International Journal of Engineering Research And Management (IJERM)
ISSN: 2349- 2058, Volume-12, Issue-11, November 2025

Research on Optimization of Metro Transfer Passenger Flow Organization

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***Abstract*— Focusing on the congestion and safety issues of urban rail transit, this paper takes the Wangfuzhuang Transfer Station of Jinan Metro as the object and, based on the social force model, uses AnyLogic to construct a two-level passenger flow simulation model for the station hall and platform. The parameters are derived from research and literature. The size and speed of pedestrians, the capacity of stairs/escalators, the service time of turnstiles and ticket vending/security checks, etc. are set to construct the flow lines for entering and leaving the station and transfer as well as the train arrival and departure rhythm. The passenger flow density and the average transfer time are selected as the evaluation indicators. The simulation reveals that the north and south stairs and escalator entrances of the concourse are the main bottlenecks. The peak density of the platform stairs reaches 4.8 and 4.0 people per square meter respectively, and the average transfer time is approximately 448 seconds. Three types of optimizations are proposed: improving the guidance signs and on-site guidance, optimizing the flow lines to reduce intersections, and coordinating the time of Line 1/2. After the comprehensive implementation, the density of the platform stairs was reduced to 3.4 and 2.5 people per square meter, and the average transfer time was reduced to approximately 334.9 seconds, significantly enhancing the transfer efficiency and safety margin. The research has formed a methodological framework of "investigation - modeling - evaluation - optimization - verification", providing quantitative basis for the passenger flow organization and renovation of similar transfer stations. It also points out that the introduction of the Internet of Things and big data can further improve the parameter accuracy and model applicability.**

***Index Terms*— Subway transfer station; Anylogic; Social force model; Passenger flow organization**

I. Introduction

Qin Jingzhuo [1] The optimization of spatial functions at transfer stations is the core approach to achieving integrated operation: under the framework of integrated station spatial functions, it is necessary to identify the differences between intercity and metro stations. Meanwhile, the spatial layout needs to be coordinated with the traffic organization, passenger flow demand and construction sequence to form an integrated system solution path of "space - organization - transportation capacity - connection". Cheng Guozhu [2] constructed a multi-objective collaborative optimization model considering three main objectives: passenger transfer convenience, travel time cost, and load balance of bus stops. He presented a model solution method based on the social spider optimization algorithm and introduced a dynamic learning rate adjustment method and a Pareto optimal solution set to optimize the algorithm. Li Changyu [3] utilized the AnyLogic simulation platform based on the social force model to simulate the passenger transfer process within the station and deeply analyzed the passenger flow congestion phenomenon in the corner areas of buildings. Li Huan [4] took Xi 'an Metro Keji Road Station as an example and constructed a model using AnyLogic simulation software. Based on the simulation results, optimization measures are proposed for the passenger flow lines and equipment and facility configuration of the station. Then, taking the passenger flow density map and the average transfer time as evaluation indicators, the simulation results before and after optimization are compared. Wang Peiheng [5] constructed a collaborative optimization model for the operation of two-way train transfer stations and passenger flow control on a single metro line, minimizing the waiting delay time and transfer delay time for passengers at the starting station. Secondly, the relevant nonlinear constraints are approximately linearly substituted to transform the original model into a linear integer programming model. Ye Yuling [6] combined AFC card swiping data and, through data processing and refined analysis, grasped the spatio-temporal distribution patterns of passenger flow at stations. The current situation and bottlenecks of passenger flow organization in the station were analyzed. AnyLogic was applied to construct a passenger flow simulation scenario during the peak hours of holidays, and an organization plan adapted to the travel demands of passenger flow was designed. Wei Yuhao [7] proposed optimization measures such as changing the right-angle corners in bottleneck areas to arc-shaped corners, guiding the flow lines with high passenger flow pressure to distribute part of the passenger flow to the flow lines with low passenger flow pressure, and adjusting the arrival time of trains to ensure that two-way trains arrive at off-peak hours. HU[8] studied the collaborative optimization problems of timetable scheduling, passenger flow control and cross-station mode of metro lines. A mixed integer nonlinear programming (MINLP) model is proposed, which requires achieving a performance balance between service level and operating cost. Based on the division of cellular automata methods, Wang[9] proposed a static analysis method for facility adaptability and a dynamic analysis method for pedestrian simulation, and developed a new facility layout design method. To further enhance service quality and reduce accident risks, Shi[10] proposes an effective collaborative optimization method for train schedules and an accurate passenger flow control strategy for supersaturated metro lines.

In conclusion, this paper constructs models of the station environment, passenger movement, and train based on

Manuscript received November 01, 2025
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the social force model. Three optimization methods, namely improving the guidance signs and on-site guidance, optimizing the flow lines to reduce intersections, and coordinating the schedules of Line 1/2, are proposed to optimize the metro transfer stations.

II. CONSTRUCTION OF THE SIMULATION MODEL

2.1 The basic principles of the social force model

The social force model was proposed by Helbing and Molna by drawing on the classical laws of Newtonian mechanics. Its fundamental principle is that when walking, the laws exhibited by pedestrians are influenced by two aspects: internal factors and external factors. Among them, internal factors refer to the purpose of pedestrians' walking, while external factors refer to the influences such as the external environment that pedestrians are exposed to during the walking process. The internal and external factors of pedestrians when they are walking can be regarded as a resultant force that enables them to move forward. According to the different sources of action, the resultant force acting on pedestrians can be divided into three types of forces, namely the self-driving force of pedestrians, the interaction force between pedestrians, and the interaction force with obstacles. The expression of the social force model is:

$$m_i \frac{d\vec{v}_i(t)}{dt} = \vec{f}_i + \lambda = \vec{f}^{dri} + \vec{f}_{ij} + \vec{f}_{ib} + \lambda \qquad (2.1)$$

In the formula: $\vec{f}_i$ represents the total social force of the pedestrian i ; $\vec{f}^{dri}$ represents the self-motivation of the pedestrian i ; $\vec{f}_{ij}$ indicates that the pedestrian i is subjected to the force exerted by the pedestrian j ; $\vec{f}_{ib}$ it indicates that the pedestrian i is subjected to the force exerted by the obstacle b ; λ the random error variable represents the amount of risk interference.

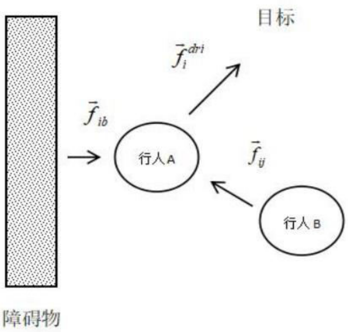

Fig 2.1 Schematic diagram of force analysis of the social force model

(1)Self-motivation formula. Firstly, in the social force model, $\vec{f}^{dri}$ represents the force exerted on a pedestrian when it fails to reach the desired speed and does not move in the desired direction. The formula for $\vec{f}^{dri}$:

$$\vec{f}^{dri} = m_i \frac{\vec{v}_i^0(t) - \vec{v}_i(t)}{\tau_i} \qquad (2.2)$$

In the formula: m_i- the mass of pedestrian i; $\vec{v}_i^0(t)$- expected speed of pedestrian i; $\vec{v}_i(t)$ - the actual speed of pedestrian i; τ_i- Pedestrian i reaction time.

(2)Formula for the interaction force between pedestrians. Secondly, $\vec{f}_{ij}$ is a repulsive force. To maintain a safe distance from other pedestrians, pedestrians will generate an interaction force. This interaction force can be divided into two parts. One part is the psychosocial force at the psychological level that occurs when pedestrians have not yet come into contact but psychologically to maintain a safe distance. The formula $\vec{f}_{ij}$ for the collision contact force at the body level that another part of pedestrians have already come into contact with is:

$$\vec{f}_{ij} = \vec{f}_{ij}^{soc} + \vec{f}_{ij}^{phy} \qquad (2.3)$$

In the formula: $\vec{f}_{ij}^{soc}$ - the psychological force exerted by pedestrian j on pedestrian i; $\vec{f}_{ij}^{phy}$ - the contact force exerted by pedestrian j on pedestrian i.

When the distance between pedestrian *j* and pedestrian *i* is crossed, the actual distance d_{ij} being greater than the sum of radii r_{ij} is only manifested as a psychological force:

$$\vec{f}_{ij}^{soc} = A_{ij} exp\left[(r_{ij} - d_{ij})/B_{ij}\right]\vec{n}_{ij} \qquad (2.4)$$

In the formula: A_{ij} - Interaction intensity; B_{ij} - The range of repulsive interaction; d_{ij} - Actual distance between pedestrians; r_{ij} - The sum of the radii of pedestrian *j* and pedestrian *i*; $\vec{n}_{ij}$ -- the unit vector of the position of pedestrian j pointing to the position of pedestrian *i*.

(3)The interaction formula between pedestrians and obstacles

Then, $\vec{f}_{ib}$ is also a repulsive force. To maintain a safe distance from the obstacle, a repulsive force will be generated between the pedestrian and the obstacle, such as the interaction force between pedestrians. The interaction force between pedestrians and obstacles is also divided into psychological force and physical force. The formula for $\vec{f}_{ib}$ is:

$$\vec{f}_{ib} = \vec{f}_{ib}^{soc} + \vec{f}_{ib}^{phy} \qquad (2.5)$$

In the formula: $\vec{f}_{ib}^{soc}$ - the psychological force exerted by obstacle b on pedestrian *i*; $\vec{f}_{ib}^{phy}$ - the physical force exerted by obstacle *b* on pedestrian *i*.

$$\vec{f}_{ib}^{soc} = A_{ib} exp\left[(r_i - d_{ib})/B_{ib}\right]\vec{n}_{ib}$$

(2.6)

In the formula: A_{ib} - Interaction intensity; B_{ib} - The range of repulsive interaction; d_i - The actual distance between pedestrian *i* and obstacle *b*; r_i - the radius of pedestrian *i*; $\vec{n}_{ib}$ -- the unit vector of the position pointing to the position of pedestrian *i*.

2.2 Construction of the in-station environment model

Based on the actual research situation, the dimensions of the platform and concourse of Wang fu zhuang Station, the locations of each entrance and exit, as well as the positions, dimensions and parameters of the stairs and elevators were determined. According to the actual situation of the subway station, the station will be built into two levels, namely the first underground level B1 and the second underground level B2, and the height of each level will be set. Drag "rectangles" from the demonstration panel as the floor of each level, and drag "walls" from the spatial markers in the pedestrian storage panel as the physical boundaries of the station, and drag "rectangular walls" as the columns in the station to simulate the physical environment of the station. Drag in the "automatic ticket vending machine", "metal detector" and "turnstile" from the airport on the three-dimensional object panel, and drag in the "online service" to simulate the processes of ticket purchasing, security check and ticket checking. Drag the escalator group from the spatial markers in the pedestrian reservoir to simulate the behavior of passengers taking the escalator. Use "rectangles" to construct the staircase to simulate the process of passengers going up and down the stairs. The passenger boarding and alighting areas are defined by using "rectangular nodes". Moreover, a three-dimensional window has been set up in the model to more realistically simulate the actual operation of the station. The specific simulation model. The in-station environment model is shown in the following figure.

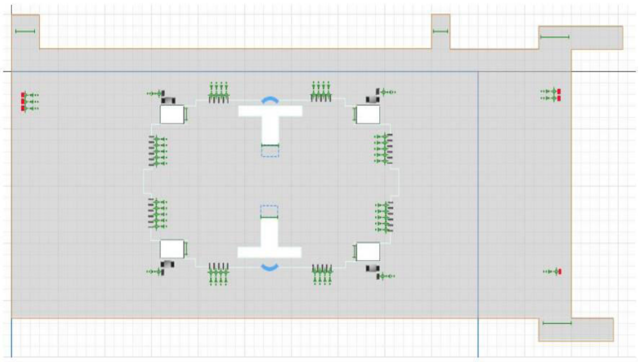

Fig 2.2 Schematic diagram of the concourse level model of Wangfuzhuang Station

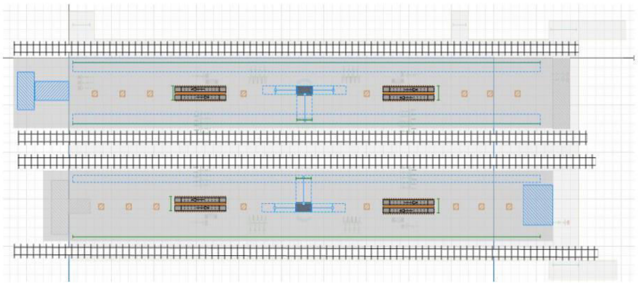

Fig 2.3 Schematic diagram of the platform level model of Wangfuzhuang Station

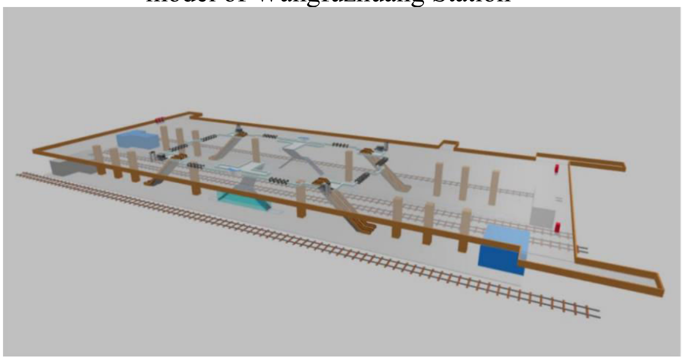

Fig 2.4 Schematic diagram of the 3D model inside Wangfuzhuang Station

2.3 Establishment of the passenger movement model

After the physical model of the station is established, a passenger movement model needs to be established. Based on the actual research situation, models were constructed for different passenger flow lines respectively using the pedestrian database.

(1)Inbound flow line model

According to the research, Wangfuzhuang Station has four entrances and exits, namely A, D, E and F. Pedestrian sources (Ped SourceA, Ped SourceD, Ped SourceE, Ped SourceF) are respectively set up at the four entrances and exits. According to whether passengers choose to purchase tickets at the automatic ticket vending machine, the selection Output point (Select Output) represents the choice of two paths. And at the pedestrian Service point (Ped Service) at the automatic ticket vending machine, passengers will go through security checks after purchasing tickets or those using electronic tickets, and then have their tickets checked at the turnstile. And pedestrian service points should be set up respectively at security checks and turnstiles.

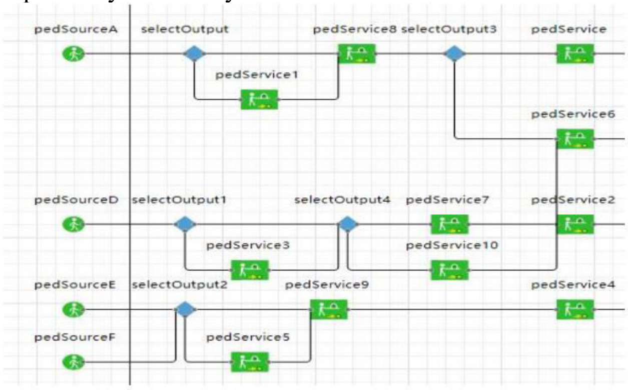

Fig 2.5 Model diagram of passengers from the entrance and exit to the turnstile

After entering the paid area, passengers can choose to take either Line 1 or Line 2 of Jinan Metro. They can choose to take the stairs or the escalator to the platform level. The floor Change modules (Ped Change LevelN, Ped Change LevelS) respectively represent entering the platform level of Line 1 from the north staircase and entering the platform level of Line 2 from the south staircase; The Ped Escalator module indicates that pedestrians can enter the platform level from the concourse level via the escalator. Afterwards, a model for passengers to board the train was established. Rectangular nodes (node1up, node1down, node2down) were set up at the platform to represent the waiting areas for passengers heading to Fangte on Line 1, the waiting areas for passengers heading to the Institute of Industrial Technology, and the waiting areas for passengers heading to Pengjiazhuang on Line 2 And set events (event1up, event1down, event2up) to indicate that the train enters the station and passengers board and leave the station.

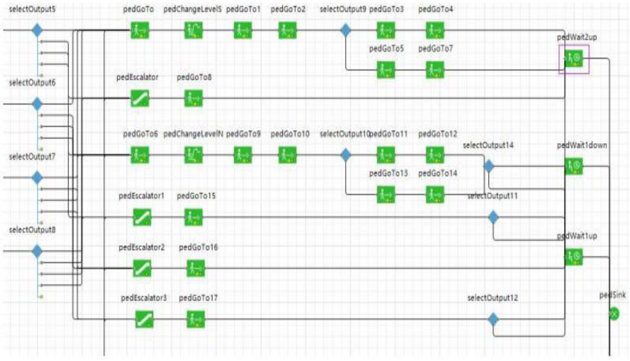

Fig 2.6 Model diagram of passengers waiting from the concourse level to the platform

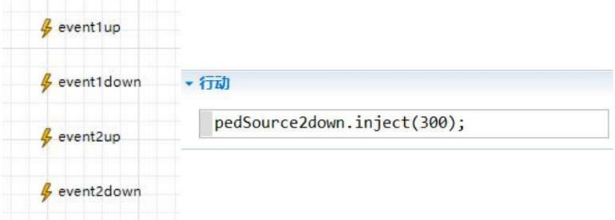

Fig 2.7 The incident of passengers boarding the vehicle

(2)Exit and transfer passenger flow lines

As Wangfuzhuang Station is the terminal station of Jinan Metro Line 2, only passengers boarding the train from Wangfuzhuang to Pengjiazhuang Station, while only passengers getting off the train from Pengjiazhuang to Wangfuzhuang Station. Pedestrian sources (PedSource1up, PedSource1down, PedSource2down) are set up on the side of the terminal station of Line 1 and Line 2 platforms to indicate passengers getting off at Wangfuzhuang Station. And set a Select output point (Select Output5) to indicate that passengers can make multiple choices to take the escalator or the stairs from the platform level to the concourse level.

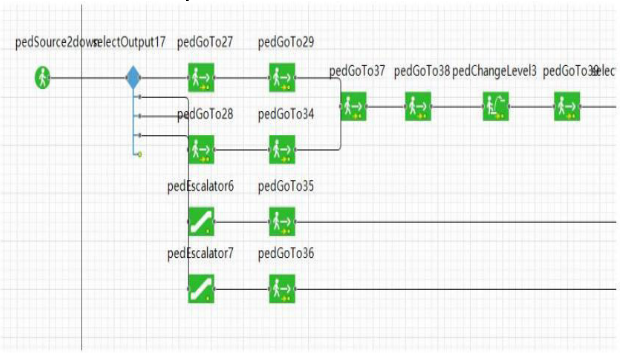

Fig 2.8 Model diagram of passenger transfer after getting off

Fig 2.9 The event of passengers getting off

After entering the concourse level, passengers can choose to exit the station or transfer. According to the actual research situation, the vast majority of passengers at Wangfuzhuang Station are transfer passengers. Setting the Select Output point (Select Output5) indicates that passengers can choose to exit the station or transfer. When passengers choose to exit the station, setting the Ped Service point (Ped Service) indicates that passengers leave the paid area through ticket checking at the gate. Then, the departure of passengers from the station is indicated by the set target lines (targetLineA, targetLineD, targetLineE, targetLineF). When passengers choose to transfer, they can enter the platform level from the concourse level via Ped Change LevelN or Ped Change LevelS, or from the concourse level to the platform level via Ped Escalator.

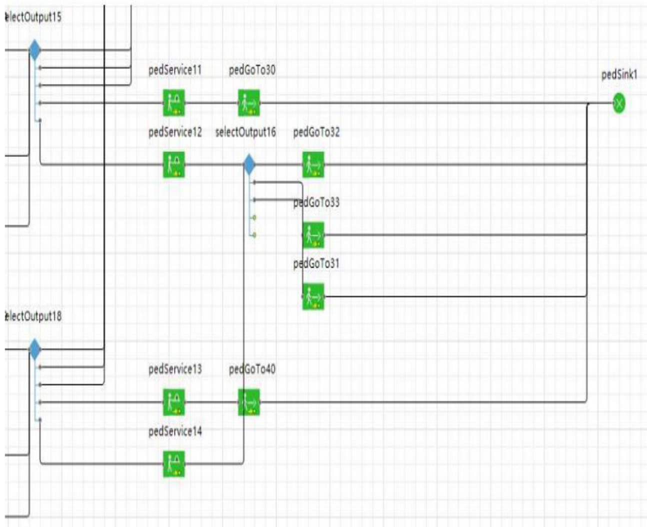

Figure 2.10 Model diagram of passengers exiting the station from the concourse

2.4 The establishment of the train model

Drag the "Track" module into the track library to draw the track lines in the model, and drag the "Position on Track" module to mark the positions where the train appears, stops and disappears. Drag trainSource to generate the train, control the train's arrival at the designated position through trainMoveTo, and drag delay from the process modeling library to control the train's stop time.

Fig 2.11 Train model diagram

III. Analysis of Simulation Results

3.1 Analysis before optimization

When simulating the passenger flow lines within Wangfuzhuang Station, a pedestrian density map was added to the simulation model to more clearly observe the pedestrian movement at the station and analyze the service levels of various facilities and equipment, thereby determining the congested areas of passengers at the station. During the simulation process, the bottleneck of the transfer passenger flow organization can be identified by the depth of the color on the density map. If the color on the density map leans towards red, it indicates high density, while if it leans towards blue, it indicates low density. As the simulation time extends, it becomes very easy to find the blocking points.

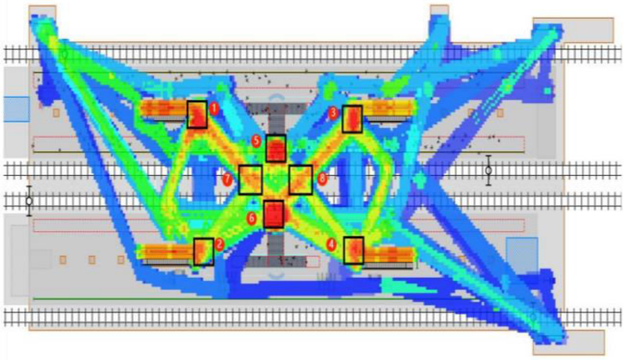

Fig 3.1 Passenger Flow density map of the concourse level at Wangfuzhuang Station

When the simulation software has been running for about 20 minutes, as can be seen from figure 3.1 above, passenger flow congestion has occurred at the north and south staircase entrances and four escalator entrances in the concourse level of Wangfuzhuang Station, as shown at points 1 to 6 in figure 3.1. Moreover, the two staircase entrances (points 5 and 6) are the main passenger flow congestion points in the concourse level. The areas circled by the black boxes in the figure have created passenger flow intersections, as shown at 7 and 8. Due to the fact that different passengers make different choices on the concourse level, conflicts are inevitable among different passenger flow lines.

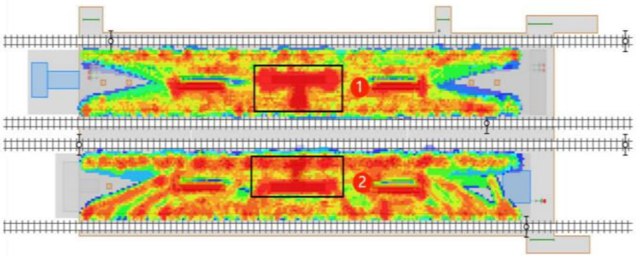

Fig 3.2 Passenger Flow density map of the platform level at Wangfuzhuang Station

As can be seen from figure 3.2 above, when the train arrives at the station, pedestrians will gather a large amount of passenger flow on the stairs when moving from the concourse level to the platform level, causing passenger flow congestion. As shown in figure 4.2, the black boxes circled 1 and 2, which are displayed in dark red in the figure, indicate that the passenger flow accumulation is relatively serious. Moreover, if a large amount of passenger flow accumulates at the stairs, it is very likely to cause stampede accidents, etc. There is a certain degree of safety hazard. Secondly, there will also be passenger flow congestion at the escalator entrances of each platform.

(1)Passenger flow density

Drag the time line chart from the analysis panel and enter the code "node.density(SQ _meter)" in the "Value" section of the line chart to set the line chart as a passenger flow density table.

Based on the selected passenger flow organization evaluation indicators and referring to the passenger flow density map of the platform level, the statistical results of the passenger flow density of the two staircases are shown in the following figure.

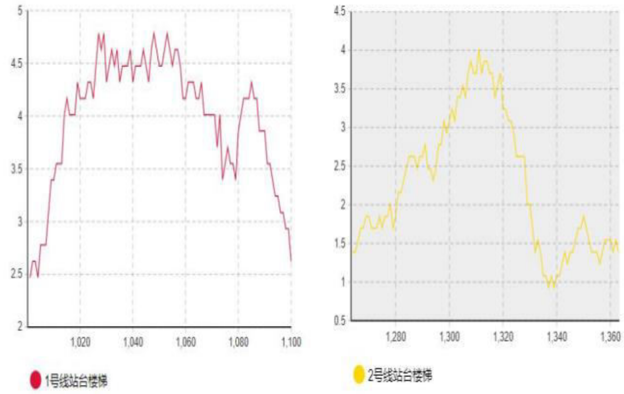

Fig 3.3 Statistical chart of staircase density on the platform level

According to the data in figure 3.3 above, it can be shown that the peak passenger flow density in the staircase of the platform on Line 1 is approximately 4.8 people per square meter, and in the staircase of the platform on Line 2, it is approximately 4 people per square meter.

（2）Average transfer time

Drag a variable into the established pedestrian agent "Person" and name it "time" (time, time1, timne2, time3), and enter the code "ped.time= time();" at the pedestrian Source (Ped Source) on the platform level. Enter the code "ped.time1=time();" at the Ped Sink. "data.add(ped.time1-ped.time);" ; Drag the histogram and histogram data (data) into the analysis panel, and enter the code "Data" in the "Histogram" field of the icon to calculate the time required for passengers to transfer.

Based on the selected average transfer time index, the time for transferring from Line 1 to Line 2 and from Line 2 to Line 1 can be respectively calculated.

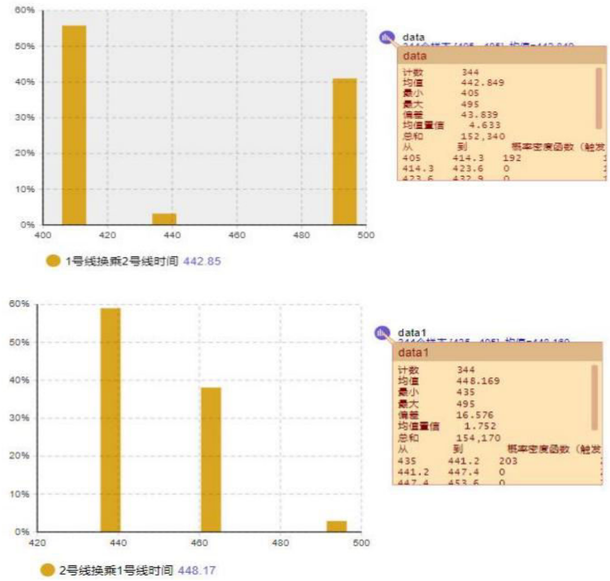

Fig 3.4 Statistical Chart of Average Passenger Transfer Time

The statistical results shown in figure 3.4 above indicate that the transfer time from Line 1 to Line 2 ranges from 05 seconds to 495 seconds, with an average time of 443.86 seconds. The transfer time from Line 2 to Line 1 ranges from 435 seconds to 495 seconds, with an average time of 448.333 seconds.

3.2 Analysis after optimization

3.2.1 Optimization method

Passenger transport organization and management measures to enhance passenger transfer efficiency and reduce congestion within stations can be implemented from the following aspects.

(1)Set up guide information signs reasonably

It is necessary to increase the setting of guiding information in crowded areas. Due to the large number of pedestrians in the crowded areas of transfer stations and their slow walking speed in these areas, there are many intersections of passenger flow lines. Therefore, it is necessary to reasonably set up guiding signs in crowded areas and rationally divert passengers to reduce the intersections and accumulation of passenger flow. During peak hours or important occasions, staff can be arranged to set up service desks or temporary guides at transfer stations to provide passengers with more comprehensive transfer guidance. By setting up voice broadcast devices, transfer information is broadcast regularly to remind passengers, enabling them to obtain transfer information at any time. Clear line indications, including maps, signs and color bands, should be set up at the entrance, waiting room, station hall and other locations to facilitate passengers' quick understanding of the transfer lines, directions and station locations. At the platform level of Wangfuzhuang Station, passengers can be reasonably guided to take the escalators. If too many passengers take the stairs, it will cause passenger flow conflicts on the stairs. By guiding some passengers to take the escalators, the number of passengers taking the stairs can be reduced, the pressure of the staircase's movement can be alleviated, the passenger flow density on the stairs can be lowered, and safety accidents caused by excessive passengers can be avoided.

(2)Optimization of passenger flow lines at transfer stations

To reduce the travel time for passengers during transfer, for the passenger flow in the main transfer direction, the shortest route should be given priority to increase the travel speed of passengers. At the same time, it should adapt to the passengers' walking habits as much as possible, simplify the routes, and separate the transfer passenger flow, inbound passenger flow and outbound passenger flow to reduce the main conflict points. At the concourse level of Wangfuzhuang Station, the passenger flow lines can be optimized to avoid passenger flow intersections, alleviate the passenger flow intersections at 7 and 8 in the concourse level shown, and reduce the passenger flow time.

(3)Coordinate and optimize the timetables among different lines

The matching and coordination of train operations on different lines at transfer stations have a significant impact on the organization of passenger flow within the stations. When transferring between multiple lines, priority should be given to formulating the train operation plan for the line with the largest passenger flow, and the travel time for passengers' transfer should be taken into account. The train operation plans for other lines should be coordinated to establish more sequence connections. At Wangfuzhuang Station, the arrival times of Line 1 and Line 2 trains can be coordinated, reducing the average transfer time for passengers transferring from Line 2 to Line 1.

3.2.2 Simulation analysis of optimization results

Based on the above optimization methods, the three optimization methods have different degrees of optimization effects on the passenger flow organization of the station. Therefore, the three optimization methods can be combined for use. The optimized data results are shown in figure 3.5 below.

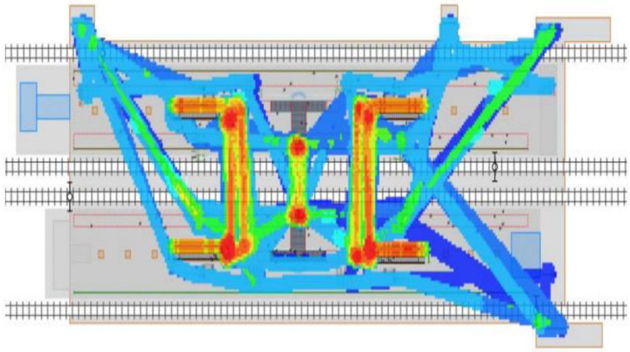

Fig 3.5 Passenger flow lines on the optimized concourse level

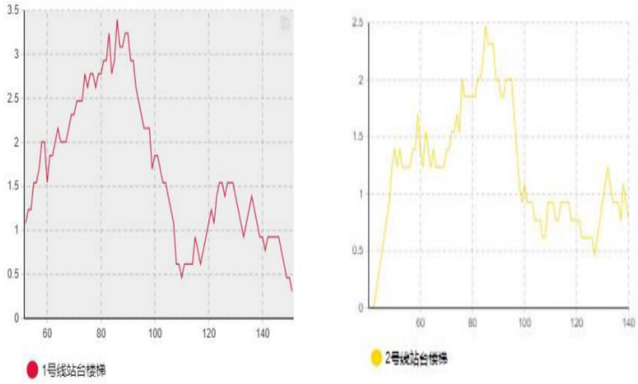

Fig 3.6 Passenger flow density of the optimized platform staircase

Fig 3.7 Optimized passenger transfer time

As can be seen from the simulation data in the above figure, this optimization has effectively alleviated the conflict of passenger flow lines on the concourse level, and the phenomenon of passenger congestion has also decreased accordingly. The passenger flow density of the platform level stairs has been reduced. The density of the platform level stairs on Line 1 has dropped from 4.8 people per square meter to 3.4 people per square meter, and that on Line 2 has decreased from 4 people per square meter to 2.5 people per square meter. There is no longer a phenomenon of a large number of passengers piling up on the stairs, reducing the possibility of safety accidents. The average transfer time for passengers has been reduced from 448.333 seconds to 334.926 seconds, improving the transfer efficiency. Therefore, the optimization plan is reasonable and feasible.

IV. CONCLUSION

This paper takes Wangfuzhuang Station of Jinan Urban Rail Transit as the research object, analyzes the relevant theories of passenger flow organization, and uses Anylogic software based on the social force model to simulate the passenger flow organization of the station. It discovers the bottlenecks existing in the transfer passenger flow organization of Wangfuzhuang Station and proposes optimization measures. The main work contents and conclusions of this article are as follows:

(1)The relevant basic principles of the social force model and the Anylogic simulation platform based on the social force model are introduced. Moreover, the simulation parameters are set according to the research data and literature review, laying a foundation for establishing the simulation model of transfer passenger flow at Wangfuzhuang Station.

(2) Through on-site investigation, the station plan and passenger flow data of Wangfuzhuang Station were obtained. The station structure and transfer characteristics of Wangfuzhuang Station were analyzed. The transfer passenger flow organization model of the station was established by using simulation software. Combined with the chart data output by the model, the problems in the passenger flow organization of the station were identified.

(3) Propose optimization measures based on the passenger flow organization issues of the station, and separately analyze the effects brought by each optimization plan. Finally, comprehensively apply all optimization plans and verify the rationality of the optimization plans through evaluation indicators such as passenger flow density and average transfer time.

The comparison of parameters before and after optimization proved that the optimization method for Wangfuzhuang Station was reasonable and feasible. By optimizing the information signs for guiding passengers, the congestion level of the transfer passage has been reduced. By optimizing the passenger flow lines, conflicts in passenger flow lines have been reduced and the transfer efficiency has been improved. By optimizing the train schedules between different lines, the average transfer time has been reduced. Moreover, after combining the three optimization methods, it was verified that they have a better optimization effect, providing practical and feasible optimization suggestions for the passenger flow organization optimization of Wangfuzhuang Station.

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