Simulation Study of Passenger Flow Characteristics in Subway Passage

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Abstract. The characteristic of passenger flow in subway passage is an important factor in allocating transfer facilities, evaluating service level and increasing operational efficiency. This paper took the example of Dongzhimen subway station in Beijing as simulation scenario. A simulation model of passenger flow in transfer passage was developed using Anylogic software. An optimized path-choice algorithm had been made to improve the Anylogic, avoiding passenger congestion in the simulation. Through survey data, parameters in the model were calibrated and the model validation was proved. Moreover, the paper analyzed the sensitivity of passage width and width proportion of different transfer directions. The results show that: the improved simulation model has greatly relieved the blocked condition in the passage, caused by the original shortest path-choice algorithm in Anylogic model; the simulation data is in accord with measured data, verifying that the model is applicable in practice. From the sensitivity analysis, it is found that when passage width varies from 5 m to 7 m, the passenger intensity decreases, but the rate of the change increases first and decreases afterwards with the increasing passage width; when the bidirectional passenger volume is high, the variation of width proportion of different transfer directions has an obvious effect on passenger density and passenger intensity.

Introduction

Nowadays, urban rail transit has been developing rapidly in China. Subway lines have been formed a network in many cities. In urban rail transit network, transfer station is a key factor to the operational performance of the transit system. Subway passage, as a way for passengers transfer between different lines, is widely used in most transfer stations. As a result, study on characteristics of passenger flow in subway passage becomes crucial to the operational performance of a transfer station, even the whole network.

There are many research activities that focus on passenger flow characteristics of transfer passage. Henderson was the pioneer in this field who applied fluid-dynamic models to pedestrian crowds [1]. Helbing developed a kind of fluid dynamic description for pedestrians’ movement based on a Boltzmann-like gas-kinetic model. He observed the movements through footprints of pedestrians in the snow and quick-motion pictures of pedestrians [2]. Knoppers et al. believed that the walking time distribution of transfer pedestrian flow followed the normal distribution [3]. Victor et al. used cellular automata (CA) microsimulation for modeling bi-directional pedestrian walkways, the model could provide for simulating three modes of bi-directional pedestrian flow [4], while Cao established a CA model based on ant colony algorithms to simulate bidirectional pedestrian flow in urban rail transit passages [5]. Serge et al. applied the dynamic microscopic pedestrian flow model NOMAD to simulate pedestrian traffic operations for different station designs [6]. Ye et al. studied on pedestrian flow characteristics for four different types of walking facilities in Shanghai subway stations, meanwhile, developed pedestrian flow–density–speed relationships for each kind of walking facility such as one-way, two-way passageway [7]. Seyfried et al. experimentally studied unidirectional pedestrian flow through bottlenecks of different width under laboratory conditions [8]. Shi et al.
attempted to formulate the simulation model for evacuation of passengers in subway transfer station, used software Legion to simulate the passenger flow in transfer passage, and then proposed strategies to reduce the evacuation risk [9,10]. Chen et al. constructed an M/G/c/c-based model to analyze the procedure of passenger movement and estimate evacuation capacity of stairs and passages in subway stations [11]. Tong took the transfer passage of Xinjiekou Subway Station in Nanjing for example, developed a bi-layer cooperative simulation model of bidirectional pedestrian flows [12]. Yang set up a passenger flow simulation model in subway station based on Anylogic, and obtained the optimal opening number of the entrance ticket windows through simulation [13]. A set of studies of pedestrian flow characteristics under different traffic conditions was discussed in Reference [14].

In most of the current studies, the effect of passage width variation on bidirectional passenger flow has not yet been considered. In fact, when there is only one passage for passengers transfer between different lines, making a reasonable choice of using either unidirectional or bidirectional transfer mode, will be of great help to alleviate the congestion in subway passage and improve transfer efficiency, according to the actual situation while meeting the larger transfer passenger flow. Additionally, passenger flow may be blocked still in passage with the increasing passenger volume, when using Anylogic to simulate. Therefore, it’s necessary to optimize the Anylogic software and study the effect of transfer passage width of different directions on passenger flow characteristics. The paper takes the example of Dongzhimen subway station in Beijing, sets up a simulation model of passenger flow in transfer passage based on Anylogic, then analyzes the passenger flow characteristics (e.g. passenger volume, passenger density, passenger intensity) in rush and non-rush hours, with variable passage width proportion of different transfer directions. The results could be helpful in allocating transfer facilities and thus offer reference for passenger flow organization.

Modeling

Anylogic software is a multi-method simulation modeling tool. It supports agent-based, discrete event and system dynamics simulation methodologies. As Anylogic has an advanced pedestrian library based on Social Force Model, and uses an open architecture that allows for a high degree of customization to match the passengers' movement, the paper uses Anylogic to simulate the passenger flow. As to the simulation case, we choose Dongzhimen subway station in Beijing. It is a transfer station for Line 2, Line 13 and Airport Express line with large passenger flow. And passages are used for passengers transfer between platforms of different lines. For convenience of the study, we focus on the passage for passengers transfer from Line 2 to Line 13 to analyze the passenger flow characteristics.

Model Construction

There are two steps for developing the simulation model. The first step is drawing the graphics for
simulation scenario and the next is constructing the corresponding logic module. Specifically, the structure graph of Dongzhimen station drawn by computer aided design (CAD) software is imported into the simulation scenario, then the logic module is set based on the drawn graph. Fig.1 shows the logic flow of the model.

From the simulation, we can get four output statistical data, which are passenger volume \((N)\), passenger intensity in a certain cross-section of the transfer passage \((I)\), passenger number and walking time in designated area, respectively. Passenger intensity is equal to passenger volume divided by the width of the cross-section in the passage \((L)\).

**Parameter Setting**

When constructing the simulation model, passenger walking speed and total passenger volume has been re-set based on the data from field survey, and the other parameters are set as system defaults.

From investigation and statistical analysis, we can get walking speed distribution of transfer passengers in the morning and evening rush hours, as is shown in Fig.2.

![Figure 2. Walking speed distribution of transfer passengers during rush hours.](image)

Fig.2 indicates that, walking speed of transfer passenger is mainly concentrated in the range of 1.5m/s-2m/s in the morning rush hours, the average speed is 1.61 m/s; while in the evening rush hours, walking speed is distributed in the range of 1 m/s-1.4 m/s, the average speed is 1.19 m/s. From the trend of cumulative frequency, it is found that passengers walk faster in the morning rush hours, the cumulative frequency is close to 100% when the average speed is round 2.5 m/s; on the contrary, passengers walk more slowly in the evening rush hours, the cumulative frequency approaches to 100% when the average speed is 1.8 m/s or so. This phenomenon is due to the commuting of passenger flow. Passengers are stressed or harried as they make their way to work, but have much relaxation time after work during the evening rush hours.

Through the curve fitting, we can see that passenger walking speed follows lognormal distribution, \(\ln(v_{\text{mr}}) \sim N(0.4049, 0.3343^2)\), \(\ln(v_{\text{er}}) \sim N(0.1502, 0.2382^2)\), in both morning and evening rush hours. The comfortable walking speed range for passengers has been calibrated, \(v_{\text{mr}}\sim\text{Truncated-Lognormal}(0.4049, 0.3343^2, 1.4, 2.2)\), and \(v_{\text{er}}\sim\text{Truncated-Lognormal}(0.1502, 0.2382^2, 1.0, 1.6)\), where, \(v_{\text{mr}}\) is walking speed in the morning rush hours, and \(v_{\text{er}}\) is walking speed in the evening rush hours.

In order to simulate the actual passenger flow more accurate, we investigate the total passenger volume in transfer passage every 5 minutes, in the morning and evening rush hours separately. The survey data shows that, in the morning rush hours, the least passenger volume is 513 and highest 1026 in the direction of transfer from Line 2 to Line 13, the corresponding passenger volume is 13 and 594 in the opposite direction. While in the evening rush hours, the least passenger volume is 700 and highest 1300 in the direction of transfer from Line 2 to Line 13, and the corresponding passenger volume is 6 and 45 in the opposite direction.
Model Optimization

The shortest path algorithm is used for passengers choosing their trajectory to the destinations in Anylogic model. When running the program, there will be some unreasonable blocks around the corner with the increase of the passenger flow, as is shown in A and B areas of Fig.3. The reason may be that the shortest path is automatically chosen by the path-choice mode in the software. When the passenger flow increases to certain extent, some individuals with higher speed will be blocked as the result of being unable to pass the slower ones, thus they have to wait still, which causes congestion. However, based on Social Force Model, when passenger is confronted with obstacles that are hard to pass, there will be strong mutual or reciprocal action resulting from repulsive force. Under this repulsive force, passenger will give up its previous shortest path and choose a new one. As a result, the situation shown in Fig.3 appears scarcely in practice. To avoid such passenger congestion, we introduce turning points of passage corner to improve the path-choice algorithm in Anylogic model. In the optimized algorithm, the trajectory can also be chosen automatically as it used to be, but we set intermediate destination points at passage corner, so the passage is divided into different sections by these points, passenger will choose the shortest path in each section, therefore, the trajectory passenger getting to the destination becomes a polyline. Fig.4. illustrates the optimized simulation result.

Model Validation

Running the simulation model, we can get a three-dimensional passenger flow graph in Dongzhimen subway passage. As speed-density relationship and passenger density are the main indicators to describe the passenger flow characteristics, the paper compares speed-density relationship and passenger density of the simulation result with measured data in the morning rush hours, to verify the validity of the model.

Fig. 5 shows the Density-speed comparison between simulation data and measured data. The diagram in Fig. 5 indicates that speed-density relationship follows the power function distribution, the curve fits better at low density, and simulation value is slightly lower than measured value at high density.

Comparing measured data with simulation data in the morning rush hours, it shows that the biggest passenger density is 0.39 and 0.38 respectively, and the smallest value is 0.16 and 0.14, as is shown in
The histogram in Fig. 6 suggests that there is only small difference between simulation data and the measured data. Therefore, the simulation result is well in accord with measured data, the simulation model is valid.

Parameter Sensitivity Analysis

In China, there is usually a subway passage between two different lines in transfer station. Passengers can transfer from one line to another through the passage. There may be only one passage that connects two lines, e.g., line 1 and line 2, in this case, passengers transfer from line 1 to line 2 and the opposite direction share the same passage, that is to say, the passenger flow is bidirectional. It is common to set up isolation facility in passage, to reduce mutual interference between passengers of different walking directions. Therefore, according to walking direction, passenger flow can be divided into 2 parts independently by this facility. The isolation facility position will determine the available passage width of different directions, for example, if the total passage width is 6 m, and the available width for passengers transfer from line 1 to line 2 is 4.5 m, we can get the available width for passengers transfer from line 2 to line 1, with total width (6 m) minus available width of the opposite direction (4.5 m), the value is 1.5 m. We define divided proportion as the ratio of one direction available passage width to the opposite direction available width.

In other cases, there may be two passages between different lines, one is for passengers transfer from line 1 to line 2, and the other is from line 2 to line 1, however, there may be reverse passenger flow in each passage. From a practical point of view, passage width as well as variable divided proportion has a great effect on the characteristics of passenger flow. Thus, it needs to analyze the sensitivity of the above two parameters using Anylogic model.

Sensitivity Analysis of Passage Width

The paper takes the example of subway passage in DONGZHIMEN transfer station in Beijing, the passage for passengers transfer from line 2 to line 13 is chosen as study subject. By changing the passage width, from 5 m to 5.5 m, 6 m, 6.5 m, 7 m, the passenger intensity ($I$) and passenger volume ($N$) are calculated by Anylogic model, Table 1 shows the passenger intensity and passenger volume with variable passage width, where $\Delta I$ is the value of current $I$ minus the latter one, and $\Delta N$ is the value of current $N$ minus the latter $N$.

<table>
<thead>
<tr>
<th>Passage width [m]</th>
<th>5</th>
<th>5.5</th>
<th>6</th>
<th>6.5</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I$ [p/m]</td>
<td>3984.43</td>
<td>3539.57</td>
<td>3476.14</td>
<td>3440.14</td>
<td>3229.71</td>
</tr>
<tr>
<td>$N$ [p/m]</td>
<td>796.89</td>
<td>643.56</td>
<td>579.36</td>
<td>529.25</td>
<td>461.39</td>
</tr>
</tbody>
</table>

From Table 1, we can see that, when the total passenger volume is certain, with passage width varying from 5 m to 7 m gradually, both passenger intensity and passenger volume decrease. When
the passage width changes from 5 m to 5.5 m, passenger intensity and volume has declined dramatically, \( \Delta I \) reaches 444.86 and \( \Delta N \) 153.33. While, when the width changes from 5.5 m to 6.5 m, there is only small change of \( \Delta I \) and \( \Delta N \). When the width changes from 6.5 m to 7 m, the values of \( \Delta I \) and \( \Delta N \) increase again. The above analysis shows that, when the width is about 5 m, the passage is crowded; when the width varies from 5.5 m to 6.5 m, the passenger flow remains stable; when the width reaches around 7 m, the passenger flow becomes loose and passengers can walk freely in the passage.

### Sensitivity Analysis of Divided Proportion

As mentioned earlier in the chapter, there may be reverse passenger flow in one-way passage. This has been proved through traffic survey in Dongzhimen transfer station. The survey found that, there are some passengers transfer from line 13 to line 2 in the passage that is only used for transfer from line 2 to line 13, during both rush and non-rush hours. Thus, we take the passage for passengers transfer from line 2 to line 13 as simulation scenarios, define transfer direction from line 2 to line 13 as forward direction and line 13 to line 2 as reverse direction, and then use the Anylogic model to simulate passenger flow in two situations. One is the passage without isolation facility; the other is the passage with variable divided proportion.

According to the survey data, in the morning rush hours, the passenger volume of reverse direction is higher than the evening and non-rush hours, so the total passenger volume in the morning rush hours is taken as input volume data, while output passenger volume, passenger intensity and passenger density as evaluation indexes to analyze the passenger flow.

**Passenger flow without division.** In this situation, there is no isolation facility in the passage. Therefore, passengers of the two transfer directions share the same passage. Fig.7 shows the simulation results of passenger flow in the passage using Anylogic. Fig.7 (a) is the simulation result at 10 minutes and Fig.7 (b) 30 minutes.

![Legend](image)

(a) Simulation result at 10 minutes   (b) Simulation result at 30 minutes

Figure 7. Graph of the simulation result in transfer passage without division.

Fig.7 (a) shows the passenger density in passage when the bidirectional passenger volume is low. The red areas represent the locations with highest passenger density, and passenger congestion is likely to occur in these areas. And yet there is no congestion with lower passenger volume, as shown in Fig.7 (a). When the passenger volume of two directions increases to a certain extent, some places in the passage are prone to be congested, such as the red areas in Fig.7 (b). Dongzhimen is a transfer station, passenger volume is high, once the passage is congested, stampede will easily to happen.
(a) divided proportion 3.5:3  (b) divided proportion 4:2.5  (c) divided proportion 4.5:2  (d) divided proportion 5:1.5

Figure 8. Graph of the simulation result at 30 minutes in transfer passage with variable divided proportion.

*Passenger flow with isolation facility.* In this situation, the passage width is 6.5 m. Isolation facility is set up in the passage, as shown by a dashed line in Fig. 8. The passenger flow in the morning rush hour is simulated by Anylogic. Fig. 8 shows the simulation results at 30 minutes with variable divided proportion, the proportion is 3.5:3, 4:2.5, 4.5:2 and 5:1.5, respectively.

Fig. 8 indicates that, with the increase of passenger volume in reverse direction, the reverse direction available passage width will decrease gradually and passenger density increase greatly. When the divided proportion is 4.5:2, there will be obvious congestion in the passage. Table 2 gives the passenger intensity and passenger volume with variable divided proportion.

<table>
<thead>
<tr>
<th>divided proportion</th>
<th>3.5:3</th>
<th>4:2.5</th>
<th>4.5:2</th>
<th>5:1.5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>N [p/h]</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Line 2 to line 13</td>
<td>3193.55</td>
<td>3054.97</td>
<td>3124.26</td>
<td>3231.10</td>
</tr>
<tr>
<td>Line 13 to line 2</td>
<td>1588.06</td>
<td>1522.06</td>
<td>1330.84</td>
<td>967.35</td>
</tr>
<tr>
<td><strong>I [p/m]</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Line 2 to line 13</td>
<td>912.44</td>
<td>763.74</td>
<td>694.28</td>
<td>646.22</td>
</tr>
<tr>
<td>Line 13 to line 2</td>
<td>519.35</td>
<td>608.33</td>
<td>665.42</td>
<td>644.90</td>
</tr>
</tbody>
</table>

From Table 2, we can see that, with the increase of divided proportion, the passenger volume of forward direction (from line 2 to line 13) has changed slightly, the value remains around 3200 persons per hour. However, with the available passage width reduction, the passenger volume of reverse direction (from line 13 to line 2) gradually decreases. When the available passage width changes from 2 m to 1.5 m, the passenger volume has declined dramatically, \( \Delta I \) reaches 363.49. In addition, with the increase of divided proportion, the passenger intensity of forward direction has decreased from 912.44 to 646.22; on the contrary, the intensity of reverse direction has a rising trend, when the divided proportion is 5:1.5, the passenger intensity ratio of forward direction to reverse direction approximates to 1.

**Conclusions**

The paper takes the example of Dongzhimen subway station in Beijing as simulation scenario, develops the simulation model of passenger flow in transfer passage using Anylogic software. An optimized path-choice algorithm has been made to improve the Anylogic, avoiding passenger congestion in the simulation. Through survey data, parameters in the model have been calibrated and the model validation proved. Moreover, the paper analyzes the sensitivity of passage width and width proportion of different transfer directions. The conclusions are as follow:

1. In transfer passage, walking speed of transfer passengers follows lognormal distribution. The comfortable walking speed range is between 1.0 m/s and 2.2 m/s, and the average speed is higher in the morning rush hour than the evening rush hour. The relationship between walking speed and passenger density follows the power function distribution. With the increase of walking speed, passenger density has a declining trend.
(2) Intermediate destination points have been set at passage corner, thus the whole passage is divided into different sections by these points, and passenger can choose the shortest path in each section. This improvement has greatly relieved the blocked condition in the passage, caused by the original path-choice algorithm in Anylogic model. The simulation result is in accord with measured data, verifying that the model is applicable in practice.

(3) The sensitivity analysis results show that, when passage width varies from 5 m to 7 m, the passenger intensity decreases, but the rate of the change increases first and decreases afterwards with the increasing passage width. When the bidirectional passenger volume is high, the variation of width proportion of different transfer directions has an obvious effect on passenger density and passenger intensity.

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