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Time prediction model of subway transfer

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Abstract

Walking time prediction aims to deduce waiting time and travel time for passengers and provide a quantitative basis for the subway schedule management. This model is founded based on transfer passenger flow and type of pedestrian facilities. Chaoyangmen station in Beijing was taken as the learning set to obtain the relationship between transfer walking speed and passenger volume. The sectional passenger volume of different facilities was calculated related to the transfer passage classification. Model parameters were computed by curve fitting with respect to various pedestrian facilities. The testing set contained four transfer stations with large passenger volume. It is validated that the established model is effective and practical. The proposed model offers a real-time prediction method with good applicability. It can provide transfer scheme reference for passengers, meanwhile, improve the scheduling and management of the subway operation.

Keywords: Time prediction, Subway transfer, Passenger flow, Pedestrian facilities

Background

As an indispensable transportation system of big cities, subway has the merit of time reliability and vast capacity. With the development of urban subway system, passenger flow has increased significantly on peak time. The great concentration of passenger flow in transfer station has put enormous pressure on the subway system. Not only the underground network design decision, but also a huge range of consequential information service for passengers including transfer waiting time, travel time, reliability and even mode choice depend on the assumption about how long passengers will spent on walking from one subway line to the other.

It is shown from the literature about the subway interchange that Virkler and Elayadath (1994) established a relationship for speed-flow-density based on Transport and Traffic survey. Feng et al. (2009) drew the relation curve of speed and passenger flow density at the subway loading areas and upstairs in Beijing. Lu et al. (2002) founded the dynamical equation of evacuation speed for personnel. Fang et al. (2007) verified the dynamical equation of evacuation speed and the parameters in the equation. Kirchner and Schadschneder (2002) used a bionics-inspired cellular automaton model to analyze the pedestrian dynamics. Sarkar and Janardhan (1997) reported different speed relationships built for different pedestrian facilities. In the previous research, transfer time

prediction was found region-specific. Bookbinder and Désilets (1992) developed its own emphasis on the evaluation of transfer time cost. Osorio and Bierlaire (2009) analyzed the capacity of the queuing network model which could capture the propagation of congestion and predict the travel time. Chen et al. (2008) analyzed the evacuation capacity and the level of the service for passengers at Metro station. Xuejun (2006) studied the characteristics of the transfer behavior from different transfer stations design. In the congestion situation, Singh and Srivastava (2008) proposed a traffic flow model which were applied to elevator configuration based on Markov network queuing theory. A new elevator-dispatching method was deduced theoretically using queuing theory by Zong et al. (2005). According to the survey on pedestrian walking characteristics, Blue and Adler (2001) established the cellular automata (CA) model based on the ant colony algorithms. Cao et al. (2009) put forward the update rules that could embody the walking characteristics of pedestrian counter flow.

Although the above researches cover most contents of the transfer behavior, there is less study for the walking time prediction by pedestrian facilities. Besides transfer speed characteristics, this paper analyzes the passenger walking behavior with respect to different pedestrian facilities in subway transfer stations. In "Transfer time prediction function" section, the time prediction model of the platform, the elevator and the horizon passage is established based on transfer flow volume and walking time on different facilities. In "Parameter estimation" section, model parameters are estimated according to the learning set. In "Transfer time model validation" section, the accuracy of transfer time model is validated by testing set including four transfer stations. Calculation results indicate that the transfer time prediction model can not only reduce waiting time for passengers, but also improve the subway operation efficiency.

Transfer time prediction function

Transfer time T is considered as the time between passengers getting off one subway train and boarding another (Pepple and Adio 2014), which is divided into two parts: transfer walking time T_w and transfer waiting time T_d. It is under the influence of transfer passenger flow and different facilities. Transfer walking time T_w includes the walking time on the platform T_1, the time in the horizon passage T_2 and that on the escalator T_3.

$$T = T_w + T_d = T_1 + T_2 + T_3 + T_4 \tag{1}$$

Transfer walking time T_i on different facilities is calculated partly by:

$$T_i = \frac{L_i}{v_i} \tag{2}$$

For the facility i, L_i means the length, v_i means the speed.

When $i = 1, 2$, the section passenger flow p_i of transfer pedestrian facility i is:

$$p_i = \frac{N}{B_i} \tag{3}$$

where N means the number of transfer pedestrians, B means the width of different facilities.

Transfer speed on different facilities v_i is:

$$v_i = a_i p_i^2 + b_i p_i + c_i \tag{4}$$

where a_i, b_i and c_i are estimable parameters.

Transfer walking on the platform

It is obvious that transfer walking time on the platform is related to the passenger distribution and the position of passages. Assume the transfer passenger distribution on the platform is uniform (Peng et al. 2009). Suppose l_1 is the length of the platform, $D(x)$ is the distance from a passenger's position x to the position of the passage entrance, then the average length for transfer passengers walking to the passage is:

$$l_1 = \int_0^{l_1} \frac{D(x)}{l_1} dx \tag{5}$$

Transfer walking in the horizon passage

In the horizon passage, where is straight, long and non-stair, the main factor of walking speed is passenger volume. Pedestrians can walk freely when the transfer passenger volume is properly low (Canónico-González et al. 2013). However, in case the passengers get crowded, walking speed will decline gradually at peak time.

Walking on the stairs is also regulated with passenger volume while the speed is related to the climbing direction. According to the former research (Chen et al. 2011), the rate of upstairs walking time to horizon passage was 1.30 and the downstairs rate was 1.20. It should be noted that people would be more inclined to use the escalator instead of stairs.

Transfer behavior on the escalator

As passengers on the escalator are restricted by the group behavior and the speed of the escalator, it is difficult for them to fascinate others. When transfer passengers overflow the escalator capacity, they have to pack together waiting for the queue in front of the escalator which will cause a sudden change of walking speed. In this case, the pedestrian arrivals distribution and the distribution of escalator service time are respectively assumed to be Poisson and negative exponential (Chen et al. 2012). Since the transfer station has more than one escalator, the queue system can be reduced M/M/S model (Li et al. 2014). Suppose n is the number of pedestrians in the queue system, s is the number of escalators. The pedestrian arrival rate is formulated as follows:

$$\lambda = v_1 \cdot p_1 \tag{6}$$

The service rate of the escalator is:

$$\mu = C_1 \cdot B_3 \cdot \omega \tag{7}$$

where C_1 is the capacity of the escalator in units, B_3 is the effected width of the escalator and ω is the saturation coefficient.

Based on the conclusion of the birth and death process, the stationary distribution in the queuing system is:

$$p_n = \frac{\lambda^n}{\mu^n s! s^{n-s}} p_o \tag{8}$$

p_0 is the empty system probability, given by:

$$p_0 = \sum_{n=0}^{s-1} \frac{\rho^n}{n!} + \frac{\rho^s}{s!(1-\rho^s)} \tag{9}$$

The average length of the queue is:

$$L_q = \sum_{n=s+1}^{\infty} (n-s)p_n = \frac{p_0\rho^s}{s!} \sum_{n=s}^{\infty} (n-s)\rho_s^{n-s} \tag{10}$$

The average waiting time for the escalator is:

$$W_q = \frac{L_q}{\lambda} \tag{11}$$

Transfer time on the escalator is:

$$T_3 = \begin{cases} \frac{L_3}{v_t} & \lambda \le \rho \\ W_q + \frac{L_3}{v_t} & \lambda > \rho \end{cases} \tag{12}$$

where L_3 means the length of the escalator, v_t is the speed of the escalator.

Waiting time

Another main factors affecting transfer time is the time passengers spend on waiting for the next train. Suppose one passenger gets off the subway at the time t_0. When the passenger arrives at the receiving platform, the next schedule arrives at t_1. The time one passenger spend in waiting is:

$$T_d = t_1 - t_0 - T_w \tag{13}$$

As can be seen from the above formula, the waiting time is influenced by the subway timetable and the time passengers spend in walking. If transfer walking time is equal to transfer time, the waiting time is reduced to zero. In such case, when a passenger arrives at the receiving platform, the subway is just about to leave.

Parameter estimation

Data acquisition

In Beijing, Chaoyangmen station is an important transfer station between subway Line 2 and Line 6 with 12,000 passengers per day. The research time lasted from 6:00 a.m. to 9:59 a.m. and from 4:00 p.m. to 7:59 p.m. The survey data set was divided into two parts. In the first subset, transfer volume was counted to analyze the sectional number of the transfer pedestrian. In the second one, walking time of transfer passengers was recorded to analyze the regulation of walking speed.

The map of transfer passages at Chaoyangmen station is shown in Fig. 1. The passages are marked by the number 1, 2, and 3. Survey inspectors counted the number of passengers in each passage every 15 min. The survey got 96 records of transfer passenger

volume including three passage, 8 h. The collected sample data of each passage was gathered into six cluster groups by the ranking of passenger volume.

Figure 2 indicates that the number of transfer passengers from Line 2 to Line 6 is 26,876 in the survey and 46.10 % of that are counted during 5:00 p.m.–6:59 p.m. It's found in Fig. 3 that the number of transfer passengers is 37,698 from Line 6 to Line 2, and 55.92 % of that are from 7:30 a.m. to 9:30 p.m. As transfer volume has significantly increased during the peak hour with reversibility, it is appropriate to select Chaoyangmen station for the survey.

The second subset aimed to investigate transfer time and the area size of different transfer facilities. Every quarter, the inspector selected a passenger at random and walking following through the transfer passage by the passenger's choice. These survey data groups in different passages are shown in Table 1.

The walking time spending on platform, escalator and horizon passage are recorded separately. The size of different areas and facilities were measured as below:

- Platform (Passage 1: effected width = 10.5 m and length of measurement section = 3.3 m; Passage 2: effected width = 8.0 m and length of measurement sec-

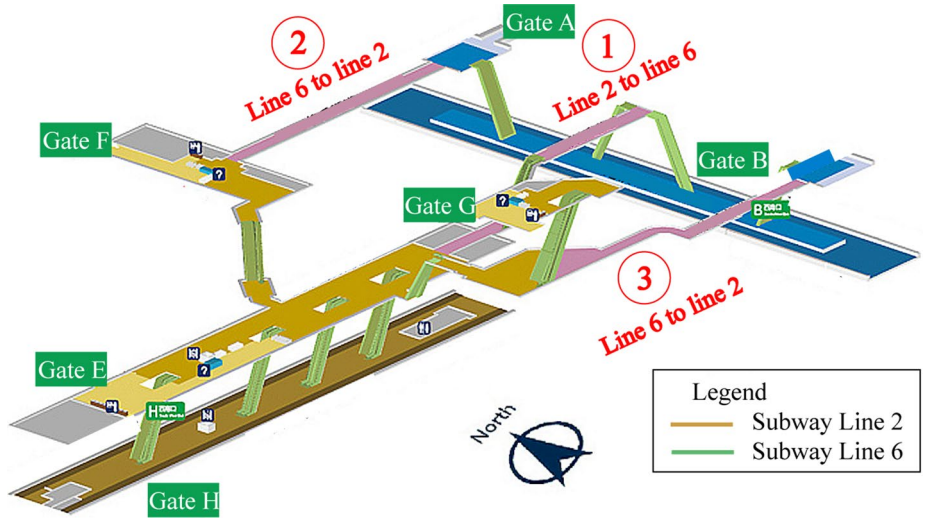

Fig. 1 Transfer passages at Chaoyangmen station

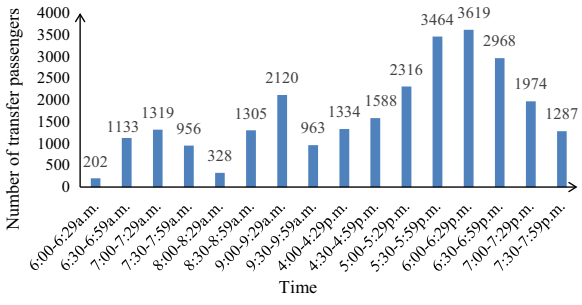

Fig. 2 Transfer passenger volume from Line 2 to Line 6

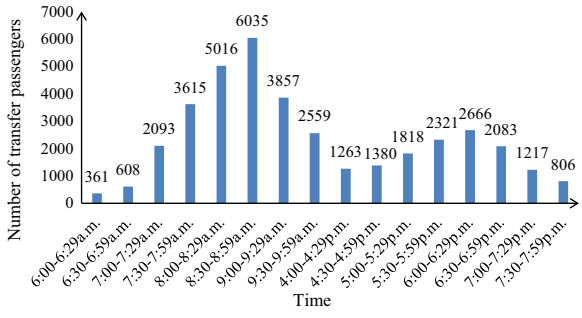

Fig. 3 The transfer passenger volume from Line 6 to Line2

Table 1 The data groups in different passages

Passage no.	Group no.	N (p/min)	v_1 (m/s)	p_1 (p/m s)	T_1 (s)	v_2 (m/s)	p_2 (p/m s)	T_2 (s)	v_3 (m/s)	p_3 (p/m s)	T_3 (s)	T_w (s)
1	1	11	1.73	0.02	4.91	1.25	0.05	85.60	0.50	0.15	50.04	140.55
	2	32	1.56	0.05	5.45	1.11	0.15	96.40	0.50	0.44	50.00	151.85
	3	45	1.46	0.07	5.82	1.05	0.21	101.90	0.50	0.63	50.10	157.83
	4	70	1.33	0.11	6.39	0.97	0.33	110.31	0.50	0.97	50.00	166.70
	5	121	1.27	0.19	6.69	0.88	0.58	121.59	0.41	1.68	69.26	197.54
	6	126	1.25	0.20	6.80	0.86	0.60	124.42	0.40	1.75	74.62	205.84
2	1	38	1.41	0.08	5.67	1.15	0.16	126.96	0.50	0.58	48.00	180.63
	2	42	1.39	0.09	5.76	1.12	0.20	130.36	0.50	0.64	47.86	184.07
	3	46	1.41	0.10	5.67	1.07	0.22	136.45	0.50	0.70	48.06	190.14
	4	71	1.26	0.15	6.35	1.00	0.34	146.00	0.50	1.08	48.10	200.35
	5	99	1.22	0.21	6.56	0.98	0.47	148.98	0.46	1.50	55.46	211.00
	6	119	1.17	0.25	6.84	0.95	0.57	153.68	0.38	1.80	66.54	227.06
3	1	7	1.75	0.01	4.57	1.31	0.03	103.05	0.50	0.11	47.92	155.54
	2	32	1.46	0.07	5.48	1.17	0.15	115.38	0.50	0.48	47.98	168.84
	3	44	1.42	0.09	5.63	1.15	0.21	117.39	0.50	0.67	48.06	171.09
	4	85	1.27	0.18	6.30	0.95	0.40	142.11	0.49	1.29	48.76	197.16
	5	129	1.17	0.27	6.84	0.93	0.61	145.16	0.36	1.95	72.50	224.50
	6	167	1.03	0.35	7.77	0.88	0.80	153.41	0.28	2.53	94.72	255.90

p number of transfer passengers, v_3 means transfer speed on the escalator

tion = 3.5 m; Passage 3: effected width = 8.0 m and length of measurement section = 3.5 m);

- Escalator (Passage 1: effected width = 1.2 m and length of measurement section = 12.0 m; Passage 2: effected width = 1.1 m and length of measurement section = 12.0 m; Passage 3: effected width = 1.1 m and length of measurement section = 12.0 m; the speed of escalators: 0.5 m/s);
- Horizon passage (Passage 1: effected width = 3.5 m and length of measurement section = 107 m; Passage 2: effected width = 4.0 m and length of measurement section = 146.0 m; Passage 3: effected width = 4.0 m and length of measurement section = 135.0 m).

Assume v_1, v_2 and v_3 come from the same population. The statistical software SPSS is applied to verify the independent sample with Mann–Whitney U method and Kolmogorov–Smirnov Z method. The test result is shown in Table 2.

Table 2 Results of Mann–Whitney and Kolmogorov–Smirnov tests

Mann–Whitney tests	v_i
Mann–Whitney U	0.000
Wilcoxon W	4656.000
Z	−12.153
Significance (both tails)	0.000
Kolmogorov–Smirnov tests	
Extreme difference	
Absolute value	1.000
Positive	1.000
Negative	0.000
Kolmogorov–Smirnov Z	6.928
Significance (both tails)	0.000

H_0: v_1, v_2 and v_3 come from the same population.

$\alpha = 0.05$.

In Table 2, results indicate that the both tails from Mann–Whitney U test and Kolmogorov–Smirnov Z are $p_1 = 0.000 < \alpha$ and $p_2 = 0.000 < \alpha$. Thus, H_0 is rejected. It means v_1, v_2 and v_3 show significant differences. Therefore, to analyze the walking speed and transfer time with respect to various pedestrian facilities has necessity.

Walking time model on the platform

Passengers tend to get impatient easily, since they get off from the crowded subway. As transfer volume increases, the sectional number of transfer pedestrians is getting higher. It leads to the decline of the walking speed. As shown in the Table 2, the speed obtained from the platform concentrates on 1.2–1.5 m/s, which is higher than usual. When the sectional number increases to 0.35 (p/m s), the average speed declines to 1.03 m/s. The formula (4) below is built by the fitting method in MATLAB 2013.

The collected data is fitted by the quadratic function. The formula for the speed and the sectional number from the platform is:

$$v_1 = 5.427p_1^2 - 3.72p_1 + 1.729 \tag{14}$$

The value R^2 of significant degree of regress is 0.937, which indicates that v_1 is highly related to p_1 when p_1 is from 0.01 to 0.35. Based on the position of the platform and the sectional number, the formula for the walking time and the sectional number from the platform is:

$$T_1 = \frac{L_1}{v_1} = \frac{\int_0^{l_1} \frac{D(x)}{l_1} dx}{5.427p_1^2 - 3.721p_1 + 1.729} \tag{15}$$

Walking time model in horizon passage

The data of the speed obtained from horizon passage concentrates on 0.9–1.2 m/s. Passengers in horizon passage have less space than that on the platform. Thus the speed in horizon passage is slower. Therefore, the sectional number in horizon passage is the

main factor affects the walking time. Formula (4) is built by the fitting method in MATLAB 2013.

The collected data is fitted by the quadratic function. The formula for the speed and the sectional number from the platform is:

$$v_2 = 1.023p_2^2 - 1.572p_2 + 1.732 \tag{16}$$

The value R^2 of significant degree of regress is 0.966, which shows that v_2 is highly related to p_2 when p_2 is the range of 0.03–0.80. The formula for the walking time and the sectional number from the horizon passage is:

$$T_2 = \frac{L_2}{v_2} = \frac{L_2}{1.023p_2^2 - 1.572p_2 + 1.732} \tag{17}$$

Walking time model on the escalator

The speed of the transfer passengers is almost identical to the escalator speed when the number of people is under the capacity of the escalator. Passengers will not wait in line to get on the escalator until the sectional transfer number increases to 1.29 (p/m s). The capacity of the escalator is $A_1 = 8100$ (p/m h) (Chen et al. 2008). The speed of the escalator is $v_T = 0.5$ m/s. Based on the collected data in Fig. 4, the saturation coefficient ω in the formula (7) is 0.092.

Through the above analysis, the model parameters in formula (1) are defined step by step. In case the sectional number of transfer pedestrians is known, transfer walking time can be calculated through the model in Fig. 5.

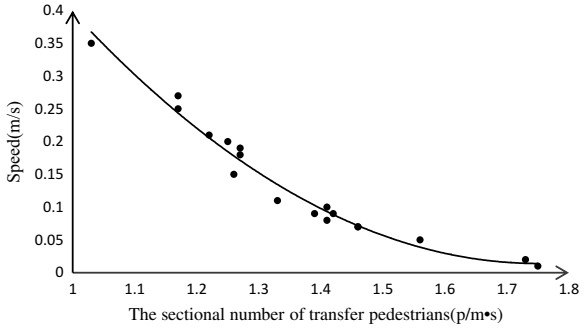

Fig. 4 Relation between speed and the sectional number of platform

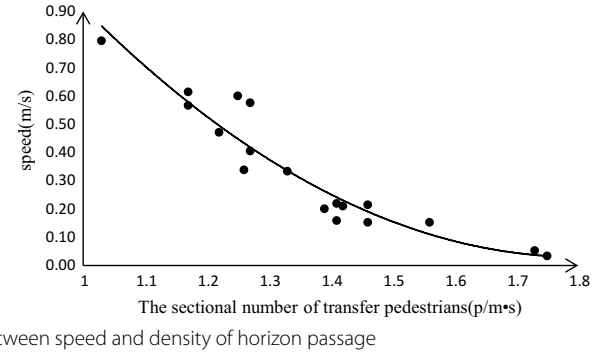

Fig. 5 Relation between speed and density of horizon passage

Transfer time model validation

Considering transfer volume and the affection of different facilities, four other transfer stations of different lines were selected to be the texting set. The data from Songjiazhuang station (Line 5, Line 10 and Line Yizhuang), Chegongzhuang station (Line 2 and Line 6), Liuliqiao station (Line 9, Line 10 and the coach station) and Gongzhufen station (Line 1 and Line 10) (Fig. 6) were collected every quarter during 3:00 p.m.–5:00 p.m. as off-peak time and from 5:00 p.m. to 7:00 p.m. as peak hours, on October 28th, 2014. The survey lasted for 4 h in these four stations connecting seven lines. The 64 sample data were clustered into 16 groups by the ranking of transfer time. Assuming the waiting time takes up half of the departure time interval, the survey data and calculates results through the texture model are given below by the transfer volume ranking using GIS (Li et al. 2014).

From Table 3, the measured time is counted in single digits which have a sampling error of ±1 s to the real time. The error rate of measured time is tiny compared to the real time within the range of 0.002–0.005. The average value and the standard deviation of the error rate for the texture model are 3.50 % and 0.025. As the results based on different transfer stations and subway lines, it is indicated that the proposal transfer time prediction model is stable and practical. Besides, the testing set which includes various transfer passages and different transfer volume illustrates that the model has good robustness.

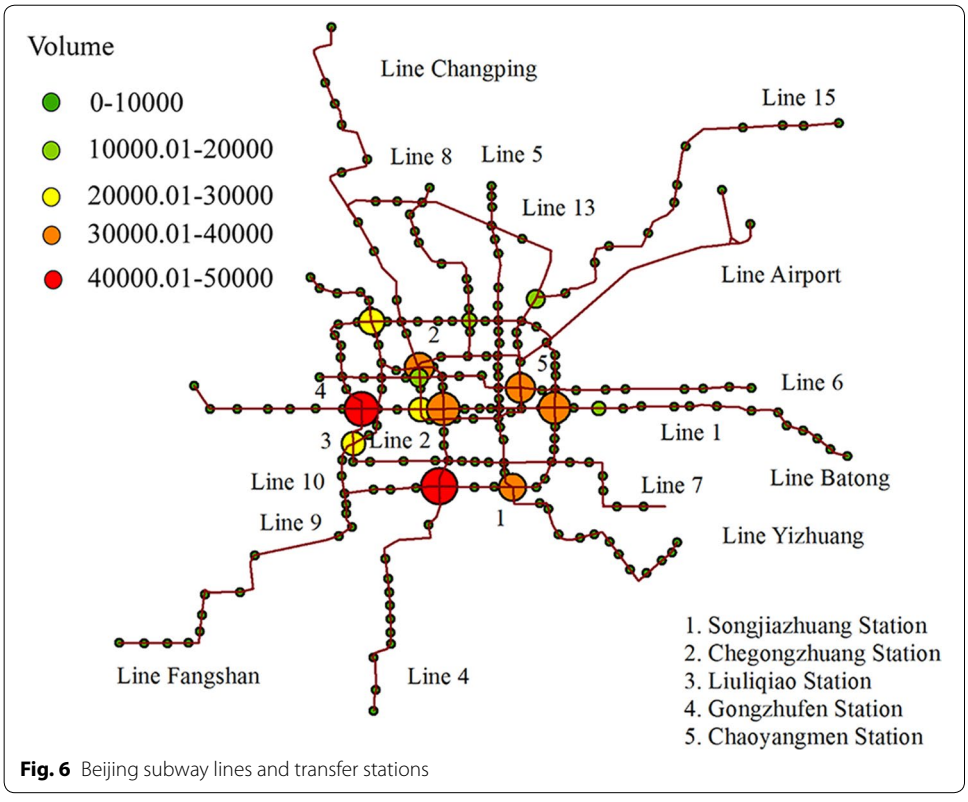

Fig. 6 Beijing subway lines and transfer stations

Table 3 The calculation results in different stations

Group no.	N (p/min)	L_1 (m)	B_1 (m)	v_1 (m/s)	p_1 (p/m s)	L_2 (m)	B_2 (m)	v_2 (m/s)	p_2 (p/m s)
1	6	2.80	11.50	1.73	0.01	88.50	4.50	1.29	0.02
2	9	3.20	9.00	1.26	0.02	123.00	3.50	1.26	0.04
3	15	2.60	10.50	1.40	0.02	142.50	4.50	1.21	0.06
4	29	3.50	8.50	1.53	0.06	105.50	4.50	1.14	0.11
5	33	3.30	8.00	1.45	0.07	152.50	4.50	1.12	0.12
6	34	4.20	6.50	1.48	0.09	115.50	4.50	1.10	0.13
7	43	4.00	6.00	1.34	0.12	133.00	3.50	1.07	0.20
8	64	3.50	6.00	1.24	0.18	97.00	4.50	1.03	0.24
9	82	3.50	6.00	1.76	0.23	97.00	4.50	0.94	0.30
10	96	4.20	6.50	1.23	0.25	115.50	4.50	0.96	0.36
11	105	2.60	10.50	1.43	0.17	142.50	4.50	0.94	0.39
12	110	4.00	6.00	1.19	0.31	133.00	3.50	0.89	0.52
13	122	3.20	9.00	1.41	0.23	123.00	3.50	0.91	0.58
14	143	3.30	8.00	1.24	0.30	152.50	4.50	0.83	0.53
15	151	2.80	11.50	1.39	0.22	88.50	4.50	0.81	0.56
16	158	3.50	8.50	1.29	0.31	105.50	4.50	0.80	0.59

Group no.	L_3 (m)	B_3 (m)	v_3 (m/s)	p_3 (p/m s)	T (s)	T_{tr} (s)	Error rate (%)
1	24.00	1.20	0.50	0.08	190.76	191	0.13
2	28.00	1.10	0.50	0.14	334.73	343	2.41
3	25.00	1.20	0.50	0.21	307.56	307	0.18
4	25.00	1.10	0.60	0.44	228.10	231	1.26
5	25.00	1.20	0.60	0.46	316.25	333	5.03
6	25.00	1.10	0.50	0.52	249.65	241	3.59
7	28.00	1.10	0.60	0.65	348.78	339	2.88
8	24.00	1.20	0.50	0.89	214.93	224	4.05
9	24.00	1.20	0.49	1.14	223.37	236	5.35
10	25.00	1.10	0.46	1.45	270.50	255	6.08
11	25.00	1.20	0.41	1.46	351.75	359	2.02
12	28.00	1.10	0.38	1.67	397.62	408	2.54
13	28.00	1.10	0.38	1.85	386.48	388	0.39
14	25.00	1.20	0.31	1.99	402.03	442	9.04
15	24.00	1.20	0.28	2.10	270.76	256	5.77
16	25.00	1.10	0.27	2.39	317.34	335	5.27

T_{tr} true time measured by the survey

Conclusions

This paper proposed a transfer time prediction model which was appropriate for different transfer stations. On the basis of the learning set, the model parameters of transfer speed and transfer volume were established with respect to the sectional number of transfer passengers. Through the testing set including 64 samples on four different transfer stations, the results demonstrated that the average error rate and the standard deviation were 3.50 % and 0.024. Results indicated that this transfer time model had the merits of accuracy, feasibility and reliability. By means of the model, transfer time could be predicted accurately. Furthermore, the proposal model was helpful for the operation department to coordinate subway trains between lines.

With more application of the model in the future, the regulation of transfer time should be further studied to analyze the distributions of waiting time and the transfer passage choice of passengers.

Authors' contributions

All authors took part in the experiment of time prediction model. YZ designed the research and wrote the manuscript. LY completed the survey project and wrote the manuscript. YG deduced the formula and verified the accuracy of the established model. YC supported the data processing and reviewed the manuscript. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

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