Modeling and Simulation of Passenger Flow Distribution in Urban Rail Transit Hub Platform

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Abstract: Urban rail transit has become the main mode to ease traffic congestion. Researches on the dynamic variation regularity of passenger flow distribution and passenger flow volume of urban rail transit hub platform have important implication in hub capacity design, operation organization and risk prevention. This paper proposes a passenger flow distribution integrating model (PFDIM) based on the basic theory analysis and basic parameter models of passenger flow distribution in hub platform. Simulation designs of PFDIM are built with Java and Anylogic, which contain simulation system functional framework, implementation path, simulation processes and simulation models. By case study, the performance comparison between two simulation methods indicates that simulation designs are scientific and accordant with the reality scene; calculation results prove that PFDIM has a good performance on describing the dynamic variation regularity of passenger flow distribution. Moreover, the experiments with different departure intervals could provide the reference for train scheduling under the viewpoint of traffic safety and service level.

Keywords: passenger flow distribution integrating model; urban rail transit hub platform; simulation and application; performance evaluation; traffic safety and service level

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1. **Introduction**

In recent years, with the rapid development of urban rail transit system, passenger traffic demand has increased quickly and sustainably. Urban rail transit has become the main mode to ease traffic congestion. As we know, urban rail transit hub is the core node of urban rail transit system. For an urban rail transit hub, hub platform is the most important area for passenger flow distribution. Under the viewpoint of traffic safety and service level, researches on the dynamic variation regularity of passenger flow distribution and passenger flow volume of hub platform are very necessary and meaningful. The prospective research findings could provide the reference for train scheduling, hub capacity design and operation management.

Aiming at the researches on modeling, simulation and application of passenger flow distribution in urban rail transit field, domestic and foreign scholars have done mountains of work and achieved abundant findings. Generally, there were two sides to the related researches, one side was the research on modeling and simulation of passenger flow distribution; the other side was the research on application of passenger flow distribution. The purposes of these researches were to improve passenger traffic service quality and reliability.

According to the hierarchy of modeling and simulation, passenger flow models consist of macroscopic model, mesoscopic model and microscopic model. Early researches of passenger traffic mainly focused on the relations among traffic flow, speed and density, research findings represented by Fruin [1] were adopted as an effective macroscopic analysis approach for passenger traffic in the US Highway Capacity Manual [2]. As a representative of mesoscopic model, lattice gas

model was firstly proposed to passenger traffic simulation by Muramatsu et al. [3]. With the rapid development of computer technology, microscopic model was proposed and applied to passenger traffic simulation, which mainly included magnetic model [4], benefit cost cellular model [5], queuing network model [6], social force model [7] and cellular automata model [8,9]. On the other hand, application of passenger flow distribution mainly concerned with passenger traffic system planning, operation organization design, facility performance evaluation, emergency evacuation and so on. Due to the different development stages, major cities of the western developed countries had reached an advanced level, such as New York, Berlin, Copenhagen and London [10,11].

With respect to transit hub distribution efficiency and passenger behavior analysis, passenger individual behavior model was firstly set up by Gipps et al. [5], they supposed that passenger movement obeyed the short circuit law, and put forward a simple route choice model. Helbing [12] illustrated the complex characteristics of passenger flow, and built social force model. Xiong. H. et al. [13] proposed a continuous-time random walk model for pedestrian flow walking behavior simulation. Lu. L. L. et al. [14] explored the effects of different walking strategies on bi-directional pedestrian flow in the channel with cellular-automata formulation. Daamen et al. [15,16] summed up that passenger flow crowd degree in hub interlayer facility as the key factor directly affected route choice behavior by analyzing the relations between interlayer facility layout and passenger path-finding behavior. Lin. Y. D. et al. [17] analyzed passenger flow characteristics inside of the hub, and identified passenger flow distribution bottleneck. Similarly, scholars researched on the passenger flow through corridor bottlenecks, experiments results showed that the bottleneck capacity was almost linearly increased with the width, and jamming occurred below the maximum capacity [18,19,20]. In recent researches, Duive et al. [21] proposed the state-of-the-art crowd motion simulation models to explain the different phenomena of crowd motion such as lane formation, stop-and-go waves, faster-is-slower effect, turbulence and zipper effect. Guillermo H. G. [22] built a mathematical model of the formation of lanes in crowds of pedestrians moving in opposite directions. Bandini et al. [23] improved the traditional floor field cellular automata model to simulate the negative interaction among pedestrians of high density. Xie. Z. Y. and Wang. S. W. et al. proposed the forecasting methods of passenger flow based on hybrid temporal-spatio forecasting model and modular neural network [24,25]. In addition, Gao. L. et al. proposed the distribution service network model of comprehensive passenger transport hub, simulation results showed that research findings were of practical significance in performance evaluation of passenger flow distribution [26,27]. Wang. S. W. [28] also built the transit station congestion index based on pedestrian simulation and gray clustering evaluation, which could reflect the congestion degree of transit stations.

Especially, aiming at the researches on passenger flow distribution in the platform, Seriani et al. [29] researched on the pedestrian traffic management of boarding and alighting in metro stations, and obtained the criteria for pedestrian traffic management in platform and metro doors by means of pedestrian traffic micro-simulator and laboratory experiments, results which were expressed in service level, service time, passenger density of platform and vehicle could give some references for pedestrian traffic management in metro systems. Wang. G. and Gao. S. S. proposed the calculation method of passenger flow volume in transit platform [30,31]. What's more, some studies were related with passenger dwell time. Schelenz et al. [32,33,34] proposed an agent-based simulation method to calculate passenger dwell time and analyze passenger preferences with different vehicle layout designs, case results proved that the number of vehicle doors had the direct effect on passenger dwell time.

In view of the above researches, it could be found that kinds of models and methods were widely used to explore passenger flow characteristics and behavior in transit hub. Their findings motivate the present work. However, there were few researches related with passenger flow distribution in hub platform. Therefore, the objective of this paper is to modeling and simulation of passenger flow distribution in urban rail transit hub platform, and explore the practical application. The rest of this paper is organized as follows. In section 2, basic theory and parameter models of passenger flow in hub platform are proposed, and then passenger flow distribution integrating

model of the hub platform is built. In section 3, simulation designs of passenger flow distribution integrating model are built by using Java and Anylogic. In section 4, practical investigation, case study and results analysis are carried out. At last, the conclusion is summarized and the direction of future research is illustrated.

2. Passenger Flow Distribution Models

2.1. Basic Theory

2.1.1. Passenger Flow Classification

In urban rail transit hub platform, passenger flow can be divided into boarding passenger flow and alighting passenger flow according to passenger flow direction; what's more, it also can be divided into transfer passenger flow and non-transfer passenger flow according to passenger flow transfer demand. Passenger flow classification is shown in Figure 1. PF-i is the simplified symbol to the corresponding passenger flow, i=1,2,3,4.
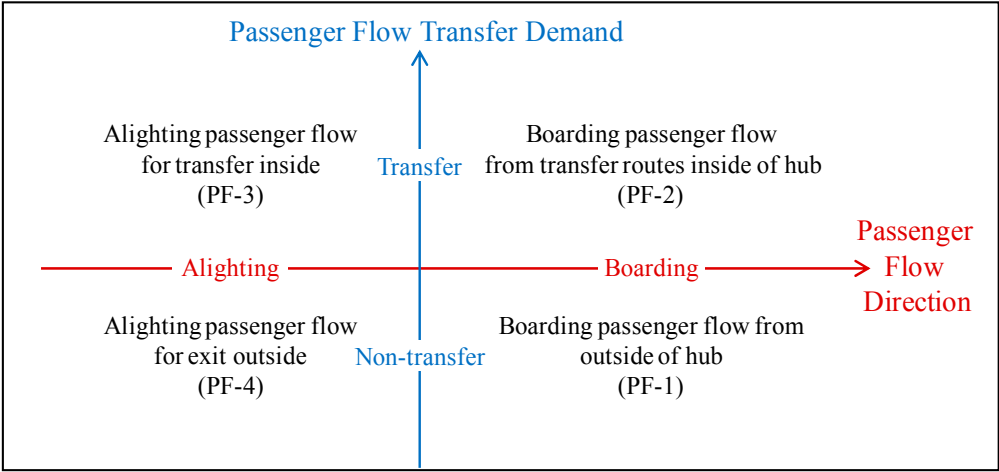
Figure 1. Passenger flow classification in hub platform

2.1.2. Passenger Flow Distribution Process

In urban rail transit hub platform, passenger flow distribution process refers to traffic behaviors of passenger group dynamics influenced by platform facilities and train scheduling. Passenger flow distribution morphology is regularly changed with train departure interval. Passenger flow distribution process is shown in the following figures.

Figure 2. Passenger flow distribution process in hub platform

Figure 3. Distribution process of PF-1 in hub platform

Figure 4. Distribution process of PF-2 in hub platform

Figure 5. Distribution process of PF-3 in hub platform

Figure 6. Distribution process of PF-4 in hub platform

What's more, passenger flow distribution process presents obvious phases during one departure interval. Especially after the train door opening, the process of passenger getting on or off the train can be divided into three phases, which are shown in the following figures.
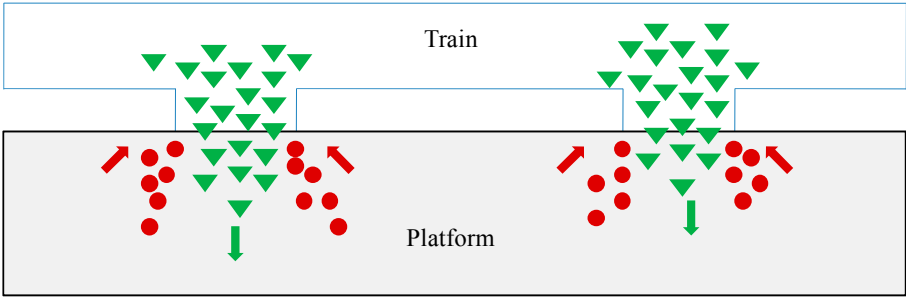
Figure 7. Alighting phase of passenger flow (phase 1)
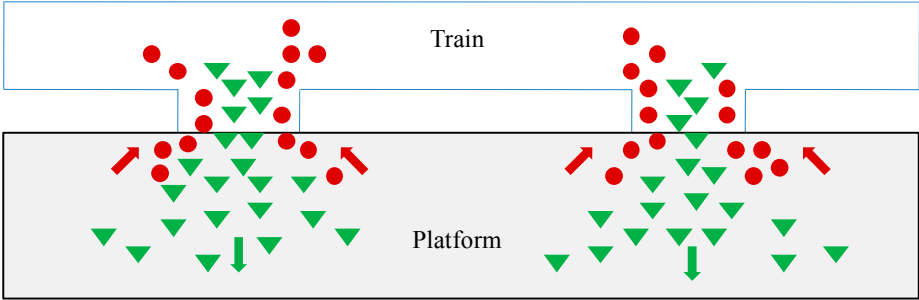
Figure 8. Mixed phase of boarding and alighting (phase 2)
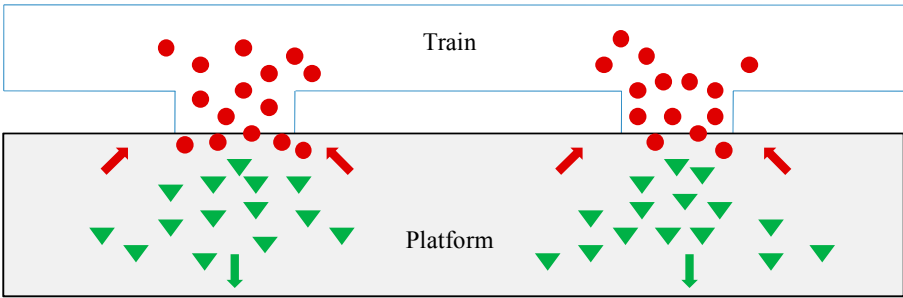
Figure 9. Boarding phase of passenger flow (phase 3)

2.1.3. Influence Factors of Passenger Flow Distribution

Based on the relationship between interaction agents, influence factors of passenger flow distribution are derived from three parts, which are platform, train and passenger flow, as follows in Table 1.

Table 1. Influence factors of passenger flow distribution

No.	Influence factor	
	First class item	**Second class item**
1	platform	available area of platform
		traffic capacity of passage
		traffic capacity of stairs
		traffic capacity of escalator
2	train	train type
		train formation
		train departure interval
		train dwell time
3	passenger flow	temporal distribution of passenger flow
		spatial distribution of passenger flow

2.1.4. Definition of This Research

In this research, the following four basic definitions are proposed.

(1) One departure interval is defined as the research period, which refers to a time interval between the departure time of adjacent trains in same direction.

(2) Passenger flow distribution morphology is defined as the research object.

(3) In one departure interval, it is assumed that all the boarding passenger flow in platform can get on the train, and all the alighting passenger flow can leave the platform.

(4) Because of the same target attribute to PF-3 and PF-4 which is to leave the platform, PF-3 and PF-4 are combined as the alighting passenger flow (PF-5) for this research.

2.2. Basic Parameter Models

In this paper, island-type platform is selected for this research which has the most widely applied among the typically types of urban rail transit hub platform in reality. Basic parameter models of passenger flow in island-type platform are built as follows, moreover, "+" and "-" refer to the uplink and downlink respectively.

2.2.1. Basic Parameter Model of PF-1

As a general rule, the temporal distribution of PF-1 arriving at hub entrance shows the stochastic distribution. Then, because the traffic capacity of ticket turnstile and security instrument has a strict restriction on the influx rate of PF-1 in hub entrance, so the temporal distribution of PF-1 arriving at hub platform shows the uniform distribution, no matter in rush hours or not.

(1) the average flow rate of arriving at hub platform (AFR1)

$$\begin{cases} v_0^+ = \dfrac{Q_0^+}{T_0} \\ v_0^- = \dfrac{Q_0^-}{T_0} \end{cases} \tag{1}$$

Where, AFR1 refers to the average flow rate of arriving at hub platform for PF-1; v_0^+ and v_0^- refer to AFR1 of uplink PF-1 and AFR1 of downlink PF-1 respectively in period T_0, p/s; Q_0^+ and Q_0^- refer to the passenger flow volume of uplink PF-1 and the passenger flow volume of downlink PF-1 respectively in period T_0, p; T_0 refers to the research time period, usually a rush hour, *3600s*.

(2) the average flow rate of getting on the train (AFR1')

$$\begin{cases} v_1^+ = \dfrac{q_1^+}{t_1^+} \\ v_1^- = \dfrac{q_1^-}{t_1^-} \end{cases} \tag{2}$$

Where:

$$\begin{cases} q_1^+ = v_0^+ \cdot \Delta t^+ \\ q_1^- = v_0^- \cdot \Delta t^- \end{cases} \tag{3}$$

So:

$$\begin{cases} v_1^+ = \dfrac{Q_0^+ \cdot \Delta t^+}{T_0 \cdot t_1^+} \\ v_1^- = \dfrac{Q_0^- \cdot \Delta t^-}{T_0 \cdot t_1^-} \end{cases} \tag{4}$$

Where, AFR1' refers to the average flow rate of getting on the train for PF-1; v_1^+ and v_1^- refer to AFR1' of uplink PF-1 and AFR1' of downlink PF-1 respectively, p/s; q_1^+ and q_1^- refer to the number of boarding passengers of uplink PF-1 in period t_1^+ and the number of boarding passengers of downlink PF-1 in period t_1^- respectively, p; t_1^+ and t_1^- refer to the boarding time of uplink PF-1 and the boarding time of downlink PF-1 respectively, s; Δt^+ and Δt^- refer to one departure interval of uplink train and one departure interval of downlink train respectively, s. Because $\Delta t^+ > t_1^+$ and $\Delta t^- > t_1^-$, so, $v_1^+ > v_0^+$ and $v_1^- > v_0^-$.

2.2.2. Basic Parameter Model of PF-2

In this paper, walking time of PF-2 is defined as the period in which transfer passenger arrives at hub platform from other routes inside of hub. Based on the study, the walking time distribution of PF-2 shows the uniform distribution, i.e. $t^k \sim U[t_{min}^k, t_{max}^k]$. Moreover, the temporal distribution of PF-2 arriving at hub platform shows the impulse type discrete distribution, which is influenced by the train departure interval of other transfer routes.

(1) the average flow rate of arriving at hub platform (AFR2)

$$\begin{cases} v_k^+ = \dfrac{q_k^+}{t_{k_2}^+ - t_{k_1}^+} \\ v_k^- = \dfrac{q_k^-}{t_{k_2}^- - t_{k_1}^-} \end{cases} \tag{5}$$

Where:

$$\begin{cases} q_k^+ = \dfrac{Q_k^+}{N_k} \\ q_k^- = \dfrac{Q_k^-}{N_k} \end{cases} \tag{6}$$

$$\begin{cases} t_{k_1}^+ = t_k^+ + t_{min}^k \\ t_{k_2}^+ = t_k^+ + t_{max}^k \end{cases} \tag{7}$$

$$\begin{cases} t_{k_1}^- = t_k^- + t_{min}^k \\ t_{k_2}^- = t_k^- + t_{max}^k \end{cases} \tag{8}$$

$$N_k = \frac{T_0}{\Delta t_k^+} + \frac{T_0}{\Delta t_k^-} = T_0 \cdot \left(\frac{1}{\Delta t_k^+} + \frac{1}{\Delta t_k^-}\right) \tag{9}$$

So:

$$\begin{cases} v_k^+ = \dfrac{Q_k^+}{T_0 \cdot \left(\dfrac{1}{\Delta t_k^+} + \dfrac{1}{\Delta t_k^-}\right) \cdot (t_{max}^k - t_{min}^k)} \\[3em] v_k^- = \dfrac{Q_k^-}{T_0 \cdot \left(\dfrac{1}{\Delta t_k^+} + \dfrac{1}{\Delta t_k^-}\right) \cdot (t_{max}^k - t_{min}^k)} \end{cases} \tag{10}$$

Where, AFR2 refers to the average flow rate of arriving at hub platform of PF-2; k refers to the transfer route No. inside of hub; v_k^+ and v_k^- refer to AFR2 of uplink PF-2 from route k and AFR2 of downlink PF-2 from route k respectively, p/s; q_k^+ and q_k^- refer to the number of uplink PF-2 and the number of downlink PF-2 respectively in one departure interval, p; $t_{k_1}^+$ and $t_{k_1}^-$ refer to the time when the first passenger of uplink PF-2 arriving at hub platform and the time when the first passenger of downlink PF-2 arriving at hub platform respectively, s; $t_{k_2}^+$ and $t_{k_2}^-$ refer to the time when the last passenger of uplink PF-2 arriving at hub platform and the time when the last passenger of downlink PF-2 arriving at hub platform respectively, s; t_k^+ and t_k^- refer to the alighting time of uplink PF-2 and the alighting time of downlink PF-2 respectively in route k, s; t_{min}^k and t_{max}^k refer to the minimum walk time of PF-2 and the maximum walk time of PF-2 respectively, s; Q_k^+ and Q_k^- refer to the passenger flow volume of uplink PF-2 and the passenger flow volume of downlink PF-2 respectively in period T_0, p; Δt_k^+ and Δt_k^- refer to one departure interval of uplink train and one departure interval of downlink train respectively in route k, s. N_k refers to the number of departure times of route k in period T_0.

   (2) the average flow rate of getting on the train (AFR2′)

$$\begin{cases} v_2^+ = \dfrac{q_2^+}{t_1^+} \\[1.5em] v_2^- = \dfrac{q_2^-}{t_1^-} \end{cases} \tag{11}$$

Where:

$$\begin{cases} q_2^+ = v_k^+ \cdot \Delta t^+ \\ q_2^- = v_k^- \cdot \Delta t^- \end{cases} \tag{12}$$

So:

$$\begin{cases} v_2^+ = \dfrac{Q_k^+ \cdot \Delta t^+}{T_0 \cdot \left(\dfrac{1}{\Delta t_k^+} + \dfrac{1}{\Delta t_k^-}\right) \cdot (t_{max}^k - t_{min}^k) \cdot t_1^+} \\[3em] v_2^- = \dfrac{Q_k^- \cdot \Delta t^-}{T_0 \cdot \left(\dfrac{1}{\Delta t_k^+} + \dfrac{1}{\Delta t_k^-}\right) \cdot (t_{max}^k - t_{min}^k) \cdot t_1^-} \end{cases} \tag{13}$$

Where, AFR2′ refers to the average flow rate of getting on the train for PF-2; v_2^+ and v_2^- refer to AFR2′ of uplink PF-2 and AFR2′ of downlink PF-2 respectively, p/s; q_2^+ and q_2^- refer to the number of boarding passengers of uplink PF-2 in period t_1^+ and the number of boarding passengers of downlink PF-2 in period t_1^- respectively, p.

2.2.3. Basic Parameter Model of PF-5

(1) the average flow rate of arriving at hub platform (AFR3)

$$\begin{cases} v_3^+ = \dfrac{q_3^+}{t_3^+} \\ v_3^- = \dfrac{q_3^-}{t_3^-} \end{cases} \tag{14}$$

Where:

$$\begin{cases} q_3^+ = \dfrac{Q_3^+}{N_3^+} \\ q_3^- = \dfrac{Q_3^-}{N_3^-} \end{cases} \tag{15}$$

$$\begin{cases} N_3^+ = \dfrac{T_0}{\Delta t^+} \\ N_3^- = \dfrac{T_0}{\Delta t^-} \end{cases} \tag{16}$$

So:

$$\begin{cases} v_3^+ = \dfrac{Q_3^+ \cdot \Delta t^+}{T_0 \cdot t_3^+} \\ v_3^- = \dfrac{Q_3^- \cdot \Delta t^-}{T_0 \cdot t_3^-} \end{cases} \tag{17}$$

Where, AFR3 refers to the average flow rate of arriving at hub platform for PF-5; v_3^+ and v_3^- refer to AFR3 of uplink PF-5 and AFR3 of downlink PF-5 respectively in period T_0, p/s; q_3^+ and q_3^- refer to the passenger flow volume of uplink PF-5 in period t_3^+ and the passenger flow volume of downlink PF-5 in period t_3^- respectively, p. Q_0^+ and Q_0^- refer to the passenger flow volume of uplink PF-5 and the passenger flow volume of downlink PF-5 respectively in period T_0, p; t_3^+ and t_3^- refer to the alighting time of uplink PF-5 and the alighting time of downlink PF-5 respectively, s; N_3^+ and N_3^- refer to the number of uplink train departure times and the number of uplink train departure times respectively in period T_0.

(2) the average flow rate of leaving the platform (AFR3′)

$$\begin{cases} v_4^+ = \dfrac{q_3^+}{t_4^+} \\ v_4^- = \dfrac{q_3^-}{t_4^-} \end{cases} \tag{18}$$

Where:

$$\begin{cases} v_4^+ = \dfrac{Q_3^+ \cdot \Delta t^+}{T_0 \cdot t_4^+} \\ v_4^- = \dfrac{Q_3^- \cdot \Delta t^-}{T_0 \cdot t_4^-} \end{cases} \tag{19}$$

Where, AFR3′ refers to the average flow rate of leaving the platform for PF-5; v_4^+ and v_4^- refer to AFR3′ of uplink PF-5 and AFR3′ of downlink PF-5 respectively in period T_0, p/s; t_4^+ and t_4^- refer to the walk time of leaving the platform of uplink PF-5 and the walk time of leaving the platform of downlink PF-5, s.

Because $t_4^+ > t_3^+$ and $t_4^- > t_3^-$, so, $v_3^+ > v_4^+$ and $v_3^- > v_4^-$. What's more, the traffic capacity of interlayer facility in platform has a strict restriction on AFR3′. In general case, $v_4^+ > v_0^+$ and $v_4^- > v_0^-$.

2.3. Passenger Flow Distribution Models

Based on the above research, it is concluded that passenger flow distribution morphology of urban rail transit hub platform is regularly changed with the train departure interval. Therefore, the sub-objectives of building passenger flow distribution models of urban rail transit hub platform are as follows.

(1) Setting up the change rule of passenger flow distribution of hub platform in one period.

(2) Calculating the maximum passenger flow volume and passenger flow intensity value gathered in hub platform.

(3) Summarizing the dynamic loads of hub platform facilities, and then analyzing the service level of hub platform.

In hub platform, no matter to uplink train or downlink train, one departure interval Δt is defined as the research period, which refers to a time interval between the departure time of adjacent trains in same direction, i.e. $t \in [t_0, t_0 + \Delta t]$.

2.3.1. Passenger Flow Distribution Model of PF-1

In hub platform, during one departure interval, passenger flow distribution model of PF-1 can be divided into four phases, as shown in Figure 10.
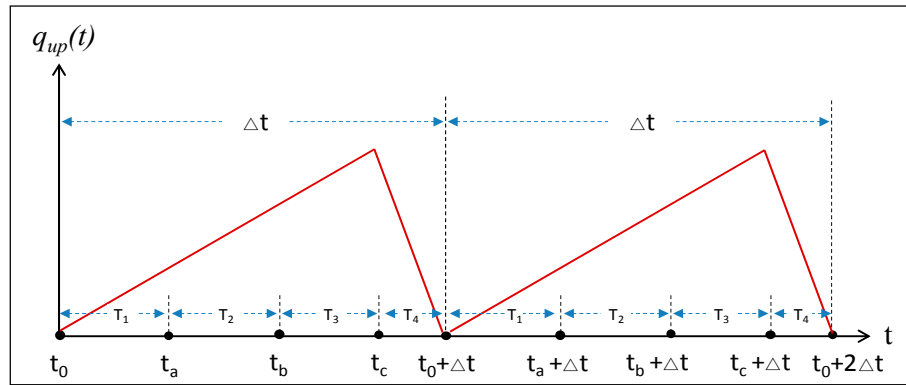
Figure 10. Variation curve of passenger flow volume of PF-1 in hub platform

Where, Δt refers to one departure interval, s; t_0 refers to the time when the prior train leaves hub platform, s; t_a refers to the time when PF-5 from the prior train completely leave the hub platform, s; t_b refers to the time when the current train door opens, s; t_c refers to the time when PF-1 begin to get on the train, s; $t_0 + \Delta t$ refers to the time when the current train leaves the hub platform, s; T_i refers to the duration of phase i, $i = 1, 2, 3, 4$, s.

During one departure interval, passenger flow volume of PF-1 in hub platform is shown as follows.

$$\begin{cases} q_{up}(t)^+ = \begin{cases} v_0^+ \cdot (t_c^+ - t_0^+) & t \in [t_0^+, t_c^+) \\ -v_1^+ \cdot (t_0^+ + \Delta t^+ - t_c^+) & t \in [t_c^+, t_0^+ + \Delta t^+] \end{cases} \\ q_{up}(t)^- = \begin{cases} v_0^- \cdot (t_c^- - t_0^-) & t \in [t_0^-, t_c^-) \\ -v_1^- \cdot (t_0^- + \Delta t^- - t_c^-) & t \in [t_c^-, t_0^- + \Delta t^-] \end{cases} \end{cases} \quad (20)$$

Where, $q_{up}(t)^+$ and $q_{up}(t)^-$ refer to the passenger flow volume of uplink PF-1 and downlink PF-1 in hub platform respectively, *p*.

2.3.2. Passenger Flow Distribution Model of PF-2

During one departure interval, passenger flow volume of PF-2 in hub platform is shown as follows.

$$\begin{cases} q_{transfer}^{k}(t)^{+} = q_{transfer}^{k}(t_0^{+})^{+} + \int_{t_0^{+}}^{t} f_k^{+}(t)dt - \int_{t_0^{+}}^{t} f_2^{+}(t)dt, t \in [t_0^{+}, t_0^{+} + \Delta t^{+}] \\ q_{transfer}^{k}(t)^{-} = q_{transfer}^{k}(t_0^{-})^{-} + \int_{t_0^{-}}^{t} f_k^{-}(t)dt - \int_{t_0^{-}}^{t} f_2^{-}(t)dt, t \in [t_0^{-}, t_0^{-} + \Delta t^{-}] \end{cases} \tag{21}$$

And:

$$\begin{cases} f_k^{+}(t) = \begin{cases} v_k^{+} & t \in [t_{k_1}^{+}, t_{k_2}^{+}] \\ 0 & t \in \{[t_0^{+}, t_{k_1}^{+}) \cup (t_{k_2}^{+}, t_0^{+} + \Delta t^{+}]\} \end{cases} \\ f_k^{-}(t) = \begin{cases} v_k^{-} & t \in [t_{k_1}^{-}, t_{k_2}^{-}] \\ 0 & t \in \{[t_0^{-}, t_{k_1}^{-}) \cup (t_{k_2}^{-}, t_0^{-} + \Delta t^{-}]\} \end{cases} \end{cases} \tag{22}$$

$$\begin{cases} f_2^{+}(t) = \begin{cases} v_2^{+} & t \in [t_c^{+}, t_0^{+} + \Delta t^{+}] \\ 0 & t \in [t_0^{+}, t_c^{+}) \end{cases} \\ f_2^{-}(t) = \begin{cases} v_2^{-} & t \in [t_c^{-}, t_0^{-} + \Delta t^{-}] \\ 0 & t \in [t_0^{-}, t_c^{-}) \end{cases} \end{cases} \tag{23}$$

Where, $q_{transfer}^{k}(t)^{+}$ refers to the platform passenger flow volume of uplink PF-2 from transfer route k at time t, p; $q_{transfer}^{k}(t)^{-}$ refers to the platform passenger flow volume of downlink PF-2 from transfer route k at time t, p; $\int_{t_0^{+}}^{t} f_k^{+}(t)dt$ refers to the platform passenger flow cumulative volume of uplink PF-2 from transfer route k from t_0^{+} to t, p; $\int_{t_0^{-}}^{t} f_k^{-}(t)dt$ refers to the platform passenger flow cumulative volume of downlink PF-2 from transfer route k from t_0^{-} to t, p; $\int_{t_0^{+}}^{t} f_2^{+}(t)dt$ refers to the cumulative volume of boarding passenger flow among uplink PF-2 from transfer route k from t_0^{+} to t, p; $\int_{t_0^{-}}^{t} f_2^{-}(t)dt$ refers to the cumulative volume of boarding passenger flow among downlink PF-2 from transfer route k from t_0^{-} to t, p. Based on the definition in section 2.1.4, $q_{transfer}^{k}(t_0^{+})^{+} = q_{transfer}^{k}(t_0^{-})^{-} = 0$.

2.3.3. Passenger Flow Distribution Model of PF-5

As similar with section 2.3.1, during one departure interval, passenger flow distribution model of PF-5 also can be divided into four phases, as shown in Figure 11.
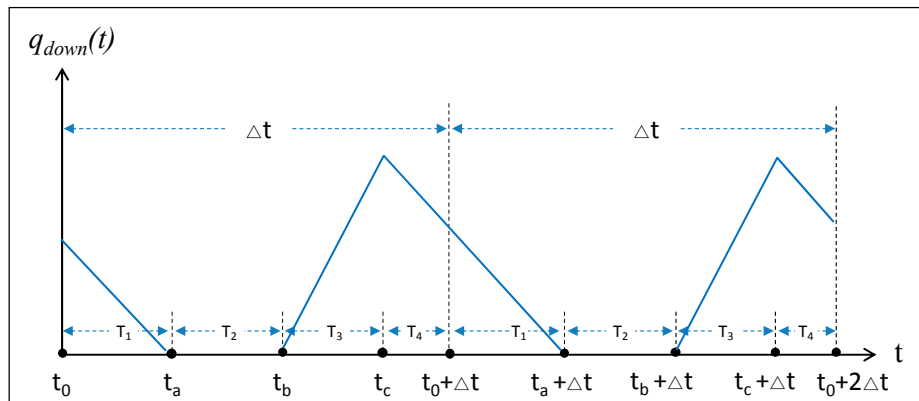
Figure 11. Variation curve of passenger flow volume of PF-5 in hub platform

During one departure interval, passenger flow volume of PF-5 in hub platform is shown as follows.

$$
\begin{cases}
q_{down}(t)^+ = \begin{cases}
-v_4^+ \cdot (t_a^+ - t_0^+) & t \in [t_0^+, t_a^+] \\
0 & t \in [t_a^+, t_b^+] \\
v_3^+ \cdot (t_c^+ - t_b^+) & t \in [t_b^+, t_c^+] \\
-v_4^+ \cdot (t_0^+ + \Delta t^+ - t_c^+) & t \in [t_c^+, t_0^+ + \Delta t^+]
\end{cases} \\
q_{down}(t)^- = \begin{cases}
-v_4^- \cdot (t_a^- - t_0^-) & t \in [t_0^-, t_a^-] \\
0 & t \in [t_a^-, t_b^-] \\
v_3^- \cdot (t_c^- - t_b^-) & t \in [t_b^-, t_c^-] \\
-v_4^- \cdot (t_0^- + \Delta t^- - t_c^-) & t \in [t_c^-, t_0^- + \Delta t^-]
\end{cases}
\end{cases} \tag{24}
$$

Where, $q_{down}(t)^+$ and $q_{down}(t)^-$ refer to the platform passenger flow volume of uplink PF-5 and downlink PF-5 at time t respectively, *p*.

2.3.4. Passenger Flow Distribution Integrating Model of Hub Platform

Based on the above research, passenger flow distribution integrating model of hub platform is proposed by using the superposition principle for passenger flow. That means, during one departure interval, passenger flow volume in hub platform is shown as follows.

$$
Q(t) = Q(t)^+ + Q(t)^-, \quad t \in [t_0, t_0 + \Delta t] \tag{25}
$$

And:

$$
\begin{cases}
Q(t)^+ = q_{up}(t)^+ + \sum_1^k q_{transfer}^k(t)^+ + q_{down}(t)^+, \quad t \in [t_0^+, t_0^+ + \Delta t^+] \\
Q(t)^- = q_{up}(t)^- + \sum_1^k q_{transfer}^k(t)^- + q_{down}(t)^-, \quad t \in [t_0^-, t_0^- + \Delta t^-]
\end{cases} \tag{26}
$$

Where, $Q(t)$ refers to the passenger flow volume in hub platform at time *t*, *p*; $Q(t)^+$ and $Q(t)^-$ refer to the uplink passenger flow volume and the down passenger flow volume in hub platform at time t respectively, *p*.

3. Simulation Design

In this chapter, based on the passenger flow distribution models of hub platform, functional framework and simulation process of simulation system are designed by Java 8.0. On the other hand, passenger flow distribution simulation environment of hub platform is built by using Anylogic 7.2.0. Simulation design research in this chapter can provide technical approaches for the case study and model performance verification following.

3.1. Simulation Design by Java

3.1.1. Simulation process

By using the event marching method, simulation process of passenger flow distribution models in hub platform is built, as shown in Figure 12. Meanwhile, event is defined as the variation of passenger flow volume in hub platform, which pushes the simulation clock forward.
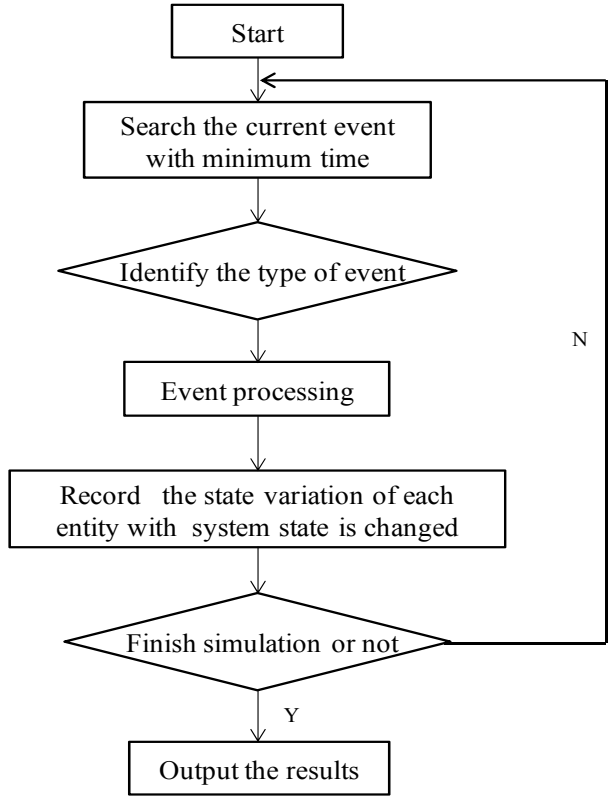
Figure 12. Simulation process of simulation system

3.1.2. Functional framework and implementation path

In this section, functional framework and implementation path of simulation system are designed by Java 8.0., as shown in Figure 13.
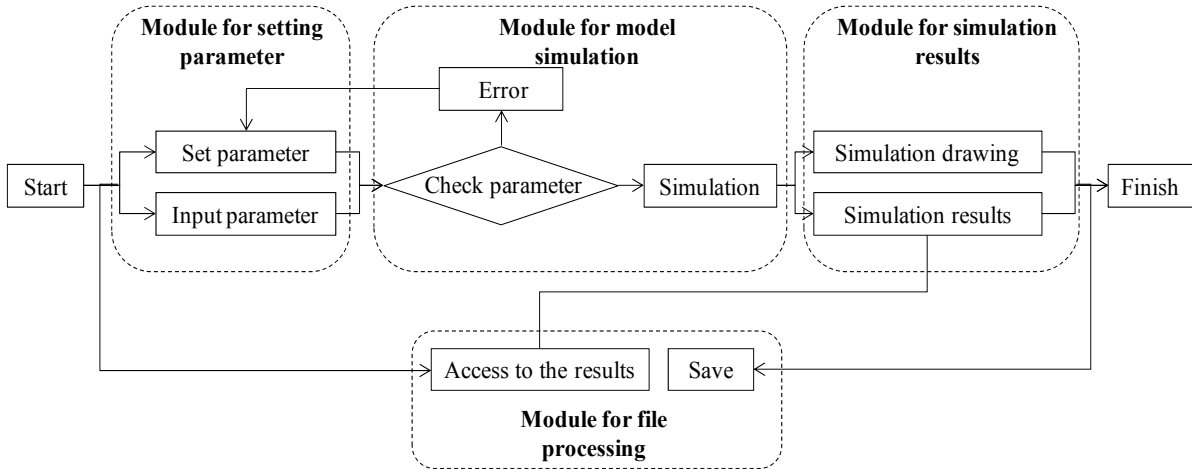
Figure 13. Functional framework and implementation path of simulation system

3.2. Simulation Design by Anylogic

Anylogic software is a professional simulation environment for virtual prototyping based on UML-RT, Java and differential equation. It is efficiently used for the simulation of complex systems which contain discrete system, continuous system and hybrid system [35]. So far, Anylogic is widely applied to the dynamic simulation in traffic and transportation. In this paper, pedestrian library and rail library in Anylogic are adopted to set up the simulation environment of passenger flow distribution of hub platform. Simulation process of Anylogic is shown in Figure 14.
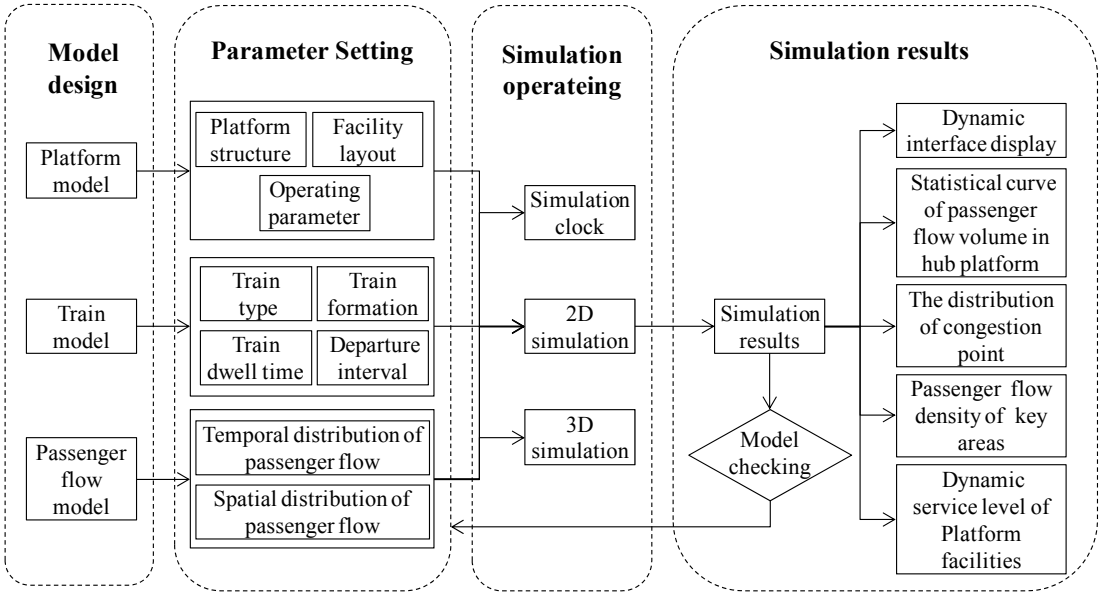
Figure 14. Simulation process of Anylogic

3.2.1. Platform Model

Based on the parameters of platform structure and facility layout, simulation model of platform is built by using Anylogic, which is shown in Figure 15.

Figure 15. Simulation model of platform by Anylogic

3.2.2. Train Model

The rail library is a functional module which supports modeling and simulation of various urban rail vehicles, and visual operation. In this paper, the rail library is adopted to set up the simulation model of urban rail vehicle, which is shown in Figure 16.
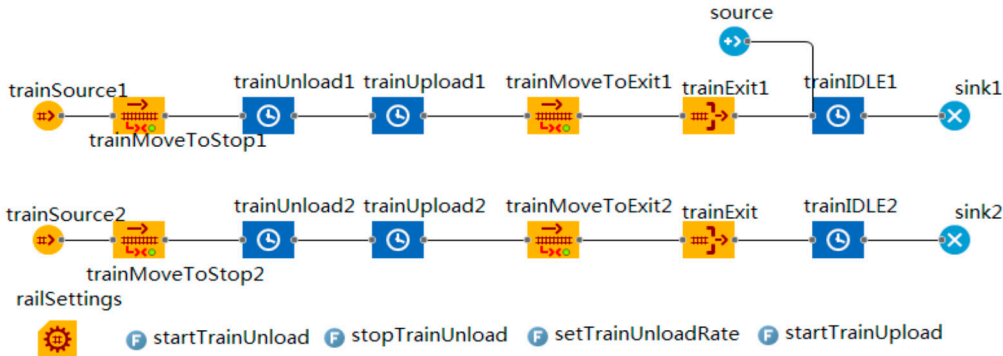
Figure 16. Simulation model of urban rail vehicle by Anylogic

3.2.3. Passenger Flow Model

The pedestrian library is used to set up passenger flow model in the physical space and accurately simulate the traffic behavior of passenger which core algorithm is social force model.

And in general, the walking speed value of passenger flow is set as 1.0-1.5m/s. In this paper, the pedestrian library is adopted to set up the simulation model of passenger flow distribution in hub platform, which is shown in Figure 17.
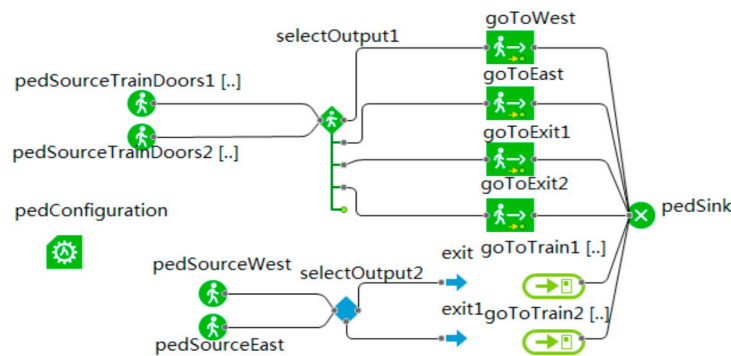
Figure 17. Simulation model of passenger flow distribution in hub platform by Anylogic

4. Case Study and Results Analysis

As an urban rail transit hub station, Beijing South Subway Station is located in the first floor underground of Beijing South Railway Station, which contains Beijing subway line 4 and line 14. Passenger can transfer among the different traffic modes such as high-speed railway, urban rail transit and urban public bus. The structure schematic of Beijing South Subway Station is shown in Figure 18.
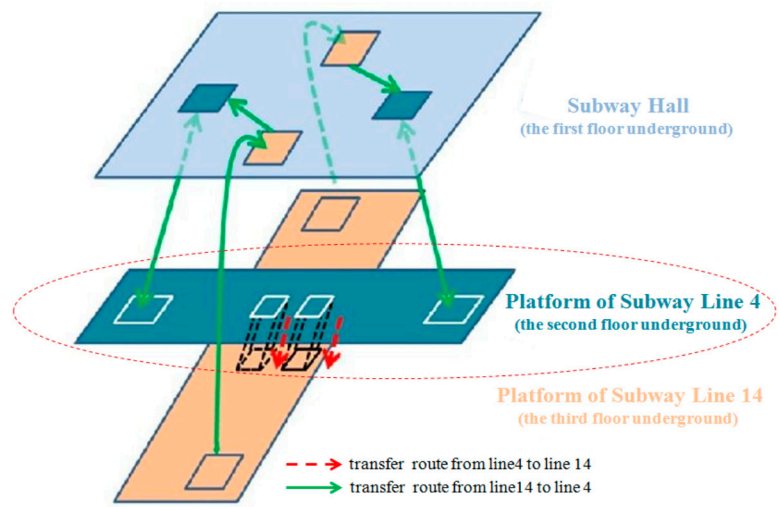
Figure 18. The structure schematic of Beijing South Subway Station

In Figure 18, subway hall is located in the first floor underground; the platform of subway line 4 is located in the second floor underground; the platform of subway line 14 is located in the third floor underground. In this paper, the platform of subway line 4 is selected as the hub platform for research, meanwhile, the passenger flow in the platform of subway line 4 is selected as the research object.

4.1. Data Collection and Analysis

In this paper, to the passenger flow in the platform of subway line 4, the practical investigation data of Beijing South Subway Station in Table 2 is adopted for case study.

Table 2. The practical investigation data of Beijing South Subway Station

Item	Detail
location of practical investigation	the platform of subway line 4 in Beijing South Subway Station
uplink direction of subway line 4	to Anheqiao North Station
downlink direction of subway line 4	to Tiangongyuan Station
dates of practical investigation	June 6-8, 2016
peak hour of practical investigation	07:30-08:30
data contents of practical investigation	platform facilities data of subway line 4 train data of subway line 4 passenger flow data

By means of practical investigation and data processing, parameters values of the platform facilities data are listed in Table 3; parameters values of the train data of subway line 4 are listed in Table 4; parameters values of the passenger flow distribution integrating model for case study are calculated and listed in Table 5.

Table 3. Parameters values of the platform facilities data

Item	Value	Unit
available length of platform	115	m
available width of platform	17	m
available length of escalator	15.5	m
available width of escalator	1	m
the number of escalator	4	-
available length of stairs	15.5	m
available width of stairs	2.5	m
the number of stairs	2	-
available area of platform	1650	m^2

Table 4. Parameters values of the train data of subway line 4

Item	Value	Unit
train type	type B	-
train formation	6	-
train length	115	m
train width	2.8	m

Table 5. Parameters values of the passenger flow distribution integrating model

Symbol	Value	Unit	Symbol	Value	Unit
Q_0^+	6650	p	Q_0^-	950	p
Q_k^+	2100	p	Q_k^-	300	p
Q_3^+	4590	p	Q_3^-	1800	p
q_1^+	196	p	q_1^-	38	p
q_2^+	175	p	q_2^-	25	p
q_3^+	135	p	q_3^-	72	p
q_k^+	175	p	q_k^-	25	p
v_0^+	1.85	p/s	v_0^-	0.26	p/s
v_1^+	9.80	p/s	v_1^-	1.27	p/s
v_2^+	8.75	p/s	v_2^-	0.83	p/s
v_3^+	27	p/s	v_3^-	14.4	p/s
v_4^+	4.5	p/s	v_4^-	2.4	p/s

v_k^+	8.75	p/s	v_k^-	1.25	p/s
t_1^+	20	s	t_1^-	30	s
t_3^+	5	s	t_3^-	5	s
t_4^+	30	s	t_4^-	30	s
t_{min}^k	120	s	t_{max}^k	140	s
Δt^+	103	s	Δt^-	140	s
Δt_k^+	300	s	Δt_k^-	300	s
$T_1^+ = t_a^+ - t_0^+$	30	s	$T_1^- = t_a^- - t_0^-$	30	s
$T_2^+ = t_b^+ - t_a^+$	48	s	$T_2^- = t_b^- - t_a^-$	75	s
$T_3^+ = t_c^+ - t_b^+$	5	s	$T_3^- = t_c^- - t_b^-$	5	s
$T_4^+ = t_0^+ + \Delta t^+ - t_c^+$	20	s	$T_4^- = t_0^- + \Delta t^- - t_c^-$	30	s
N_3^+	34	-	N_3^-	25	-
T_0	3600	s			

4.2. Simulation Models

Based on the practical investigation data of Beijing South Subway Station in Table 2 and the parameters values in Table 3,4,5, the simulation models by Anylogic for case study are built, as shown in the following Figures.

Firstly, the simulation model of platform is built according to parameters values of the platform facilities data in Table 2,3, and then the scale of this simulation model is defined as 10.5 pixels per meter. Simulation model of the subway line 4 platform in Beijing South Subway Station is shown in Figure 19.
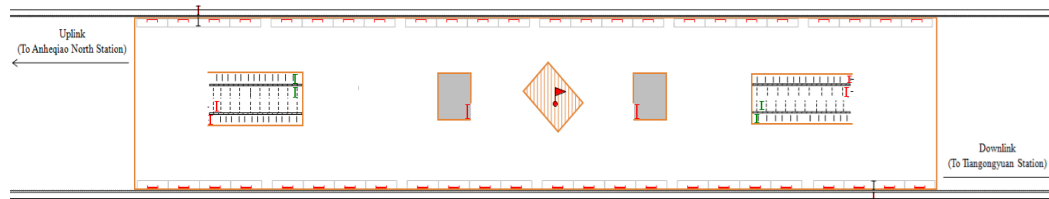
Figure 19. Simulation model of the subway line 4 platform in Beijing South Subway Station

Secondly, simulation model of the subway line 4 train is built according to parameters values in table 4,5, as shown in Figure 20.
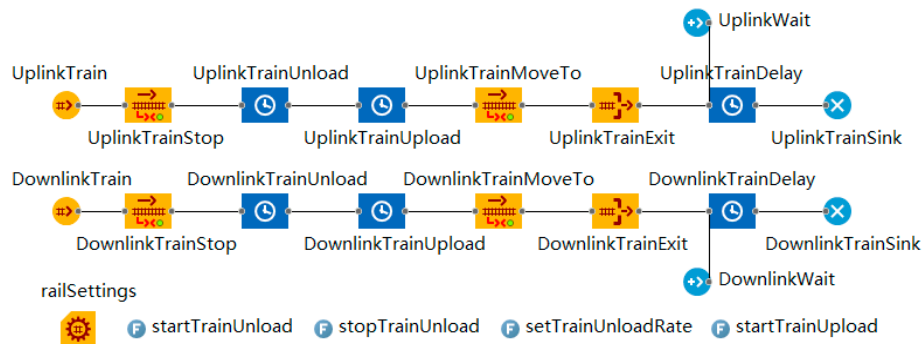
Figure 20. Simulation model of the subway line 4 train in Beijing South Subway Station

Then, simulation model of the passenger flow of the subway line 4 platform is built according to parameters values in table 5, as shown in Figure 21.
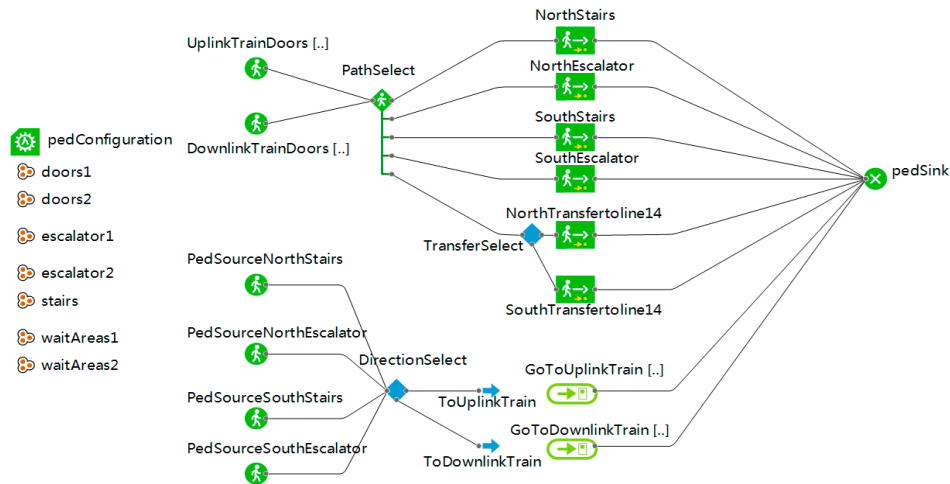
Figure 21. Simulation model of the subway line 4 platform in Beijing South Subway Station

What's more, The schematic diagrams of simulation interface display are shown in the following Figures.

Figure 22. Schematic diagram of simulation interface display without density map showing
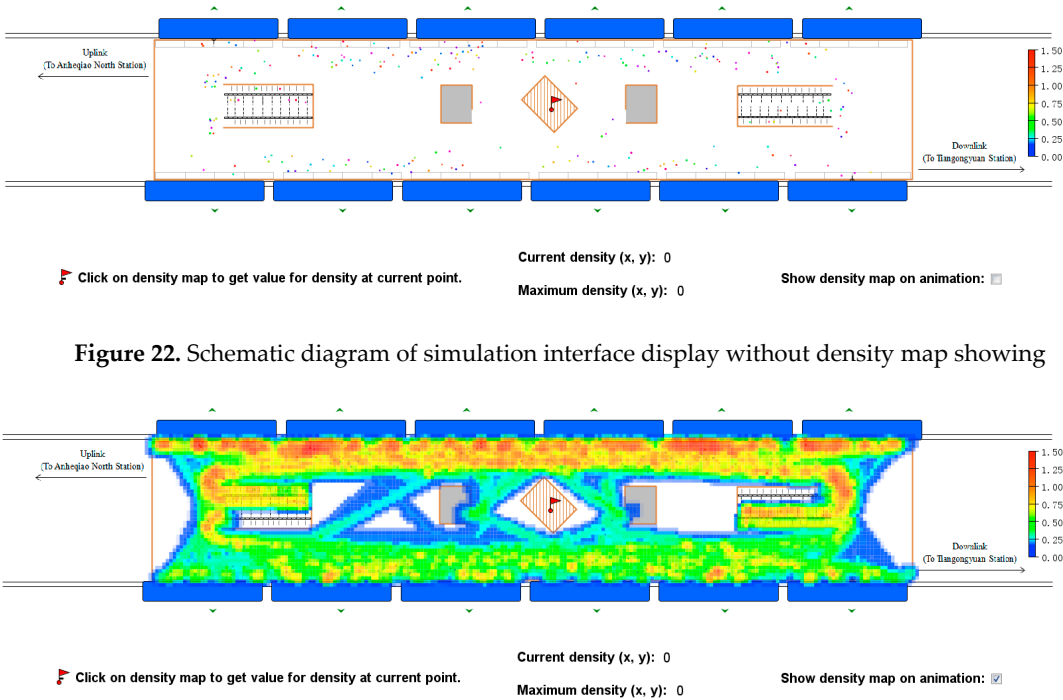
Figure 23. Schematic diagram of simulation interface display with density map showing

4.3. Calculation Results

4.3.1. Model Performance Experiment

According to the above research and practical investigation data, the value of passenger flow volume in the hub platform is calculated by Java 8.0 and Anylogic 7.2.0. Statistical curves of passenger flow volume in the hub platform are shown in Figure 24, 25.
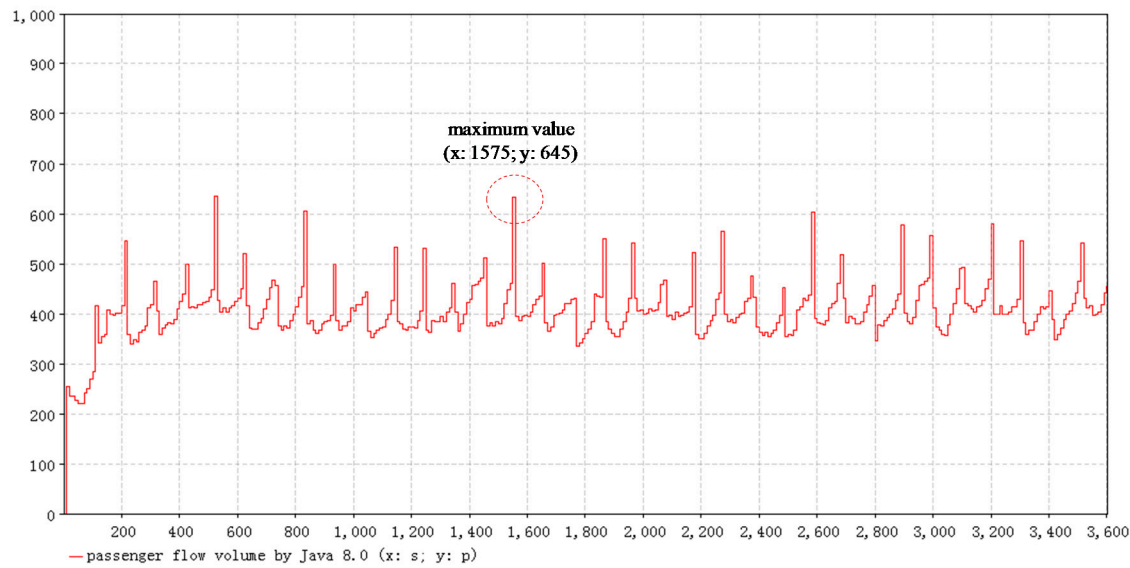
Figure 24. Statistical curve of passenger flow volume in the hub platform by Java 8.0
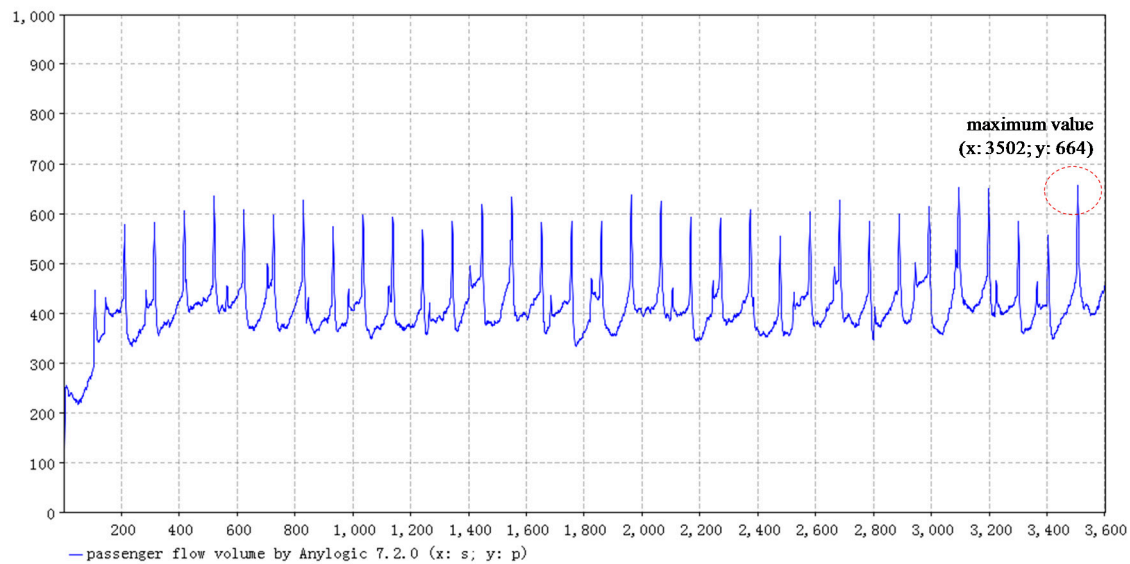
Figure 25. Statistical curve of passenger flow volume in the hub platform by Anylogic 7.2.0

Then, by using contrastive analysis based on the calculation results in Figure 24, 25, more results could be obtained, as shown in Table 6.

Table 6. Parameters values of the train data of subway line 4

Item	Calculation result	
	Calculating by Java	**Calculating by Anylogic**
maximum value of passenger flow volume	$645p$	$664p$
average density	$0.39p/m^2$	$0.40p/m^2$
average error	2.86%	

By the model performance experiment, some conclusions are summarized as follows.

(1) It is proved that passenger flow distribution models which are built in chapter 2 have a good performance on describing passenger flow distribution process of the hub platform.

(2) From the above calculation results, it is shown that simulation designs by Java and Anylogic for passenger flow distribution models which are built in chapter 3 are scientific and accordant with the reality scene.

(3) The average error between two simulation methods is 2.86%, it is indicated that the simulation precision is comparatively ideal.

(4) The average density of passenger flow in the hub platform is less than $0.40p/m^2$, it is indicated that the service level of hub platform is reliable.

4.3.2. More Experiments with Different Departure Intervals

In this section, more experiments are taken with different departure intervals of subway line 4 in Beijing South Subway Station. Calculation results of passenger flow volume in the hub platform are shown in Table 7 and Figure 26.

Table 7. Calculation results of maximum passenger flow volume with different departure intervals of subway line 4

Departure interval of subway line 4 (Δt : s)	Time lag between uplink line and downlink line ($\left|\Delta t^+ - \Delta t^-\right|$: s)						
	0	10	20	30	40	50	60
90	637	625	610	598	624	643	675
120	765	730	708	685	710	742	758
150	874	793	772	743	765	815	876
180	937	882	855	812	848	887	943
210	1082	975	961	930	970	998	1136
240	1235	1150	1085	1032	1078	1123	1218
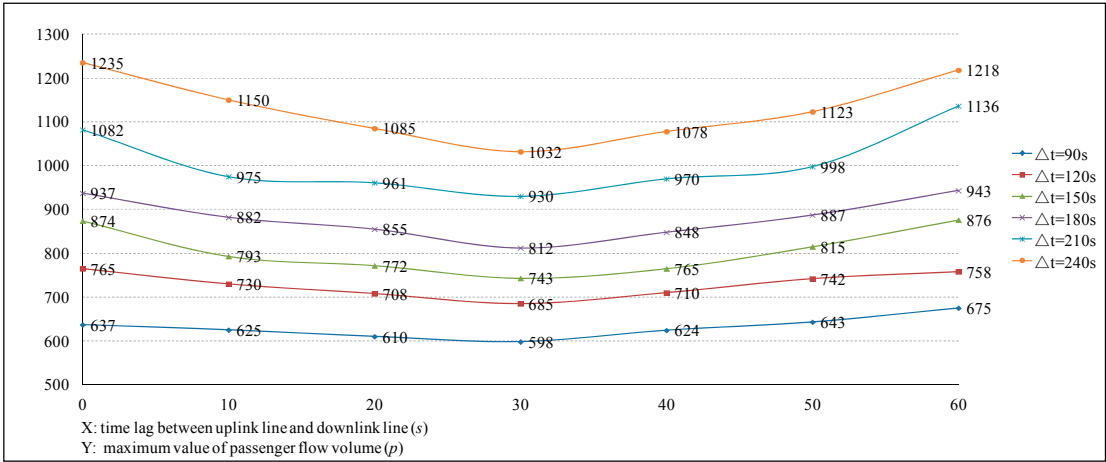
Figure 26. Statistical curve of maximum passenger flow volume with different departure intervals of subway line 4

From Table 7 and Figure 26, it is shown that the minimum value among the calculation results is 598, as Δt=90 and $\left|\Delta t^+ - \Delta t^-\right|$=30 .

5. Conclusion

For an urban rail transit hub, hub platform is the most important area of passenger flow distribution. Passenger flow volume of hub platform has become a fundamental and crucial data for hub capacity design, operation organization and management. In this paper, in order to research the dynamic variation regularity of passenger flow distribution and calculate the passenger flow volume of hub platform, some studies are carried out and some conclusions are obtained as follows.

First, on the basis of basic theory analysis and basic parameter models, passenger flow distribution integrating model is proposed by using the superposition principle of passenger flow. And then, simulation designs of the passenger flow distribution integrating model are built by using Java 8.0 and Anylogic 7.2.0, which contain simulation system functional framework, implementation path, simulation processes and simulation models.

Second, this paper selects the platform of subway line 4 in Beijing South Subway Station as case study. By means of practical investigation and data processing, parameters values of simulation models are listed. Next, by the model performance experiment, it is proved that passenger flow distribution integrating model has a good performance on describing the dynamic variation regularity of passenger flow distribution. The average error between two simulation methods is 2.86%, which indicates that the simulation precision is comparatively ideal, and simulation designs are scientific and accordant with the reality scene. The average density of passenger flow is less than $0.40p/m^2$, which indicates that the service level of hub platform is reliable.

Third, more experiments are taken with different departure intervals. The minimum value among the calculation results is 598, as $\Delta t=90$ and $\left|\Delta t^+ - \Delta t^-\right|=30$. This experiment results can provide the reference for train scheduling and operation management under the viewpoint of traffic safety and service level.

Because there are four basic definitions proposed in this research, so this paper has certain limitations. In addition, this research is not free of mistakes and inconveniences. Future researches could be conducted to further improve the performance and practicality of passenger flow distribution models for more scientific and reasonable.

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