Hindawi
Advances in Mathematical Physics
Volume 2020, Article ID 3862157, 16 pages
https://doi.org/10.1155/2020/3862157

Research Article

Adaptive Multilevel Collaborative Passenger Flow Control in Peak Hours for a Subway Line

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Received 25 June 2020; Revised 1 August 2020; Accepted 19 August 2020; Published 24 September 2020

Academic Editor: Ping Li

Due to contradiction of large-scale passenger demand and limited transportation capacity, the passengers who cannot be transported away in time accumulate and congest in stations. To ensure travel safety, improve travel efficiency, and ameliorate waiting environments for passengers, this paper proposes an adaptive multilevel collaborative passenger flow control strategy integrating the control of station entrance and station hall. An integer linear programming model is constructed, which aims at minimizing the total passenger waiting time and taking the safe capacity of each key area of all stations as the necessary constraints. The model is applied in two scenarios with different scales of passenger demand in the morning peak of the Batong line. The results show that the proposed model can adaptively activate the appropriate control level, limit the amount of accumulated passengers in each key area of the station within its safe capacity, and shorten the total passenger waiting time.

1. Introduction

With the acceleration of urbanization and increase of urban population in China, more and more passengers choose to travel via a subway system that is characterized by large capacity, fast speed, and high efficiency. The average amount of passengers increased by 41.93% in the Beijing subway system [1], 40.56% in the Shanghai subway system [2], and 40.23% in the Guangzhou subway system [3] from 2011 to 2017. The booming travel demands have tremendously challenged the limited transportation capacity, especially during peak hours. For instance, in the Beijing subway system, the average daily passenger flow reached more than 10 million, in which 39.3% of the total passenger volume happens during mornings and evenings [1]. Meanwhile, large numbers of passenger surge into the subway system during peak hours and the stations are overcrowded due to the limited transport capacity, which may lead to potential safety problems such as door squeezing, passengers falling into the tracks, and trampling [4, 5].

Passenger flow control, as a practical and effective method to avoid overcrowding and ensure safe operation at subway stations, has been widely implemented at subway stations during peak hours in some metropolises of China [6]. In the Beijing subway system, more than 90 stations have been implemented passenger flow control in peak hours [7]. Currently, operation staff is guided by the regulation [8] when implementing the passenger flow control; they restrict the inbound passenger volume by closing some entrances, ticket vending machines, and gates to ensure the total passenger volume does not exceed the warning line of the station. Operation staff can ensure passengers' safety of the current station they manage through these control methods. However, to our knowledge, they only control passenger flow that concerns the station they managed and mainly rely on their subjective work experience. They pay

less attention to travel efficiency and the waiting environment of passengers. Hence, it is necessary to explore a more accurate passenger flow strategy that can achieve the following goals for passengers: ensure travel safety, improve travel efficiency, and ameliorate waiting environments.

The essence of passenger flow control is to resolve the imbalance relationship between passenger flow demand and the restriction of transport infrastructure, whose effect is achieved by changing the spatial and temporal passenger flow distribution. The influence factors on passenger flow control mainly include two categories: transport equipment and facilities (e.g., train operation plan, the capacity of station facilities, the passing capacity of equipment) and passenger flow demand (e.g., passenger volume, OD distributions, passenger route). By analysing the influencing factors, the corresponding passenger flow control can be divided into indirect and direct passenger flow control, respectively.

Indirect passenger flow control indirectly affects the spatial and temporal distribution of passenger flow by methods such as optimizing train schedules and changing the limited capability of infrastructure. In terms of indirect passenger flow control, extensive works have concentrated on problems of optimizing train schedules involving the train schedule during normal operational periods and the schedule for the last train. For the train schedule during normal operational periods, some researchers studied the optimization of service-oriented train timetabling for the congested subway line to improve the efficiency of transport service [9–15]. For example, Niu and Zhou [9] formulated the dynamic passenger loading process and proposed a timetabling model under oversaturated conditions, in which the number of boarding passengers was estimated based on the limited capacity of each train at each station. Wang et al. [10] developed an event-driven timetabling model for an urban rail transit network under oversaturated situations, which is a nonlinear nonconvex model and solved by a genetic algorithm. Shang et al. [14] proposed a multicommodity flow-modelling model to optimize the equity-oriented skip-stopping schedule for an oversaturated metro network. The train skip-stopping pattern adopted in their study can hold back parts of passengers at stations and reroute their journeys with limited train capacity in the time dimension. Chen et al. [15] formulated a discrete model collaboratively designing the dispatch headway and vehicle capacity for the congestion subway line, which was solved by an improved DP algorithm. In addition, some scholars focused on the optimization of last train scheduling/timetabling to improve the transport service level [16–22]. The optimization objectives mainly include decreasing transfer time [16], minimizing the running/dwell time and maximizing the average redundancy of transfer time [17], maximizing transfer connection headways for passengers [18], maximizing passenger destination accessibility [19], maximizing the amount of successfully transferred passengers and promoting the priority of the subway travel [20], minimizing energy consumption and transfer waiting and in-train times [22], etc.

Although indirect passenger flow control methods, like timetabling optimizing, can reduce the total passenger waiting time and improve transport service quality, the congestion situation can hardly relieve large passenger flow. During those times, it is more effective to directly control the number of passengers entering the subway system with a limited capacity of transport equipment and facilities. From reviewing existing literature, direct passenger flow control methods include inbound control and station hall control. Inbound control, which requires passengers to wait outside the station, was taken as the control method in literatures [23–29]. For instance, Zhao et al. [23] established a multiobjective mathematical programming model aiming at minimizing the passenger delay and maximizing the passenger turnover volume. Yao et al. [24] proposed a multiobjective programming model to maximize the matching degree of capacity and demand and minimize the number of delayed passengers. Jiang et al. [26] developed a new reinforcement learning-based method to optimize the inflow volume with the aim of minimizing the safety risks imposed on passengers at the metro stations. Further, Jiang et al. [28] proposed a coordinated optimization scheme, which combined both the coordinated passenger inflow control and train rescheduling strategies, to minimize the penalty value of passengers being stranded along the whole line. In addition, the station hall control method, which requires passengers to wait in the station hall, was studied in literatures [30–34]. For example, Jiang et al. [32] constructed a mathematical model to maximize the profits of passengers by simultaneously controlling nonstop stations and limiting boarding. Shi et al. [34] proposed a mathematical model aiming at minimizing the total waiting time for passengers and passenger accumulation risks in an oversaturated network.

It is undeniable that scholars paid effort to study passenger flow control, but there are still several insufficient aspects. On the one hand, most of the previous studies only concerned the train transport capacity or platform loading capacity and ignored the capacity of the station hall. On the other hand, both the inbound control strategy and the station hall control strategy have their shortcomings. The former is easily affected by severe weather (e.g., exposure, snow, rain, wind) due to the lack of protection outside the station. The latter can also cause accident risks when the accumulated and overcrowded passengers in the station hall are substantially increasing. Focusing on the above problems, we consider four types of capacity affecting passenger flow control, which are the train capacity, the platform loading capacity, the station hall capacity, and the passing capacity of station equipment. Besides, to ameliorate passenger waiting environments, we take the control method integrating the station hall control and the inbound control.

In summary, the contributions of this paper are threefold: first, we proposed an adaptive multilevel collaborative passenger flow control strategy integrating the control of station entrance and station hall. According to different scales of arrival passenger volume, the appropriate control level can be activated, which can not only help the subway staffs accurately determine the control position of the station so as to save staffing but can distribute passengers waiting in the station hall or outside the station to ameliorate passenger waiting environments. Second, an integer linear programming model is developed, which aims to enhance the service

efficiency by optimizing the total passenger waiting time (including the waiting time on the platform and the other key area of the station). Meanwhile, the model guarantees passengers' safety in each key area of the station by taking the safe capacity of each key area of all stations as the necessary constraints. Third, related factors that influence the process of collaboratively controlling the passengers are analysed, which contain the trains, stations, and passengers. The capacity of in-service trains, the safe capacity of station area (including platform, paid zone of station hall, nonpaid zone of station hall, and station entrance), and the passing capacity of each gate from one area to another in the station are all considered in this paper.

The remainder of this paper is organized as follows. In Section 2, the system with multiple stations on a subway line is introduced and the AMLC passenger flow control strategy is described. In Section 3, an integer linear programming model integrating different control levels is formulated and the adaptive control methodology is proposed. In Section 4, a real-case study is provided to validate the effectiveness of the proposed model. Finally, the conclusions and recommendations for further research are presented in Section 5.

2. Problem Description

2.1. The System with Multiple Stations on a Subway Line. The system with multiple stations on a bidirectional subway line is a dynamic system consisting of interactive elements such as time, stations, in-service trains, and passengers [35]. The set $g \in G = \{1, 2\}$ is used to represent the involved directions, in which $g = 1$ represents the up direction and $g = 2$ represents the down direction. The stations and trains on g direction are denoted by sets $S_g = \{1, 2, \cdots, k, \cdots, m\}$ and $I_g = \{1, 2, \cdots, i, \cdots, n\}$, respectively.

In Figure 1, the horizontal axis shows the time range, denoted by $[T_S, T_E]$, while the vertical axis shows m stations along g direction on the subway line. It can be seen from Figure 1 that passengers entering different stations at the same time do not board the same train (e.g., passengers A and B), and passengers entering different stations at different times may board the same train (e.g., passengers A and E). To ensure all involved passengers complete the travel process (from their origins to destinations), we rescale the time range studied correspondingly for each station. With the time spending for trains to travel from one station to another, the start and end times of the time range studied of each station parallelly move afterward. For any station $k \in S_g$, the offset (k) is the value parallelly moving afterward. Offset (k) can be calculated with $\sum_{j=1}^{k-1} R_j + \sum_{j=2}^{k} S_j$, where R_j represents the train running time from stations j to $j+1$ and S_j represents the train dwelling time at station j.

To feature passenger flow with characteristics of dynamic and time-dependent [36, 37], the continuous time range is discretized into p time intervals, while the time length of each time interval is t_p. All the begin times of these time intervals are denoted by an index number set $T = \{1, 2, \cdots, p\}$. The actual time corresponding to any index number t can be calculated with $T_s + (t-1) * t_p$ [33].

2.2. Definition of the AMLC Passenger Flow Control Strategy. Due to the limited number and capacity of in-service trains, the total transportation capacity of the subway line cannot sustain the continuously increasing inflows in peak hours. A lot of passengers who cannot be transported away in time are left and congested in the station, which may cause an operational safety risk. To avoid the congestion in each key area of the station, and meanwhile enhance the service efficiency for the subway line, the AMLC passenger flow control strategy is proposed in the study.

In this strategy, the station area is divided into four parts, i.e., the platform, the paid zone of the station hall, the nonpaid zone of the station hall, and the station entrance, denoted by $M_{(1)}$, $M_{(2)}$, $M_{(3)}$, and $M_{(4)}$, respectively. For each station $k \in S_g$, there are three sets of gates used to control the passengers from one station area to another, denoted by the gates I, II, and III, respectively (as shown in Figure 2). Practically, the gate I, gate II, and gate III can be replaced by the existing equipment in stations, such as flexible boundary fences, ticket gates, and security machines. It is necessary to describe the two parts of the station hall. The area outside the gate II is the nonpaid zone of the station hall, and the area inside the gate II is the paid zone of the station hall. Usually, passengers need to swipe an IC card on the ticket gates to enter the paid zone from the nonpaid zone of the station hall. Practically, to make the best use of the platform, the $M_{(1)}$ area can be reduced to a part of the platform, and the $M_{(2)}$ area can be expanded to the sum of the remaining area of the platform and the paid zone of the station hall.

According to the division of station areas and different scales of arrival passenger volume, multilevel passenger flow control is identified into three levels, respectively, control levels one, two, and three (i.e., $L = 1, 2, 3$). Under the situation of small-scale arrival passenger volume, the passenger flow control need not be activated when the number of accumulated passengers on the platform is within its safe capacity. Without passenger flow control, passengers arrive at the platform (i.e., $M_{(1)}$) and wait for the approaching train. Under the situation of large-scale arrival passenger volume, the passenger flow control should be activated when the number of accumulated passengers on the platform exceeds its safe capacity. The larger-scale the arrival passenger volume is, the higher level of passenger flow control should be activated.

With the passenger flow control of level one, passengers are required to arrive at the paid zone of station hall first (i.e., $M_{(2)}$) and queue behind gate I to wait for the permission to enter the platform and take trains. Aiming to accurately control the passenger volume on the platform, it is required that passengers on the platform can all board the next coming train. Whether the control level one is adequate or not, it can be judged by comparing the number of accumulated passengers in the paid zone of the station hall with its safe capacity. If the number of accumulated passengers is less than the safe capacity of the paid zone of the station hall, the control level one is adequate and can be adopted. In contrast, the control level one should be upgraded to level two. With the passenger flow control of level two, passengers are

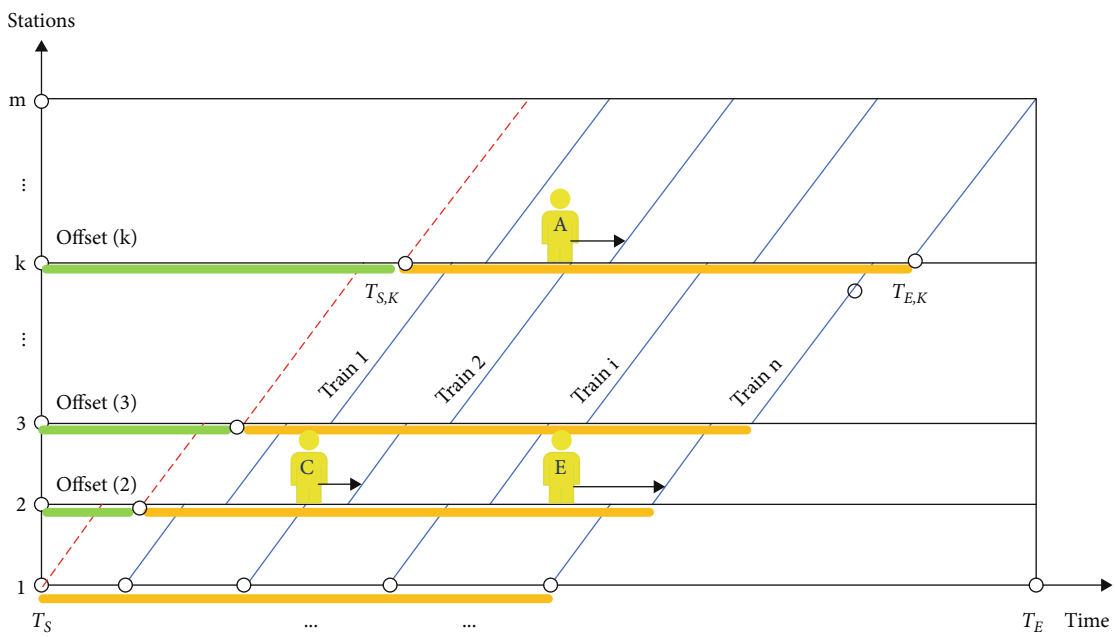

Figure 1: Illustration of the time range studied at different stations.

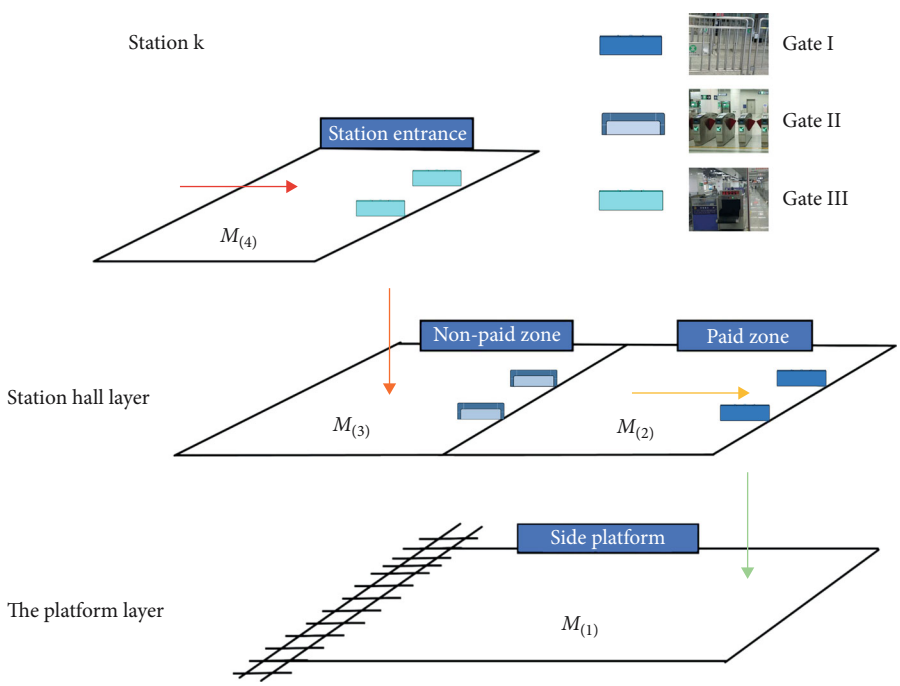

Figure 2: Illustration of the passenger flow control process at a single station.

required to arrive at the nonpaid zone of station hall first (i.e., $M_{(3)}$) and queue behind gate II; then, they are gradually permitted to enter the paid zone of the station hall. After passengers enter the paid zone of the station hall, the control process is the same as the process of control level one. Similarly, it is identified whether the control level two is adequate by comparing the number of accumulated passengers in the nonpaid zone of the station hall with its safe capacity. With the passenger flow control of level three, passengers are required to arrive at the station entrance first (i.e., $M_{(4)}$) and queue behind gate III; then, they are gradually permitted to enter the nonpaid zone of station hall. In the same way, the control process is the same as the control level two after passengers enter the nonpaid zone of the station hall.

With different levels of passenger flow control, passengers permitted to enter the platform can all board the next coming train according to the control strategy. That is, the remaining capacity of the next coming train determines the

number of passengers allowed to enter the platform. However, the remaining capacity of the approaching train is affected by the number of boarding and alighting passengers at the previous station. With the remaining capacity of the train as a link, the adaptive multilevel collaborative passenger flow control strategy can achieve the following three goals. Firstly, the number of passengers entering the platform can be adjusted in accordance with the remaining capacity of the approaching train, so as to accurately control the passenger volume on the platform at each station. Secondly, according to the number of passengers entering the platform, we can further adjust the number of passengers entering the paid zone of the station hall, nonpaid zone of the station hall, and the station entrance. The number of accumulated passengers in each key area of the station can be balanced by collaboratively controlling on the subway line. Finally, we can minimize the total passenger waiting time by making the best use of the remaining capacity of in-service trains in the view of optimizing the system.

3. The AMLC Passenger Flow Control Model

3.1. Model Assumptions and Symbols. For modeling, influence factors are assumed as follows:

(1) All trains operated according to pregiven timetables with neither any delay nor any unexpected events [38]

(2) At each station, the arrival passenger demands and the OD demands are known. All passengers will not turn to transfer by other transportation modes under the passenger flow control [6]

(3) Ignore the walking time for passengers from the control position gate I to the platform before boarding

(4) As the station entrance can extend to the area outside the station, the acreage of the station entrance is regarded as infinite and its safe capacity is unlimited

The symbols involved are shown in Table 1.

3.2. Matrix of Passenger Arrival Demand. According to the previous studies, the passenger arrival demand can be modeled by a time-dependent origin-destination matrix [9, 12, 33]. Under the current passenger flow control level L, for each $t \in T$, the passengers required to arrive at area $M_{(L+1)}$ of each station on g direction of the subway line with m stations can be expressed by

$$A^g(t) = \begin{bmatrix} 0 & d_{1,2}^{g,M_{(L+1)}}(t) & \cdots & d_{1,m-1}^{g,M_{(L+1)}}(t) & d_{1,m}^{g,M_{(L+1)}}(t) \\ 0 & 0 & \cdots & d_{2,m-1}^{g,M_{(L+1)}}(t) & d_{2,m}^{g,M_{(L+1)}}(t) \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & 0 & d_{m-1,m}^{g,M_{(L+1)}}(t) \\ 0 & 0 & \cdots & 0 & 0 \end{bmatrix}, g \in G. \tag{1}$$

3.3. The Waiting Passengers in Each Key Area of the Station. Under the current passenger flow control level L, the total passengers arriving at area $M_{(L+1)}$ of station k on g direction from timestamp 1 to timestamp t can be calculated by

$$C_k^{g,M_{(L+1)}}(t) = \sum_{\tau=1}^{t} d_k^{g,M_{(L+1)}}(\tau) = \sum_{s=k+1}^{m} \sum_{\tau=1}^{t} d_{k,s}^{g,M_{(L+1)}}(\tau), L = 1, 2, 3, t \in T, k \in S_g, g \in G. \tag{2}$$

Under the current passenger flow control level L, the total passengers allowed to enter the control area $M_{(j)}$ of station k on g direction from timestamp 1 to timestamp t can be calculated by

$$C_k^{g,M_{(j)}}(t) = \sum_{\tau=1}^{t} \theta_k^{g,M_{(j)}}(\tau), j = 1, 2, \cdots, L, t \in T, k \in S_g, g \in G. \tag{3}$$

Passengers need to wait in different areas of stations when different control levels are activated at the station. Under the current passenger flow control level L, the number of passengers waiting at area $M_{(j)}$ of station k on g direction from timestamp 1 to timestamp t can be calculated by

$$W_k^{g,M_{(j)}}(t) = C_k^{g,M_{(j)}}(t) - C_k^{g,M_{(j-1)}}(t), j = 2, \cdots, L + 1, t \in T, k \in S_g/\{m\}, g \in G. \tag{4}$$

Under the current passenger flow control level L, the total passenger arriving at area $M_{(L+1)}$ of station k are composed of the passengers with the destinations on the up and down directions of the subway line. For station k, the arriving passengers in each direction occupy a certain acreage of area $M_{(L+1)}$ from timestamp 1 to timestamp t. The percentage of the acreage at area $M_{(L+1)}$ assigned to the passengers on g direction is calculated by

$$r_k^{g,M(L+1)} = C_k^{g,M_{(L+1)}}(t)/C_k^{M_{(L+1)}}(t), L = 1, 2, 3, t \in T, k \in S_g, g \in G. \tag{5}$$

According to the above percentage, the acreage of each key area at station k occupied by the passengers along g direction is calculated by

$$M_{(j)}^{g,k,\text{area}} = M_{(j)}^{k,\text{area}} \times r_k^{g,M(L+1)}, j = 1, \cdots, L + 1, t \in T, k \in S_g, g \in G. \tag{6}$$

Here, we note that the platform area $M_{(1)}^{g,k,\text{area}}$ assigning has a relationship to the structure of the platform. For the island platform, the $M_{(1)}^{g,k,\text{area}}$ can be calculated by equation (6). For the side platform, considering the passengers going to different directions are not in the same space, the

Table 1: The symbols involved in the model.

Symbols	Definition
Sets/parameters	
G	Set of directions, the up direction ($g = 1$), the down direction ($g = 2$).
I_g	Operating train set on g direction, $I_g = \{1, 2, \cdots, i, \cdots, n\}$.
L	The current passenger flow control level, $L = \{0, 1, 2, 3\}$.
S_g	Station set on g direction, $S_g = \{1, 2, \cdots, k, \cdots, s, \cdots, m\}$.
T	Discrete time range of the study, $T = \{1, 2, \cdots, p\}$.
C_{TR}	The maximum capacity of the train.
$F_k^{g,M_{(j),\min}}$	The minimum fluctuant range of each gate at the timestamp t allowing passengers to enter the control area $M_{(j)}$ of station k on g direction.
$F_{k,s}^{g,M_{(j),\max}}$	The maximum fluctuant range of each gate at the timestamp t allowing passengers to enter the control area $M_{(j)}$ of station k on g direction.
$M_{(j)}$	The key area of the station, $j = \{1, 2, 3, 4\}$.
$M_{(j)}^{k,\text{area}}$	The acreage of $M_{(j)}$ area at station k.
$M_{(j)}^{g,k,\text{area}}$	The acreage of $M_{(j)}$ area at station k occupied by the passengers on g direction.
$T_{g,i,k}^d$	The actual departing time of the train i at the station k on g direction.
$Y_k^{g,M_{(j)},\max}$	The maximum passing capacity of each gate at the timestamp t on g direction allowing passengers to enter the control area $M_{(j)}$ of station k.
$d_k^{g,M_{(L+1)}}(t)$	Under the current control level L, the number of passengers arrived at area $M_{(L+1)}$ of station k on g direction at timestamp t.
$d_{k,s}^{g,M_{(L+1)}}(t)$	Under the current control level L, the number of passengers arrived at area $M_{(L+1)}$ of station k with trip $k \longrightarrow s$ on g direction at timestamp t.
$r_k^{g,M_{(L+1)}}$	Under the current control level L, the percentage of the acreage at area $M_{(L+1)}$ assigned to the passengers along g direction.
$t_{g,i,k}$	The timestamp index of the actual departing time $T_{g,i,k}^d$.
t_p	The length of two adjacent timestamps.
φ	Safety limitation factor.
$\varepsilon_{g,v,k}(t)$	The dynamic percentage of passengers with trip $v \longrightarrow k$ accounting for the total passengers boarding train i at station v on g direction.
Intermediate variable	
$A_k^{g,i}$	The number of passengers alighting from train i at station k on g direction.
$AP_k^{g,i}(t)$	The number of accumulated passengers entering the platform between departure time of train i-1 and i on g direction at timestamp t.
$B_k^{g,i}$	The boarding passengers for train i at station k on g direction.
$C_k^{M_{(L+1)}}(t)$	Under the current control level L, the total passengers arriving at area $M_{(L+1)}$ of station k from timestamp 1 to t.
$C_k^{g,M_{(L+1)}}(t)$	Under the current control level L, the total passengers arriving at area $M_{(L+1)}$ of station k on g direction from timestamp 1 to t.
$C_k^{g,M_{(j)}}(t)$	Under the current control level L, the total passengers allowed to enter the control area $M_{(j)}$ of station k on g direction from timestamp 1 to t.
$C_k^{g,M_{(1),i}}$	The total passengers allowed to enter platform and board train i at station k on g direction.
$N_k^{g,i}$	The loading passengers in train i between station k and k +1 on g direction.
$T_{i,k}^{g,M_{(1)}}$	The waiting time on platform for passengers to board train i on g direction.
$T_k^{g,M_{(j)}}$	The waiting time for passengers in area $M_{(j)}$ of station k on g direction.
$T_k^{g,total}$	Under the current control level L, the total passenger waiting time at station k on g direction.

Table 1: Continued.

Symbols	Definition
$W_k^{g,M_{(j)}}(t)$	Under the current control level L, the number of waiting passengers at area $M_{(j)}$ of station k on g direction from timestamp 1 to t.
Decision variable	
$\theta_k^{g,M_{(j)}}(t)$	The number of passengers allowed to enter the control area $M_{(j)}$ of station k on g direction at the timestamp t.

$M_{(1)}^{g,k,\text{area}}$ is the acreage of the side platform itself on g direction.

3.4. The Dynamic Loading Process for Passengers. As the train timetable is pregiven, the timestamp corresponding to the actual departing time $T_{g,i,k}^d$ of train i at station k can be calculated as follows:

$$t_{g,i,k} = \left(T_{g,i,k}^d - T_S\right)/t_p + 1, i \in I_g, t_{g,i,k} \in T, k \in S_g/\{m\}. \quad (7)$$

According to the passenger flow control strategy, passengers being allowed to enter the platform can all take the approaching train. Thus, the number of passengers allowed to enter and board train i at station k on g direction is calculated by

$$C_k^{g,M_{(1),i}} = \begin{cases} \sum\limits_{t\in\left[1,t_{g,i,k}-1\right]} \theta_k^{g,M_{(1)}}(t), & \text{if} \quad i=1 \\ \sum\limits_{t\in\left[t_{g,i-1,k},t_{g,i,k}-1\right]} \theta_k^{g,M_{(1)}}(t), & \text{if} \quad 1<i\le n \end{cases}, i \in I_g, t_{g,i,k} \in T, k \in S_g, g \in G. \quad (8)$$

Additionally, the boarding passengers for train i must be equivalent to $C_k^{g,M_{(1),i}}$ to ensure that the passengers on the platform can board the first approaching train, which can be formulated as follows:

$$B_k^{g,i} = C_k^{g,M_{(1),i}}, i \in I_g, k \in S_g, g \in G. \quad (9)$$

The number of passengers alight from train i at station k consists of passengers with different origin stations along g direction. To calculate the number of passengers with each origin station v to alight from train i at station k, we need to know $\varepsilon_{g,v,k}(t)$, which represents the dynamic percentage of passengers with trip $v \longrightarrow k$ accounting for the total passengers boarding train i at station v. To get closer to the characteristic of passenger flow, $\varepsilon_{g,v,k}(t)$ is obtained according to the collecting AFC data and calculated by

$$\varepsilon_{g,v,k}(t) = d_{v,k}^{g,M_{(L+1)}}(t)/d_v^{g,M_{(L+1)}}(t), i \in I_g, v < k \in S_g/\{1\}, g \in G. \quad (10)$$

Meanwhile, the number of passengers alighting from train i at station k is calculated by

$$A_k^{g,i} = \begin{cases} \sum\limits_{v=1}^{k-1} \sum\limits_{t\in\left[1,t_{g,i,v}-1\right]} \theta_v^{g,M_{(1)}}(t) \times \varepsilon_{g,v,k}(t), & \text{if} \quad i=1 \\ \sum\limits_{v=1}^{k-1} \sum\limits_{t\in\left[t_{g,i-1,v},t_{g,i,v}-1\right]} \theta_v^{g,M_{(1)}}(t) \times \varepsilon_{g,v,k}(t), & \text{if} \quad 1<i\le n \end{cases}, i \in I_g, t_{g,i,v} \in T, v \in S_g, g \in G. \quad (11)$$

When train i arrives at station k, passengers on train i are changed dynamically in the process of passengers boarding and alighting. The dynamic change of loading passengers can be presented as

$$N_k^{g,i} = \begin{cases} B_k^{g,i}, & \text{if} \quad k=1 \\ N_{k-1}^{g,i} - A_k^{g,i} + B_k^{g,i}, & \text{if} \quad 1<k<m \end{cases}, i \in I_g, k \in S_g, g \in G. \quad (12)$$

3.5. The Total Waiting Time for Passengers. Under the current passenger flow control level L, the total waiting time (i.e., $T_k^{g,\text{total}}$) consists of two parts: the waiting time on the platform (i.e., $M_{(1)}$) and the waiting time in other key areas of the station. The specific calculation of the two parts is discussed below.

(1) The passenger waiting time on the platform (i.e., $M_{(1)}$)

The total waiting time for passengers in $M_{(1)}$ area is affected by twofold: train timetable and the number of passengers allowed to enter $M_{(1)}$ area. It can be observed from Figure 3 that passengers are increased cumulatively on the boarding area at timestamp $t_{g,i-1,k}$. Since all passengers entering the boarding area can board the next coming train based on the constraint (9), the number of accumulated passengers becomes zero when train i departs at timestamp $t_{g,i,k}$ and a new accumulative process begins. As shown in Figure 3, the effective loading time ranges of the 1st train and ith train are $[1, t_{g,1,k} - 1]$ and $[t_{g,i-1,k}, t_{g,i,k} - 1]$, respectively; squares in different colors represent the number of passengers entering the platform at different timestamps. For instance, the square in gray represents the number of passengers entering the platform waiting for the 1st train at the timestamp 1, and the square in purple represents the number of passengers

entering the platform waiting for the ith train at timestamp $t_{g,i-1,k}$. Thus, $AP_k^{g,i}(t)$ can be calculated as follows:

$$AP_k^{g,i}(t) = \begin{cases} \sum_{\tau\in[1,t]} \theta_k^{g,M_{(1)}}(\tau), & \text{if} \quad i=1 \\ \sum_{\tau\in[t_{g,i-1,k},t]} \theta_k^{g,M_{(1)}}(\tau), & \text{if} \quad 1<i\le n \end{cases}, i\in I_g, t_{g,i,k}\in T, k\in S_g, g\in G. \tag{13}$$

The waiting time in $M_{(1)}$ area for passengers who can board the 1st train is equal to the total acreage of all squares surrounded by the blue line, and the waiting time for boarding the ith train is equal to the total acreage surrounded by the red line, as shown in Figure 3. Then, $T_{i,k}^{g,M_{(1)}}$ can be calculated by

$$T_{i,k}^{g,M_{(1)}} = \begin{cases} \sum_{t\in[1,t_{g,i,k}-1]} AP_k^{g,i}(t)\times t_p, & \text{if} \quad i=1 \\ \sum_{t\in[t_{g,i-1,k},t_{g,i,k}-1]} AP_k^{g,i}(t)\times t_p, & \text{if} \quad 1<i\le n \end{cases}, i\in I_g, t_{g,i,k}\in T, k\in S_g, g\in G. \tag{14}$$

For all trains in-service, the waiting time $T_k^{g,M_{(1)}}$ on the platform area for passengers at station k can be calculated as follows:

$$T_k^{g,M_{(1)}} = \sum_{i\in I_g} T_{i,k}^{g,M_{(1)}}, k\in S_g, g\in G. \tag{15}$$

(2) The passenger waiting time in other key areas of the station

According to the constraint (4), passengers waiting time in area $M_{(j)}$ of station k for passengers can be calculated by

$$T_k^{g,M_{(j)}} = \sum_{t\in T} W_k^{g,M_{(j)}}(t)\times t_p, j=2,\cdots,L+1, k\in S_g, g\in G. \tag{16}$$

(3) *The total passenger waiting time*

Under the current passenger flow control level L, the total passenger waiting time at station k can be calculated by

$$T_k^{g,\text{total}} = \sum_{j=1}^{L+1} T_k^{g,M_{(j)}}, k\in S_g/\{m\}. \tag{17}$$

3.6. The AMLC Passenger Flow Control Model.

$$\text{Minimize} \sum_{k\in S_g} T_k^{g,\text{total}}. \tag{18}$$

Subject to

$$0\le \theta_k^{g,M_{(j)}}(t) \le Y_k^{g,M_{(j),\max}}, j=1,2,\cdots,L, t\in T, k\in S_g, g\in G, \tag{19}$$

$$\begin{aligned} F_k^{g,M_{(j),\min}} &\le \theta_k^{g,M_{(j)}}(t) - \theta_k^{g,M_{(j)}}(t-1) \\ &\le F_k^{g,M_{(j),\max}}, j=1,2,\cdots,L, t\in T, k\in S_g, g\in G, \end{aligned} \tag{20}$$

$$0\le AP_k^{g,i}(t) \le M_{(1)}^{g,k,\text{area}}\times\alpha, t\in T, k\in S_g, g\in G, \tag{21}$$

$$0\le W_k^{g,M_{(j)}}(t) \le M_{(j)}^{g,k,\text{area}}\times\varphi, j=2,\cdots,L, L\in\{2,3\}, t\in T, k\in S_g, g\in G, \tag{22}$$

$$N_k^{g,i} \le C_{\text{TR}}, i\in I_g, k\in S_g/\{m\}, g\in G. \tag{23}$$

Constraint (19) represents that the number of passengers on g direction allowed to enter $M_{(j)}$ area through each gate at each timestamp should be limited by its passing capacity. To guarantee the stationarity of the passenger flow control, the constraint (20) denotes that the number of passengers on g direction permitted to enter $M_{(j)}$ area between two contiguous timestamps should be within a certain fluctuation range. Constraints (21) and (22) show that the number of accumulated passengers on the platform and key areas of the station under control are limited by their safe capacity, respectively. Here, the safe capacity is defined as the product of the occupying acreage of each area $M_{(j)}^{g,k,\text{area}}$, and the safety limitation factor, of which the safety limitation factor represents the up boundary of the amounts of accommodated passengers in each square meter under the acceptable safety range. In constraint (23), the number of in-vehicle passengers should not exceed the maximum capacity of each train.

3.7. Methodology of Adaptive Control. Without passenger flow control, passengers could enter the platform of the station freely, accumulating on the platform and waiting for the approaching trains. Under the situation of certain-scale arrival passenger volume, whether implementing the passenger flow control or not depends on the comparison between the number of accumulated passengers on the platform and its safe capacity. There is no need to implement the passenger flow control if the number of accumulated passengers on the platform is within its safe capacity. On the contrary, the passenger flow control must be implemented. It is very important to accurately identify the appropriate control level by certain-scale arrival passenger volume when implementing the passenger flow control. The methodology of adaptive control we proposed can achieve this goal, whose process is shown in Figure 4. In this process, under any control level L, the AMLC passenger flow control model is an integer linear programming independently that can be solved by ILOG CPLEX solver, whose key algorithm is the branch and bound method.

The process of the adaptive control methodology in detail is described as follow:

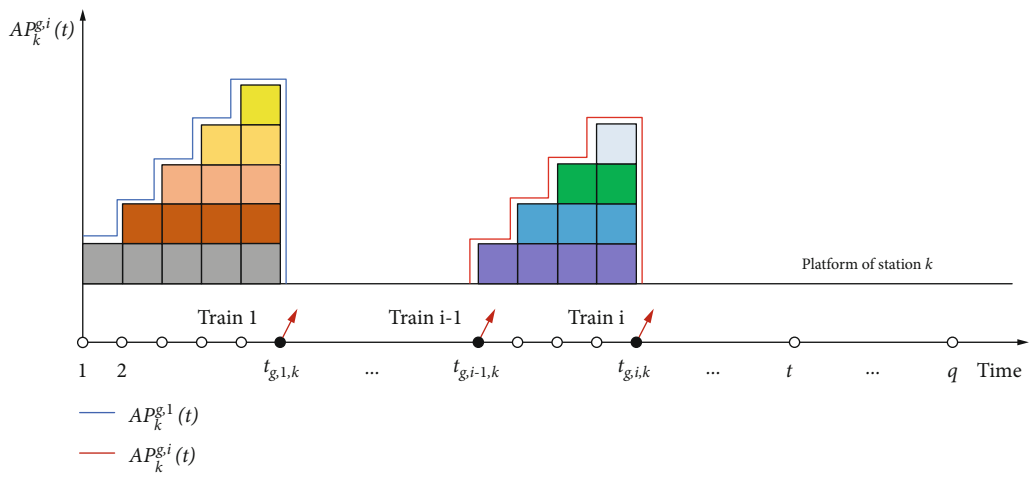

Figure 3: Illustration of passenger accumulating process on the platform for the approaching train.

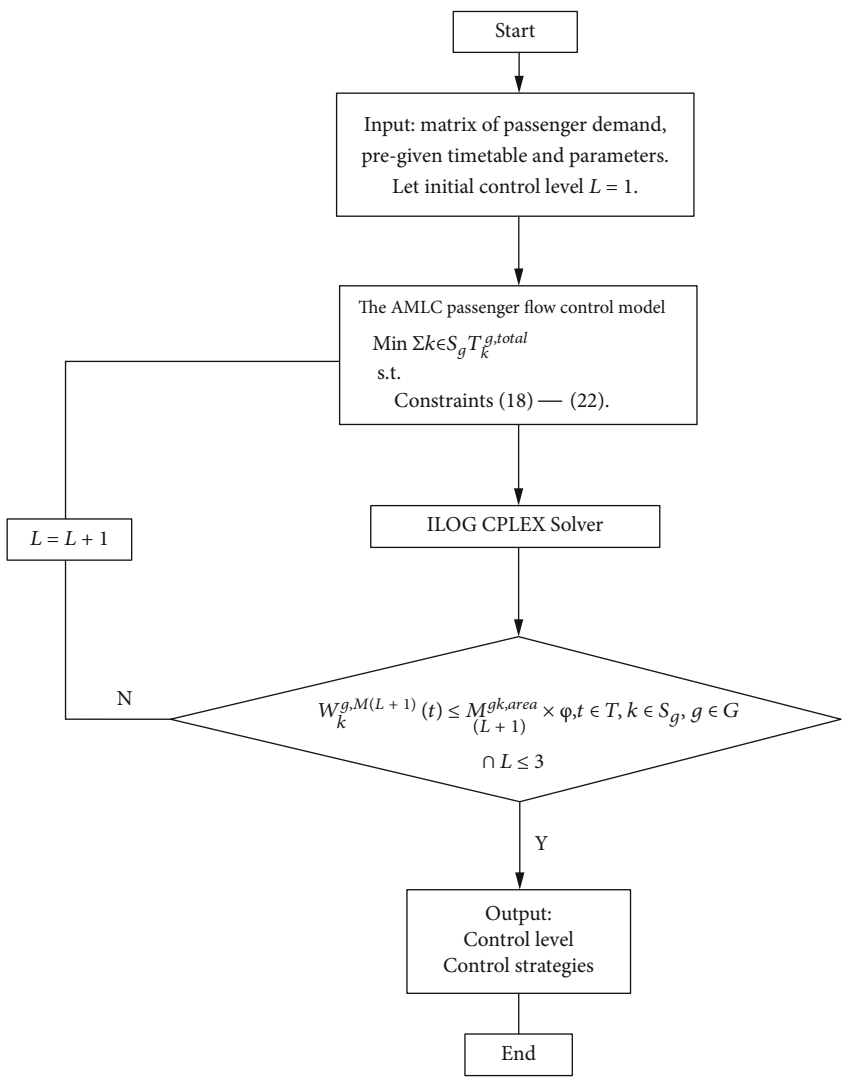

Figure 4: The process of the adaptive control methodology.

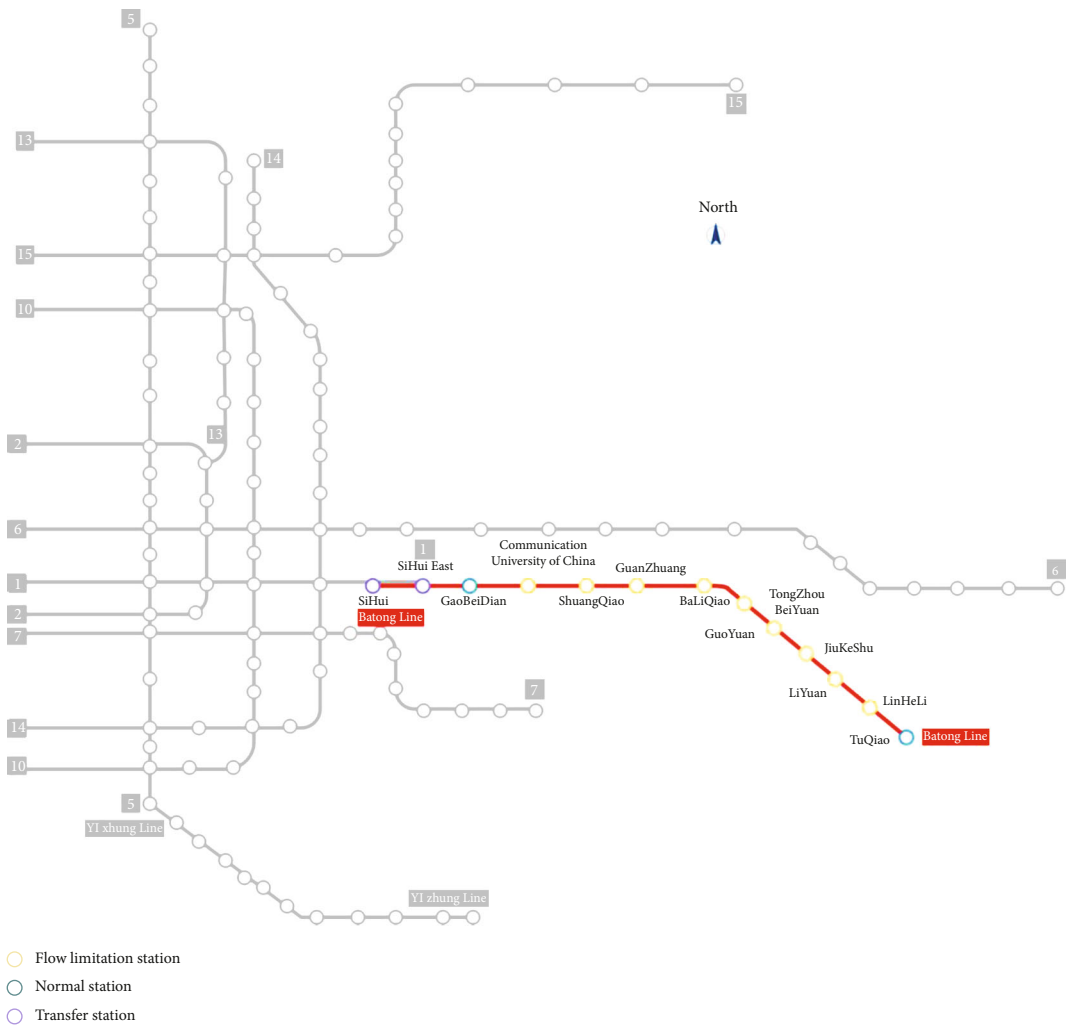

Figure 5: Illustration of Batong line in Beijing subway.

Step 1: input pregiven timetable, passenger arrival demand, and the corresponding parameters. Let initial control level $L = 1$, go to step 2.

Step 2: activate the AMLC passenger flow control model, by using the ILOG CPLEX solver to solve this model. The control strategies under the current control level L can be obtained. According to the results, the accumulated passengers in area $M_{(L+1)}$ can be calculated, go to step 3.

Step 3: if the following two conditions are met at the same time: (1) the accumulated passengers in area $M_{(L+1)}$ is within its safe capacity under the current control level L and (2) the current control level L is less than or equal to three. Accept and output the current control level L and the corresponding optimal passenger flow control strategies and termination; otherwise, go to step 4.

Step 4: let $L = L + 1$; go to step 2.

4. Real-World Case Study

4.1. Case Information and Model Parameters. A real-world case study of the Batong line in Beijing subway is considered to test the performance of the proposed AMLC passenger flow control model. The Batong line is a bidirectional subway line consisting of 13 stations with a total length of 18.94 km, as shown in Figure 5. The up direction is from SH station to TQ station, and the down direction is from TQ station to SH station.

The time range studied in this case study is set as 7:00-10:15. In each direction, the total number of involved trains is 37, the equal headway is 240 (s) according to the pregiven timetable, and the maximum train capacity is 1850 (persons). In addition, the maximum passing capacity of each gate I, II, and III are set as 300, 400, and 500 (persons) at each timestamp, respectively. And the certain fluctuate range between two contiguous timestamps of each gate is set in the interval [-50, 50] (persons). Table 2 displays the net acreage of each key area of all stations on the Batong line. And the safety limitation factor on the platform and other key areas are given as $\alpha = 1.41$ and $\varphi = 3$ (persons/m^2), respectively [39]. The percentage of the acreage at the entrance, the nonpaid zone of the station hall, and the paid zone of the station hall assigned to the passengers at each station in each direction are shown in Table 3. When implementing the passenger flow control, 40% of the total platform acreage can be reduced and added

Table 2: The net acreage of each area of all stations on the Batong line.

Stations	Station hall (m^2)		Side platform (m^2)
	Nonpaid zone	Paid zone	
TQ	496	445	635
LHL	475	425	692
LY	447	423	692
JKS	465	424	692
GY	497	441	917
TZ-BY	404	516	824
BLQ	476	510	638
GZ	665	680	585
SQ	441	732	587
CU	608	779	611
GBD	622	762	612
SH-E	788	3780	620
SH	829	2348	470

Table 3: The percentage of the acreage assigned to the passengers on each direction of all stations.

Stations	Up direction	Down direction	Stations	Up direction	Down direction
TQ	10%	90%	BLQ	5%	95%
LHL	10%	90%	GZ	5%	95%
LY	10%	90%	SQ	10%	90%
JKS	15%	85%	CU	5%	95%
GY	5%	95%	GBD	15%	85%
TZ-BY	15%	85%	SH-E/SH	80%	20%

to the acreage of the paid zone of station hall at each station in order to make the best use of the platform. To trade off the realistic situations and computational efficiency, the time length of each time interval is set as $t_p = 1$ (min).

The computational calculation in two scenarios is solved by calling ILOG CPLEX with MATLAB on a Windows 10 personal computer with Intel Core 5 CPU with 1.8 Gb processor.

5. Results and Analysis

5.1. Scenario 1: The Normal-Scale Passenger Demand during Morning Peak Hours. In this scenario, the real-world passenger demand we used were collected from the Automatic Fare Collection (AFC) System for every one minute in Beijing subway on a working day in 2018. The passenger demand at each station on the up and down direction are illustrated in Figure 6. It is observed that all stations on the up direction, except for SH station and SH-E station, have small arrival passenger flow volume. On the contrary, most stations on the down direction have massive inflows, except for SH station, SH-E station, and GBD station.

Without passenger flow control, the number of accumulated passengers on the platform of the up direction is within its safe capacity during the whole-time range, while the down direction is not. This indicates that the down direction of the Batong line requires passenger flow control, which is consistent with the judgment based on the large-scale passenger flow volume on the down direction. According to the methodology of adaptive control in Section 3.7, after the computational process of 419 s, the appropriate control level for passenger demand on the down direction is control level one (i.e., $L = 1$). Here, we use the computational experiments for the passenger demand on the down direction to illustrate the performance of the proposed AMLC passenger flow control model.

With the passenger flow control (denoted by WPC), the total waiting time for passengers can easily be calculated by the proposed model. For comparison, without the passenger flow control (denoted by NPC), we can calculate the total waiting time for passengers according to the following idea. With NPC, all passengers enter the platform freely. As the massive arrival passenger volume during the morning peak, a large part of them cannot board the first approaching train and have to queue up to wait for the next several trains. We assume that passengers with different destinations are well mixed and boarding randomly at each station [10, 11] to estimate the number of boarding passengers with different OD trips. The number of boarding passengers for a train is simultaneously constrained by the remaining capacity of the train and the total waiting passengers on the platform. And the total waiting time for passengers is calculated by the sum of the waiting time for each passenger from arriving at the station to boarding the station.

The total waiting time for passengers with NPC and WPC are shown in Table 4. In contrast to the results with NPC, the total passenger waiting time can be shortened to 2388 min with WPC, corresponding to the reduction percentage of 0.25%. Practically, this result is influenced by the passenger flow characteristics of the Batong line. Passengers with SH-E station or SH station as destinations make up 94% of total passenger demands in the morning peak. Owing to such passenger flow characteristics of lacking diversity, it is hard to adjust passengers with different OD trips boarding trains in a rational order. The total passenger waiting time is difficult to be obviously shortened, but the proposed model guarantees the number of accumulated passengers in each key area of the station within its safe capacity.

Table 5 shows the time range for exceeding the safe capacity in each key area of all stations, in which TRESC denotes the time range for exceeding the safe capacity, SC denotes the safe capacity, MAP denotes the maximum number of accumulated passengers during the study time range, and '—' means not existing the time range for exceeding the safe capacity. Under the situation of NPC, the number of accumulated passengers on the platform of GZ station, SQ station, and CU station are exceeding their safe capacity of the platform at the time interval of [77, 115], [38, 150], and [43, 173], respectively, and the maximum number of accumulated passengers reach up to 1772, 4340, and 4907, respectively, which will cause potential threats to the operational safety. On the contrary, under the situation of WPC (i.e., $L = 1$), the number of accumulated passengers on the

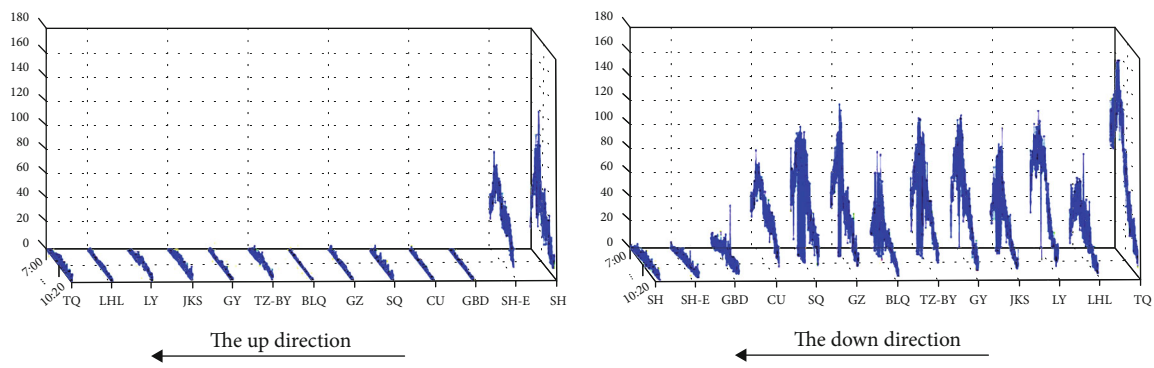

Figure 6: The arrival passenger volume on the up and down direction of the Batong line.

Table 4: Comparison of the total passenger waiting time with NPC and WPC ($L = 1$).

Evaluation indicators	NPC ($L = 0$)	WPC ($L = 1$)	Difference
Total passenger waiting time (min)	955713	953325	-2388
Waiting time in the paid zone (min)	—	738259	—
Waiting time on the platform (min)	955713	215066	—
Computation time (s)	—	419	—

platform at each station is accurately controlled, and the numbers of accumulated passengers in the paid zone at each station hall are guaranteed to be within their safe capacity during the study time range.

Under the situation of NPC, the number of boarding passengers is mainly constrained by the remaining capacity of the coming train. At each station, a large part of passengers are taking SH-E station or SH station as destinations, and few of them getting off at the intermediate stations. With the train capacity continuously occupied by the passenger demands at the upstream, there is less and less remaining capacity of the train to satisfy the passenger demands at subsequent stations. It is for this reason that the total arrival passengers at the CU station and SQ station are not much larger than the other stations, but the number of accumulated passengers on the platform of these two stations is significantly larger than those on the other stations. As for WPC, by accurately controlling the number of passengers entering the platform and boarding trains, the number of boarding passengers at each station is balanced and large amounts of accumulated passengers are prevented.

Next, we take CU station as an example to give a detailed comparison of the amounts of boarding passengers (represented by BOP) for each train, accumulated passengers on the platform (represented by $P_{M_{(1)}}$), and accumulated passengers in the paid zone of station hall (represented by $PS_{M_{(2)}}$) for the situations with WPC and NPC. Under the situation of NPC, few passengers can board the 1st to the 31st trains (see Figure 7), because these trains are occupied by passengers at the upstream stations, which leads to large amounts of passengers at the current station accumulated on the platform (see Figure 8). Under the situation of WPC, more passengers have a chance to board trains due to the collaborative control on the subway line. Moreover, since passengers are distributed to wait on the platform and nonpaid zone, large amounts of accumulated passengers on the platform are effectively prevented.

5.2. Scenario 2: The Abnormal Large-Scale Passenger Demand during Morning Peak Hours. The passenger demand applied in this scenario is the hypothetical abnormal large-scale passenger demand on the Batong line. The passenger flow on the up direction is the same as that in scenario 1, and the passenger flow in the down direction is 1.5 times as much as that in scenario 1. In this scenario, since the passenger flow on the down direction is more than that in scenario 1, it is necessary to activate passenger flow control to prevent passenger accumulation. In the same way, the experiments are conducted to test the effectiveness of the AMLC passenger flow control model only using the passenger demand on the down direction.

Under this circumstance, the computational process is terminated in 804 s, the proposed model automatically activates the appropriate control level, and the current activated control level is level three (i.e., $L = 3$). The total passenger waiting time we obtained is 4872132 min, which includes 220532 min on the platform, 2879104 min in the paid zone of station hall, 1149835 min in the nonpaid zone of station hall, and 622661 min at the station entrance. Table 6 shows the time interval for exceeding the safe capacity in the key area of all stations. We can see that, under the situation of WPC, when the current activated level is level one (i.e., $L = 1$), the number of accumulated passengers in the paid zone of 7 station halls exceed their safe capacity at different time ranges. And when the current activated level is level two (i.e., $L = 2$), the number of accumulated passengers in the nonpaid zone of 7 station halls exceed their safe capacity at different time ranges. Nevertheless, when the current activated level is level three (i.e., $L = 3$), the number of accumulated passengers at the station entrance of all stations is within their safe capacity. By comparing different control

Table 5: The time range for exceeding the safe capacity in each key area of all stations ($L = 1$).

	NPC ($L = 0$)			WPC ($L = 1$)					
		Platform			Platform		Paid zone of station hall		
	TRESC	SC	MAP	TRESC	SC	MAP	TRESC	SC	MAP
TQ	—	895	545	—	537	537	—	1964	326
LHL	—	976	189	—	585	317	—	1978	801
LY	—	976	361	—	585	585	—	1973	1972
JKS	—	976	325	—	585	269	—	1912	247
GY	—	1293	364	—	776	776	—	2357	2354
TZ-BY	—	1162	380	—	697	622	—	2305	1620
BLQ	—	900	351	—	540	113	—	2219	403
GZ	[77, 115]	825	1772	—	495	492	—	2640	1339
SQ	[38, 150]	828	4340	—	497	406	—	2681	577
CU	[43, 173]	862	4907	—	517	517	—	2953	1819
GBD	—	863	84	—	518	83	—	2678	4
SH-E	—	874	23	—	525	23	—	3012	1

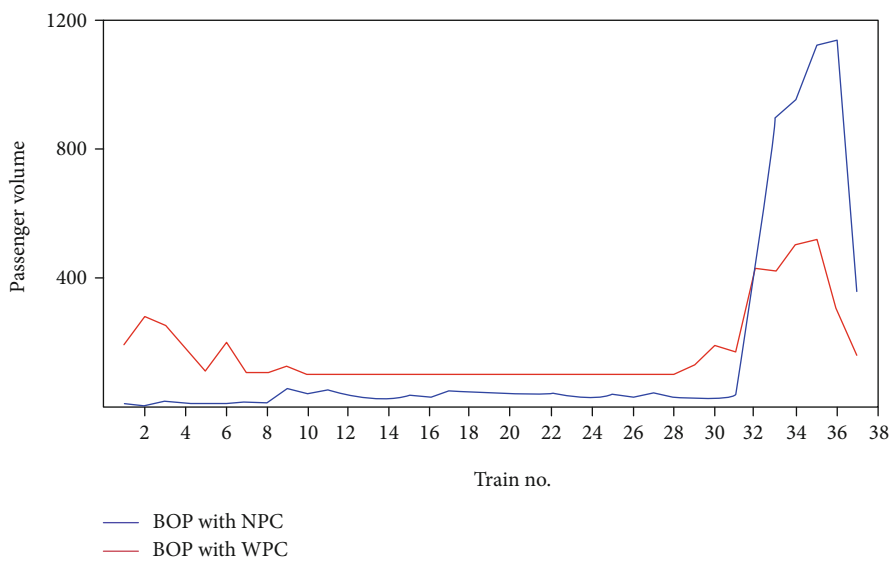

Figure 7: Boarding passengers at CU station.

levels (i.e., $L = 1,2,3$), we can see that the control level three (i.e., $L = 3$) automatically activated by the proposed model is reasonable for the demand of this case. With WPC of control level three, it is guaranteed that the number of accumulated passengers in each key area of the station is within its safe capacity, which makes the operational safety for the subway system.

Next, under the situations of WPC with each control level (i.e., $L = 1,2,3$), we also take CU station as an example to display the MAP on the platform, in the paid zone, in the nonpaid zone and at the station entrance, respectively. In Figure 9, we can see that the MAP in each key area is within its safe capacity with control level three, which is fulfilled by simultaneously controlling the number of passengers entering the platform, the paid zone, and the nonpaid zone. Comparing to the inbound control and station hall control, the passengers are distributed in each key area of the station with the multilevel control strategy in this paper, which ameliorates the waiting environments of most passengers and meanwhile guarantees their safety. In practice, when the control level three is activated, the operation staff should be arranged at the location of gates I, II, III at the same time to ensure the safety of each key area of the station. In contrast, with regard to the scale passenger volume in this scenario, the control levels one and two are not adequate, for the MAP in the paid zone and in the nonpaid zone are exceeding their safe capacity (see Figure 9), respectively, thus leading to potential safety problems. Therefore, we can conclude that activating the appropriate control level is very important, which not only avoids the security problems caused by insufficient control levels but avoids the situation of wasting staff due to high control levels.

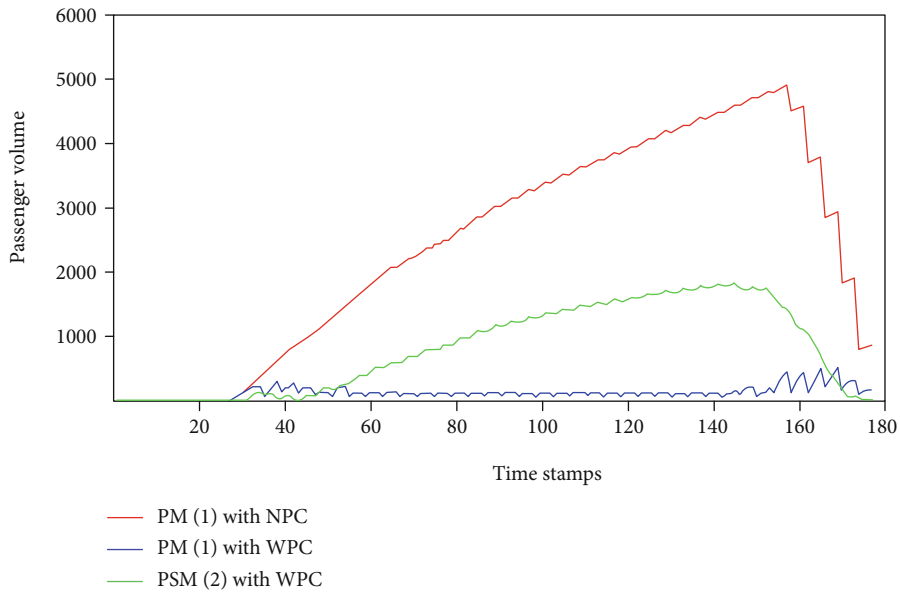

Figure 8: Accumulated passengers in the key area at CU station.

Table 6: The time range for exceeding the safe capacity in the key area of all stations ($L = 3$).

	WPC ($L = 1$) Paid zone of station hall			WPC ($L = 2$) Nonpaid zone of station hall			WPC ($L = 3$) Station entrance		
	TRESC	SC	MAP	TRESC	SC	MAP	TRESC	SC	MAP
TQ	[21, 150]	1964	10437	[62, 150]	1339	5016	—	+∞	2332
LHL	—	1978	1101	—	1283	581	—	+∞	259
LY	[43, 156]	1973	8284	[72, 156]	1207	3852	—	+∞	1279
JKS	—	1912	1073	—	1186	1179	—	+∞	1068
GY	[58, 162]	2357	4407	[89, 162]	1416	3309	—	+∞	1820
TZ-BY	[55, 165]	2305	6776	[84, 165]	1030	3310	—	+∞	478
BLQ	—	2219	234	—	1357	826	—	+∞	962
GZ	[63, 171]	2640	5753	[113, 137]	1895	2352	—	+∞	518
SQ	[76, 174]	2681	5612	[92, 174]	1191	4690	—	+∞	2590
CU	[80, 177]	2953	5176	[122, 177]	1733	3153	—	+∞	1602
GBD	—	2678	22	—	1586	22	—	+∞	0
SH-E	—	3012	1	—	473	1	—	+∞	0

+8 means infinity.

6. Conclusion

In this paper, the multilevel collaborative passenger flow control strategy integrating the control of station entrance and station hall was investigated to ameliorate the waiting environment for passengers. In order to keep transport efficiency, an adaptive multilevel collaborative passenger flow control model is proposed with the total passenger waiting time including the waiting time on the platform and the other key area of the station as the objective. By considering the train transport capacity, the safe capacity of key area in station and the passing capacity of each gate, the problem was established as an integer linear programming model that can be solved by CPLEX solver. A methodology of adaptive control was formulated that can activate the appropriate control level under different scales of passenger demands. Real-world case study with two scenarios shows that the appropriate control level can be accurately activated under different scales of passenger demands. In comparison to the situation without passenger flow control or with the inappropriate control level, the formulated model that ensure the amounts of accumulated passengers in each key area of the station is within its safe capacity, distributing passengers waiting in the station hall or outside the station, and to some extent reducing the total passenger waiting time.

Further research will focus on the following two major aspects. (1) For some passengers, travels are mostly across different subway lines. In that case, considering the passenger route selecting and transfer activity will be a research direction for controlling passenger flow in peak hours under the

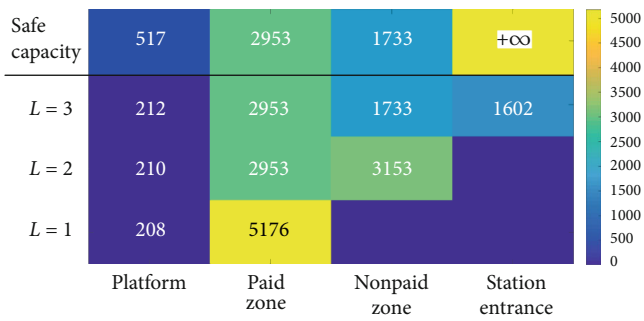

Figure 9: The MAP in the key area with different control levels at CU station.

network operation. (2) The process of passenger activity and train operation are mutually related. Hence, researching the combination of passenger flow control with train operation control will be another research direction for solving the problem of crowded passenger flow in the subway system.

Data Availability

The data used to support the findings of this study have not been made available because they are the internal operation data of the Beijing subway. The author was not granted the right to disclose.

Conflicts of Interest

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

Acknowledgments

This study was funded by the Fundamental Research Funds for the Central Universities (2019JBM032).

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