Passenger Transfer Conflict Delay in Large Passenger Transport Hubs

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Abstract. In the passenger transfer process, passenger congestion conflict is a very important factor in transfer delays in large passenger transport hubs. By analyzing passenger walking speed, passenger arrival rate, the capacity of walking facilities and passengers’ expected travel time, a model for calculating conflict delay in the passenger transfer process is established in this paper. The relationship between the average delay due to passenger conflict, the arrival rate and the absolute value of the difference in passenger arrival rates from different directions is calculated, and a simulation platform of passenger travel behavior, which is based on NetLogo, is established to simulate the passenger transfer conflict process. The outcomes verify that the model is effective, feasible and accurate. Therefore, the research results make great contributions towards the evaluation of the layout plans of passenger transfer facilities in large hubs, and provide a theoretical foundation for perfecting hub transfer facilities.

Introduction

In recent years, with the rapid development of the Chinese society and economy, many urban, comprehensive passenger transfer hubs have been built in China’s cities. Rapid transportation has brought great convenience to people's travel, which has attracted large volumes of passengers, for example on high-speed rail. However, this has led to conflicts in the flow in hubs at peak hours, which inconveniences and causes discomfort to the passengers, while seriously affecting the transfer efficiency. Therefore, domestic and foreign scholars have conducted much research exploring the topic from different directions.

From the aspect of hub transfer delay, scholars have carried out a great deal of research on flight delays [Santos et al., 2010; Wesonga et al., 2012] and train delays [Briggs, et al., 2007; Yuan et al., 2007], looking for example at the causes of such delays, the relevant factors and improvement measures, etc, but focusing less on the analysis of passenger transfer time. Landeghem [Landeghem et al., 2002] surveyed passenger boarding times in different boarding modes, and proposed an improved boarding mode for reducing passenger boarding times, based on a simulation method. Also looking to reduce boarding times, Steffen [Steffen, 2008] researched the best boarding order of passengers using the Markov Monte Carlo optimization algorithm and computer simulation. Tang [Lee et al. 1991] constructed a boarding model considering the characteristics of passengers, again to investigate boarding times under different boarding modes. Comparing total boarding times and boarding delays under three kinds of boarding policy, the author found the most effective boarding strategy to be one that considered the number of passenger seats and the passengers’ own characteristics.

From the aspect of the factors that influence transfer, Lee [Lee et al. 1995] studied bus and rail transit and proposed that a rational relaxation time for bus departures (the difference between the actual and theoretical departure times) could improve transfer efficiency. Knoppers [Knoppers et al., 1995; Chien et al., 2005] pointed out that, while people were in the transfer process, the average transfer time was not only related to the interval between vehicle arrivals, but also to the interval
between departure times of coordinated bus lines. HSU [Hsu et al., 2010] established a passenger transfer time estimation model in a multi-mode [including buses, trains, taxis etc] transfer hub, which analyzed the transfer vehicle arrival interval and the vehicle capacity effect on the transfer time. Solak [Solak et al., 2009] studied the problem of airport planning with regards to the overall service capacity, creating a function to estimate the maximum passenger transfer time. By quantitatively analyzing the relationship between passengers’ transfer time, passengers’ costs and passenger complaint ratio, Bhadra [Bhadra et al., 2009] found that passengers pay more attention to the transfer time than the cost. Chowdhury [Chowdhury et al., 2002] pointed out that the transfer time is one of the most important indicators in the evaluation of multi-mode transfer services, and provided a vehicle departure time optimization method.

Domestic scholars have carried out a lot of research on vehicle travel times. However, the study of passenger transfer times in hubs is not sufficiently mature, and there is a lack of theory and a systematic analysis method. Shen Y.S.[ Shen et al., 2009 ]built a passenger time delay model for stairs and escalators using queuing theory, and discussed the influence on the time delay of the number of passengers and width of stairs. Xie Z.Y. [Xie et al, 2012] pointed out that the transfer time delay is an important parameter, which results from queuing, congestion and waiting, and explained the mechanism of transfer delays. Qi K. [Qi et al., 2012; Qi et al., 2011] studied the generalized cost of passenger transfers in passenger hubs, calculating the transfer conflict delay in passenger hubs based on the conflict delay for vehicles at unsignalized intersections. He also analyzed and calculated the passengers’ travel time in passenger hub channels, but ignored the huge difference between motor vehicle and pedestrian traffic.

Zhao L. [Zhao et al., 2011] analyzed the transfer delays in all kinds of transportation facilities in rail transportation hubs. She considered congestion delay to be the cause of transfer delays in channel class facilities, and obtained the function of this delay using pedestrian flow theory and the Taylor series. Next, she considered the queuing delay to cause delays in service class facilities, and obtained the function of this delay using the area method. Finally, she considered the waiting delay to be the cause of delays in riding class facilities, and obtained the function of this delay by using a Taylor series to approximate the arrival of passengers. Du P. [Du et al., 2009] studied the passenger travel time in a subway station transfer channel, finding it to approximately follow a lognormal distribution, finding crowding to interact with the travel time mean and variance, and finding a secondary relation between the travel time and the transfer channel length within a certain range. Xie L.H. [Xie et al., 2010] studied the waiting times of passengers transferring from rail to BRT [Bus Rapid Transit] and qualitatively described the factors affecting passenger transfer time. Ma H.[ Ma et al., 2010; Mao et al., 2015] quantitatively analyzed the influencing mechanism of mass transit hub transfer efficiency using a neural network model, and simulated the transfer behavior of passengers and rail network passengers using Petri net, before optimizing the transfer efficiency of passengers based on the simulation results.

In summary, domestic and foreign scholars have conducted much meaningful research on pedestrian transfer delays and pedestrian characteristics, with the results more heavily concentrated on the layout of functional areas, and the characteristics of pedestrian queuing and pedestrians, but less heavily concentrated on conflict delays to transfer times. Thus, this paper expands on the existing research.

Transfer Conflict Delay Model

Expected Walking Time

In large passenger hubs, passengers require multiple travel facilities (channel transfer hall, stairs, escalators, etc.) to complete the transfer process. If a passenger requires n travel facilities to complete the entire transfer, then the passenger’s distance traveled in the i th travel facility is $L_i$. If the expected traveling speed (FFS) is $v_{di}$, then the expected travel time over the whole transfer process is $t_{des}$, defined as follows:
\[ t_{des} = \sum_{i=1}^{n} \frac{L_i}{v_{di}} \]  

Where \( t_{des} \) —— the average expected travel time, in s;
\( n \) —— number of walking facilities;
\( L_i \) —— the length of walking facility \( i \), in m;
\( v_{di} \) —— the expected traveling speed on walking facility \( i \), in m/s

If the walking facility is a staircase or escalator, then \( L_i \) is the vertical height, and \( v_{di} \) is the running speed in the vertical direction.

When it comes to travel facilities [escalator or stairs], the distance traveled refers to the vertical height of the escalator or stairs, and the expected traveling speed on the escalator refers to the speed of the escalator in the vertical direction, which is determined by the electrical equipment of the escalator.

**Congestion Delay**

According to the definition of congestion delay, it is equal to the travel time minus the expected time spent on the travel facilities, as in the following equation:

\[ d_{crowd} = t_{walk} - t_{des} = \frac{L}{v} - \frac{L}{v_d} = \frac{L(v_d - v)}{vv_d} \]  

Where \( d_{crowd} \) —— congestion delay, s;
\( t_{walk} \) —— walking time, s;
\( t_{des} \) —— expected walking time, s;
\( L \) —— distance walked, m;
\( v \) —— actual walking speed, m/s;
\( v_d \) —— expected walking speed, m/s.

**Capacity of Walking Facilities**

According to Equation 2, the key to calculating the congestion delay is obtaining \( t_{walk} \), and in order to get \( t_{walk} \), we should analyze the capacity of the walking facilities firstly.

The capacity of a travel facility is the maximum number of passengers per unit of time and section. When the arriving passenger flow is constant, the travel capacity of the facilities directly determines the passengers’ travel delay. The relationship between the passenger flow rate and the passenger density in a one-way passage is as follows:

\[ q = -0.395k^2 + 1.362k \]  

Where \( q \) —— passenger flow rate, p/(s∙m);
\( k \) —— passenger density, p/m².

The passenger flow in the channel is as follows:

\[ Q_T = (-0.395k^2 + 1.362k)W_T \]  

Where \( Q_T \) —— passenger flow in the channel, p/s;
\( W_T \) —— passageway width, m.

The maximum number of passengers in the channel (the capacity of the channel) is as follows:

\[ Q_{T_{MAX}} = 1.174W_T \]  

Similarly, the capacities of the walking facilities for moving in the up and down directions are given by Equations 6 and 7.
$Q_{\text{arr,max}} = 0.418 W_{\text{f}}$ \hfill (6)

$Q_{\text{dr,max}} = 0.472 W_{\text{f}}$ \hfill (7)

On the basis of the above analysis, when the arrival passenger flow $Q_{\text{arr}}$ is less than the capacity of the walking facilities, $Q_{\text{max}}$, the passenger traffic is smooth; when $Q_{\text{arr}} > Q_{\text{max}}$, then the arriving passengers cannot evacuate in a timely fashion, the passageway becomes congested, and the queue length and walking delay will grow. The mechanism of congestion in a one-way passage is illustrated in Figure 1. This paper only considers the condition where $Q_{\text{arr}} < Q_{\text{max}}$.

![Figure 1. Mechanism of congestion in a one-way passage.](image)

**Calculation of Congestion Delay under the Condition Where $Q_{\text{arr}} < Q_{\text{max}}$**

Taking a one-way passage as an example, if the passengers' arrival times follow a negative exponential distribution, and the passengers are uniformly distributed in the passage, with $Q_{\text{arr}} < Q_{\text{max}}$, then the number of arriving passengers is equal to the number of leaving ones, $Q_{\text{arr}} = Q_{\text{max}} = Q$, and the density of passengers in the passage equals:

$$k = \frac{-1.362 + \sqrt{1.855 - 1.58(Q_{\text{arr}}/W_{r})}}{-0.79}$$ \hfill (8)

According to the relationship between the velocity and density, the passengers’ average walking speed equation is as follows:

$$v = -0.395 k + 1.362$$ \hfill (9)

Where $v$ —— the passengers’ average walking speed, m/s;

$k$ —— density of passengers, p/m²;

Substituting Equation 8 into Equation 9, the passengers’ average walking speed equals:

$$v = 0.681 + \sqrt{0.464 - 0.395(Q_{\text{arr}}/W_{r})}$$ \hfill (10)

Substituting Equation 10 into Equation 2, the congestion delay equals:

$$d_{\text{crowd}} = \frac{L(v_{d} - v)}{v_{d} V}$$ \hfill (11)

In order to verify the effectiveness of Equation 11, a passengers’ walking simulation platform was built using the simulation software NetLogo. Take a one-way passage of length 10m and width 6m to simulate the passengers’ travel behavior. The scatter diagram between the passenger arrival rate and the congestion delay is shown in Figure 2, and the comparison of the simulation and calculation of the congestion delay is shown in Figure 3.

From the figures, when $Q_{\text{arr}} < Q_{\text{max}}$, the average relative error between the calculation and the simulation is 6.02%, and the maximum relative error is 9.65%, while when $Q_{\text{arr}} \geq Q_{\text{max}}$, the
relative error between the calculation and the simulation is 27.14%, indicating that Equation 11 for the congestion delay calculation is reasonable.

Figure 2. Scatter diagram between passengers’ arrival rate and congestion delay.

Figure 3. Comparison of simulation and calculation of congestion delay.

Similarly, when $Q_{\text{arrive}} < Q_{\text{max}}$, the $d_{\text{ucrowd}}$ and $d_{\text{dcrowd}}$ equations are as follows, where $H$ is the total height of the stairs:

$$
\begin{align*}
    d_{\text{ucrowd}} &= \frac{H(v_d - 0.145 - \sqrt{0.021 - 0.05(Q_{\text{arrive}} / W_s)})}{v_d (0.145 + \sqrt{0.021 - 0.05(Q_{\text{arrive}} / W_s)})} \\
    d_{\text{dcrowd}} &= \frac{H(v_d - 0.196 - \sqrt{0.038 - 0.081(Q_{\text{arrive}} / W_s)})}{v_d (0.196 + \sqrt{0.038 - 0.081(Q_{\text{arrive}} / W_s)})}
\end{align*}
$$

Simulation Analysis

Data Acquisition Method

The passenger crossover clash delay is influenced by the number and angles of cross-conflicts per unit time. Thus, the different passenger arrival rates and passenger crossover clashes under different conflict angles are simulated using the passengers’ travel behavior simulation platform, and the results are shown in Figure 4.

With conflict in the pedestrian flow appearing, the passengers’ diffusion phenomenon occurs [in order to avoid conflict, pedestrians will walk away from the conflict area]. The more passengers arrive, the more obvious the phenomenon is, as shown in Figure 5.
In the simulation, the moments when each passenger crosses the start and stop lines are recorded, and the crossing conflict delay is the difference between the expected travel time and the actual travel time. The calculation is as follows:

\[ d_c = T_c - \frac{L_c}{v_d \cdot \sin(\theta)} \]  

Where:
- \( d_c \) — crossing conflict delay, s;
- \( T_c \) — walking time to pass the conflict area, s;
- \( L_c \) — distance between start and finish lines, m;
- \( v_d \) — expected walking speed, m/s;
- \( \theta \) — conflict angle.

**Effect of Conflict Angle on Conflict Delay**

Assuming passenger arrival rates of 0.5p/s, 1.0p/s, 1.5p/s and different conflict angles, the passengers’ walking mode was simulated, producing the average conflict delay across 800 passengers as the final simulation result. Each scenario was repeated 10 times, and the final results are shown in Figure 6. The figure indicates that, when the conflict angle is 90°, the conflict delay is the lowest. As the conflict angle increases or decreases, the conflict delay increases slowly. Furthermore, as the passenger arrival rate increases, the impact of the conflict angle on the conflict delay becomes more obvious, and the conflict angle of the minimum conflict delay is gradually reduced. Finally, as the conflict angle increases, the conflict delay increases more obviously.
Effect of Passenger Arrival Rate on Conflict Delay

Again, under different conflict angles, the passengers’ walking mode was simulated. By changing the passengers’ arrival rate, the simulation platform produced average delay data, with 1000 passengers’ average conflict delay as the final simulation result, and each scenario repeated 10 times. At a conflict angle of 130°, 49 groups of data of passenger arrival rates and conflict delays were obtained, as shown in Figure 7. The curved surface is shown in Figure 8.

According to Figure 8, the passengers’ average delay will increase with the total passenger arrival rate.

Similarly, the other curved surfaces of the arrival rate and conflict delay with different crossing conflict angles could be calculated as in the previous steps. Taking the total passenger flow as the dependent variable, and the absolute value of the passenger arrival rate as the independent variable, the regression model can be obtained by the Levenberg-Marquardt algorithm, as shown in Table1.
<table>
<thead>
<tr>
<th>Conflict angle</th>
<th>Arrival rate-conflict delay</th>
<th>Coefficient&lt;sup&gt;①&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>150°</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$p_1 = 2.0682$; $p_2 = 0.1162$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$p_3 = 0.8464$; $p_4 = 0.3368$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$p_5 = 0.0843$; $p_6 = 0.0068$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$p_7 = 0.4701$; $p_8 = 2.5019$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$p_9 = 0.9704$; $p_{10} = 0.7213$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(R&lt;sup&gt;2&lt;/sup&gt; = 0.995)</td>
</tr>
<tr>
<td>120°</td>
<td></td>
<td>$p_1 = 1.7581$; $p_2 = 1.4715$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$p_3 = 3.8188$; $p_4 = 3.8561$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$p_5 = 1.5073$; $p_6 = 0.2049$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$p_7 = 4.3224$; $p_8 = 10.9153$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$p_9 = 8.7068$; $p_{10} = 2.8906$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(R&lt;sup&gt;2&lt;/sup&gt; = 0.995)</td>
</tr>
<tr>
<td>90°</td>
<td></td>
<td>$p_1 = 0.0258$; $p_2 = 0.0835$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$p_3 = 0.0132$; $p_4 = 0.1254$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$p_5 = 0.0308$; $p_6 = 0.0008$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$p_7 = 0.2490$; $p_8 = 0.0527$</td>
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<tr>
<td></td>
<td></td>
<td>$p_9 = 0.0069$; $p_{10} = 0.0002$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(R&lt;sup&gt;2&lt;/sup&gt; = 0.998)</td>
</tr>
<tr>
<td>60°</td>
<td></td>
<td>$p_1 = 0.7832$; $p_2 = 0.0053$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$p_3 = 0.0867$; $p_4 = 0.1721$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$p_5 = 0.0771$; $p_6 = 0.0103$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$p_7 = 1.6932$; $p_8 = 4.7561$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$p_9 = 3.6484$; $p_{10} = 1.1367$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(R&lt;sup&gt;2&lt;/sup&gt; = 0.997)</td>
</tr>
<tr>
<td>30°</td>
<td></td>
<td>$p_1 = 0.7701$; $p_2 = 0.4418$</td>
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<tr>
<td></td>
<td></td>
<td>$p_3 = 1.3193$; $p_4 = 1.2838$</td>
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<td></td>
<td></td>
<td>$p_5 = 0.5136$; $p_6 = 0.0713$</td>
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<td></td>
<td></td>
<td>$p_7 = 0.0383$; $p_8 = 1.0101$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$p_9 = 0.3882$; $p_{10} = 0.1587$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(R&lt;sup&gt;2&lt;/sup&gt; = 0.995)</td>
</tr>
</tbody>
</table>

NOTE ①: crossing conflict delay equals

$$d_c^\theta = p_1 + p_2 x + p_3 x^2 + p_4 x^3 + p_5 y + p_6 y^2 + p_7 y^3 + p_8 y^4 + p_9 y^5$$  \hspace{1cm} (15)$$

Where $d_c^\theta$——average crossing conflict delay at conflict angle $\theta$, s;

$x$——absolute value of passenger arrival rate, p/s;

$y$——total passenger flow, p/s;
Calculation of Crossing Conflict Delay

On the basis of the above analysis, the average passenger conflict delay is affected by the total passenger arrival rate, the passenger arrival rates in different directions, and the conflict angle. The first two factors show a similar relationship to the average delay and conflict. Thus, the conflict impact angle formula is introduced to explain the relationship between the three factors and the average conflict delay, as shown in Equation 16 ($R^2=0.981$), and the optimized values are shown in Table 2.

\[
d_c = d_c^\theta + (P_{11}x + P_{12}y + P_{13}xy)\exp(P_{14}\theta^{\text{rad}} + P_{15})
\]

(16)

Table 2. Optimized parameters of crossing conflict delay calculation model.

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Optimized value</th>
<th>Coefficient</th>
<th>Optimized value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_1$</td>
<td>0.226</td>
<td>$P_9$</td>
<td>-4.4306</td>
</tr>
<tr>
<td>$P_2$</td>
<td>0.1969</td>
<td>$P_{10}$</td>
<td>1.5354</td>
</tr>
<tr>
<td>$P_3$</td>
<td>0.0022</td>
<td>$P_{11}$</td>
<td>0.3085</td>
</tr>
<tr>
<td>$P_4$</td>
<td>0.0005</td>
<td>$P_{12}$</td>
<td>-4.4171</td>
</tr>
<tr>
<td>$P_5$</td>
<td>-0.0171</td>
<td>$P_{13}$</td>
<td>3.8387</td>
</tr>
<tr>
<td>$P_6$</td>
<td>0.0034</td>
<td>$P_{14}$</td>
<td>2.5002</td>
</tr>
<tr>
<td>$P_7$</td>
<td>-1.1149</td>
<td>$P_{15}$</td>
<td>0.2861</td>
</tr>
<tr>
<td>$P_8$</td>
<td>4.6195</td>
<td>$P_{16}$</td>
<td>-13.4055</td>
</tr>
</tbody>
</table>

After calculating conflict angles of 45° and 135° using the above equation, the crossing conflict delays for each passenger arrival rate were calculated and the comparative results are shown in Fig.10 and Fig.11. The maximum relative error compares the results with the simulation results, showing the equation for crossing conflict delay to be valid.

Conclusions

Passenger transfer delay is an important index for evaluating the service level of a passenger transport hub. Meanwhile, conflict between passengers is an important factor affecting passengers’ transfer delay and comfort. This paper analyzed the passengers’ walking characteristics, arrival rate and crossing conflict angle, which have a significant impact on the transfer delay.

The following conclusions can be drawn:

1. This paper proposed a passenger conflict delay model, and gave the main influencing factors of the model, including the passenger walking speed, the passenger arrival rate, the walking facility capacity, and the passenger expected travel time.
2. According to the Levenberg-Marquardt algorithm, a solution algorithm for the proposed model was studied.
3. Using the simulation software NetLogo, a passengers’ walking simulation platform for a large transfer hub was built, and the effectiveness and accuracy of the proposed model was verified.

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References


