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Research Article

Calculation Method for Load Capacity of Urban Rail Transit Station considering Cascading Failure

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The load capacity of urban rail transit station is of great significance to provide reference in station design and operation management. However, it is difficult to carry out quantitative calculation quickly and accurately due to the complex interaction among passenger behaviors, facility layout, and the limit capacity of single facility. In this paper, the association network of facilities is set up based on the analysis of passenger service chain in station. Then the concept of cascading failure is introduced to the dynamic calculation model of load capacity, which is established on the user-equilibrium allocation model. The solution algorithm is optimized with node attack strategy of complex network to effectively reduce the computational complexity. Finally, a case study of Lujiabang Road Station in Shanghai is carried out and compared with the simulation results of StaPass, verifying the feasibility of this approach. The proposed method can not only search for the bottleneck of capacity, but also help to trace the loading variation of facilities network in different scenarios, providing theoretical supports on passenger flow organization.

1. Introduction

The networked process of urban rail transit (URT) in China's major cities has been expedited, and the demand of passenger flow is further unleashed. It brings great challenge on operational security, transport capacity and efficiency, service level, and other aspects to URT management department. Taking Shanghai as an example, in 2016, the whole rail transit system provided service to over 9 million passengers every weekday averagely, the extreme passenger volume hit a new record by exceeding 10 million people, and over 10 metro stations handled more than 100,000 passengers every day.

In the context of this, pressures are increased on URT stations which served as the basic operation unit of URT and the distribution hub for passenger. Prominent problems emerge from the daily work of passenger organization, which can be summarized as follows:

(1) The design load capacity of some stations does not match with the actual passenger flow, resulting in the increasing risk of emergencies like passenger stranded, severe congestion, and so on.

(2) Varying levels of inflow-limiting strategies have been carried out in order to coordinate mass passenger flow, however lacking the quantitative basis for formulation.

(3) The specific treatments are usually formulated by the subjective work experience of URT operators in emergency strategy, while disregarding the interrelation of different facilities in stations and failing to take full advantage of it.

The problems mentioned above could be ascribed to the inaccuracy of passenger flow forecasting during the design phase. Yet the underlying reason is the lack of mathematical assessment on the load capacity of URT stations.

The load capacity of URT stations is defined as the quantity of passengers when the passenger services cannot be provided because some key facilities are unavailable or in congestion. At present, static calculation methods for capacity are generally adopted in the design stage of the rail transit station. In China, a Cannikin Law based method is applied to analyze the load capacity of the station, that is, taking the minimum

Table 1: Calculation methods for load capacity of URT station.

Method	Precision	Complexity	Quantified	Comprehensiveness
Queueing Theory	☆☆	☆☆	☆☆☆	Not consider the influence of passenger motor behaviors
Macroscopic Simulation (System Dynamics)	☆	☆☆	☆☆	Not consider the influence of passenger motor behaviors and station layout
Microscopic Simulation (simulation of passenger motor process)	☆☆	☆☆☆	☆	Basically comprehensive

value as the overall load capacity from all facilities and equipment whose maximum capacities have already stipulated by national standard [1]. Some European urban rail transit, such as the London Subway [2], divided service quality into several levels with the consideration of passenger characteristics. The design work and capacity assessment of the station is carried out under the guidance of service and safety level. However, URT station is a complex system consisting of various types of facility, providing multiple routes for passengers to reach their destination, and passenger motional characteristics are closely related to the layout of facilities and equipment in station. Thus static or discrete calculation for capacity would be a straightforward solution, but it is not feasible in reflecting the load capacity of station in practice.

In the case of dynamic methods, Queueing Theory and system simulation are methods mostly used to evaluate the load capacity of rail transit station (Table 1). Approaches based on Queueing Theory establish particular congestion state-dependent queueing model [3–5] for each facility in station such as gates, staircases, and corridors according to the analysis of the passenger flow characteristics, then modeling the M/G/C/C state-dependent queueing network [6, 7] in a systematic way. It takes the coordination between capacities of different facilities into account, neglecting the dynamic impact exerted on the load capacity of station when passengers make choice on routing. The system simulation method is to simulate passengers' motion in the urban rail transit station through specific models or tools, which are separated into two large fields of microscopic and macroscopic researches. The latter commonly regard the station as a dynamics system and models with diverse theories, including mixed Petri net [8, 9] and system dynamics [10–12]. But the model fails to consider the influence of the facilities layout on the load capacity. At the microscopic level, cellular automata [13], social force model [14], potential field [15], and other approaches are used to simulate individual behaviors; meanwhile some commercial pedestrian simulation software programs like Legion, Step, StaPass, and so on are also applied to search the bottleneck of station capacity. They can evaluate the load capacity of URT station in different scenarios, but have many defects such as the complexity of modeling and time-consuming simulation.

Since the load capacity of URT station is not only restricted to the capacity of single piece of equipment but also influenced by passenger behaviors and the layout of facilities in the station, it is insufficient to calculate the accurate load capacity if only considering one of these factors. The review of the literature indicates the necessity to develop a novel method for load capacity calculation. In URT station, passengers receive the service from a series of facilities having strong interrelation with each other. Though the capacity limit of a single facility does not necessarily represent the vulnerability of the whole station, the cascading failure properties of the network composed of all facilities can lead to congestion [16]. This is quite similar to the dynamics of network flow in the traffic system.

Therefore, this paper sets up the association network of facilities and its passenger flow assignment mechanism considering the cascading failure effect. On the basis of the user-equilibrium assignment model, we propose a dynamic method to calculate the load capacity of URT station. It is able to trace the loading variation of facilities network, search for the bottleneck of load capacity, and provide staff with the theoretical support on passenger flow organization.

The rest of this paper is organized as follows. We analyze the service chain of passenger flow in the URT station and set up the association network of facilities and its property in Section 2. Section 3 provides the methodology to assign passenger flow with the cascading failure effect and the user-equilibrium assignment model considering passenger choice behavior is presented. Then the solution algorithm that combines node attack strategy with Frank-Wolfe algorithm is given in Section 4. Afterwards, a case study on real-world station is expatiated with the comparison to pedestrian simulation in Section 5. Finally, conclusions and future research are discussed.

2. Association Network of Facilities in URT Station

In this section, we propose the association network of facilities in URT station based on the service chain of passenger flow.

2.1. Service Chain of Passenger Flow. Passenger flow in URT stations can be classified into three distinctive categories, that is, ingress passenger flow, egress passenger flow, and transfer passenger flow. And the gathering and distributing process of passenger is denoted as receiving specific services from a series of facilities successively, which is the definition of "service chain" in the URT station. Indeed, the service chain varies with the type of passenger flow [17]:

(1) Ingress passenger flow: enter station → purchase tickets → check tickets → go through staircases or escalators (if station hall and platform are on different floors) → wait for the train and board

(2) Egress passenger flow: alight → go through staircases or escalators (if station hall and platform are on different floors) → check tickets → exit station

(3) Transfer passenger flow: alight → go through staircases or escalators → check tickets (if necessary) → walk to another platform (through corridors, staircases, or escalators) → wait for the train and board.

According to the description of the service chain, each service is provided by one kind of facility, including corridors. To be noteworthy, train is not strictly the facility that belongs to the station, but it is the only server in the event of boarding and alighting. Thus we regard the train as one piece of equipment in this paper. Consequently, the service chain can be translated into the facility chain in station, shown in Figure 1.

2.2. Association Network of Facilities. The motion of passenger flows brings forth the coupling between facilities, and the facility chain in station makes it feasible to depict that relationship. In each strand of facility chain, every single node represents a specific piece (or group) of equipment, fusing together and then forming an open-loop and directed association network of facilities.

Explanations of association network are given as follows.

Item 1. A set of nodes D_i ($i \in N^*$) denotes a certain link L_u ($u \in N^*$) in the service chain. In Figure 2, the automatic fare gates (AFG) D_5 to D_8 constitute the facility set of checking tickets service for ingress and egress passenger flow.

Item 2. Directed edge $E_{i\text{-}j}$ indicates the accessibility of the path from node D_i to node D_j ($j \in N^*$, $j \neq i$), while there would not be a directed edge if two nodes are disconnected. $l_{i\text{-}j}$ is the length of directed edge $E_{i\text{-}j}$, defined as the linear distance between midpoints of two connected facilities. Meanwhile, the transition from one link to another is completed via directed edges. Figure 2 shows that $E_{3\text{-}5}$, $E_{3\text{-}7}$, and $E_{4\text{-}7}$ are involved in the process that passenger flow moves from purchasing link L_2 to checking link L_3.

Item 3. C_i is the limit capacity of node D_i, except for those representing entrance and exit, under a certain service level. It is defined as maximum passenger flow which the facility can handle in unit time, quantified with

$$C_i = C_{si} + C_{qi}. \quad (1)$$

The maximum number of people that facility node D_i can serve in unit time without queueing is defined as the maximum service capacity C_{si}, and its formula is given in [1]. C_{qi} is the maximum queueing number in unit time under a certain service level, called maximum queueing capacity, and defined as

$$C_{qi} = S_{\text{queue}\_i} * p_i, \quad (2)$$

where S_{queue_i} is the size of queueing area for facility node and p_i is the number of passengers per unit area, which suggested quantifying with Fruin level of service (LOS) [18] in this study.

Item 4. Let VI_i denote the inflow volume of node D_i and VO_j denote the outflow volume of node D_j. Then VI_i should satisfy (3) if node D_j is the former point that connected to node D_i at steady state.

$$\text{VI}_i = \sum_{j \to i} \text{VO}_j. \quad (3)$$

For each node D_i, there is an upper limit to how many passengers could be handled. Thus the outflow volume of node D_i is supposed to be updated according to the inflow volume VI_i which is in the same flow direction.

If the inflow volume of node D_i exceeds its maximum service capacity, only part of passengers can move to the next node while the rest of them are counted as queueing volume VQ_i. Moreover, if VQ_i is beyond the maximum queueing capacity, node D_i is considered as overloaded. Whereas the inflow volume of node D_i is less than the maximum service capacity, all passengers receive service in time and leave the node. Then the formula for outflow volume VO_i is given by

$$\text{VO}_i = \begin{cases} C_{si}, \text{VQ}_i = \text{VI}_i - C_{si}, & \text{if } \text{VI}_i > C_{si} \\ \text{VI}_i, \text{VQ}_i = 0, & \text{if } \text{VI}_i \leq C_{si}. \end{cases} \quad (4)$$

3. Methodology

Cascading failure is a failure in a system of interconnected parts where the crash of one part can trigger the failure of successive parts [19]. In a similar way, if the inflow volume is far beyond the maximum capacity of the facility in URT station, failure occurs and there is a call for the reassignment of passenger flow. Yet the crash of one node in the association network of facilities will not alter the network structure, either the volume or distribution of that node remains in the collapsing state. Only passenger flows on other nodes will be reallocated and trigger the crash of vulnerable nodes.

The failure will radiate from the crash node successively until the station can no longer maintain the service chain of any type of passenger flow. In other words, the load capacity of the station is the quantity of passengers when all nodes in one link of the facility chain have collapsed. Hence, the model in this section elaborates on the mechanism of assigning passenger flow to the facility network.

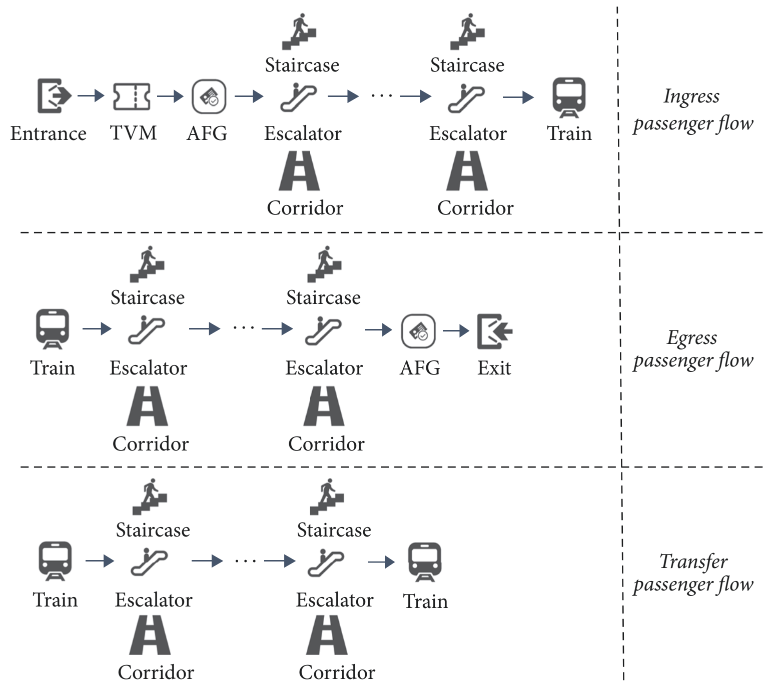


Figure 1: Illustration for facility chains in station.

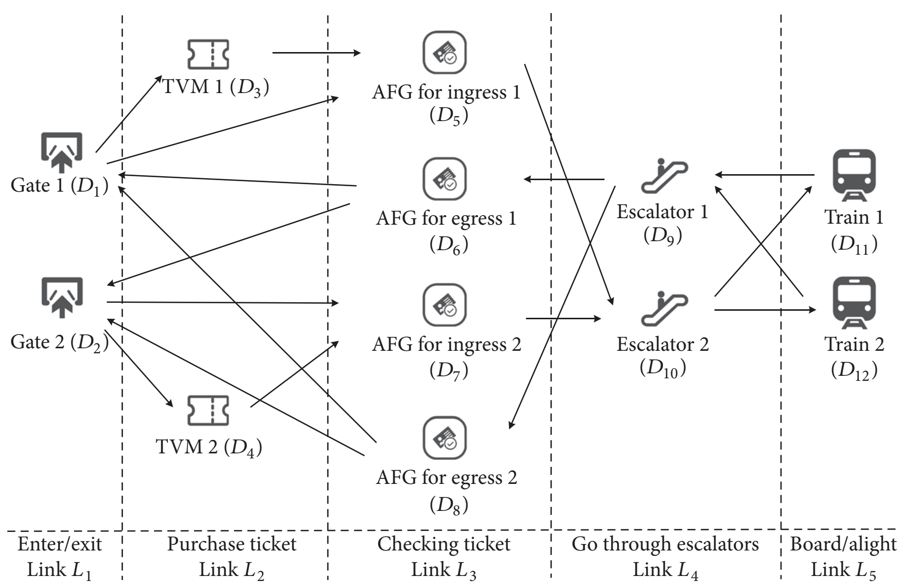


Figure 2: The association network of facilities in nontransfer station.

3.1. Assumptions. Due to the complex interaction among passenger behaviors, facility layout, and single facility capacity, assumptions are proposed as follows to ensure a high computational efficiency and the appropriate accuracy of the model.

(1) The capacity of directed edge $E_{i\text{-}j}$ is unlimited, which means the walking space of accessible paths from node D_i to node D_j is able to accommodate infinite passengers. This term is supposed since the load capacity of opening area is usually much higher than other facilities. Meanwhile, it can be improved by avoiding intercross and queueing in serpentine line in either the designing or operation phase.

(2) The maximum load capacity is an intrinsic property of the facility (node D_i). It does not change with the service intensity and time.

(3) It is assumed that velocity of passenger flow remains constant, taking no account of individual attributes, motor process, and the loss of speed.

(4) The service of boarding and alighting is available when trains arrive periodically. It needs to be

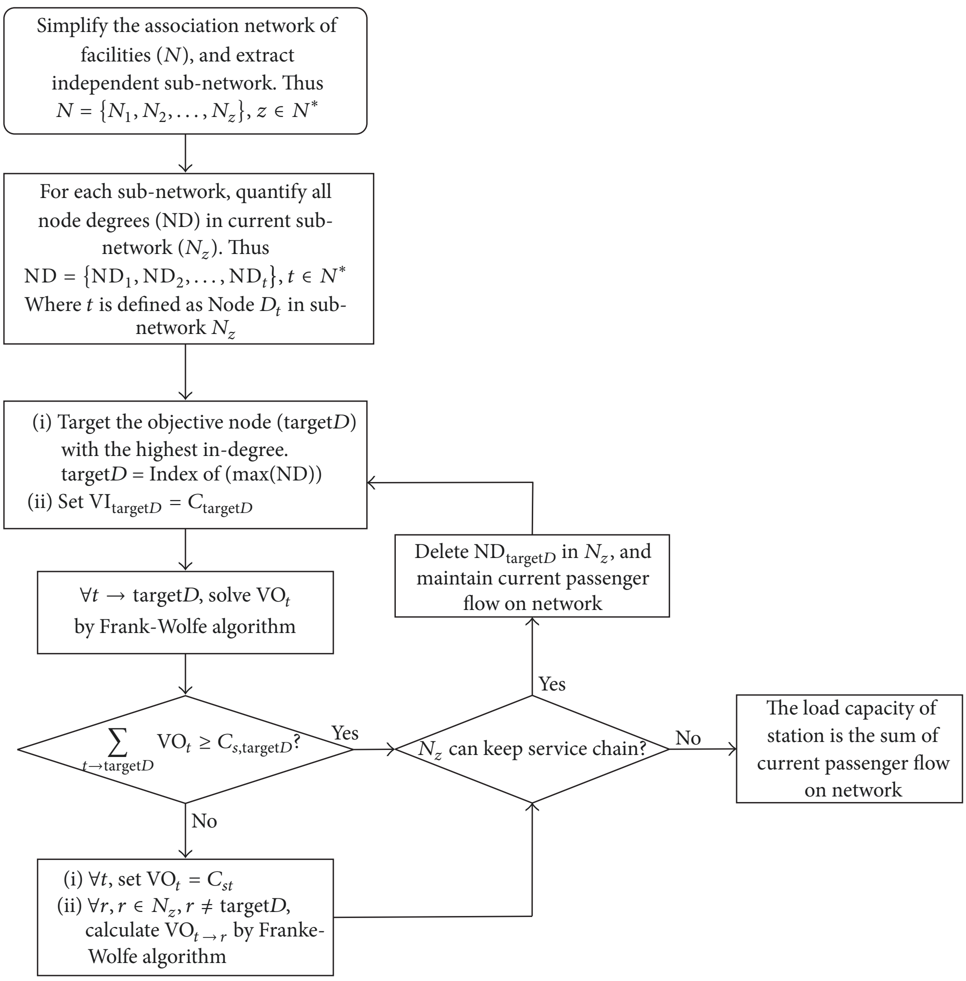


Figure 3: The flow chart of algorithm for calculating load capacity.

converted into the passenger flow volume handled per unit time so that all fundamental capacities of facilities are in uniform dimension.

(5) Passengers need to decide on which node to choose next every time before moving to the successive link of service chain. Once the choice is determined, it is unable to be reselected.

(6) The action of leaving the node is completed in a moment; that is, passengers will not be stranded in the node after receiving the service.

(7) All individual motor processes in the same passenger flow category are viewed as a whole fluid motion. On this basis, we suppose that passengers arrive at the same time and receive service from different nodes in one link.

3.2. Passenger Flow Assignment Mechanism. Commuter and residents are the majority of URT users, having a command of the layout of facilities and equipment in stations. The frequent trip by URT enables these passengers to acquire the guidance information in a short time. Therefore, it is reasonable to assume that passengers make decisions on which route to take with a complete knowledge of information in station.

The user-equilibrium (UE) model [20, 21] is a typical method for traffic assignment. It is based on the fact that people choose a route so as to minimize their travel time and on the assumption that such a behavior on the individual level creates an equilibrium on the network. In this paper, the flow loading on the association network of facilities and equipment is described by the UE model.

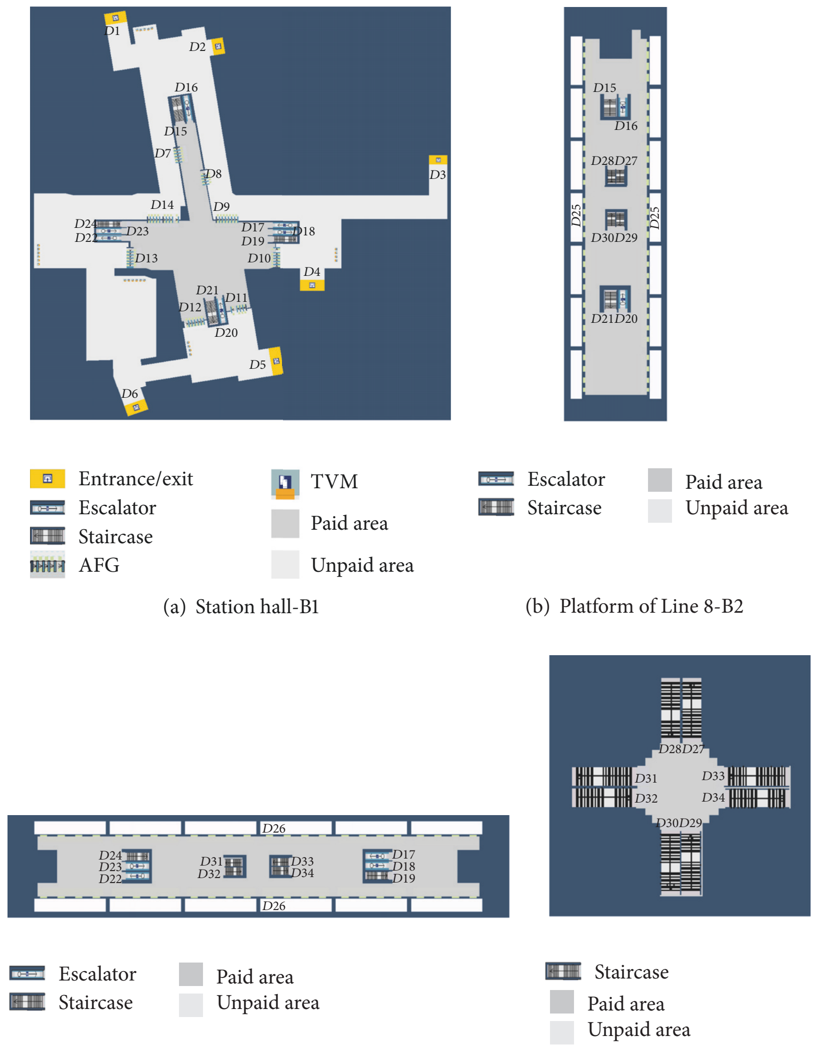
Let x_{ij} denote the flow volume on directed edge $E_{i\text{-}j}$. And the impedance function is defined as $w_{ij}(x)$ to quantify the choice behavior of passengers. f_k^{uv} is the flow volume of edge k ($k \in N^*$) between links L_u and L_v ($v \in N^*$, $v \neq u$), while d_{uv} denotes the total flow of links (L_u, L_v). Then the UE model is formulated as follows:

$$\min \quad Z(X) = \sum_{(i,j)} \int_0^{x_{ij}} w_{ij}(x)\, dx \tag{5}$$

$$\text{st.} \quad \sum_k f_k^{uv} = d_{uv} \quad \forall u, v \tag{6}$$

$$f_k^{uv} \geq 0 \quad \forall u, v, k \tag{7}$$

$$x_{ij} = f_k^{uv} \delta_{ij,k}^{uv} \quad \forall i, j. \tag{8}$$



(a) Station hall-B1

(b) Platform of Line 8-B2

(c) Platform of Line 9-B2

(d) Transferring floor sandwich between B2 and B3

Figure 4: Sketches of LJB station: (a) station hall, (b) platform of Line 8, (c) platform of Line 9, and (d) interlayer for transfer.

If the directed edge is the right edge k between links (L_u, L_v), $\delta_{ij,k}^{uv} = 1$ in (8). Otherwise, $\delta_{ij,k}^{uv} = 0$.

3.3. Choice Behavior on Nodes. Actually, a multitude of passengers prefer to choose the node which is characterized by short distance and convenient service [17]. Thus we take distance, number of people, and congestion into account and formulate the impedance function $w_{ij}(x)$ in Section 3.2, using BPR function as reference.

$$w_{ij}(x) = w_{ij}^0 \left[1 + a_0 \left(\frac{x_{ij}}{C_j} \right)^b + a_1 * \frac{(x_{ij} - C_{sj})}{C_{qj}} \right] \tag{9}$$
$$a_0, b, a_1 \geq 0.$$

Equation (9) is composed of the following elements.

Firstly, the distance impedance from node D_i to node D_j indicates the initial impedance of a node before being selected, denoted as w_{ij}^0. It is an innate property of the node, positively associated with $l_{i\text{-}j}$, given in

$$w_{ij}^0 = e^{h * l_{i\text{-}j}}, \quad h > 0, \tag{10}$$

where h has relationship with the scale of URT station (0.1 is suggested).

Secondly, $a_0(x_{ij}/C_j)^b$ is used to denote the impedance of passenger number at node D_j. It refers to circumstances such as low velocity at node caused by the increasing number of people which reduces service level. For parameters a_0 and b, $a_0 = 0.15$ and $b = 4$ are set in general [22].

Thirdly, the congestion impedance $a_1 * (x_{ij} - C_{sj})/C_{qj}$ indicates the crowded degree of queueing area in the case that inflow volume at node D_j exceeds the maximum service capacity C_{sj}. The parameter a_1 is initialized as zero and updated only when $x_{ij} > C_{sj}$ (0.2 is suggested).

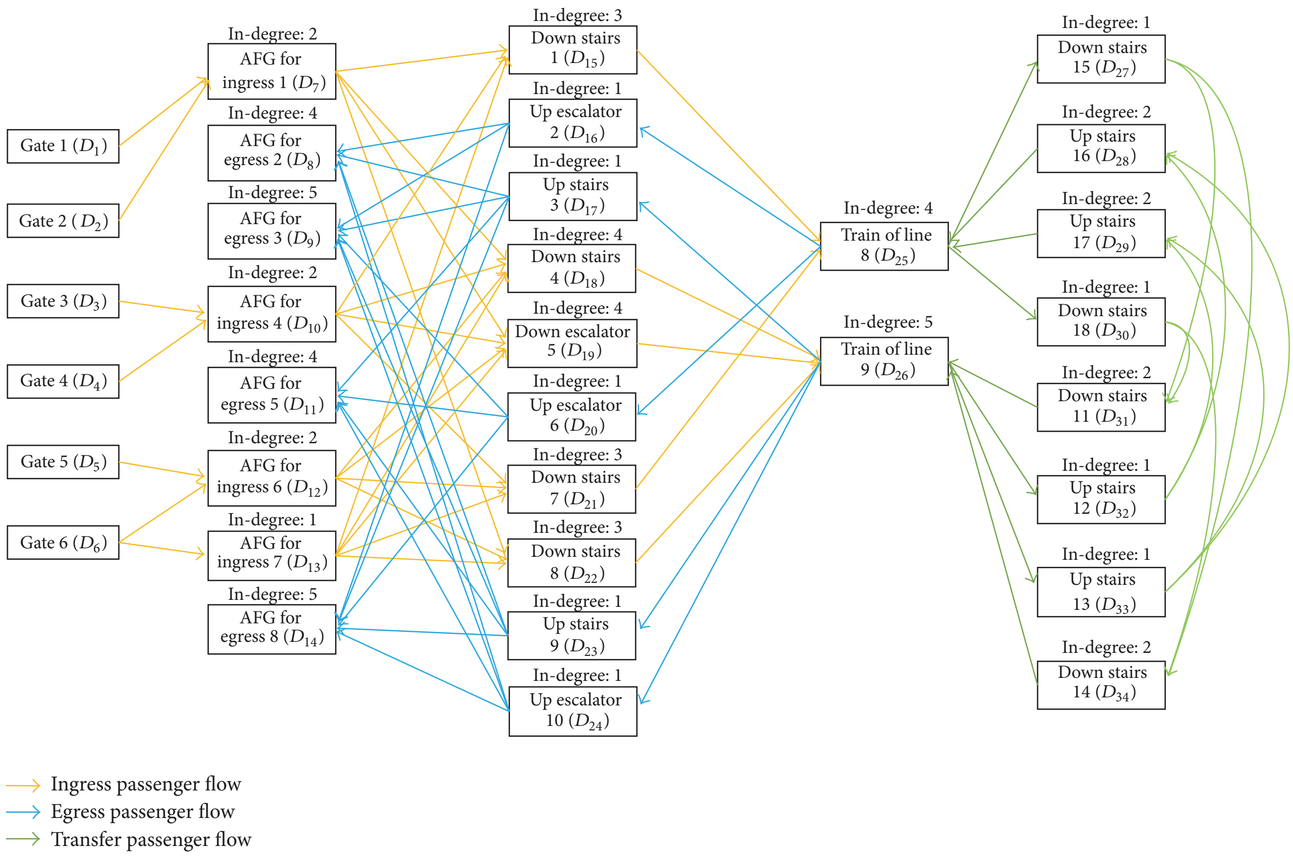


FIGURE 5: The association network of facilities in LJB station.

4. Algorithm

The Frank-Wolfe algorithm [23] is an effective method to solve the user-equilibrium model. In this algorithm, however, passenger flow assignment under condition of variable demand will lead to the exponential growth of computational complexity. In order to improve the calculating efficiency of station load capacity, attack strategy in communication network is introduced in this section to assist in approaching the verge of facility crash.

4.1. Node Attack Strategy. The core principle of node attack strategy is attacking crucial node in priority. Taking topological properties as the reference to evaluation index, node degree (ND) is used to quantify the node function and influence on the network. Considering that the association network of facilities in URT station is a directed network, node degree should be classified into in-degree and out-degree. The in-degree of nodes is accepted as the evaluation index in this paper, and the higher the in-degree rises with edges pointing to the node, the more significant it is in the network.

4.2. Solution Algorithm. The association network of facilities can reflect passenger flow's motion in the station, while there is a problem in circumstance of transfer stations. Different types of passenger flow have to share some facilities in station, which makes it hard to distinguish the impact on one facility from separate passenger flows. Thus we optimize the input of passenger flow by setting proportion on passenger types.

Based on the Frank-Wolfe algorithm and node attack strategy, the algorithm procedure for load capacity of URT station is as follows (shown in Figure 3).

Step 1. Simplify the association network of facilities, extract the subnetwork which is independent of the whole, and then remove edges with large initial impedance.

Step 2. Quantify all node degrees (in-degree) in the current subnetwork.

Step 3. Target the node with the highest in-degree (denoted as objective node) in a directed chain and launch attacks until it crashes. According to Item 4 in Section 2.2, if passengers are allocated to all out-direction edges and total outflow is less than the maximum service capacity, the node inflow volume equals the total outflow volume. Otherwise, the inflow volume of the node is the loading limit.

Step 4. Allocate the inflow of objective node in reverse direction in order to ascertain the outflow volume from those nodes which point to the objective node.

	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12	D13	D14	D15	D16	D17	D18	D19	D20	D21	D22	D23	D24	D25	D26	D27	D28	D29	D30	D31	D32	D33	D34
D1	-																																	
D2		-																																
D3			-																															
D4				-																														
D5					-																													
D6						-																												
D7	38.9	31.4					-																											
D8								-								18.4	24.1						28.5	27.3										
D9									-							31.1	16.2			24.3			30.1	30										
D10			49.9	12						-																								
D11											-						25.8			3.6			39.9	40.4										
D12					23.5	40						-																						
D13						27.1							-																					
D14														-		30.3	31.7			27.2			15.6	15.1										
D15							11			46.1			41.7		-																			
D16																-									6									
D17																	-									6.5								
D18							33.7			6.8		33.6	41.1					-																
D19							35.1			5.5		32	40.9						-															
D20																				-					6									
D21										23		5.4	25.4								-													
D22							28.5					31.1	7.3									-												
D23																							-			6.5								
D24																								-		6.5								
D25															6						6				-									
D26																		6.5	6.5			6.5				-					6.5			6.5
D27																									6		-							
D28																												-				9.8	7.3	
D29																													-			7.6	9.5	
D30																									6					-				
D31																											5.8			9.9	-			
D32																										6.5						-		
D33																										6.5							-	
D34																											8.7			6.4				-

FIGURE 6: The distance matrix of association network of facilities.

Step 5. If the outflow volume exceeds the maximum service capacity, go to Step 8. Otherwise, go to Step 6.

Step 6. Attack adjacent nodes which connect with the objective node. The outflow volume of new objective node is equivalent to its maximum service capacity except when the out-degree is 1 (skip this node).

Step 7. Keep the flow volume of crash nodes invariant and assign the rest of the passenger flow by the Frank-Wolfe algorithm.

Step 8. Judge on whether network can keep offering service to all kinds of passenger flow. If all links for one kind of passenger flow turn to be infeasible, the load capacity of station is equivalent to the current passenger flow on network. If not, keep on implementing the node attack strategy, redoing Steps 4 to 8.

5. Case Study

In this section, we illustrate the application and evaluate the effect of the method to calculate the load capacity of URT station on real-world instance. The example is based on a URT station in Shanghai and all data are collected from Shanghai Metro Operation Co., Ltd., in November 2016.

5.1. Basic Scenario. Lujiabang (LJB) station is a transfer station for Metro Line 8 and Line 9, sharing the station hall on underground floor as shown in Figure 4(a). Staircases and elevators arranged in north-south position lead to the platform of Line 8 on underground two, shown in Figure 4(b), while those arranged in east-west position lead to the platform Line 9 on underground three, shown in Figure 4(c). Meanwhile, Figure 4(d) depicts the intersection

Table 2: The Limit capacity of nodes.

Node	Type	Limit Capacity (ped/h)
D_7	AFG	9000 + 3 × 25 = 9075
D_8	AFG	7200 + 3 × 20 = 7260
D_9	AFG	12600 + 3 × 35 = 12705
D_{10}	AFG	10800 + 3 × 30 = 10890
D_{11}	AFG	7200 + 3 × 20 = 7260
D_{12}	AFG	10800 + 3 × 30 = 10890
D_{13}	AFG	10800 + 3 × 30 = 10890
D_{14}	AFG	14400 + 3 × 40 = 14520
D_{15}	Staircase	10080 + 3 × 12 = 10116
D_{16}	Escalator	6720 + 3 × 8 = 6744
D_{17}	Staircase	5460 + 3 × 7 = 5481
D_{18}	Staircase	5460 + 3 × 7 = 5481
D_{19}	Escalator	10080 + 3 × 7 = 10101
D_{20}	Escalator	6720 + 3 × 8 = 6744
D_{21}	Staircase	10080 + 3 × 12 = 10116
D_{22}	Staircase	5460 + 3 × 7 = 5481
D_{23}	Staircase	5460 + 3 × 7 = 5481
D_{24}	Escalator	10080 + 3 × 8 = 10104
D_{25}	Train	10560 + 3 × 80 = 10800
D_{26}	Train	14880 + 3 × 80 = 15120
D_{27}	Staircase	12025 + 3 × 16 = 12093
D_{28}	Staircase	13650 + 3 × 16 = 13698
D_{29}	Staircase	13650 + 3 × 16 = 13698
D_{30}	Staircase	12025 + 3 × 16 = 12093
D_{31}	Staircase	13650 + 3 × 16 = 13698
D_{32}	Staircase	12025 + 3 × 16 = 12093
D_{33}	Staircase	12025 + 3 × 16 = 12093
D_{34}	Staircase	13650 + 3 × 16 = 13698

staircases for directly transferring from one platform to another.

(1) *Station network*: with analyzing the service chain in LJB station, we build the association network of facilities and equipment and calculate in-degree for all nodes, which is shown in Figure 5.

(2) *Data of passenger flow and train*: firstly, the passenger flow proportion of Line 8 to Line 9 is about 6 : 4. Secondly, the interval time of trains for two lines is 3 minutes in each operational direction, and the number of alighting passengers in LJB station is approximately 20 percent of train seating capacity.

(3) *Limit capacity of nodes*: level F in LOS (3 ped/m^2) is regarded as the criterion of node failure, and the limit capacity of nodes is calculated, given in Table 2.

(4) *Distance of edges*: distance information of facilities and equipment was collected from CAD design drawings of LJB station, denoted as the matrix in Figure 6.

5.2. Results and Analysis. The association network shown in Figure 4 can be divided into two subnetworks. Subnetwork N_1 is for egress flow and the other one N_2 is for ingress and transfer flow.

Figure 7 depicts that attack was launched first on nodes D_9 and D_{14} in N_1, showing the assignment of current flow volume. Obviously, the outflow of nodes D_{16} and D_{20} equals 7383 ped/h and 8951 ped/h, respectively, which are beyond their maximum capacity. Thus these two nodes crash firstly, resulting in the cascading failure of egress service chain for Line 8. The load capacity of N_1 is equivalent to the sum of D_{16} and D_{20} limit capacities, namely, 13488 ped/h.

Figure 8 illustrates the similar process that happened in N_1. After node D_{26} was attacked at first, none of the allocated outflow volume on nodes D_{18}, D_{19}, D_{22}, D_{31}, and D_{34} exceeded their maximum capacity. Meanwhile, out-degrees of those nodes equal 1, indicating that the crash of node D_{26} would not cause congestion on others. Then attack was launched on node D_{25} whose out-degree is 4, while the outflows of related nodes D_{15}, D_{21}, D_{28}, and D_{29} were less than their maximum capacities. The crash of node D_{25} did not lead to cascading failure either. Therefore, the load capacity of

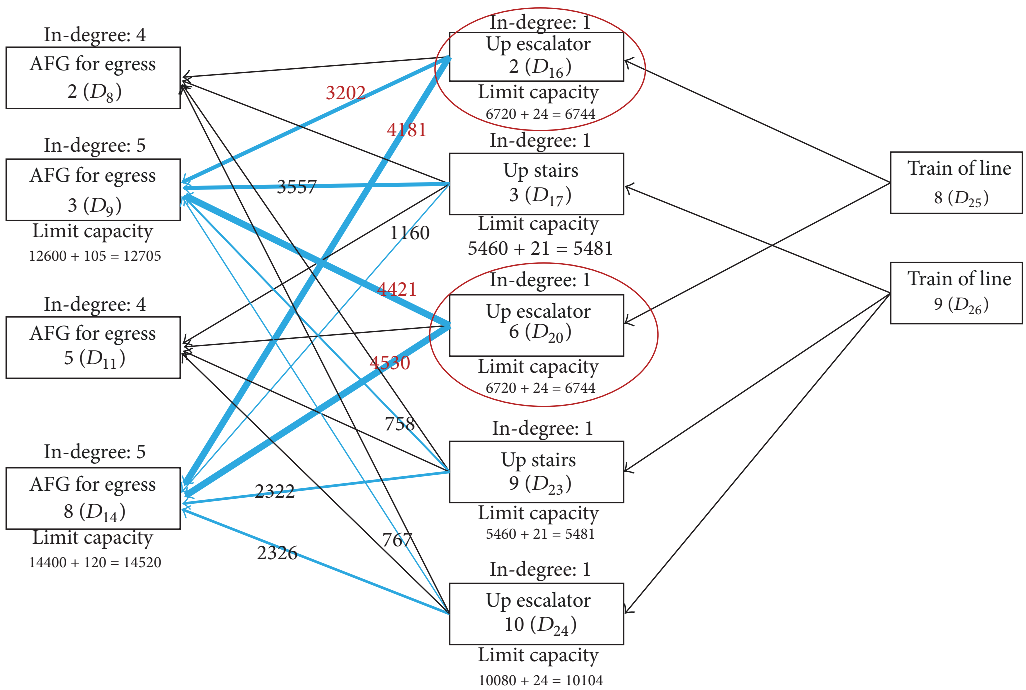


FIGURE 7: The cascading failure in subnetwork N_1.

N_2 is equivalent to the sum of D_{25} and D_{26} limit capacities; that is, alighting passengers reach 10800 ped/h for Line 8 or 15120 ped/h for Line 9.

In order to verify the accuracy of results, the microscopic simulation software StaPass is used in this paper. StaPass specializes in simulating the motor process of passengers specifically in URT station. It is developed by Tongji University and has been successfully applied in station design projects in Shanghai, Guangzhou, Nanjing, and so on.

Set calculation results on the input of the specific scenario. And after one-hour simulation, the density map of passenger flow is shown in Figure 9.

In Figure 9, facilities in dark yellow and red zone are those under F level of service. This is approximately consistent with the calculation result, except that

(1) in simulation, the density of node D_{17} (denoted as "Outlier") is under F level while it is not one of the collapsed nodes in algorithm. But we find that node D_{17} is the next target to be attacked after the crash of nodes D_{16} and D_{20}. It is simulation time that leads to the high density of node D_{17};

(2) the density of collapsed nodes in simulation is much higher than the recommended F value of LOS. In simulation environment, the overlap of different passenger flows in one area will increase the density, while motor progress is simplified in the algorithm. However, the result does not matter.

6. Conclusion

In this paper, we analyzed the service chain of passenger flows in URT station, which could reflect the coupling relationship between separate types of facility. On the basis of that, an association network was built up. Cascading failure theory was introduced to elaborate the influence mechanism of three elements: the motion of passenger flow, the capacity of single piece of equipment, and the layout of facilities. Then we proposed dynamic calculation model for station load capacity based on the user-equilibrium assignment principle. As to the algorithm, the Frank-Wolfe algorithm is a traditional approach for flow assignment, and node attack strategy of complex network was presented to lower the computational complexity. In the case study, we took Lujiabang station in Shanghai Metro as an example to demonstrate the performance of the method and algorithm. In comparison with the result of pedestrian simulation, the vulnerable nodes to facility network and the load capacity of station deduced from this approach are verified to be correct.

The proposed method can be considered as a step towards the quantification of station load capacity. This paper could thus stimulate further research to expend application for more complex stations in urban rail transit system. Moreover, security is a particular problem drawing more attention nowadays. Events related to station security like safety inspection are not considered in this method. The issue on how the interaction of different passenger flows affects load capacity should be studied further. All these will be addressed in future research.

Disclosure

This work has been presented at Transportation Research Board 97th Annual Meeting, but not for publication.

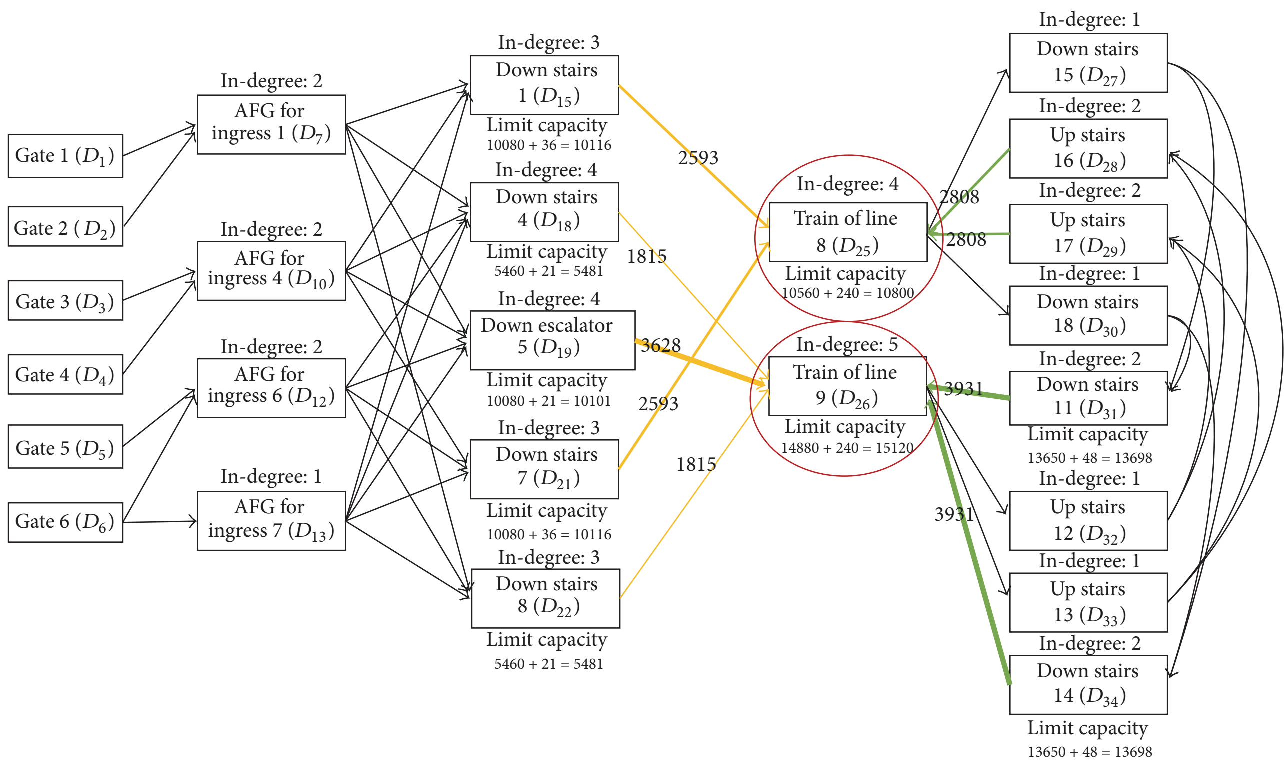


Figure 8: The cascading failure in network N_2.

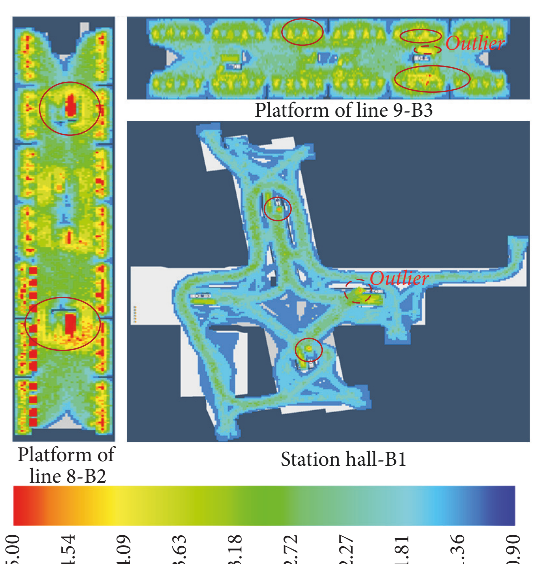


Figure 9: The density map exported from StaPass.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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