Study on the bottleneck of urban rail transit station based on the operation safety

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Abstract: The present solution for bottleneck of urban rail transit station is identification and relief. This paper considers this solution may make a large number of passengers enter the station, causing excess passengers in platform and hidden danger of operation. Then the concept of controllable bottlenecks is proposed. Further, based on the idea that controllable bottlenecks such as security inspection machine and automatic ticket checker can control the number of passengers in platform in an appropriate range, system dynamics are used to build the model. Then controllable bottlenecks are proved to perform well in control passengers of platform by using a example. At last, different controllable bottlenecks methods are given for corresponding mass-passenger stations.

1. Introduction

Urban rail transit has been developed fast in China in the past years. The urban rail transit lines of big cities have entered the forward stage operation period while the capacities of most lines that they can accommodate passengers are saturated in peak hours. Some stations are suffering the pressure that too many passengers brings and further bottleneck appears.

The present studies on bottleneck of urban rail transit station are mainly about identification and relief. Through investigating, Zhang et al. compared the actual capacities of facilities in the station with the maximum capacities suggested by 《Code for design of metro》, then comes out the conclusion that entrance of security inspection machine, ascending stair and escalator easily become bottlenecks [1]. Shan et al. thought bottleneck appeared in the facility or the area which is congested. Bottleneck identification method based on the congestion level was put forward and the facility or area with the highest congestion level was bottleneck [2]. Kou et al. classified bottleneck into static bottleneck and dynamic bottleneck. Static bottleneck was the facility with the minimum capacity in the system under the condition of no passenger. Dynamic bottleneck was related to passenger flow and the congestion level of facility and studied by capability utilization formulas and AnyLogic simulation software [3]. Huang et al. classified dynamic bottleneck into primary bottleneck and secondary bottleneck and thought relieving primary bottleneck was important. Then they proposed the correlation bottleneck and bottleneck cluster concepts to identify two kind bottlenecks and the relationship between them. Finally, strategy of relieving bottleneck was proposed by sensitivity analysis [4]. Chen et al. considered the station as a queue system, stair and corridor as the service desk of the system. Then proposed a M/G/c/c capacity model to identify the bottleneck of passenger
evacuation [5]. Sun built a method to evaluate the matching degree among the facilities in the station, identified bottleneck based on the importance theory and proposed a bottleneck identification and relief procedures [6]. Xia thought a node can be used by more than two routes and its capacity would affect the evacuation deeply. Then proposed a screening method for bottleneck based on reverse research [7]. Wang et al. identified the shape bottleneck, capacity bottleneck, and congestion bottleneck of passenger gathering and distributing network, proposing corresponding methods to identify bottlenecks [8]. Liu et al. proposed an optimization model based on series-parallel hybrid queuing network and did simulation experiments about changing sequence of facilities [9]. Wang et al. structured a dynamic bottleneck identification method base on service level and sequenced bottlenecks of the network. The bottleneck with higher prioritization rank indicated heavy congestion and should to be solved first [10]. Kretz et al. found the relationship between passenger and bottleneck width is linear and modified the parameters of simulation at the same time [11]. Seyfried et al. did the experiment for unidirectional pedestrian flow and found bottleneck appeared even if the passengers flow didn’t exceed the maximum capacity of the facility [12]. Sun et al. found adding a funnel shape buffer zone in front of bottleneck would improve the efficiency of pedestrian traffic [13].

2. The Classification of Bottleneck in Urban Rail Transit Station

The capacities of facilities or areas are designed according to predicted long-term passenger volume in peak hour. While the actual passenger arrival rate is changing in peak hour as showed in Fig 1. There is a period that the capacity of facility can’t match the need from passengers. It’s more serious when predicted passenger volume is lower than actual passenger volume.

According to relevant references, bottlenecks are usually the facilities and areas with insufficient capacity or congestion. The solutions are identification and increasing capacity of facilities to relieve the bottlenecks. For the stations with the heavy passenger pressure in peak hours, identification and relief are not fit for all the bottleneck. Because there is a upper limit for the capacity of passenger gathering and distribution in the station[14], when bottlenecks appear in the security inspection machine or automatic ticket checker, increasing their capacity will make more passengers enter the paid area and get into platform finally. It is likely to bring security risk when the platform is congested in peak hours[15]. Therefore, based on the operation safety, bottlenecks can be classified into two kinds: controllable bottlenecks that can control passengers in a appropriate range in the boundary of paid area; ordinary bottlenecks that appears due to insufficient capacities of facilities.

The controllable bottlenecks are usually the security inspection machine and automatic ticket checker, operators can adjust their capacity to control the speed of passengers entering the station: when the passenger volume in platform is near saturation, decrease the speed of the security inspection machine and close part of automatic ticket checkers to reduce the speed of passengers entering the station. When the passenger volume in platform decreases after train departure,
increase the speed of the security inspection machine and open part of automatic ticket checkers to raise the speed of passengers entering the station.

3. Application of Controllable Bottlenecks in Station

For every streamline of passenger flow in urban rail transit station, the passenger volumes in facilities of the streamline have obvious causal relationship. Taking entrance passenger flow as an example, the increased passenger volume of security inspection machine will increase the passenger volume of automatic ticket checker, then increase the passenger volume of stair, escalator or corridor, and finally increase the passenger volume of platform. The passenger volume of platform will decrease after passengers boarding when train arrives.

Before train arrives, the passenger volume of platform should be controlled in an appropriate range. Therefore, the passenger volume of platform has negative feedback to entrance passengers. When the passenger volume of platform has reached to a certain value, decrease the speed of the security inspection machine and close part of automatic ticket checkers to reduce the speed of passengers entering the station; when the passenger volume in platform decreases after train departure, increase the speed of the security inspection machine and open part of automatic ticket checkers to make passenger get into paid area timely.

Based on the above analysis, system dynamics can be used to study the function that the controllable bottlenecks take effect to the passenger volume of platform. For the station with obvious tidal passenger flow, entrance passengers are the main passengers in the morning peak hours, so the exit passengers and transfer passengers can be not taken in account. What’s more, controllable bottlenecks have better effect on entrance passengers. The casual loop diagram of entrance passenger flow is shown as Fig 2.

Based on the Fig 2, system flow diagram can be written as Fig 3. Although alighting passengers from the train will increase the passenger volume of platform, it’s irrelevant to the decrease of passenger volume of station hall. And those passengers will get out the station after entering the station hall through ascending stair and escalator. Therefore, alighting passengers can be regarded as the passengers appeared with train arriving and disappeared in next time. All the variable and parameters are represented as corresponding letters.

The equations of system flow diagram are listed as follow:

\[
F_{\text{eff}} = F_{\text{eff}} + DT \times (FR_{1\text{eff}} - FR_{2\text{eff}}) \\
Z_{\text{eff}} = Z_{\text{eff}} + DT \times (ZR_{1\text{eff}} - ZR_{2\text{eff}}) \\
H_{\text{eff}} = H_{\text{eff}} + DT \times (HR_{1\text{eff}} - HR_{2\text{eff}})
\]
Rate variable equations:

\[ FR_{ KL} = \int \mu dt \]  
\[ FR_{ KL} = \min \left\{ \min \left\{ F_{ KL} * \alpha, a \right\} + F_{ KL} * (1 - \alpha), b_1 * b_2 \right\} \]  
\[ ZR_{ KL} = FR_{ KL} \]  
\[ ZR_{ KL} = \min \left\{ Z_{ KL}, c + d \right\} \]  
\[ HR_{ KL} = \text{delay}(ZR_{ KL}, t_1) + i \]  
\[ HR_{ KL} = \min \{ H, m * n * \text{pulse train(start, duration, f, end)} \} + \text{delay}(i, t_2) \]  

(Note: \( t_1 \) is the time of passengers working to station hall from platform; \( t_2 \) is the time of passengers evacuation time in platform)

System flow diagram also includes auxiliary variables (such as \( \mu, \alpha, b_1, b_2 \) and so on) and initial values (such as \( F, Z, H \))

4. Case Study
For the stub columns, the formulae of DSM are detailed as follows [4], in which the \( P_y \) is the yield load, the \( \lambda \) also represents the cross-section slenderness and the \( \sigma_{cs} \) is calculated through finite strip method software CUFSM. Comparison between the results of finite element models and DSM are shown in Figure 6. It is clear that the current DSM is not able to be applied in hot-rolled RHS/SHS, so it needs modification.

Huilongguan station is a station of subway line 13 in Beijing with obvious tidal passenger flow near the Huilongguan residential area. The unpaid area is in the middle of the station hall with one security inspection machine, and the paid area is in both sides. There are four entrance automatic ticket checkers and four exit automatic ticket checker in west paid area, and four entrance automatic ticket checkers and three exit automatic ticket checker in east paid area. Its two islands type platform is shown as Fig 4. The trains operate on up-and-down lines while the middle line is used for trains returning depot.
Table 1 shows the recommended values of capacities of facilities given by 《Code for design of metro》. According to operation, recommended values are usually higher than the actual capacities. Some researchers give the reference values through investigating[1][17]. In this chapter, reference values of facilities in Huilongguan station have been investigated in Table1.

| Facility                          | Recommended value (persons/min) | Reference value (persons/min) |
|----------------------------------|---------------------------------|------------------------------|
| One security inspection machine  | -                               | 43                           |
| One automatic ticket checker (door type) | 30                              | 30                           |
| Escalator (/m)                   | 112                             | 90                           |
| Stair (m)                        |                                 |                              |
| Ascending                        | 62                              | 43                           |
| Descending                       | 70                              | 49                           |
| Bidirectional                    | 53                              | 47                           |

Based on the investigated, the passenger volume of 7:30-8:30 in morning peak hours in Huilongguan station is shown in Table 2.

Table 2 Passenger Volume in Morning Peak hours in Huilongguan Station
(Note: Enpv is short for entrance passenger volume and Expv is short for exit passenger volume)

| Time   | Enpv | Expv | Time   | Enpv | Expv |
|--------|------|------|--------|------|------|
| 7:30-7:3 | 867 | 57 | 5 | 8:00-8:0 | 1215 | 67 |
| 7:35-7:4 | 1002 | 55 | 5 | 8:05-8:1 | 1076 | 69 |
| 7:40-7:4 | 1207 | 69 | 5 | 8:10-8:1 | 962 | 63 |
| 7:45-7:5 | 1329 | 74 | 5 | 8:15-8:2 | 894 | 78 |
| 7:50-7:5 | 1398 | 70 | 5 | 8:20-8:2 | 806 | 71 |
| 7:55-8:0 | 1303 | 69 | 5 | 8:25-8:3 | 717 | 68 |

Table 2 shows entrance passengers is the main passengers in morning peak hours in Huilongguan station. Exit passenger volume only account for about 5.9% of the total, having little influence on passengers of platform. Average arrival rate (μ) can be calculated in every five minutes in Table 3.
Table 3 Average arrival rate

| Time    | 7:00-7:05 | 7:05-7:10 | 7:10-7:15 | 7:15-7:20 | 7:20-7:25 | 7:25-7:30 |
|---------|-----------|-----------|-----------|-----------|-----------|-----------|
| $\mu$   |    173    |    201    |    241    |    266    |    280    |    261    |

| Time    | 7:30-7:35 | 7:35-7:40 | 7:40-7:45 | 7:45-7:50 | 7:50-7:55 | 7:55-8:00 |
|---------|-----------|-----------|-----------|-----------|-----------|-----------|
| $\mu$   |    243    |    215    |    192    |    179    |    161    |    143    |

The ratio of passenger volume of direction to Xizhimen to passenger volume of direction to Dongzhimen is about 3:2. Thus the passenger volume of platform in direction to Xizhimen will affect the strategy of controllable bottleneck. The train of subway line13 has six cars, train arrival interval is 2.5 minutes and dwell time is about 1 minute.

《Regulations on the operational safety management of urban rail traffic》 gives the cordon is 70% of maximum loading capacity. The maximum loading capacity of platform in direction to Xizhimen is 450 persons, then the appropriate passenger volume is 315 persons. The ratio of passengers needing security check is 0.6. The other parameters related to the platform in direction to Xizhimen are one ascending escalator with the width of 1 meter; two bidirectional stairs with the width of 1.5 meters; the range of waiting passengers in each door is from 12 persons to 8 persons; the range of reminder of car is from 56-32; the time of passengers working to station hall from platform and the time of passengers evacuation time in platform are both about 1 minute.

Using system dynamic software Vensim to analyze the passenger volume of platform with and without controllable bottleneck, the result is shown in Fig5. The equation of efficiency of security inspection machine (a) in Vensim software is that IF THEN ELSE("the difference between H and j (k)" > 0, 43 , 30 ); and The equation of the number of entrance automatic ticket checks (b1) is that IF THEN ELSE("the difference between H and j (k)" > 0, 8 , 8 )

![Fig 5 Result with and without Bottleneck](image)

According to Fig 5, controllable bottlenecks keep the passenger volume of platform in 450 persons, fluctuating bear 315persons. If the bottlenecks like security inspection machine and automatic ticket checker are been relieved, the passenger volume of platform will increase quickly and exceed the maximum loading capacity eventually, bringing security risks.

To further study the controlling effect of security inspection machine and entrance automatic ticket checker, the experiments of changing the efficiency of security inspection machine and the number of entrance automatic ticket checker are did respectively. The results are shown in Fig 6 and Fig 7.
Fig 6 Changing Security Inspection Machine  

Fig 7 Changing Entrance Automatic Ticket Checker

Fig6 indicates that only decreasing the efficiency of security inspection machine has no significant influence on controlling platform’s passenger volume. While increasing the ratio of passengers needing security check to 1 will keep the platform’s passenger volume in a low level (range from 45 to 93). When heavy passenger flow happens in holiday and festival, all passengers needing to be checked, adding some security inspection machines can help to keep the platform’s passenger volume in an appropriate range.

Fig7 indicates that only reducing the number of entrance automatic ticket checker can keep the platform’s passenger volume in an appropriate range. But many passengers will be held up in the area between security inspection machine and entrance automatic ticket checker, which also brings security risks. Therefore, entrance automatic ticket checker should be used with security inspection machine.

5. Conclusion
This paper analyze the bottlenecks in urban rail transit station, proposing the concept of controllable bottlenecks. Based on the relationship among passenger volumes of facilities, system dynamic is used to verify the effect of controllable bottleneck in controlling passenger volume of platform. With case study, three conclusions have been reached as followed:

1. Controllable bottleneck can keep the passenger volume of platform in an appropriate range for the station with heavy entrance passenger flow in peak hours, reducing security risks.

2. Only decreasing the efficiency of security inspection machine has no significant influence on controlling passenger volume of platform. Increasing the ratio of passengers needing security check to 1 will keep the platform’s passenger volume in a low level. For the station with heavy passenger flow in holiday and festival, all passengers needing to be checked, adding some security inspection machines can help to keep the platform’s passenger volume in an appropriate range.

3. Even if only reducing the number of entrance automatic ticket checker can keep the platform’s passenger volume in an appropriate range, this would make many passengers be held up in the area between security inspection machine and entrance automatic ticket checker. Therefore, entrance automatic ticket checker should be used with security inspection machine.

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