}}} \geq t_l \geq t_{l_{\text{min}}} \quad (6)$$

$$\sum_l n_l = n \quad (7)$$

$$z_p = \sum_{i} \sum_{j} \sum_{m} x_{ij}^m q_{ip}^m \quad p = 1, 2, \ldots, S \quad (8)$$

$$q_{ij} = \sum_{m} x_{ij}^m \quad (9)$$

$$x_{ij}^m \geq 0 \quad (10)$$

$$\frac{d_{ij}^m - d_{ij}}{d_{ij} \min} \leq \beta \quad (11)$$

Here, the passenger flow demand of section can be obtained by adding passenger flow demand of paths through the section as (3). Equation (4) is used to calculate the capacity of station, which is related to the train departure interval and train capacity in the line. Equation (5) and (6) are constraints
for train departure interval. The train departure interval is mainly related to the number of trains and the one-way running time of the line as (5) shows. Realistically, there is a minimum departure interval for each line due to various factors such as signal system restrictions, and we set a maximum interval to avoid excessive waiting times for passengers. Equation (7) ensures that the total number of trains in the network is certain. Equation (8) is used to calculate the passenger flow demand of the station. Equation (9) and (10) are passenger flow distribution constraints, that is, the passenger flow demand assigned on each path is non-negative, and the passenger flow demand of each OD pair is equal to the sum of demand of all the paths in its path set. In order to avoid assigning passengers to long-distance paths, only the paths with length within the bound given by (11) are considered, $d_{ij\text{min}}$ is the length of the shortest path of corresponding OD pair.

The optimization variables of the model are the passenger flow demand of each path $x_{ij}^m$, the train departure interval of each line $t_l$ and train number of each line $n_l$. Due to the complex constraints and objective function in the model, it is not suitable to use traditional optimization algorithms to solve the problem. As a classic intelligent optimization algorithm, GA (genetic algorithm) has the advantages of strong global search ability and good robustness, which is suitable for complex optimization problems. Therefore, this paper uses GA to solve the problem.

5. Case Study
This section takes the regional rail transit in Chengdu-Chongqing district as an example to verify the proposed global safety enhancement method. The data used in the experiment is from the public information [15-16].

5.1. Simulation Scenarios
We first simplify the topology structure of the rail transit network because the scale of network is too large. Here we only consider Chongqing Rail Transit Line 1, Line 2, Line 3, Line 5, Line 6, Line 10, Circle Line, Chengdu-Chongqing High Speed Railway and Chongqing-Wanzhou Intercity Railway, and the network topology is as shown in figure 2 after merging some ordinary stations. There are 46 stations and 53 sections in the rail transit network, and the network includes four kinds of rail transit systems: subway, monorail, high-speed railway and inter-city railway. According to the cases in practice, the situation considered in this paper is stated as follows: due to the bad weather, part of the trains on the line of Chengdu-Chongqing High Speed Railway are affected and the passenger flow in the Chongqing North Station is thus twice as much as the normal level during 17:00-18:00. A large number of passengers gathered at Chongqing North Station, resulting in a large increase in passenger flow demand starting from Chongqing North Station.

5.2. Data Set
For the sake of simplicity, the stations can be divided into three types: large stations, medium stations and small stations. The throughput of large stations, medium stations and small stations is 21600 passengers/hour, 14400 passengers/hour and 7200 passengers/hour, respectively [17]. Large stations include Shapingba station, Chongqingbei Railway Station, Ranjiaba station and Terminal 2 of Jiangbei Airport. Other interchange stations of urban rail transit, high-speed railway stations, and inter-city railway stations are regarded as medium-sized stations. The remaining stations are small stations. Referring to the public data, the information of lines in Chongqing urban rail transit is shown in table 2. Besides, the capacity of train for Chengdu-Chongqing High Speed Railway is 1328 persons and the departure interval is 20min. The capacity of train for Chongqing-Wanzhou Intercity Railway is 623 persons and the departure interval is 50min.

In this paper, we only select some representative OD pairs with large passenger flow demand for analysis and calculation. According to the simulation scenario, the OD pairs and the corresponding passenger flow demand between 17:00-18:00 are shown in table 3 (The passenger flow demand is estimated based on data in [15]). The demand of OD pairs starting with South of Jianyang is twice as much as the normal level, which doubles the number of people arriving at Chongqing North Station.
5.3. Model Parameter Setting

As it can be seen from figure 2, there are lots of loops in the rail transit network, and we only consider $K$ shortest simple paths. In this case we set $\beta = 0.6$ and $K = 5$. That is, for each OD pair, passengers are assigned to the 5 shortest paths with length within the bound given by (11). The urban rail transit system in Chongqing includes both monorail and subway systems and the types of their trains are different. So monorail and subway trains are allocated separately during optimization. For the parameters of GA, the number of iterations is 10000, and the number of populations is 5000.

Figure 2. The simplified regional rail transit topology of Chengdu-Chongqing district

Table 2. Chongqing urban rail transit line information.

| Line   | Train capacity (persons) | Departure interval in Peak hours | One-way running time | Train Number |
|--------|---------------------------|---------------------------------|----------------------|--------------|
| Line 1 | 1440                      | 3min10s                         | 56min                | 36           |
| Line 2 | 880                       | 3min                            | 57min                | 49           |
| Line 3 | 1320                      | 2min30s                         | 1h38min              | 84           |
| Line 5 | 2322                      | 8min                            | 24min                | 11           |
| Line 6 | 1440                      | 3min30s                         | 75min                | 30           |
| Line 10| 2322                      | 4min                            | 51min                | 20           |
| Line Circle | 2322                  | 6min                            | 52min                | 26           |

5.4. Result and Analysis

The optimized passenger flow assignment results are shown in table 4, and the optimized results of train scheduling are shown in table 5. The optimized passenger flow assignment plan when only passenger flow assignment strategy is applied is shown in table 6. As can be seen from table 4 and table 6, the optimal passenger assignment plan obtained by coordinative optimization method is different from the plan that only passenger flow assignment method is used. And the difference
indicates that for the coordinative optimization, the train scheduling method and the passenger flow assignment method interact and cooperate with each other rather than simply executing sequentially. The minimum risk is 137873.05 when passenger flow assignment and train scheduling are both utilized, 9.92% lower than the risk when only passenger flow assignment is used which is 153069.31, 47.68% lower than the risk with no strategy taken (we assume that passengers will travel on the shortest route under this situation) which is 263504.83. It can be seen that the method proposed by this paper can effectively reduce the risk of the rail transit network and improve the system safety.

**Table 3. OD demand for the regional rail transit in Chengdu-Chongqing district.**

| Number of OD Pairs | Origin               | Destination            | Demand (passengers/hour) |
|--------------------|----------------------|------------------------|---------------------------|
| 1                  | Jiaochangkou         | Jiandingpo             | 10230                     |
| 2                  | Jiandingpo           | Xiaoshenzi             | 12887                     |
| 3                  | Xiaoshizi            | Yudong                 | 5828                      |
| 4                  | Yudong               | Jiaochangkou           | 6255                      |
| 5                  | Central Park         | Sigongli               | 17303                     |
| 6                  | Yudong               | Terminal 2 of Jiangbei | 20196                     |
| 7                  | Dashiba              | The Garden Expo Center | 1130                      |
| 8                  | The Garden Expo Center | Dashiba                | 1053                      |
| 9                  | Liyuchi              | Wangjiazhuang          | 1038                      |
| 10                 | Sigongli             | Shapingba              | 8955                      |
| 11                 | Chongqing Library    | Jiaochangkou           | 8130                      |
| 12                 | Haixialu             | Hongqihegou            | 16667                     |
| 13                 | Lijia                | Xiaoshizi              | 525                       |
| 14                 | Chayuan              | Ranjiaba               | 696                       |
| 15                 | South of Jianyang    | Sigongli               | 2721                      |
| 16                 | South of Jianyang    | Shapingba              | 4455                      |
| 17                 | North of Wanzhou     | Jiaochangkou           | 768                       |

**Table 4. OD demand for the regional rail transit in Chengdu-Chongqing district.**

| Number of OD Pairs | First path (passengers/hour) | Second path (passengers/hour) | Third path (passengers/hour) | Fourth path (passengers/hour) | Fifth path (passengers/hour) |
|--------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
| 1                  | 8251                          | 0                             | 1979                          | 0                             | 0                             |
| 2                  | 11909                         | 0                             | 978                           | 0                             | 0                             |
| 3                  | 0                             | 11                            | 0                             | 0                             | 5817                          |
| 4                  | 0                             | 54                            | 0                             | 0                             | 6201                          |
| 5                  | 4187                          | 0                             | 0                             | 173                           | 12943                         |
| 6                  | 0                             | 7736                          | 0                             | 0                             | 12460                         |
| 7                  | 1130                          | -                             | -                             | -                             | -                             |
| 8                  | 1053                          | -                             | -                             | -                             | -                             |
| 9                  | 0                             | 10380                         | 0                             | 0                             | 0                             |
| 10                 | 7119                          | 1184                          | 652                           | 0                             | -                             |
| 11                 | 4112                          | 0                             | 415                           | 0                             | 3603                          |
| 12                 | 16667                         | 0                             | 0                             | -                             | -                             |
| 13                 | 0                             | 0                             | 525                           | 0                             | 0                             |
| 14                 | 0                             | 0                             | 696                           | 0                             | 0                             |
| 15                 | 0                             | 0                             | 2721                          | 0                             | 0                             |
| 16                 | 4448                          | 7                             | 0                             | 0                             | 0                             |
| 17                 | 0                             | 2                             | 0                             | 766                           | 0                             |
Table 5. The result of train scheduling.

| Line       | Departure interval | Train number |
|------------|--------------------|--------------|
| Line 1     | 2min53s            | 39           |
| Line 2     | 2min               | 58           |
| Line 3     | 2min37s            | 75           |
| Line 5     | 2min50s            | 17           |
| Line 6     | 3min51s            | 39           |
| Line 10    | 6min23s            | 16           |
| Line Circle| 3min15s            | 32           |

Table 6. The optimal passenger flow assignment plan by single optimization method of passenger flow assignment.

| Number of OD Pairs | First path (passengers/hour) | Second path (passengers/hour) | Third path (passengers/hour) | Fourth path (passengers/hour) | Fifth path (passengers/hour) |
|--------------------|------------------------------|-------------------------------|------------------------------|------------------------------|------------------------------|
| 1                  | 8890                         | 3                             | 1336                         | 1                             | 0                            |
| 2                  | 10013                        | 0                             | 2787                         | 87                           | 0                            |
| 3                  | 0                            | 87                            | 0                            | 8                            | 5733                         |
| 4                  | 11                           | 1327                          | 3                            | 112                          | 4802                         |
| 5                  | 5370                         | 0                             | 1                            | 17                           | 11915                        |
| 6                  | 907                          | 4888                          | 0                            | 0                            | 14401                        |
| 7                  | 1130                         | -                             | -                            | -                            | -                            |
| 8                  | 1053                         | -                             | -                            | -                            | -                            |
| 9                  | 0                            | 1035                          | 3                            | 0                            | 0                            |
| 10                 | 4452                         | 486                           | 4015                         | 2                            | -                            |
| 11                 | 1777                         | 4                             | 611                          | 44                           | 5694                         |
| 12                 | 16646                        | 1                             | 20                           | -                            | -                            |
| 13                 | 0                            | 0                             | 524                          | 0                            | 1                            |
| 14                 | 0                            | 0                             | 696                          | 0                            | 0                            |
| 15                 | 0                            | 0                             | 2719                         | 2                            | 0                            |
| 16                 | 4166                         | 289                           | 0                            | 0                            | 0                            |
| 17                 | 0                            | 6                             | 762                          | 0                            | 0                            |

6. Conclusions

In this paper, an approach to evaluate the global safety of regional rail transit network is proposed with focus on passenger flow demand load (namely, transport capacity risk of the rail transit network), and the rail transit network safety is enhanced by coordination optimization between passenger flow assignment and train scheduling. First, the matching degree of passenger flow demand and transport capacity is utilized as the input of the risk probability function, and the consequence of risk is determined by the passenger flow of stations and sections, then the global transport capacity risk of rail transit network can be obtained. Second, a mathematical model is constructed to minimize the global risk (that is, the global transport capacity risk), which utilizes departure interval, the number of trains and passenger flow assignment strategy as variables. Finally, the analysis and validation on the regional rail transit in Chengdu-Chongqing district are presented. The results show that, compared with the method when only passenger flow assignment optimization is applied, the coordinative optimization method of passenger flow assignment and train scheduling can reduce the global risk of rail transit network by about 10%. Future research will focus on the improvement and complement of the formula to calculate risk probability and risk consequence by integrating the characteristics of regional rail transit and practical data, which can further improve the practical effect of safety enhancement.
Acknowledgments

The authors would like to thank financial support from the National Key Research and Development Program of China under Grant 2017YFB1200700 and the BNRist Program under Grants BNR2019TD01009.

References

[1] J. Zhang, X. Xu, L. Hong, S. Wang, and Q. Fei, “Networked analysis of the shanghai subway network, in china,” Physica A: Statistical Mechanics and its Applications, vol. 390, no. 23-24, pp. 4562–4570, nov 2011.

[2] Y. Huang, “Research on evaluation model of urban rail transit network operational safety,” Master’s thesis, Beijing Jiaotong University, 2014.

[3] X. X. M, W. Y. H, and J. L. M, “Design of safety assessment and early warning system for rail transit network operation,” China Transportation Review, no. 08, pp. 61–68, 2013.

[4] X.-y. Xu, J. Liu, H.-y. Li, and M. Jiang, “Capacity-oriented passenger flow control under uncertain demand: Algorithm development and real-world case study,” Transportation Research Part E, vol. 87, pp. 130–148.

[5] L. Wang, X. Yan, and Y. Wang, “Modeling and optimization of collaborative passenger control in urban rail stations under mass passenger flow,” Mathematical Problems in Engineering, vol. 2015, 2015.

[6] X. Xu, H. Li, J. Liu, B. Ran, and L. Qin, “Passenger flow control with multi-station coordination in subway networks: algorithm development and real-world case study,” Transport metrica B: Transport Dynamics, vol. 7, no. 1, pp. 446–472, 2019.

[7] W. HUANG, W. DONG, and X. ya SUN, “A method for safety evaluation and enhancement of urban rail transit network based on passenger flow assignment,” DEStech Transactions on Computer Science and Engineering, no. ammso, jun 2019.

[8] D. Canca, E. Barrena, A. De-Los-Santos, and J. L. Andrade-Pineda, “Setting lines frequency and capacity in dense railway rapid transit networks with simultaneous passenger assignment,” Transportation Research Part B: Methodological, vol. 93, pp. 251–267, 2016.

[9] L. Cadarso, A’. Mar’in, and G. Maro’ti, “Recovery of disruptions in rapid transit networks,” Transportation Research Part E: Logistics and Transportation Review, vol. 53, pp. 15–33, 2013.

[10] Q. Qi, “Study on timetable optimization of urban rail train based on dynamic passenger flow,” Master’s thesis, Beijing Jiaotong University, 2019.

[11] W. Zhou, “Modeling passenger flow assignment and evolution in urban rail transit network with dispersion strategy research under congestion conditions,” Ph.D. dissertation, Beijing Jiaotong University, 2016.

[12] Q. Hu, Y. Bai, Y. Cao, Y. Chen, and Z. Chen, “Optimization of subway timetable at the railway-subway transfer station,” Journal of Railway Science and Engineering, vol. 13, no. 12, pp. 2503–2507, 2016.

[13] Z. Cai, “Timetable optimization for urban rail transit based on railway passenger hub station connecting,” Master’s thesis, Beijing Jiaotong University, 2019.

[14] P. Zhang, “Model and algorithm of train timetabling for additional trains on a urban rail network,” Master’s thesis, Beijing Jiaotong University, 2019.

[15] Chongqing Institute of Transportation Planning, “Chongqing’s urban transportation development annual report 2018,” April 2019. [Online]. Available: https://www.cqtpi.com

[16] The Chongqing Rail Transit Group website. [Online]. Available: https://www.cqmetro.cn/search-way.html

[17] Q. W. Jiang, S. Cai, W. Y. Chen, and X. D. Song, “Passenger flow control decision-making method of urban rail transit station,” Systems Engineering, 2017.