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Subway Multi-Station Coordinated Dynamic Control Method Considering Transfer Inbound Passenger Flow

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Abstract: The prominent contradiction between passenger demand and capacity in rush hours at subway stations causes inconveniences to travel and even leads to safety risks. Existing research on the cooperative control of passenger flow at stations mostly focuses on a single direction, rarely considering transfer passenger flow control. This study formulated a coordinated dynamic control strategy for multiple stations in both directions as a deterministic mathematical programming model to optimise the crowded passenger flow. The optimisation objectives were set as the warning levels of crowded passenger flow and the detention time of all passengers. The constraints included limitations on station service capacity, train capacity, and the number of people boarding trains. Additionally, considering separate control over the transfer inbound passenger flow at transfer stations, an upward- and downward-direction coordinated dynamic control model was constructed. Numerical experiments based on real-world data from the Nanjing Metro Line 1 were conducted to investigate the effectiveness of the proposed cooperative control scheme and evaluate its performance.

Keywords: upward and downward direction; subway multi-station; coordinated dynamic control; crowded passenger flow; transfer inbound passenger flow

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1. Introduction

The subway is a widely applied mode of passenger flow transportation. It has distinctive advantages in mitigating traffic issues in metropolitan areas, with the attributes of a high carrying capacity, rapid travel speed, punctuality, etc. However, during the rush hours in some cities in China, like Beijing, Shanghai, and Nanjing, there is a highly concentrated spatial and temporal distribution of passenger flow in subway stations. Particularly at major commuter stations and transfer hubs, the growing contradiction between high demand and limited traffic capacity poses safety risks, such as stampedes, panic situations, suffocation incidents, and passenger falls during emergencies [1]. Therefore, it is crucial to implement effective passenger flow control measures for maintaining an appropriate distance between passengers and alleviating platform congestion.

To improve operational efficiency in metro networks, some researchers have focused on transfer manipulation in the metro design process. Guo et al. explored the possibility of using subway maps as a planning tool to influence passengers' route choices to alleviate congestion [2]. Kim et al. utilised the bootstrap-based DEA technique to analyse the transfer efficiency of Seoul subway stations, and investigated the reasons for the low efficiency of transfer stations [3]. Based on the optimal cost-effectiveness ratio, Owais et al. introduced the no-demand criterion to develop a subway network design model, increasing the connectivity of the entire transportation system by reducing passenger transfers [4].

With regard to passenger flow control at a single station, strategies in existing research were often proposed according to the capacity of station facilities and equipment.

Diverse on–off and off-board strategies minimising passenger travel time were developed by Baee et al. to enhance passenger satisfaction and service success rates [5]. Seriani and Fernandez investigated the impacts of cost-effective pedestrian control management on passenger boarding and alighting time in subway stations, using micro-simulations and pedestrian traffic experiments [6]. Xu et al. put forward novel and comprehensive frameworks, namely, the Subway Gate Service Capability, Subway Line Service Capability, and Subway Station Service Capability models, to evaluate the service capabilities of subway stations [7]. To address a scenario in which the final destination of inbound passengers is unknown, Zhang et al. proposed a station-based dynamic constrained flow control problem, aimed at dynamically determining the optimal number of passengers boarding each train at every station [8].

Due to limitations in the capacity of various facilities and equipment within a single station, congestion here may not be effectively alleviated with the above strategies. Accordingly, some studies concentrated on passenger flow control problems for multiple stations on a line or network. By formulating a nonlinear quadratic integer programming model, Niu et al. optimised a train stopping scheme for fixed lines to minimise the overall waiting time of passengers [9]. Jiang et al. proposed a novel approach based on reinforcement learning to optimise passenger flow at each station during specific time periods, with safety risks for subway passengers minimised [10]. Shi et al. investigated a collaborative optimisation approach for the precise control of passenger flow on supersaturated subway lines by minimising the cumulative waiting time of all passengers [11]. To minimise the total waiting time of passengers while ensuring the safety capacity, Xue et al. developed an adaptive multi-level cooperative strategy integrating the station entrance and lobby control [12]. By integrating train scheduling and passenger flow control, Gong et al. put forward a comprehensive method that optimised passenger service balance and train capacity utilisation [13]. Liu et al. studied the collaborative optimisation of subway train scheduling and train connection planning to achieve a balance between train utilisation, passenger flow management, and platform waiting numbers [14]. Yin et al. introduced a single-line balanced passenger flow control model and successfully replicated various control strategies by incorporating distinct forms of delay penalty functions [15]. Xu et al. proposed a novel model for multi-station coordinated passenger flow control to regulate inbound and transfer passenger flows simultaneously entering multi-stations or multi-lines [16]. The coordination relationship between traffic demand and strict transport capacity constraints was systematically examined by Yuan et al., with a network-based control model developed to minimise the total waiting time of passengers [17]. Yuan et al. explored train scheduling and passenger flow control strategies for large-scale subway networks to minimise passenger waiting times by establishing a mixed-integer nonlinear programming model [18].

Comparatively, dynamic control strategies are more applicable in a subway transportation system, as variations in the inbound passenger flow of stations result in dynamic characteristics of lines. Cats et al. proposed a dynamic traffic analysis and assessment tool to construct transit path choices, covering a series of boarding and alighting, walking, and other decisions made by passengers during their journey [19]. Based on passenger flow origin–destination data, Li and Zhou put forward an algorithm for the dynamic analysis of transfer passenger flow, thereby optimising the operation and management of transfer stations [20]. Barrena et al. studied the design and optimisation of train schedules for rail rapid transit lines adapted to dynamic demand to minimise the average waiting time of passengers at stations [21]. Samson et al. introduced a crowd dynamics model to help understand crowd behaviour in the concourse area of the MRT3 Taft Avenue station in order to develop strategies to reduce crowding [22]. The algorithm proposed by Owais and Hassan simulated the load situation of passengers and buses arriving, which combined waiting time models to realise route selection and passenger flow dynamic allocation [23]. Gao et al. established a dynamic change model of subway station passenger flow to describe the dynamic changes in the number of passengers and facility service levels [24]. Shi et al. developed an integer linear programming model to depict the process of passenger control in order to minimise both the total waiting time for passengers and the cumulative risk they face at all stations [25]. Existing research mainly focuses on passenger flow control in a single-train direction. This does not match the actual situation where passageways, stairs, and platforms bear the burden of two-way passenger flow in many subway stations. In addition, passenger flow control strategies mostly consider passenger conditions within stations based on the inbound passenger flow, with transfer passenger flow scarcely investigated. Thus, congestion issues may not be alleviated effectively.

To address these research deficiencies, this study aims to develop an upward- and downward-direction coordinated dynamic control method for real-time passenger flow control at multiple stations. Separate control measures are integrated for passenger flow at transfer stations to manage crowded passenger flow and ensure operational safety at the station at the same time. The main contributions of this study are as follows:

(1) In the collaborative dynamic control model, passenger flow control in both the upward and downward directions are taken into account, with inbound and transfer passenger flow control measures separately implemented in transfer stations.

(2) To ensure each station on a line operates in a safe state, the concept of a warning level is defined for the safety assessment of subway stations. The sum of warning levels of all stations is taken as an optimisation objective in the optimal model, while the warning level in each station is limited by the constraint conditions.

The remainder of this paper is organised as follows. In Section 2, the collaborative dynamic control method for multi-station scenarios is constructed. Section 3 presents a case study of Nanjing metro stations, using real-world data to validate the efficiency of the proposed method. Finally, conclusions and recommendations for future research are provided in Section 4.

2. Methodology

2.1. State Variables

In this study, a subway line is considered as a dynamic system. There are e stations in the system, and S is the station set, that is, $S = \{1, 2, \ldots i, \ldots j, \ldots e\}$. Among them, i is an inbound station, and j is an outbound station. There are $e - 1$ sections divided by the above stations. L is the upward section set, $L = \{l_1, l_2, \ldots l_u \ldots l_{e-1}\}$, where l_u is the upward section between station u and $u + 1$. $\overleftarrow{L}$ is the downward section set, $\overleftarrow{L} = \left\{\overleftarrow{l}_1, \overleftarrow{l}_2, \ldots \overleftarrow{l}_v, \ldots \overleftarrow{l}_{e-1}\right\}$, where $\overleftarrow{l}_v$ is the downward section between stations $v + 1$and v. T is the control period set, $T = \{1, 2, \ldots k, \ldots a\}$, and Δt is the time length of each control period.

2.2. Passenger Flow Demand at Transfer Stations

The passenger flow demand of subway transfer stations consists of two parts, the demand for passengers entering the station normally (only counting passengers destined for this line), and the demand for passengers transferring to this line from other lines. Transfer passenger flow, as an internal passenger flow demand, enters the platform of this line through specifically designated transfer channels from the platforms of other lines. This is markedly distinct from inbound passenger flows at regular stations and necessitates separate considerations.

According to the sources of inbound passenger flow, a transfer station is divided into two different forms, Station A and Station B. As illustrated in Figure 1, Station A specifically caters to the demand for passengers entering the station normally, while Station B accommodates passenger flow demand from other lines.

Accordingly, the original station set S is adjusted to be a new set M including transfer station A and B, with g stations in this system, that is, $M = \{1, 2, 3 \ldots g\}$. Owing to the disparities in inbound passenger flow requirements between transfer and regular stations, it is imperative to establish two autonomous stations. Regarding fundamental data such as line capacity, station design service capacity, and the maximum transport capacity of the section, both stations exhibit congruence and cannot be segregated.

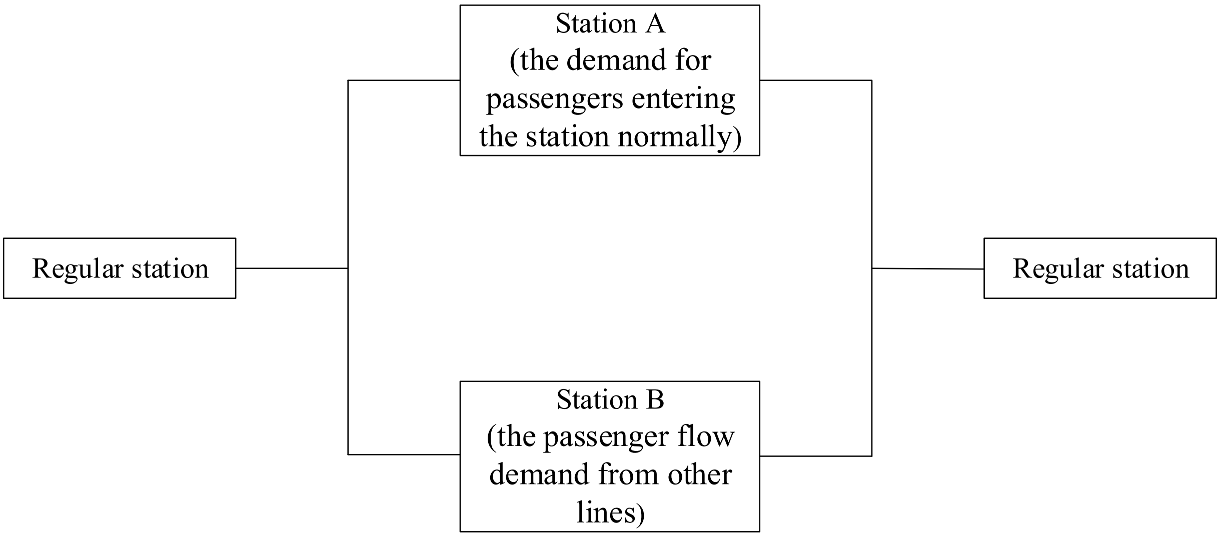


Figure 1. Diagram illustrating the division of transfer stations.

2.3. Assumptions

(1) Since there are all kinds of directional signs in subway stations which give right directions, it is assumed that most passengers can flexibly use various facilities and equipment. Also, they will not stay there for a long time.

(2) This paper studies the large commuter passenger flow during peak hours in the morning and evening. Passenger flow characteristics are relatively obvious and there is no sudden large passenger flow. Therefore, it is assumed that in all control periods, the inbound passenger flow arrival presents a uniform distribution and no sudden surges in passenger numbers.

(3) The probability of operational schedule delay is very small. If it does happen, there is usually an emergency plan to fix it and a sudden large passenger flow has occurred, which is not within the scope of this study. Therefore, it is assumed that the train strictly adheres to its operational schedule without deviations or delays, ensuring a smooth and accident-free journey for passengers.

(4) The outbound passenger flow at regular stations generally has special outbound escalators and gates. Therefore, it is assumed that the impact of the outbound passenger flow from regular stations on the overall passenger demand is negligible.

(5) Most station passages and stairs/escalators can be flexibly deployed at specific times to meet the needs of different passenger flows in and out of the station. Therefore, it is assumed that the capacity of facilities such as concourses, passageways, and stairs/escalators does not significantly affect the passenger flow demand.

(6) Although most subway lines currently have overtaking conditions, due to factors such as comprehensive management and changes in passenger demand, almost no overtaking is implemented. Therefore, it is assumed that all train formations of the line are consistent, with a strict prohibition of overtaking.

(7) The guiding regulation for almost all subway companies is that passengers alight first and board later, and there are also dedicated people to supervise on the platforms. Therefore, it is assumed that all stations follow the principle of passengers alighting first and then boarding.

2.4. Model Construction

2.4.1. Objective Function

The following two objective functions are formulated from the perspectives of station operation and passenger safety, respectively.

Minimise the Detention Time of All Passengers on the Subway Line

The detention time of all passengers on a subway line refers to their delay time.

$$\min \sum\nolimits_{m\in M}\sum\nolimits_{t\in T}\left(B_m^t-\overline{B_m^t}\right)\Delta t \tag{1}$$

where B_m^t denotes the number of passengers who need to board the train at station m during the control period t, and $\overline{B_m^t}$ means the number of passengers who actually board the train at station m during the control period t.

Minimise the Sum of the Early Warning Level Coefficients of Crowded Passenger Flow at Each Station

The early warning level coefficient of crowded passenger flow at each station represents the ratio between the real-time crowded passenger flow early warning levels and the safety levels specific to each station. For real-time responsiveness, this study adopts the station service occupancy coefficient as a determinant for assessing crowded passenger flow early warning levels at each station. It is defined as the ratio between the maximum and designed service capacities, thereby reflecting both the passenger flow occupation of the designed capacity and the overall passenger flow dynamics within a given station.

The station service occupancy coefficients are closely related to the spatial load factor. Based on results on speed, density, flow, service level, and load factor in [26,27], as well as the field investigation, the threshold intervals for spatial load factor that divide the early warning levels of crowded passenger flow are determined, as shown in Table 1.

Table 1. Threshold intervals of the spatial load factor.

Early Warning Level	Level 1	Level 2	Level 3
Threshold interval	(0, 0.3]	(0.3, 0.5]	(0.5, 1]

Level 1 is characterised by a secure flow state that represents a safe level. Both Levels 2 and 3 experience high passenger congestion, with Level 2 being relatively dangerous and Level 3 posing extreme danger.

Based on the above threshold intervals of the spatial load factor and field investigation, with the margin of error in identifying crowded passenger flows being approximately 5% using the method in [28], the threshold intervals for station service occupancy coefficients are determined, as shown in Table 2.

$$\min \sum\nolimits_{m\in M}\sum\nolimits_{t\in T}\frac{Y_m^t}{\beth} \tag{2}$$

where Y_m^t means the early warning level of station m during the control period t, and $\beth$ represents the early warning safety level.

Table 2. Threshold intervals of the station service occupancy coefficient.

Early Warning Level	Level 1	Level 2	Level 3
Threshold interval	(0, 0.75]	(0.75, 1]	(1, 1.4]

Finally, a multi-objective planning model aimed at minimising the detention time of all passengers on the subway line and minimising the sum of the early warning level coefficients of crowded passenger flow at each station is established as follows:

$$\min \sum_{m\in M}\sum_{t\in T}\left(B_m^t-\overline{B_m^t}\right)\Delta t$$

$$min \sum_{m \in M} \sum_{t \in T} \frac{Y_m^t}{\beth}$$

2.4.2. Constraints

The Number of Passengers Allowed to Enter Through the Inbound Gate

At the entrance and exit of the toll area in a subway station, the capacity of the entrance/exit gate restricts the number of passengers entering and leaving the station. Considering that outbound passenger flow tends to spread over time and has a minimal impact on inbound passenger demand, it is crucial to ensure that the influx of new inbound passengers does not exceed the capacity of the inbound gate.

It is assumed that all inbound passengers utilise non-contact IC cards or mobile QR codes along with other automated ticket-checking methods, disregarding manual ticket checks. The maximum capacity of three Auto Fare Collection (AFC) gate types, namely three-bar style $(f = 1)$, door style $(f = 2)$ and two-way door style $(f = 3)$ is respectively 1200 passenger/h, 1800 passenger/h and 1500 passenger/h [29].

The restrictions on the number of passengers entering the inbound AFC gates are expressed as follows:

$$\overline{B_s^t} \leq \alpha_s C_Z^f \Delta t, \forall t \in T, \forall s \in S \tag{3}$$

where $\overline{B_s^t}$ means the number of passengers who actually board the train at station s during the control period t, α_s denotes the number of inbound AFC gates at station s, and C_Z^f represents the maximum capacity of the fth inbound AFC gate type. S is the station set (transfer station is not split), that is, $S = \{1, 2, \ldots i, \ldots \mathrm{s}, \ldots j, \ldots e\}$.

Station Service Capacity

In the cooperative dynamic control of multi-station passenger flow in both directions, station design service capacity is considered to ensure that the number of passengers who actually board the train does not exceed the design service capacity.

$$\overline{B_m^t} \leq \varnothing C_m^w \Delta t, \forall t \in T, \forall m \in M \tag{4}$$

where $\varnothing$ means the reduction ratio of station design service capacity to ensure safe operation, and C_m^w denotes the design service capability of station m.

Meanwhile, as a part of inbound demand, the transfer inbound passenger flows for a station need to be restricted to ensure that the sum of new inbound passenger flow for this line and transfer inbound passenger flow does not surpass the platform capacity.

$$B_s^t \leq C_s^{pf} \Delta t, \forall t \in T, \forall s \in S \tag{5}$$

where B_s^t means the number of passengers who need to board the train at station s during the control period t, and C_s^{pf} represents the maximum platform capacity of station s.

The calculation formula for the maximum transfer passenger flow is as follows:

$$\overline{B_{hc}^t(s)} = C_{l_{s-1}}^t - C_{l_s}^t + C^t_{\overset{\leftharpoonup}{l_s}} - C^t_{\overset{\leftharpoonup}{l_{s-1}}} + \overline{B_s^t} - EX_s^t, \forall t \in T, \forall s \in S \tag{6}$$

where $\overline{B_{hc}^t(s)}$ denotes the maximum transfer passenger flow of this line at station s during the control period t, $C_{l_{s-1}}^t$ means the passing passenger flow of the upward section l_{s-1} during the control period t, $C^t_{\overset{\leftharpoonup}{l_s}}$ represents the passing passenger flow of the downward section $\overset{\leftharpoonup}{l_s}$ during the control period t, and EX_s^t means the number of passengers whose starting station is on this line and the terminal station is station s during the control period t.

As the transfer outbound passenger flow from this line may exert significant pressure on the transportation capacities of other lines, potential section-blocking issues may arise.

Limitations are imposed to reduce the transfer outbound passenger flow, with the following constraints on service capacity:

$$\overline{B^{t}_{hc}(s)} \leq \beta B^{t}_{hc}(s), \forall t \in T \tag{7}$$

where $B^{t}_{hc}(s)$ means the actual transfer passenger flow of this line at station s during the control period t, and β denotes the reduction ratio of transfer outbound passenger flow.

Train Capacity

To ensure the safe and efficient operation of a train, it is imperative that the number of passengers on board does not exceed the train capacity. This implies that the number of passengers who board the train should not surpass the sum of the train's residual capacity and the number of passengers alighting the train.

Train's residual capacity is calculated as follows:

$$C^{t}_{l_{s-1},max} = \eta_{max}\gamma C_{V}\varphi^{t}_{l_{s-1}}, \forall t \in T, \forall m \in M \tag{8}$$

$$C^{t}_{\overleftharpoonup{l_{s+1}},max} = \eta_{max}\gamma C_{V}\varphi^{t}_{\overleftharpoonup{l_{s+1}}}, \forall t \in T, \forall m \in M \tag{9}$$

where $C^{t}_{l_{s-1},max}$ means the maximum transportation capacity of the upward section l_{s-1} during the control period t, η_{max} means the maximum train load rate, γ represents the number of vehicle formations, C_{V} denotes the vehicle capacity, $\varphi^{t}_{l_{s-1}}$ represents the number of arriving trains of the upward section l_{s-1} during the control period t, $C^{t}_{\overleftharpoonup{l_{s+1}},\ max}$ means the maximum transportation capacity of the downward section $\overleftharpoonup{l_{s+1}}$ during the control period t, and $\varphi^{t}_{\overleftharpoonup{l_{s+1}}}$ represents the number of arriving trains of the downward section $\overleftharpoonup{l_{s+1}}$ during the control period t.

The number of passengers alighting the train is formulated as follows:

$$GO^{t}_{s,sx} = XC^{t}_{l_{s-1},sx}C^{t}_{l_{s-1}}, \forall t \in T, \forall m \in M \tag{10}$$

$$GO^{t}_{s,xx} = XC^{t}_{\overleftharpoonup{l_{s+1}},xx}C^{t}_{\overleftharpoonup{l_{s+1}}}, \forall t \in T,\ \forall m \in M \tag{11}$$

$$GO^{t}_{s} = GO^{t}_{s,sx} + GO^{t}_{s,xx} \tag{12}$$

where $GO^{t}_{s,sx}$ means the number of passengers alighting the train in the upward direction of station s during the control period t, $XC^{t}_{l_{s-1},sx}$ denotes the train alight rate of the upward section l_{s-1} during the control period t, $GO^{t}_{s,xx}$ represents the number of passengers alighting the train in the downward direction of station s during the control period t, $XC^{t}_{\overleftharpoonup{l_{s+1}},xx}$ means the train alight rate of the downward section $\overleftharpoonup{l_{s+1}}$ during the control period t, and GO^{t}_{s} denotes the number of passengers alighting the train at station s during the control period t.

And then, distinct limiting conditions for train capacity in both upward and downward directions are expressed by the corresponding calculation formulas.

$$\overline{B^{t}_{s,sx}} \leq C^{t}_{l_{s-1},max} - C^{t}_{l_{s-1}} + GO^{t}_{s,sx}, \forall t \in T, \forall s \in S \tag{13}$$

$$\overline{B^{t}_{s,xx}} \leq C^{t}_{\overleftharpoonup{l_{s+1}},\ max} - C^{t}_{\overleftharpoonup{l_{s+1}}} + GO^{t}_{s,xx}, \forall t \in T,\ \forall s \in S \tag{14}$$

$$\overline{B^{t}_{s}} = \overline{B^{t}_{s,sx}} + \overline{B^{t}_{s,xx}}, \forall t \in T,\ \forall s \in S \tag{15}$$

where $\overline{B_{s,sx}^{t}}$ means the number of passengers who actually board the train in the upward direction of station s during the control period t, and $\overline{B_{s,xx}^{t}}$ denotes the number of passengers who actually board the train in the downward direction of station s during the control period t.

The Number of Passengers Who Need to Board the Train

The number of passengers who need to board the train during the control period t comprises two parts: the number of new incoming passengers during the control period t and the number of passengers stranded during the control period $t-1$.

$$B_{m}^{t} = D_{m}^{t} + R_{m}^{t-1},\ \forall t \geq 2,\ t \in T,\ \forall m \in M \tag{16}$$

where D_{m}^{t} means the number of new incoming passengers at station m during the control period t and R_{m}^{t-1} denotes the number of passengers stranded at station m during the control period $t-1$.

In addition, the number of passengers stranded during the control period $t-1$ can be determined by subtracting the number of passengers who actually board the train during the control period t from the number of passengers who need to board the train during the control period t. The calculation formula is as follows:

$$R_{m}^{t-1} = B_{m}^{t} - \overline{B_{m}^{t}}, \forall t \geq 2,\ t \in T,\ \forall m \in M \tag{17}$$

Station m in control period 1 only has new incoming passengers; hence, $B_{m}^{1} = D_{m}^{1}$.

The number of passengers who actually board the train should not exceed the number of passengers who need to board the train; under normal circumstances, the station will remain open unless there are exceptional situations (for example, halting at a major station). Therefore, it is essential that the number of passengers who board the train also satisfies the minimum requirement.

$$\varepsilon B_{m}^{t} \leq \overline{B_{m}^{t}} \leq B_{m}^{t}, \forall t \in T,\ \forall m \in M \tag{18}$$

where ε denotes the proportion of the minimum number of passengers boarding the train.

Simultaneously, to ensure passenger safety and smooth operation, when considering the platform capacity, it is necessary to limit stranded passengers to avoid surpassing the carrying capacity of the platform.

$$R_{s}^{t} \leq C_{s}^{pf}, \forall t \in T,\ \forall s \in S \tag{19}$$

where R_{s}^{t} means the number of passengers stranded at station s during the control period t.

According to the principle of passengers alighting first and then boarding, it is imperative that the combined count of the number of passengers who need to board the train and the number of passengers alighting the train does not surpass the platform's capacity.

$$B_{s}^{t} + GO_{s}^{t} \leq \varphi_{l_{s-1}}^{t} C_{s}^{pf}, \forall t \in T,\ \forall s \in S \tag{20}$$

The Section Transportation Capacity

Section maximum transportation capacity refers to the maximum number of passengers that can pass through a specific section of the line during a given period.

$$C_{l_u}^{t} = \sum_{s \in S} \sum_{k \in T} \overline{B_{s,sx}^{k}} W_{s,l_u}^{k,t},\ \forall l_u \in L,\ \forall t \in T \tag{21}$$

$$C_{\overleftharpoon{l_v}}^{t} = \sum_{s \in S} \sum_{k \in T} \overline{B_{s,xx}^{k}} W_{s,\overleftharpoon{l_v}}^{k,t},\ \forall \overleftharpoon{l_v} \in \overleftharpoon{L},\ \forall t \in T \tag{22}$$

where $W^{k,t}_{s,l_u}$ represents the proportion of passengers who boarded the train from station s during the control period k through the upward section l_u during the control period t, and $W^{k,t}_{s,\overleftarrow{l_v}}$ means the proportion of passengers who boarded the train from station s during the control period k through the downward section $\overleftarrow{l_v}$ during the control period t.

If the actual passenger volume exceeds this capacity, it results in section obstruction, which is characterised by passenger congestion at the upstream station. In this study, separate limiting conditions for the section transportation capacity in both upward and downward directions are established using the following formula.

$$C^t_{l_u} \le C^t_{l_u,max}, \ \forall l_u \in L, \ \forall t \in T \tag{23}$$

$$C^t_{\overleftarrow{l_v}} \le C^t_{\overleftarrow{l_v},max}, \ \forall \overleftarrow{l_v} \in \overleftarrow{L}, \ \forall t \in T \tag{24}$$

Warning Levels at Stations

To ensure the safe operation of subway stations, it is necessary to maintain passenger flow warning levels within an acceptable safety range for each station.

$$Y^t_m \le Y_2, \forall t \in T, \ \forall m \in M \tag{25}$$

However, certain stations may need to relax these restrictions because of their specific land use attributes. The warning level for crowded passenger flow at each station can be determined by referring to Table 2. Herein, safety level Y_1 corresponds to Level 1, relative danger level Y_2 corresponds to Level 2, and extreme danger level Y_3 corresponds to Level 3. The higher the assigned level, the greater the associated risk of passenger flow at subway stations. The specific limitations are outlined as follows:

$$F^t_m = B^t_m + GO^t_m, \forall t \in T, \ \forall m \in M \tag{26}$$

$$Y^t_m = \begin{cases} 1 \ F^t_m \le 0.75C^w_m, \forall t \in T, \ \forall m \in M \\ 2 \ 0.75C^w_m < F^t_m \le C^w_m, \forall t \in T, \ \forall m \in M \\ 3 \ F^t_m > C^w_m, \forall t \in T, \ \forall m \in M \end{cases} \tag{27}$$

where F^t_m means the number of passengers served by station m during the control period t, and GO^t_m denotes the number of passengers alighting the train at station m during the control period t. When m is the split station of the transfer station, the corresponding number of passengers alighting is the number of passengers alighting this line at the complete transfer station.

The Intensity of Passenger Flow Control

Determining the intensity of passenger flow control at stations is crucial for achieving multi-station upward- and downward-direction coordinated dynamic control. The ratio between the number of passengers stranded during the control period $t-1$ and the number of passengers who need to board the train during the control period t is used to represent the station's passenger flow control intensity. The calculation formula is as follows:

$$G^t_m = \frac{R^{t-1}_m}{B^t_m}, \forall t \in T, \ \forall m \in M \tag{28}$$

where G^t_m means the intensity of passenger flow control of station m during the control period t.

The demand for the inbound passenger flow is significantly influenced by the characteristics of the land surrounding the station. Moreover, the transfer inbound passenger flow is a type of in-station passenger flow. Excessive control measures can result in congestion and the accumulation of passengers within a station, thereby posing safety risks. Hence, it is necessary to implement differentiated restrictions on passenger flow control based on station attributes.

The restrictions are as follows:

$$G_m^t \leq \begin{cases} 0.25, m \text{ is commuter station} \\ 0.5, m \text{ is } \mathit{general} \text{ station} \\ 0.15, m \text{ is transfer station} \end{cases} \tag{29}$$

2.5. Model Solution

Model parameters involve the inbound passenger flow at different times, the number of trains operating at each station, the number of passengers that can pass through a specific section, and other relevant parameters. Owing to the diverse and intricate nature of these parameters, the MATLAB R2018 is utilised to analyse train operation schedules and subway AFC data, thereby facilitating the calculation of each parameter's value.

The model constructed is a multi-objective linear programming model, the solution approach of which is to transform multiple objectives into a single-objective problem. Common methods for this include the ideal point method, weighted sum method, goal programming, maximum–minimum method, and fuzzy mathematical method. Considering the significant disparity in magnitude between the two objective functions, as well as numerous model constraints, the ideal point method is adopted.

By utilising the YALMIP toolbox within the MATLAB software, the optimal solutions f_1^* and f_2^* for both objective functions are obtained. Subsequently, an evaluation function is constructed using the shortest distance ideal point method to identify an approximate optimal solution closest to $[f_1^*, f_2^*]$. The specific formula is as follows:

$$\psi = \min\sqrt{(f_1 - f_1^*)^2 + (f_2 - f_2^*)^2} \tag{30}$$

3. Case Study

3.1. Experimental Background

Nanjing Metro Line 1, the first subway line in Nanjing, began operating on 3 September 2005. This line traverses the Qixia, Gulou, Xuanwu, Qinhuai, Yuhuatai, and Jiangning districts and has a total length of 38.9 km. There are 27 stations in total, including five transfer stations: Nanjing, Gulou, Xinjiekou, Andemen, and Nanjing South Stations. According to December 2020 statistics, the daily ridership on this line reached an average of approximately 1,020,000 passengers.

Line 1 operates in mixed mode, encompassing both long and short routes. The long route spans from Maigaoqiao Station to the China Pharmaceutical University Station, whereas the short route covers the distance between Maigaoqiao Station and Hedingqiao Station. The downward direction is from Maigaoqiao Station to Hedingqiao Station/China Pharmaceutical University Station, and the upward direction is from Hedingqiao Station/China Pharmaceutical University Station to Maigaoqiao Station. The first train departs at 05:42, and the last train departs at 23:19 in the downward direction, whereas in the upward direction, the first train departs at 05:47, and the last train departs at 23:27.

Line 1, a north–south rail transit line running through Nanjing City, has experienced prolonged opening times and exhibits clear commuter flow characteristics. During weekday morning and evening peak hours, the passenger flow remains relatively stable. Some stations along Line 1 experience overcrowding and supersaturation during peak hours. In addition, owing to the inclusion of Nanjing CBD in its route, Line 1 attracts a larger influx of passengers from other lines. To address these issues, Line 1 is selected for the case study to simultaneously control the normal and transfer inbound passenger flows in both the upward and downward directions.

3.2. Basic Data

Model parameters are elucidated and calculated based on both the Nanjing Metro train operating schedule and the AFC data in October 2017. According to the aforementioned analysis and the AFC data for Line 1, the passenger flow exhibits its peak between 7:00 and 9:30. Therefore, this study focuses on the research period spanning from 7:00 to 9:30.

3.2.1. Control Period Number

Considering the departure section magnitude and variations in passenger flow at different time granularities, each control period is set to 15 min. Correspondingly, the research period is divided into ten distinct control periods, with specific numbers shown in Table 3.

Table 3. Control period number.

Control Period	**Number**	**Control Period**	**Number**
7:00–7:15	1	8:15–8:30	6
7:15–7:30	2	8:30–8:45	7
7:30–7:45	3	8:45–9:00	8
7:45–8:00	4	9:00–9:15	9
8:00–8:15	5	9:15–9:30	10

3.2.2. Station and Section Number

Considering the simultaneous need to regulate normal and transfer inbound passenger flows within the transfer station, it is imperative to bifurcate the transfer station into two distinct stations: Transfer Station A, which encompasses normal inbound passenger flow, and Transfer Station B, which accommodates transfer inbound passenger flow. Therefore, the five interchange stations on Line 1 are divided into Nanjing Station A, Gulou Station A, Xinjiekou Station A, Andemen Station A, Nanjing South Station A, Nanjing Station B, Gulou Station B, Xinjiekou Station B, Andemen Station B, and Nanjing South Station B.

The model focuses on the upward and downward directions of the line as the subject of investigation, necessitating separate numbering of stations and sections in each direction. The station and section numbers for the upward and downward directions are listed in Tables 4 and 5, respectively.

Table 4. Section and station number in the upward direction.

Station	**No**	**Section**	**No**
China Pharmaceutical University	1	China Pharmaceutical University–Nanjing Jiaotong Institute	1
Nanjing Jiaotong Institute	2	Nanjing Jiaotong Institute–Nanjing Medical University	2
Nanjing Medical University	3	Nanjing Medical University–Longmian Avenue	3
Longmian Avenue	4	Longmian Avenue–Tianyin Avenue	4
Tianyin Avenue	5	Tianyin Avenue–Zhushan Road	5
Zhushan Road	6	Zhushan Road–Xiaolongwan	6
Xiaolongwan	7	Xiaolongwan–Baijiahu	7
Baijiahu	8	Baijiahu–Shengtai Road	8
Shengtai Road	9	Shengtai Road–Hedingqiao	9
Hedingqiao	10	Hedingqiao–Shuanglong Avenue	10

Table 4. *Cont.*

Station	No	Section	No
Shuanglong Avenue	11	Shuanglong Avenue–Nanjing South R Station A	11
Nanjing South Station A	12	Nanjing South Railway Station A–Huashenmiao	12
Huashenmiao	13	Huashenmiao–Software Avenue	13
Software Avenue	14	Software Avenue–Tianlong Temple	14
Tianlong Temple	15	Tianlong Temple–Andemen A	15
Andemen A	16	Andemen A–Zhonghuamen	16
Zhonghuamen	17	Zhonghuamen–Sanshanjie	17
Sanshanjie	18	Sanshanjie–Zhangfuyuan	18
Zhangfuyuan	19	Zhangfuyuan–Xinjiekou A	19
Xinjiekou A	20	Xinjiekou A–Zhujianglu	20
Zhujianglu	21	Zhujianglu–Gulou A	21
Gulou A	22	Drum Tower A–Xuanwu Gate	22
Xuanwumen	23	Xuanwu Gate–Xinmofan Road	23
Xinmofan Road	24	Xinmofan Road–Nanjing Station A	24
Nanjing Station A	25	Nanjing Station A–Hongshan Zoo	25
Red Mountain Zoo	26	Hongshan Zoo–Maigaoqiao	26
Maigaoqiao	27		
Nanjing South Station B	28		
Andemen B	29		
Xinjiekou B	30		
Gulou B	31		
Nanjing Station B	32		

Table 5. Section and station number in the downward direction.

Station	No	Section	No
Maigaoqiao	1	Maigaoqiao–Hongshan Zoo	1
Hongshan Zoo	2	Hongshan Zoo–Nanjing Station A	2
Nanjing Station A	3	Nanjing Station A–Xinmofan Road	3
Xinmofan Road	4	Xinmofan Road–Xuanwumen	4
Xuanwumen	5	Xuanwu Gate–Gulou A	5
Gulou A	6	Gulou A–Zhujianglu	6
Zhujianglu	7	Zhujianglu–Xinjiekou A	7
Xinjiekou A	8	Xinjiekou A–Zhangfuyuan	8
Zhangfuyuan	9	Zhangfuyuan–Sanshanjie	9
Sanshanjie	10	Sanshanjie–Zhonghuamen	10
Zhonghuamen	11	Zhonghuamen–Andemen A	11

Table 5. *Cont.*

Station	No	Section	No
Andermen A	12	Andemen A–Tianlong Temple	12
Tianlong Temple	13	Tianlong Temple–Software Avenue	13
Software Avenue	14	Software Avenue–Huashenmiao	14
Huashenmiao	15	Huashenmiao–Nanjing South Station A	15
Nanjing South Station A	16	Nanjing South Station A–Shuanglong Avenue	16
Shuanglong Avenue Avenue	17	Shuanglong Avenue–Hedingqiao	17
Hedingqiao	18	Hedingqiao–Shengtai Road	18
Shengtai Road	19	Shengtai Road–Baijiahu	19
Baijiahu	20	Baijiahu–Xiaolongwan	20
Xiaolongwan	21	Xiaolongwan–Zhushan Road	21
Zhushan Road	22	Zhushan Road–Tianyin Avenue	22
Tianyin Avenue	23	Tianyin Avenue–Longmian Avenue	23
Longmian Avenue	24	Longmian Avenue–Nanjing Medical University	24
Nanjing Medical University	25	Nanjing Medical University–Nanjing Jiaotong Institute	25
Nanjing Jiaotong Institute	26	Nanjing Jiaotong Institute–China Pharmaceutical University	26
China Pharmaceutical University	27		
Nanjing Station B	28		
Gulou B	29		
Xinjiekou B	30		
Andermen B	31		
Nanjing South Station B	32		

Moreover, other parameters such as the number of inbound AFC gates, inbound passenger flow, passenger flow time–space passing coefficient, section maximum transportation capacity, and train alight rate are considered.

3.3. Results and Analysis

The computation results include the number of passengers who actually boarded the train, the early warning level coefficients of crowded passenger flow at each station during each control period, and the number of passengers that can pass through each section.

3.3.1. Number of Passengers Who Actually Boarded the Train

The number of passengers who board the train in the upward and downward directions is presented in Figures 2 and 3, respectively. Prior to collaborative control, during morning peak hours on working days, the total passenger demand in the upward and downward directions is recorded as 106,364 and 109,573, respectively. Remarkably, this aligns with the total number of passengers observed after implementing the collaborative control measures, indicating that there is no significant delay in the demand for passenger flow during peak hours.

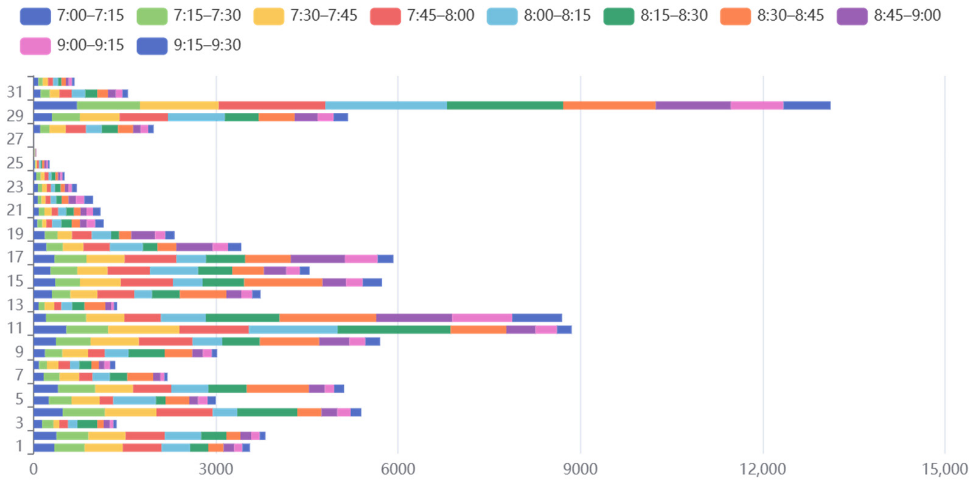


Figure 2. Number of passengers who actually board the train in the upward direction.

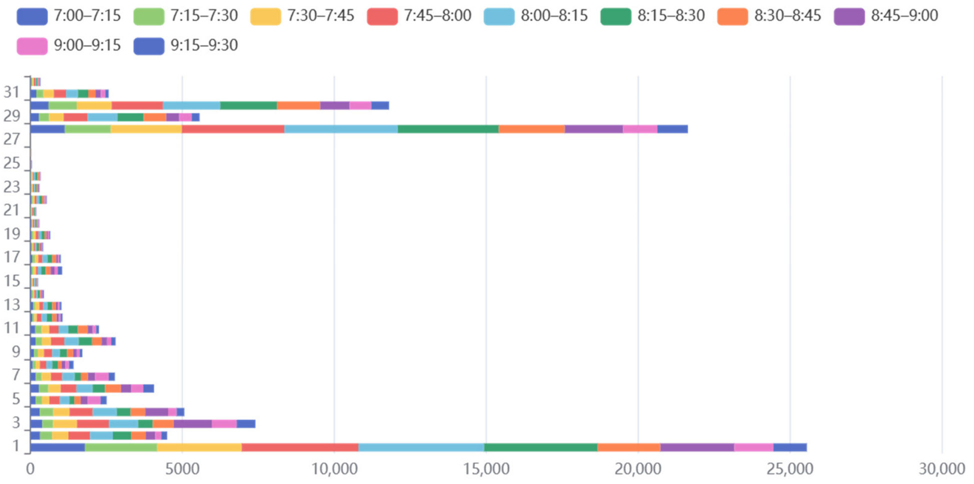


Figure 3. Number of passengers who actually board the train in the downward direction.

3.3.2. Passenger Flow Control Intensity

According to the number of passengers who needed to board the train and the number of passengers who actually board the train after collaborative control, the passenger flow control intensity for each station is calculated, as shown in Figure 4. The station number refers to the downward direction. Because the inbound passenger flows in the upward and downward directions are combined, separate calculations for the controlled passengers at different periods in these directions could not be implemented by each station. Therefore, the passenger flow control intensity in Figure 4 is calculated as the sum of the number of passengers who need to board the train in the upward and downward directions and the sum of the number of passengers who actually board the train in both directions.

The average intensity of passenger flow control at each station did not exceed 0.16. Owing to the concentration of passenger flow demand at different stations and sections in the upward and downward directions, there is a need for increased passenger flow control at multiple stations. Upwards, the concentration of passenger flow demand spanned from Xiaolongwan Station (No. 21) to Xinjiekou Station A (No. 8), whereas downwards, it is concentrated from Maigaoqiao Station (No. 1) to Zhangfuyuan Station (No. 9). Station Nos. 1–27 are classified as ordinary stations, with Station Nos. 3, 6, 8, 12, and No. 16 considered Transfer Stations A, which accommodate a normal inbound passenger flow. Station Nos. 28–32 are Transfer Stations B, solely serving transfer inbound passenger flow. In this study, different levels of passenger flow control intensity are assigned based on station types: commuter stations, such as Station Nos. 1 and 17, should have a controlled intensity below

0.25, transfer stations should have a controlled intensity set at 0.15 for safety reasons, and other ordinary stations should maintain a controlled intensity of 0.5.

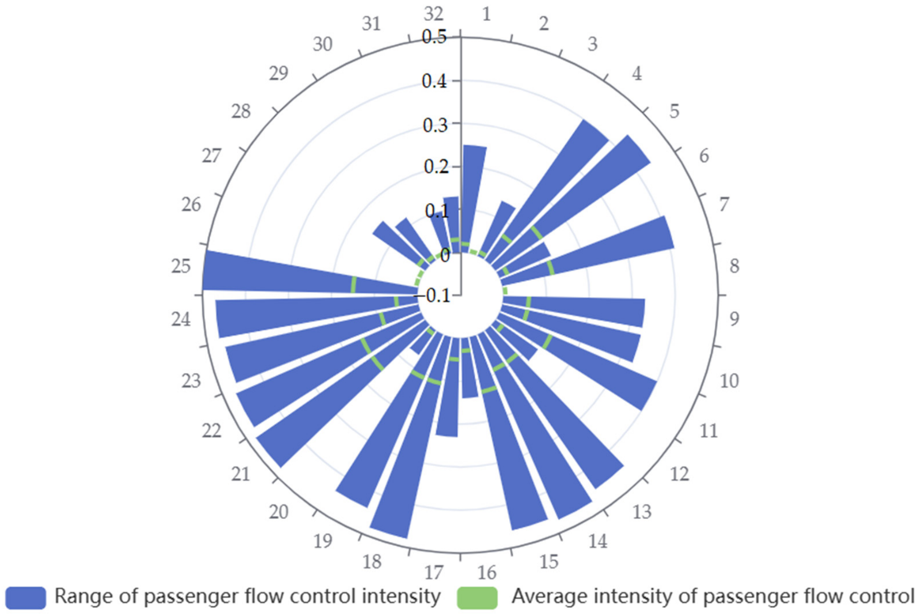


Figure 4. The range and average passenger flow control intensity.

3.3.3. Warning Levels of Stations

The warning level of each station in every control period is analysed based on the early warning level coefficients of crowded passenger flow at each station during each period after collaborative control, as presented in Figure 5. Here, the safety level is denoted by Level 1, and the station number represents the downward direction. The analysis reveals that most stations fall under Level 1, with only a few stations classified as Level 2, and none fall under Level 3. Thus, it can be concluded that cooperative control has a highly favourable effect. Notably, during the time frame from 7:30 to 9:30, Nanjing Station B and Xinjiekou B fall into Level 2 because of their significant roles as transfer hubs with a high transfer passenger flow.

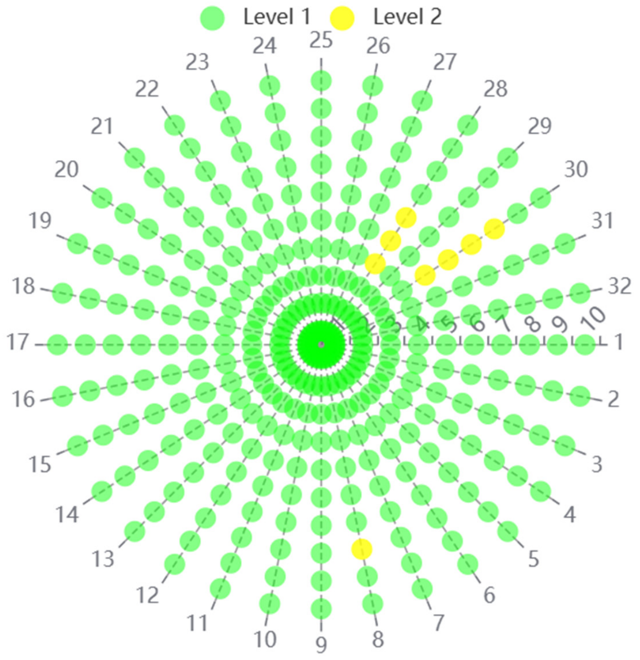


Figure 5. Warning level of each station after cooperative control.

3.4. Effectiveness of Passenger Flow Coordination Control

To demonstrate the impact of collaborative control on passenger flow, the station warning levels and section full rates before and after the implementation of collaborative control are compared. In addition, the average station retention rate and average section utilisation rate are analysed.

3.4.1. Average Retention Rate at the Station

The average station retention rate is calculated as the mean of the ratio between the number of passengers stranded and the number of passengers who need to board the train during peak hours. The calculation formula is as follows:

$$ZL_m = \frac{1}{p_m}\left[\sum_{t=1}^{p_m}\left(\frac{R_m^t}{B_m^t}\right)\right] \tag{31}$$

where ZL_m is the average retention rate at station m and p_m is the number of control periods.

Figures 6 and 7 compare the average station retention rates before and after coordinated control in the upward and downward directions, respectively.

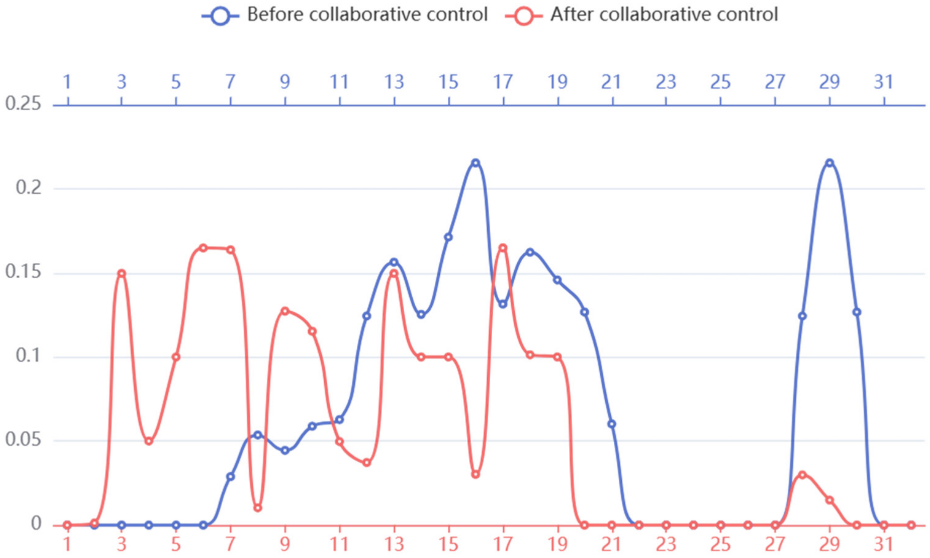


Figure 6. Station average retention rate before and after cooperative control in the upward direction.

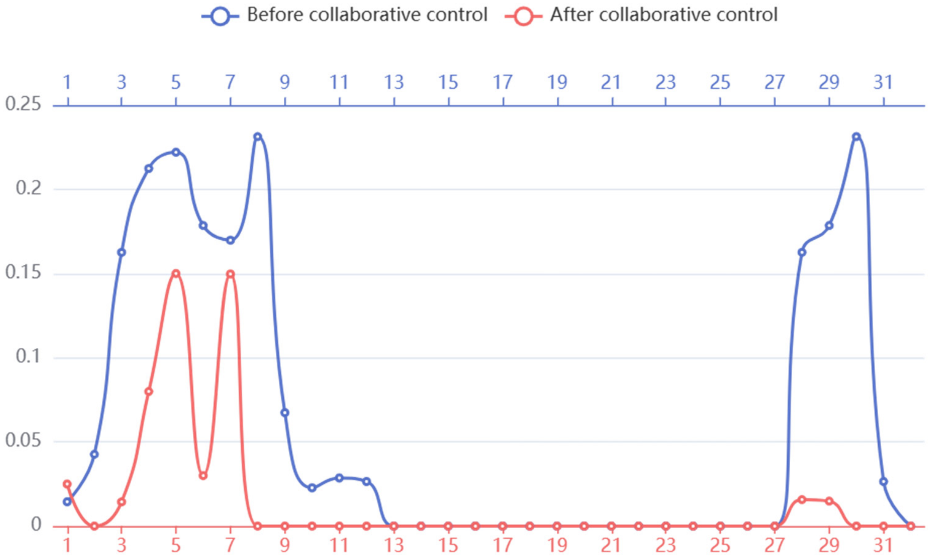


Figure 7. Station average retention rate before and after cooperative control in the downward direction.

Upwards, the retention rate after the coordinated control from Station No. 1 to 10 surpasses that before the control. The primary objective is to decrease the retention rate of Station Nos. 11–19, along with reducing the high-load rates within this range. Station No. 11 is a commuter station, Station Nos. 12 and 16 are major interchange stations, and Station Nos. 13–15 and 17–19 precede the Xinjiekou business circle. Coordinated control results in a lower retention rate for Station Nos. 11–22 compared with the pre-control conditions, demonstrating the effectiveness of coordinating operations among Station Nos. 1–10 and aligning with operational managers' actual requirements. Overall, cooperative control yields favourable outcomes.

Downwards, the average detention rate of Maigaoqiao Station No. 1 after coordinated control is slightly higher than before control, primarily because of its status as a heavily trafficked commuter station. The implementation of passenger flow control measures for Maigaoqiao Station is imperative for alleviating the significant congestion experienced during the sections between Nanjing Station A (No. 3) and Xinjiekou Station A (No. 8). However, the other stations exhibit lower average retention rates after control implementation. Specifically, prior to the coordinated control, Station Nos. 3–8 and No. 29 experience an average retention rate fluctuating around 0.2 with severe congestion at both stations and sections. After coordinated control, the average retention rate for Station Nos. 3–8 hovers around 0.1, notably dropping below 0.05 for Station No. 29. Overall, a significant collaborative control effect is observed.

3.4.2. Early Warning Levels of Stations

The warning levels of the selected stations during the specific control periods are shown in Figure 8. For the other stations at different time periods, the passenger flow control warning level remains at Level 1. The analysis and display of such data have been omitted.

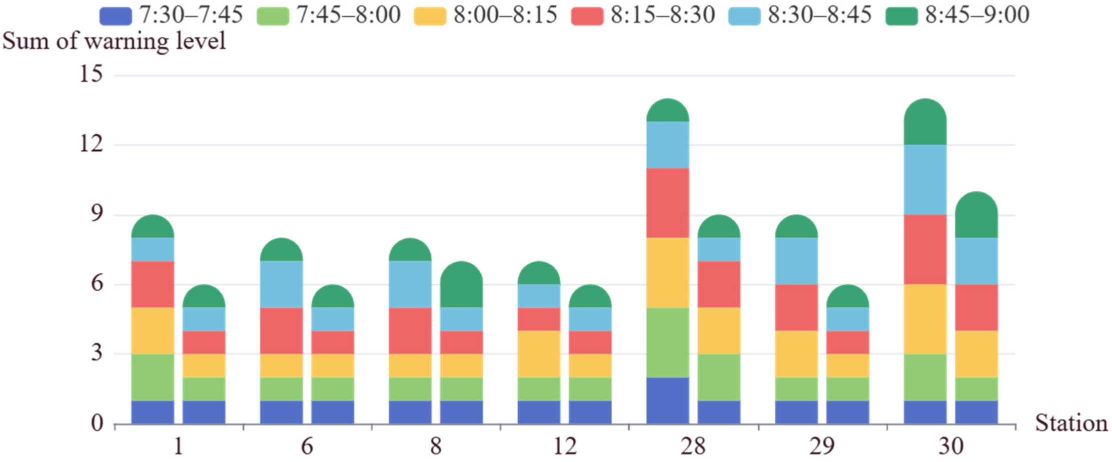
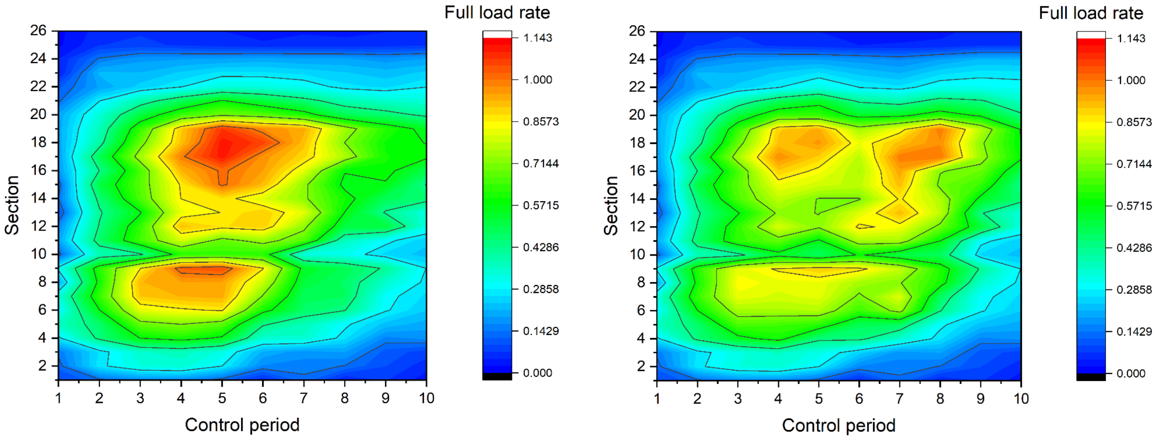


Figure 8. Station warning level before and after coordinated control.

Before implementing the coordinated control measures, the warning levels of Nanjing Station B (No. 28) between 7:45 and 8:30 and Xinjiekou B (No. 30) between 8:00 and 8:45 are at Level 3, indicating significant congestion at the stations. Furthermore, Station Nos. 1, 6, 8, and 29 experience continuous Level 2 warnings during specific time periods, raising concerns regarding passenger flow conditions. However, following the implementation of coordinated passenger flow control strategies, all stations fall into either Level 1 or 2. Notably, Stations Nos. 1, 6, 12, and 29 consistently maintain Level 1 throughout the control period. A station that previously had Level 3 is successfully downgraded to Level 2 after implementing these controls, resulting in a significantly improved overall passenger flow.

3.4.3. Full Load Rate of Sections

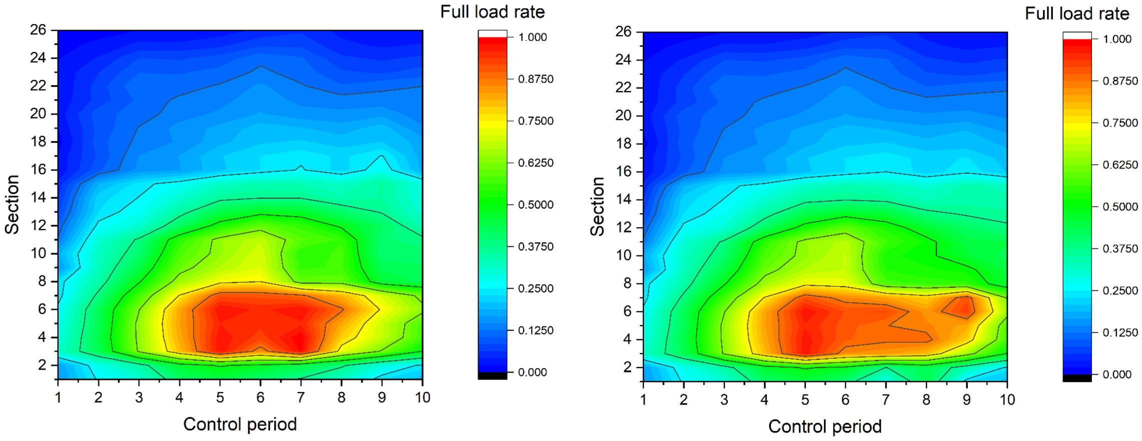
The schematics of the section load rate before and after cooperative control in the upward direction are shown in Figures 9a and 9b, respectively. The results demonstrate that prior to the implementation of cooperative control, the full load rate exceeds 100% between 7:45 and 8:15 for sections 9 and 15–19, indicating severe congestion within this time period. However, after the implementation of the collaborative control measures, none of the sections in the upward direction exhibit load rates exceeding 100%. This indicates a more balanced distribution of passenger travel demand and significantly reduced instances where the load rate ranged from 80 to 100% compared with the pre-collaborative control conditions. Overall, the effectiveness of the cooperative control is found to be highly satisfactory.



(**a**) (**b**)

Figure 9. Full load rate of sections in the upward direction. (**a**) Before cooperative control, (**b**) after cooperative control.

The load rates of sections before and after cooperative control in the downward direction are shown in Figures 10a and 10b, respectively. The results demonstrate that the load rate of sections is below 100%, both before and after cooperative control. Specifically, from 8:30 to 8:45, the load rate exceeds 90% for sections 3–7, whereas only section 6 surpasses this threshold after collaborative control. However, between 9:00 and 9:15, the load rate of section 6 also exceeds 90%, which indicates the potential influence of collaborative control, as it is previously within the range 60–70%. Overall, these findings highlight excellent performance in terms of control.



(**a**) (**b**)

Figure 10. Full load rate of sections in the downward direction. (**a**) Before cooperative control, (**b**) after cooperative control.

3.4.4. Average Utilisation Rate of Sections

The average utilisation rate of a section refers to the mean proportion of the maximum transportation capacity utilised by the number of passengers that can pass through a section during peak hours. The calculation formula is as follows:

$$\xi_l = \frac{1}{p_l}\left[\sum\nolimits_{t=1}^{p_l}\left(\frac{C_l^t}{C_{l,max}^t}\right)\right] \tag{32}$$

where ξ_l is the average utilisation rate of section l and p_l is the number of control periods.

The average utilisation rates in the upward and downward directions before and after collaborative control are shown in Tables 6 and 7, respectively. Collaborative control improves the average utilisation rate in the high-load rate section. Specifically, after implementing collaborative control, there is a slight increase in the average utilisation rate for both the upward high-load factor sections 9–18 and downward high-load factor sections 2–7, indicating effective control measures. Comparatively, no significant changes are observed in the other sections.

Table 6. Average utilisation rates of sections in the upward direction.

Section	Before Control	After Control	Section	Before Control	After Control	Section	Before Control	After Control
1	0.10	0.10	10	0.39	0.40	19	0.70	0.70
2	0.20	0.20	11	0.51	0.51	20	0.50	0.50
3	0.22	0.22	12	0.60	0.62	21	0.39	0.39
4	0.3	0.37	13	0.58	0.59	22	0.26	0.26
5	0.45	0.45	14	0.61	0.63	23	0.22	0.22
6	0.54	0.55	15	0.64	0.65	24	0.17	0.17
7	0.60	0.60	16	0.66	0.66	25	0.06	0.06
8	0.60	0.60	17	0.73	0.74	26	0.05	0.05
9	0.64	0.65	18	0.72	0.74			

Table 7. Average utilisation rates of sections in the downward direction.

Section	Before Control	After Control	Section	Before Control	After Control	Section	Before Control	After Control
1	0.31	0.31	10	0.48	0.47	19	0.15	0.15
2	0.36	0.38	11	0.46	0.46	20	0.13	0.1
3	0.68	0.69	12	0.40	0.40	21	0.12	0.12
4	0.71	0.72	13	0.34	0.34	22	0.11	0.11
5	0.71	0.72	14	0.2	0.29	23	0.09	0.09
6	0.73	0.74	15	0.27	0.27	24	0.07	0.0
7	0.68	0.69	16	0.18	0.18	25	0.0	0.05
8	0.53	0.53	17	0.18	0.18	26	0.03	0.03
9	0.49	0.49	18	0.16	0.16			

It can be shown that the multi-station cooperative dynamic control model demonstrates a significantly positive impact on passenger flow management. Through coordinated control, the retention rate and passenger flow warning level at each station are substantially reduced, ensuring that the full load rate of each section in both the upward and downward directions below 100%. Overall, the implemented strategies effectively optimise the line performance.

4. Conclusions

This paper aims to enhance subway station operation safety and efficiency by introducing a warning level and detention time to manage crowded passenger flows. A multi-station dynamic control model in both the upward and downward directions was developed to enable the independent regulation of the transfer inbound passenger flow. The proposed model method was validated through a numerical analysis using Nanjing Metro Line 1 as a case study, demonstrating its effectiveness.

This multi-station cooperative dynamic control model of crowded passenger flows addresses the deficiencies of control strategies that focused on cooperative control in a single direction or overlooked the overall decline in early warning levels across all stations along the line. It takes the sum of warning level coefficients of crowded passenger flows at each station as an optimisation objective, enabling cooperative control in both directions of the line. Furthermore, the inbound passenger flow at the transfer station is divided into two forms, normal inbound and transfer inbound, each undergoing separate control measures.

Future research could extend this multi-station collaborative dynamic control model by integrating passenger flow control measures at stations with train stop-time adjustments, parking at major stations, and other line transportation organisation strategies.

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