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A dynamic simulation model of passenger flow distribution on schedule-based rail transit networks with train delays

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ABSTRACT

In a schedule-based rail transit system, passenger route choices are affected by train delays, and, consequently, the relevant passenger flow distribution of the network will differ from the normal state. In this paper, a passenger's alternative choices, such as selecting another route, waiting, and switching to other transportation modes, and the corresponding influence mechanism are analyzed in detail. Given train time–space diagrams and the time-varying travel demands between the origin and destination (O–D), a dynamic simulation model of passenger flow distribution on schedule-based transit networks with train delays is proposed. Animation demonstration and statistical indices, including the passenger flow volume of each train and station, can be generated from simulation results. A numerical example is given to illustrate the application of the proposed model. Numerical results indicate that, compared with conventional methods, the proposed model performs better for a passenger flow distribution with train delays.

1. Introduction

In many cities, the urban rail transit (URT) system plays a significant role in urban passenger transport. Due to its advantages, such as comfort, safety, punctuality, and convenience, urban residents have become increasingly dependent on the URT system for their daily travels, contributing to a rapid growth of network traffic. The increase of URT passenger flow, however, puts heavy pressure on URT operation and management, especially when emergencies (e.g., train delays exceeding 10 min) that seriously affect operational security occur. Thus, it is important to research the passenger flow's dynamic distribution for URT networks with train delays.

Passenger route choices are greatly influenced by train delays (Hong et al., 2011; Xu et al., 2014). Moreover, the

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passenger flow distribution is a result of passenger route choice decision-making, and thus, the analysis of passenger travel behaviors are considerably important (Sun et al., 2013). A passenger flow's dynamic distribution for an entire network can change significantly, as compared with its normal state. However, few existing studies have taken into account the influence of train delays on passenger route choices. The passenger flow distribution on a URT network with train delays is still an open problem, and this study addresses it.

Specifically, the objective of this study is to provide a simulation method that analyzes passenger choice behaviors with train delays and further predicts the passenger flow distribution on schedule-based rail transit networks. This paper includes the following contributions:

(1) Passenger choice behaviors that take train delays into account are discussed, and the corresponding influence mechanism is analyzed in detail. Both of them are incorporated into a passenger flow distribution calculation when factoring train delays.
(2) A discrete event simulation method is adopted, because a passenger flow distribution calculation, especially on a large-scale and schedule-based network, is computationally complex for analytical methods.

This paper includes a review of previous literature in Section 2. Section 3 presents relevant definitions and alternative route choices, as well as the corresponding influence mechanism. Assumptions and the proposed simulation framework are described in Section 4. In Section 5, the simulation model is tested as a numerical case, in which the proposed simulation approach is compared with a conventional method, in a transit network. Section 6 concludes the paper.

2. Literature review

2.1. Transit assignment

Previous research has studied the models and methods of transit assignment based on the public traffic flow distribution theory. In summary, two main approaches exist to study the dynamic assignment of transit networks: a frequency-based approach and a schedule-based approach.

The frequency-based approach (Cepeda et al., 2006; Cominetti and Correa, 2001; Nökel and Wekeck, 2009; Tong et al., 2001) assumes that each transit line operates at a constant headway, and the travel time of each O–D pair is determined. The passenger waiting time to board is a probabilistic function of the train headway, but the train capacity and travel time are difficult to take into account with the frequency-based approach, particularly within a dynamic context. The main alternative to transit assignment is the use of a schedule-based approach, with which the train headway and speed are determined from train schedules (Hamdouch and Lawphongpanich, 2008; Nuzzolo et al., 2012; Poon et al., 2004; Sun et al., 2013; Tong et al., 2001). The passenger waiting time to board is a deterministic function of the train schedules and arrival time at the station. Also, this approach can take into account the capacity constraints of congested networks (Hamdouch and Lawphongpanich, 2008; Nuzzolo et al., 2012; Poon et al., 2004). Compared to the frequency-based approach, the schedule-based approach, which can take each run's capacity into account, is more suitable to congested transit networks. Emergencies, such as train delays, lead to overcrowding on platforms, and passengers are physically unable to leave the station even if they decide to try another mode of transportation. The frequency-based approach cannot effectively deal with transit assignment problems for congested networks, and thus, this study applies the schedule-based approach.

2.2. Train delay

Over the past years, researchers have used either analytical methods or simulation-based methods to assess delays in railway networks and rail transit networks.

Zhu (2011) studied a scenario-based route choice model and calculation method against the background of the 2010 World Expo in Shanghai, China. The model was built mainly to deal with predictably large passenger flow events but fail to forecast the network passenger flow distribution under unexpected events, such as train delay. Hong et al. (2011) discussed the transitivity of train delay caused by emergencies, as well as the calculation method for the influenced passengers. Higgins and Kozan (1998) developed an analytical model to quantify the expected delay of individual passenger trains in an urban rail network. Xu et al. (2014) analyzed the influence of train delays on passenger travel and determined the conditions of influenced passenger flow. However, this method does not consider line schedules, which are crucial to a URT system. Though existing analytical models provide good insights into the delay impacts on one line or a simple network, impacts resulting from delays in the URT system depend on not only trains and schedules but also on passenger response to delays. The simulation method can effectively assess delays in large-scale URT networks. Several delay simulation software tools, such as RailSys, SIMON, and Open Track, are widely used in railroad network simulations, which mainly optimize network and timetable design. Most of the literature focuses on train delays in railway lines and networks. Little attention has been paid to passenger delay and assignment for schedule-based networks with delayed trains. Otto (2008) presented a schedule-based route choice model, linking the model to a rail simulation software (RailSys) to forecast passenger delay relevant to the planned timetable. Li and Xu (2011) proposed a simulation method to evaluate the passenger flow distribution on the network with given O–D demands, scheduled timetables, and disruption information. Furthermore, Jiang et al. (2012) improved Li's model to investigate the relationship between train delays and passenger delays, and predict the dynamic passenger distribution on a large-scale rail transit network. The simulation model was named URT_PDSS, and it assumed that passengers did not change their path choices. This means that any impact on passenger choice behavior due to train delays is neglected, which further influences the network passenger flow distribution.

Regarding this matter, the authors believe that a schedule-based assignment method is more suitable than a frequency-based one and that a simulation-based approach is more applicable than an analytical one. According to the simulation system proposed by Jiang in 2012 (URT_PDSS), a schedule-based and simulation-based method should be developed to consider both line schedules and passenger responses to delays. The proposed model considers factors that are difficult to evaluate with conventional methods, such as line schedules, train capacity constraints, and passenger choice behavior in response to train delays.

3. Analysis of passenger route choice on a rail transit network with train delays

3.1. *Relevant definitions*

Passenger route choices and the consequent flow distributions of a schedule-based network depend on many factors, such as the transit network, O–D demand, and train schedules. In this section, important definitions pertinent to this study are described.

3.1.1. *Transit network*

The transit network is the foundation of train operations and passenger travels. Composed of one or more transit lines, the network is defined as $L = \{1, 2, \cdots, l, \cdots, N\}$. A transit line in L is defined as a fixed path through which transit vehicles run periodically at fixed schedules. Several stations ($S_l = \{1, 2, \cdots, i, \cdots, M\}$) located along the transit line have unique station codes. For example, station $S_{l,i}$ signifies station i of line l.

3.1.2. *O–D demand*

The time-varying O–D demand is a major input of the passenger flow distribution simulation. Nowadays, most URT stations are equipped with automatic fare collection (AFC) systems, which record passenger origins, destinations, and entry and exit times. Thus, the historical data of time-varying O–D demand can be derived from the AFC system and used in the simulation model.

3.1.3. *Passenger valid route set*

Let o and d represent the origin station and the destination station while $R^{o,d}$ represents the set of valid routes from o to d. $R^{o,d} = \{r_1^{o,d}, \cdots, r_i^{o,d}, \cdots, r_p^{o,d}\}$, and p is the number of routes in $R^{o,d}$. $\varphi_i^{o,d}$ is the impedance (minutes) of the ith route. The probability that passengers choose route $r_i^{o,d}$ is defined as $P_i^{o,d}$, so $\sum_{i=1}^{p} P_i^{o,d} = 1$. The list of $P_i^{o,d}$ can be obtained from the AFC system.

3.1.4. *Train time–space diagram*

Train time–space diagram is a type of schedule in the URT system. Specifically, it is a diagram that illustrates the relationship between space and time as train running. The main messages include the arrival time and departure time of all trains at each station. Arrival time $A_{l,i}^j$ and departure time $D_{l,i}^j$ of the jth train at station $S_{l,i}^j$ is described as $S_{l,i}^j(A_{l,i}^j, D_{l,i}^j)$. Therefore, the schedule of the jth train is defined as the collection $\{\forall i \in l \,|\, S_{l,i}^j(A_{l,i}^j, D_{l,i}^j)\}$.

3.2. *Passenger choice behaviors considering train delays*

Passenger flow distribution results from passenger route choice decision-making, and two types of passengers arise within the network when train delays happen: normal passengers and influenced passengers. Assume that a passenger enters station i of line l at time t, and the passenger's travel route is described in Fig. 1. Under normal conditions, the passenger will travel along the dot dash line (original route). He will choose train j by locating j, such that $D_{l,i}^{j-1} \le t \le D_{l,i}^j$, then board the jth train to arrive at station i' at time $A_{l,i'}^j$ and finally transfer to line 2 to continue his trip. However, he has to follow the dotted line (alternative choices) when train delays occur.

In the event of train delays, passengers will change their travels, as shown in Fig. 2. They make decisions based on their own experience and according to real-time information from the station's broadcast system, large screen displays, etc. A passenger's alternatives include: (1) choosing another route from valid route set $R^{o,d}$, (2) waiting on the platform until train operations resume, (3) selecting traffic modes other than URT, (4) canceling travel plans. The selection process is shown in Fig. 2, in which choice 4 relates to the passenger's travel purpose. Since this input is difficult to collect from every passenger, the paper does not consider this case an alternative choice.

3.3. *Travel disutility of alternative choices*

Denoting r as the passenger travel route index influenced by the delay in $R^{o,d}$, the route impedance of a passenger's alternative choices is described below.

(1) Choose another feasible route

$$\varphi^{o,d^1}(t) = \varphi_i^{o,d}(t) \quad \forall i \neq r, \ \ i \subset R^{o,d} \tag{1}$$

(2) Wait for the train

$$\varphi^{o,d^2}(t) = \varphi_r^{o,d}(t) + T_{delay} \tag{2}$$

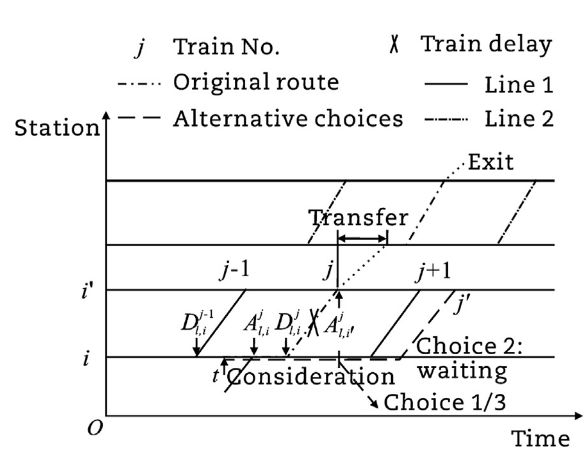

Fig. 1 – Passenger route choices based on train schedules.

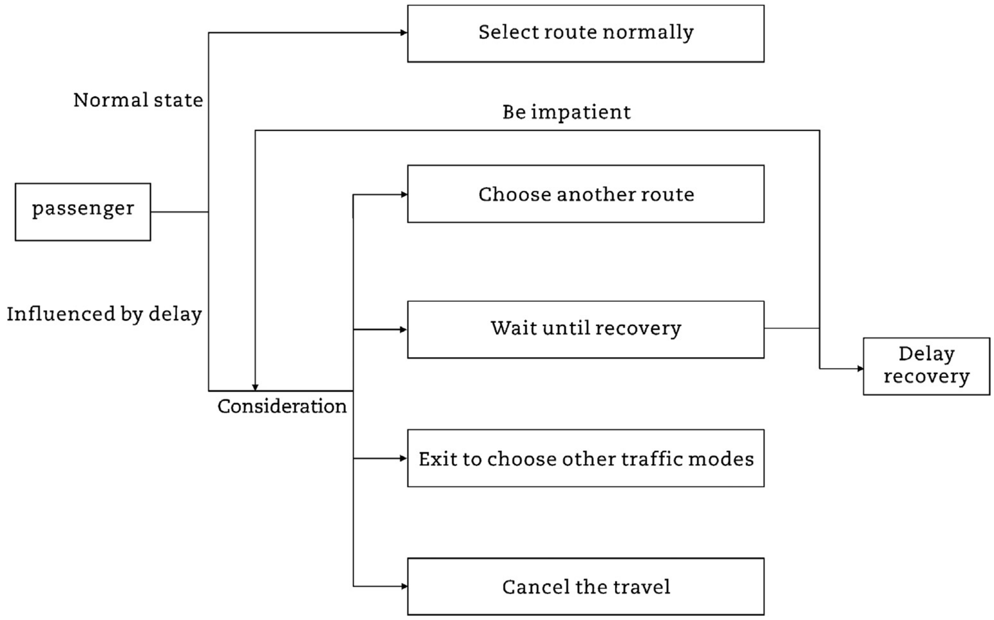

Fig. 2 – Illustration of a passenger's alternative choices.

(3) Select another traffic mode (this paper only considers bus transit as an alternative mode)

$$\varphi^{o,d^3}(t) = \delta \frac{\overline{v}_{rail}}{\overline{v}_{bus}} T^{o,d} \tag{3}$$

where t is the present moment, T_{delay} is the expected delay time, which is a dynamic variable that increases as the simulation program runs, $\overline{v}_{rail}$ denotes the average urban rail transit speed, $\overline{v}_{bus}$ denotes the average bus transit speed, $T^{o,d}$ is the metro's running time from stations o to d, δ is a penalty coefficient that passenger travel by bus instead of by subway, considering fare, comfortable, etc.

Due to the uncertainty of the alternative routes and modes, passengers will spend time considering which route or mode to choose under circumstances shown in Fig. 2. Time expense relates to the number of routes or choices that a passenger can choose.

$$\varphi_{consider} = \tau(q+2) \tag{4}$$

where q is the number of substituted feasible routes in choice 1, τ is a constant that can be obtained from passenger travel surveys, and $\tau = 5$ s is used in this simulation.

In choice 2, a passenger's "impatience" must be taken into account. Passengers will give up waiting to choose alternative choices after a certain waiting time. Denote $\max\{\varphi^{o,d}\}$ as the maximum route impedance that passengers can bear when traveling from stations o to d. Passengers will become impatient to give up waiting when the impedance they continue waiting exceeds the maximum impedance they can afford. The judgment condition is as follow

$$\varphi^{o,d^2}(t) = \varphi_r^{o,d}(t) + T_{delay} > \max\{\varphi^{o,d}\} \tag{5}$$

Therefore, a passenger's alternative choices impedance considering train delays are as follow

$$\psi^{o,d^k}(t) = \varphi^{o,d^k}(t) + \varphi_{consider} - \frac{1}{\theta}\xi^{o,d^k}(t) \quad \forall o,d,k,t \tag{6}$$

where $\psi^{o,d^k}(t)$ is the passenger's perceptive alternative choices impedance of choice k from stations o to d at moment t, and $-\frac{1}{\theta}\xi^{o,d^k}(t)$ is the stochastic error term that passengers fail to the choice (Gao and Ren, 2005).

3.4. *Selection probability*

The stochastic dynamic user optimum (SDUO) approach is used in this research to determine a passenger's probability of selecting an alternative choice (Gao and Ren, 2005). Related SDUO conditions are expressed below

$$\begin{cases} \psi^{o,d^k}(t) - \eta^{o,d}(t) \geq 0 \\ f^{o,d^k}(t) \geq 0 \\ f^{o,d^k}(t)\left[\psi^{o,d^k}(t) - \eta^{o,d}(t)\right] = 0 \end{cases} \quad \forall o,d,k,t \tag{7}$$

where $f^{o,d^k}(t)$ is the passenger flow from stations o to d in choice k at moment t, and $\eta^{o,d}(t) = \min_k\{\psi^{o,d^k}(t)\}$.

Finally, SDUO conditions can derive a logit form to determine a passenger's selection probability (Gao and Ren, 2005). Therefore, the passenger's selection probability can be expanded as follow

$$p^{o,d^k}(t) = \frac{\exp\left[-\theta\varphi^{o,d^k}(t)\right]}{\sum_{k=1}^{3}\exp\left[-\theta\varphi^{o,d^k}(t)\right]} \tag{8}$$

where θ is a non-negative parameter representing the passenger's comprehension of each alternative choice's impedance, and the value can be obtained from traffic behavior surveys. The value is higher, the more understanding passengers have to alternative choices. Moreover, to model the passenger flow distribution on a network with train delays,

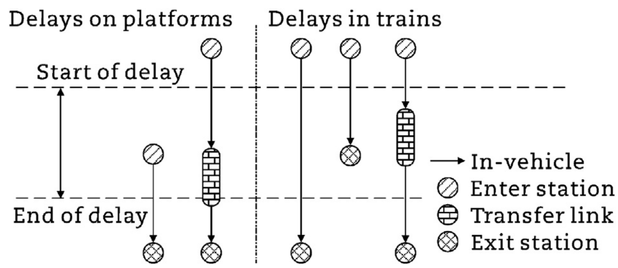

Fig. 3 – Influence mechanism of train delays.

the influence mechanism, or whether and when passengers are influenced by train delays, is discussed next.

3.5. *Influence mechanism of train delays*

There are two kinds of delays on a network: platform delays and train delays. O–D demands unaffected by an interruption will continue along their original travel routes, which are assigned according to valid route set $R^{o,d}$. On the other hand, platform delays will cause a passenger flow aggregate on the platform, which may endanger the safety of passengers. As shown in the left side of Fig. 3, two situations may contribute

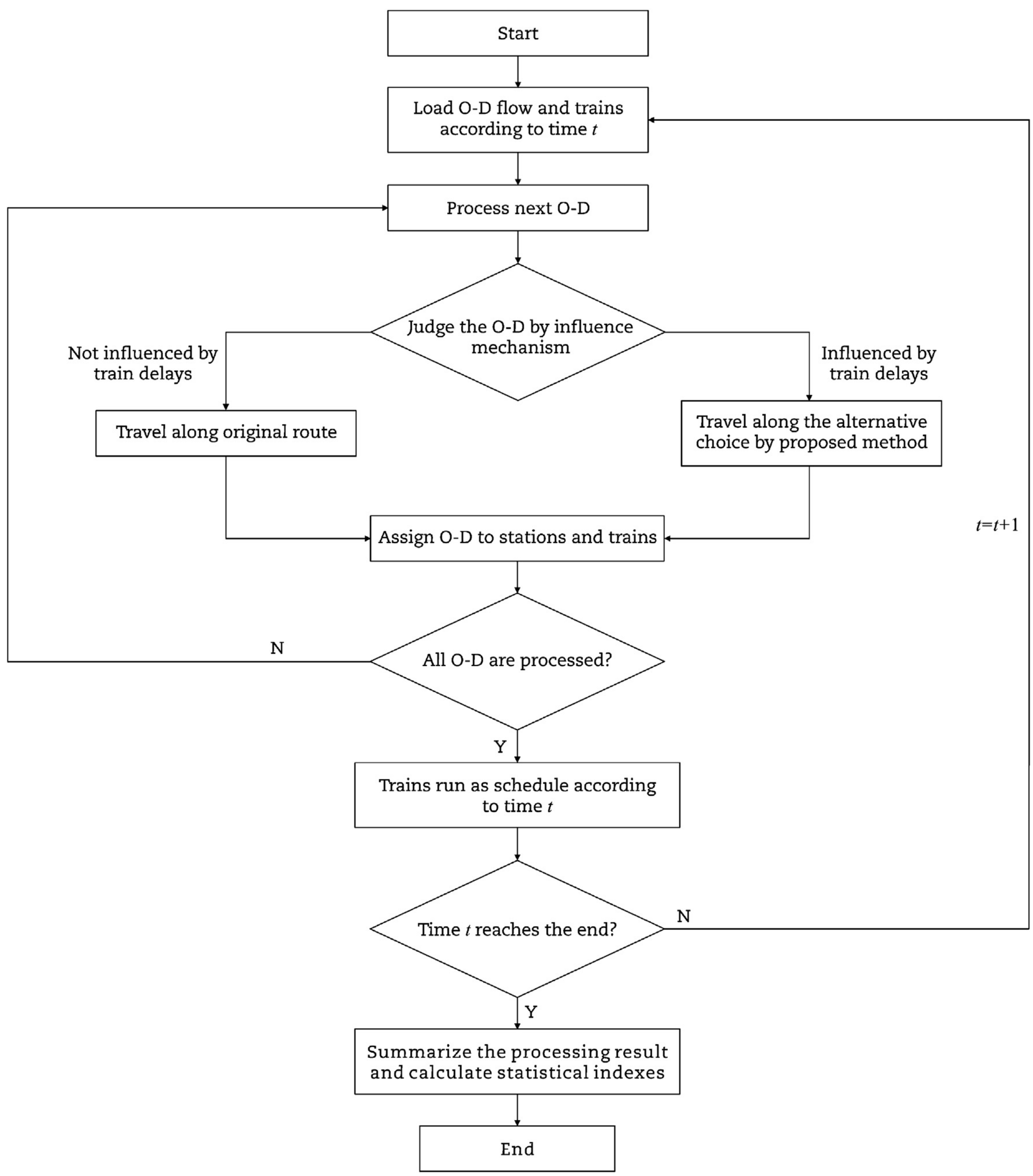

Fig. 4 – Flowchart of simulation model.

to delays. As seen in situation 1, a passenger is delayed when his entry time falls between the start and end period of the delay, or in situation 2, if his transfer time falls between the start and end period of the delay. In both cases, travel routes are influenced by the train delay. For these passengers in both situations, it is essential to determine their alternative choices according to the aforementioned rule. Another type of delay occurs when passengers aboard the delayed trains who will also be delayed in the vehicles. Three possible situations are represented in the right side of Fig. 3.

4. A dynamic simulation model for passenger flow distribution

According to the analysis of a passenger's alternative choices when faced with train delays, a dynamic simulation model for the passenger flow distribution is established based on URT_PDSS. Basic assumptions are described below.

4.1. *Assumptions and limitations*

Assumptions and limitations to this model are as follows.

(1) Passenger boarding is constrained by a fixed train capacity, and passengers will board the incoming train as long as the train is not full.
(2) Passenger discomfort to crowding in trains is not considered.
(3) Passenger queues on the platforms follow the single channel First-Come–First-Served (FCFS) queuing discipline, and the capacity of the station platform is unlimited.
(4) Not all passengers will cancel their trip when a train is delayed.
(5) Passenger transfer time from metro to bus is not considered.
(6) All trains run according to schedule, except the delayed train, which remain stopped until delay recovery.

4.2. *Discrete event simulation*

Given passenger travel behaviors, the discrete event simulation technique (Meng and Wang, 2011; Qi et al., 2013) is used to simulate the passenger flow distribution within a certain period (e.g., half a day). The flowchart of the simulation

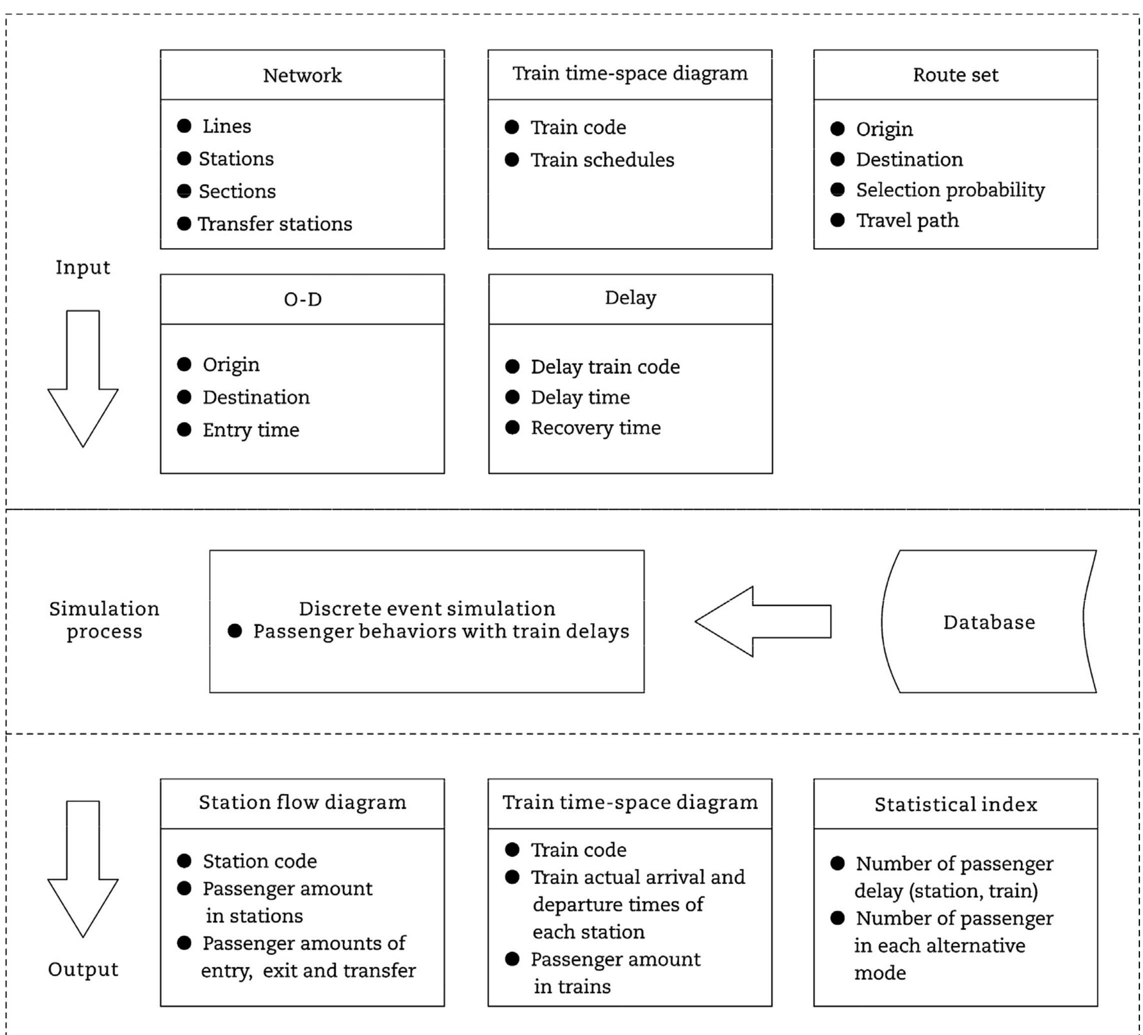

Fig. 5 – Structure of simulation program.

process is shown in Fig. 4, where all trains are empty at the beginning of the simulation process. A warm-up period (e.g., beginning from 5:00 a.m.) reduces simulation errors, but the statistical indices of these periods are not summarized in the conclusions.

4.3. *Implementation using C#.Net and ORACLE databases*

The proposed simulation model is implemented with C#.Net and ORACLE databases. There are three modules, as shown in Fig. 5, representing the input module, output module, and the process modules. The discrete event simulation block in the process module represents the steps as shown in Fig. 4.

5. Applications on a test network

A tested transit network of the Shanghai URT system is used to demonstrate the performance of the proposed simulation model and method. The network consists of 3 lines, as shown in Fig. 6, which hold 63 stations and 5 transfer stations. Each station has a unique code to identify it, and transfer stations have two codes for each line. Comprehensive information on time-varying O–D distribution and the in- and out-flows of all stations are given.

5.1. *Simulation interface*

The period used for analysis starts at 7:00 a.m., when the system operation begins, and lasts until 10:00 p.m., which is after the night peak. Inputs, including the transit network, train time-space diagram (timetable), passenger's valid route set, and time-varying O–D demands, are set in this case. Additional relevant parameters are also assumed, such as $\theta = 19.6$, and three trains along line 1 are assumed to be delayed after 8:15 a.m. With the statistical index from the simulation, passengers at each station can be obtained. Fig. 7 shows the animation displays, which are recorded every half hour. Different circle sizes and colors indicate different passenger flows, which intuitively represents the passenger service level of each station.

5.2. *Output results*

The colorful time–space train diagram shown in Fig. 8 is drawn in accordance with the statistical index of passengers in trains. Each line represents a train's travel trajectory, with both time and space features. The color of each line, by which red represents a high degree of congestion and green represents a low degree, shows the passenger density of the train. Given a vehicle capacity of 1460 passengers per vehicle, most trains are oversaturated during peak hours.

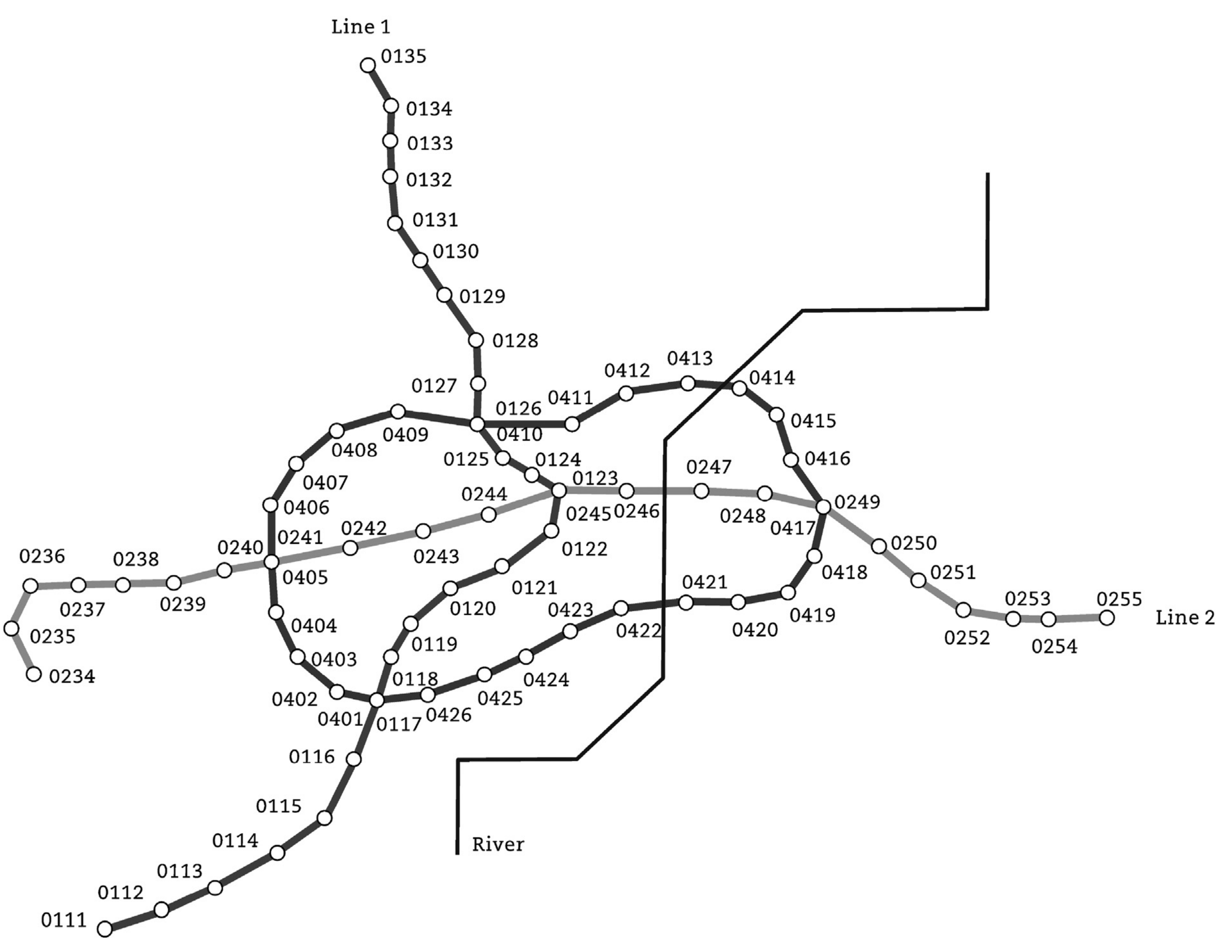

Fig. 6 – Test network.

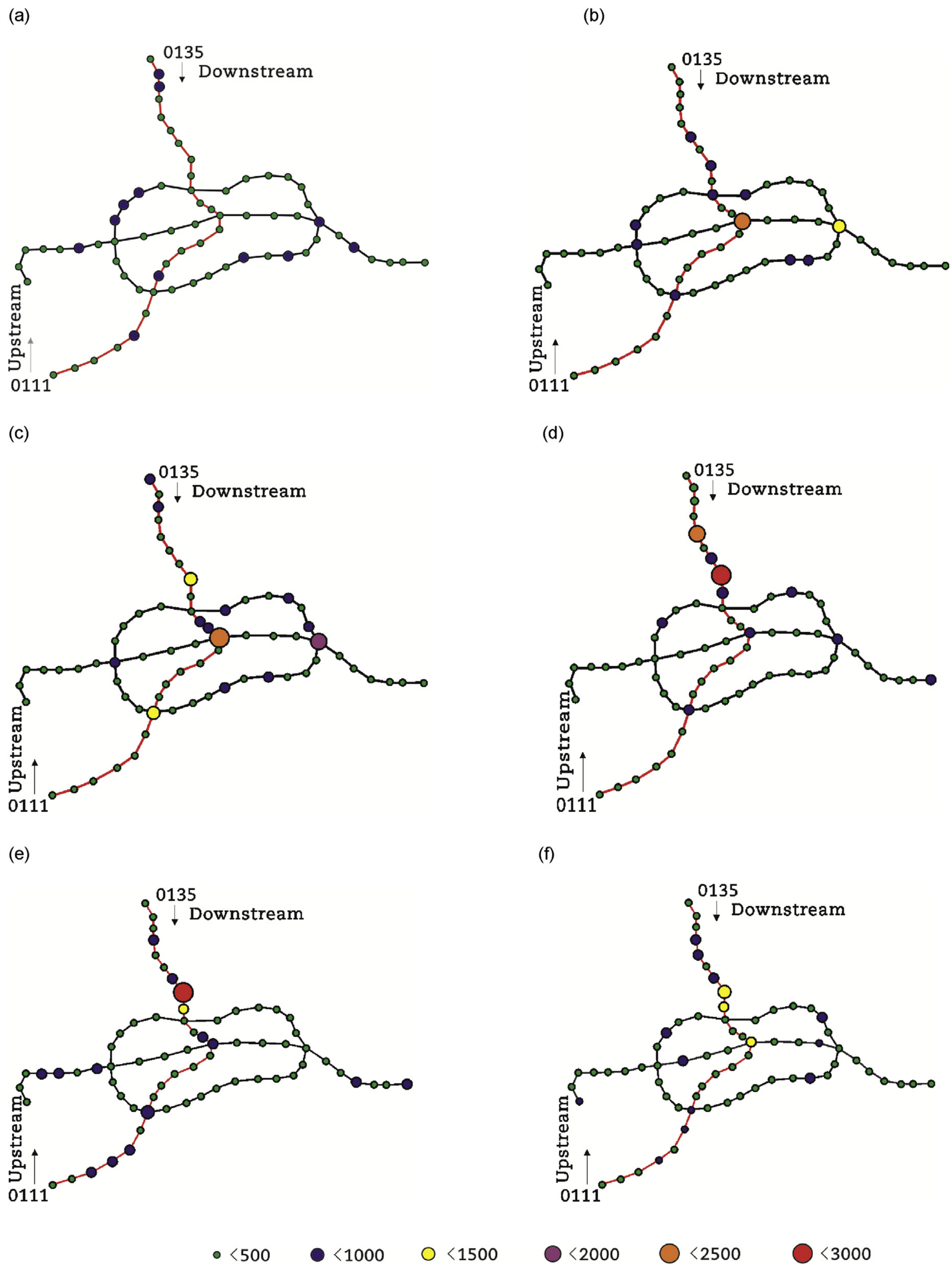

Fig. 7 – Plot of passengers at stations on the network at six different times. (a) 7:30 a.m. (b) 8:00 a.m. (c) 8:30 a.m. (d) 9:00 a.m. (e) 9:30 a.m. (f) 10:00 a.m.

When three trains are delayed at 8:15 a.m., heavy congestion results, which affects several following trains. The degree of congestion for each train gradually recovers to the normal state as time continues.

The statistical index of passengers at stations shown in a three-dimensional display provides more comprehensive information. Fig. 9 indicates passenger backlogging in relation to the space–time features, showing that passengers at some

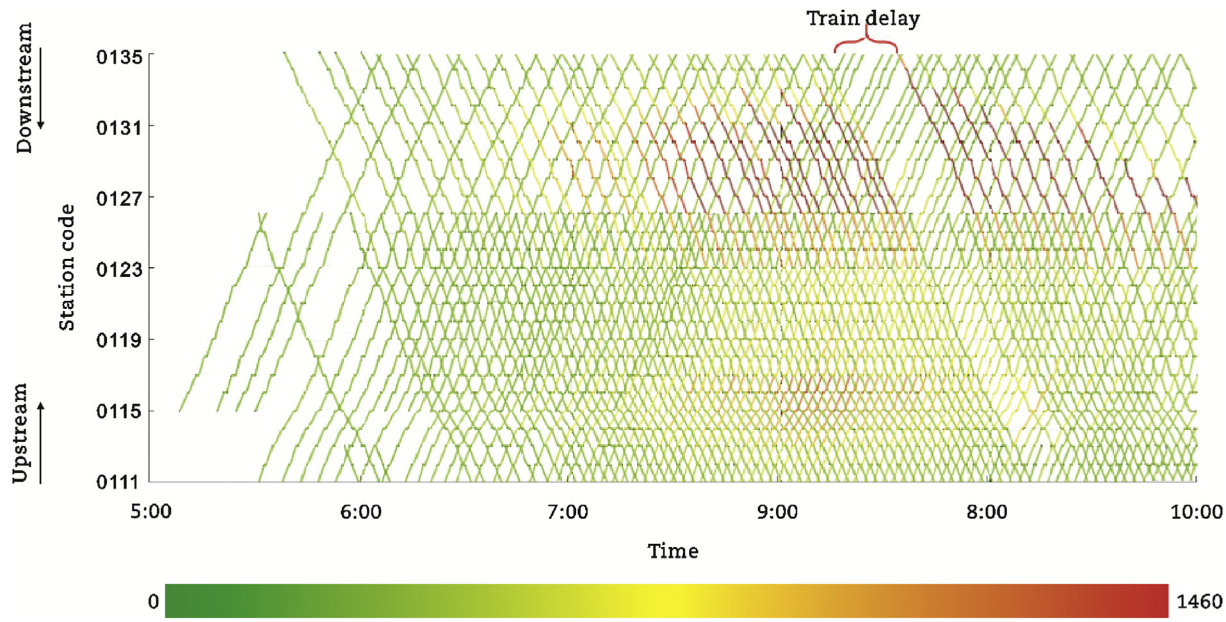

Fig. 8 – Visualized time–space train diagram.

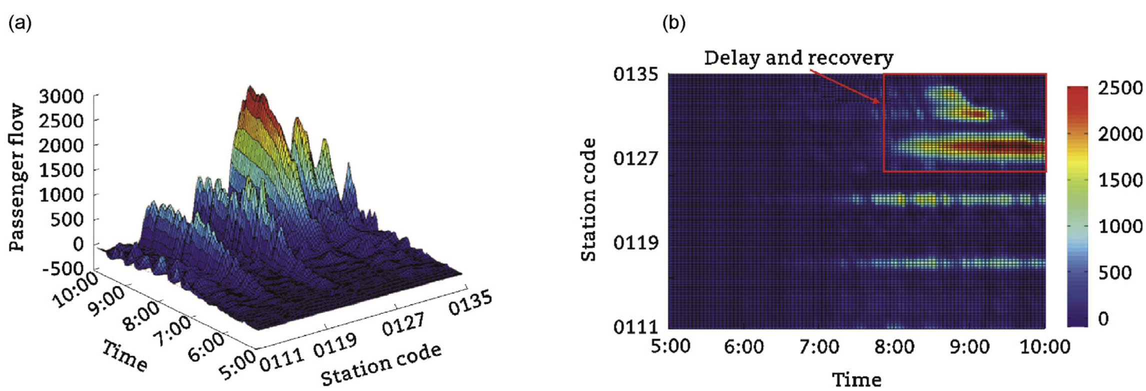

Fig. 9 – Display of passenger flows at stations. (a) 3D. (b) 2D.

stations still cannot be carried away in time even if conventional operation is recovered. Moreover, calculation of statistical indices from the simulation between 7:00 a.m. to 10:00 p.m. allows a more detailed analysis of passengers at each station, especially when compared to URT_PDSS. The authors found that during the delay period, 813 passengers chose another route, 5163 passengers chose to wait in the station until train operation resumed, and 4180 passengers chose other traffic modes. These results were not considered in conventional methods.

6. Conclusions

Unlike during normal train operations, train delays cause changes in passenger route choices and passenger flow distribution on schedule-based networks. Three alternative choices are identified, on which a simulation model and method are based to predict the passenger flow distribution on the network. A discrete event simulation technique is used to model the passenger flow distribution of a schedule-based rail transit network. The passenger flow distribution on networks can be obtained from simulation results, and the proposed method can to be used in the simulation of large-scale rail transit networks with train delays. It is a useful and practical quantitative analysis tool that is beneficial to operators dealing with problems caused by train delays.

Additional relevant issues are still needed to be addressed. Further research ideas include: (1) relevant parameters should be further calibrated through detailed investigations when the proposed simulation method is applied to real situations, (2) various changes, such as weekday vs. weekend, may lead to different selection probabilities of alternative choices, (3) passengers canceling their trips altogether should be considered as an alternative and studied.

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