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Resilience assessment of an urban rail transit network: A case study of Chengdu subway

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ABSTRACT

Existing studies seldom consider network structure and passenger travel demand jointly, and certain impractical assumptions are generally considered for assessing the resilience of an urban rail transit (URT) network. To address the abovementioned limitations, we have proposed a performance indicator called the demand-impedance (DI) indicator, in which demand and impedance are reflected by passenger trips and travel time. By considering effective travel paths (ETPs) and passengers' path choice behavior, we have proposed a node centrality called effective path betweenness (EPB) by modifying the betweenness centrality (BC) to evaluate the importance of stations. The performance curve of a URT network during the attack and repair processes is depicted using the DI indicator, and a modified resilience metric is formulated by referring to the resilience triangle. The model application in the Chengdu subway network demonstrates that the correlation coefficient between the EPB and BC of stations is 0.901, which indicates that stations with a higher EPB are inclined to have a higher BC. The Chengdu subway network demonstrates a higher resilience under random disturbances than it does under malicious disturbances. Disturbance duration, passengers' tolerance time, and rescue ability on the Chengdu subway network significantly affect its resilience. Several practical suggestions involving the management of disturbances, shortening the emergency response time, providing passenger services, and improving emergency rescue ability are provided for managing the Chengdu subway system under disturbances.

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1. Introduction

By the end of 2020, 45 cities started operating an urban rail transit (URT) system in mainland China. The number of operating stations and operating mileage were 4,681 and 7,969.7 km, respectively [1]. The URT system is the backbone of the public transit system in China's metropolises, which has greatly facilitated the daily commute of passengers. However, the URT system in mainland China faces severe challenges caused by the increasingly complex operating environment. For instance, in January 2013, the derailment of a train occurred in the Kunming subway system, which led to a fatality and an injury [2]. In April 2015, a human stampede disturbance at the Huangbeiling station in the Shenzhen subway system resulted in nine non-fatal injuries [3]. In January 2018, trains on the Xi'an subway line 2 were delayed for more than 20 min owing to the failure of the railroad turnouts of the line [4]. In January 2019, equipment failure on Shanghai subway

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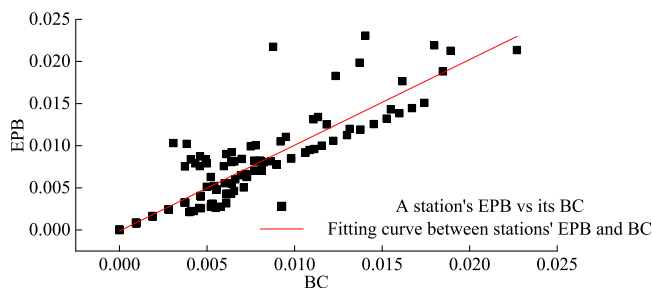


Fig. 7. Stations' EPB versus their BC on the Chengdu subway network.

Table 4

Number of affected passengers and DI indicator reduction caused by the failures of five critical stations identified with EPB and BC.

Node centrality	NoAP	DI indicator reduction ($D = 60$ s)	DI indicator reduction ($D = 360$ s)
EPB	181,216 persons	8.256×10^{-7} persons/s	2.644×10^{-5} persons/s
BC	168,539 persons	3.452×10^{-6} persons/s	2.386×10^{-5} persons/s

Note: NoAP = Number of affected passengers.

4.2. Importance of stations

The BC and EPB of stations on the Chengdu subway are calculated, and the relationship between the EPB and BC of stations is depicted in Fig. 7. The correlation coefficient between the EPB and BC of stations on the Chengdu subway is 0.901. This result implies that a station's EPB is positively related to its BC, and a station with a higher value of BC tends to have a higher EPB. The number of affected passengers and DI indicator reduction caused by the failures of five critical stations identified by EPB and BC are listed in Table 4. Passenger trip assignment result indicates that the critical stations identified with EPB are more important than the critical stations identified with BC in terms of transporting passengers. When the disturbance duration is less than the passengers' tolerance time (5 min), the DI indicator reduction caused by the failures of critical stations identified with EPB and BC is relatively small. The DI indicator reduction owing to failures of critical stations identified with EPB is smaller because the total arrival rate of passengers at five critical stations identified with EPB (2.194 persons/s) is smaller than that of stations identified with BC (2.686 persons/s). However, the failures of critical stations cause a significant reduction in the DI indicators when the disturbance duration exceeded 5 min. The DI indicator reduction owing to the failures of critical stations identified with EPB is greater than that identified with BC. Based on the above discussion, we can see that EPB is more effective for identifying critical stations in a URT network when compared to BC.

4.3. Resilience of the Chengdu subway network

4.3.1. Performance of the Chengdu subway network

The values of the Chengdu subway network's DI indicator and the total number of passenger trips on the network during the operation hours are computed and depicted in Fig. 8. The results indicate that the DI indicator of the Chengdu subway network is proportional to the total number of passenger trips on the network. According to Eq. (1), a URT network's DI indicator equals the weighted sum of the OD pairs' DI indicator. Hence, the effectiveness of a URT network's DI indicator can be verified by illustrating the effectiveness of the DI indicators among the OD pairs. The Sx1 station (station number is 2) on line 1 is considered as an example to illustrate the effectiveness of the DI indicator from the Sx1 station to other stations on line 1. The normalized DI indicator and normalized efficiency from the Sx1 station to another station on line 1 (station numbers from 1 to 35) are depicted in Fig. 9. The correlation coefficient between the normalized DI indicator and normalized efficiency depicted in Fig. 9 is 0.237, which implies that the normalized DI indicator and normalized efficiency have a low correlation. The efficiency among stations is inversely related to travel time among stations, and it does not consider the total number of passenger trips among stations. The DI indicator is proportional to the total number of passenger trips among other stations. Greater passenger trips among stations imply a higher DI indicator. The main function of a URT network is to transport passengers; thus, passenger trips are considered important for evaluating the performance of a URT network. Here, passenger trips among OD pairs and weighted average travel time on ETPs are considered in the DI indicator, which increase the effectiveness of the DI indicator when compared to the network efficiency while evaluating a URT network's performance.

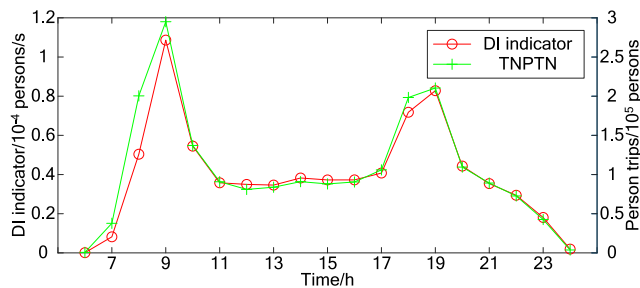


Fig. 8. Values of the network's DI indicator and the total number of passenger trips on the network during the operation hours. Note: TNPTN = Total Number of Passenger Trips on the Network.

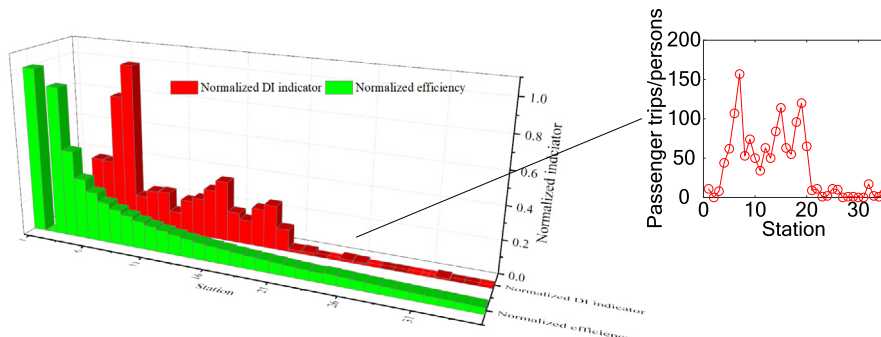


Fig. 9. Normalized DI indicator and normalized efficiency from Sxl station to other stations on line 1.

Table 5

Failure severities and passengers' arrival rates of stations chosen to simulate random and malicious disturbances.

Random disturbances			Malicious disturbances		
Station	FS	PAR	Station	FS	PAR
Sl	0.934	0.330	Yxf	3.232	0.826
Thm	1.908	0.200	Wsm	3.547	0.612
Nxa	2.194	0.411	Tsrs	3.773	0.344
Sxs	2.228	0.368	Fc	3.828	0.782
Jjh	2.449	0.191	Lms	3.976	0.537
			Tpy	2.113	0.464
			Cp	3.252	0.837
			Srs	4.476	0.401
			Cdsph	5.521	0.648
			Scg	6.808	0.605
			CuTCM&Spph	9.967	0.628
			Htz	11.705	0.820
			Lms	13.102	0.537
			Tfs	13.594	0.256
			Cxr	19.195	0.395

Note: FS = Failure Severity; PAR = Passengers' Arrival Rate.

4.3.2. Chengdu subway network's resilience

1. Simulation scenarios

The failure severities and passengers' arrival rates (persons/s) of stations that are chosen to simulate random and malicious disturbances during morning peak hours are listed in Table 5.

2. Resilience assessment of the Chengdu subway network

The DI indicator of the Chengdu subway network during the attack and repair processes under random and malicious disturbances is depicted in Fig. 10. The performance curve in Fig. 10 is more consistent with the real operation of the Chengdu subway network during disturbances than the widely applied performance curve listed in [32]. The performance curve can describe the change in a network's DI indicator in detail, and thus, it comprehensively assesses the resilience of a URT network. The resilience of the Chengdu subway network is computed using Eqs. (25)–(28). The resilience of the Chengdu subway network under malicious disturbances is 0.840, which is lower than the resilience of the Chengdu subway network under random disturbances (0.918). Malicious disturbances are more harmful to the resilience of the Chengdu subway network than random disturbances. Thus, Chengdu subway operators need to focus on the operations of critical stations (such as Tpy station, which is the bridge node among Shuangliu District and downtown Chengdu, Cp station, which connects Wenjiang District and downtown Chengdu) to avoid network paralysis caused by the failures of critical stations.

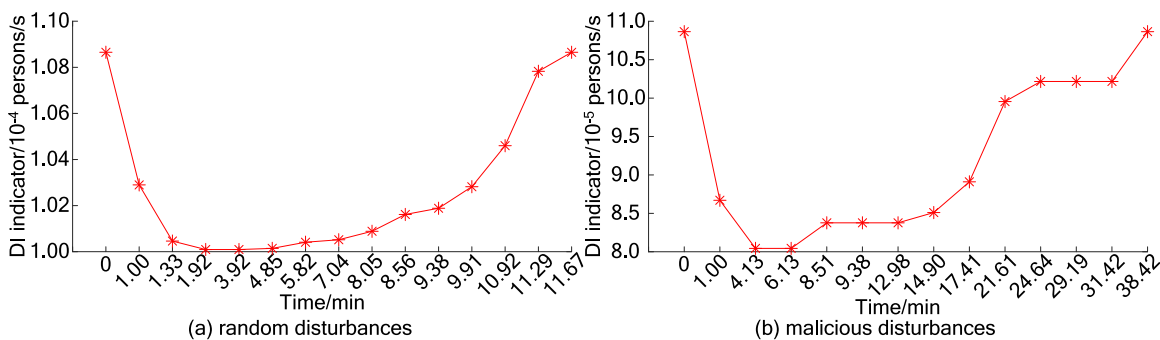


Fig. 10. Network's DI indicator during attack and repair processes under random and malicious disturbances.

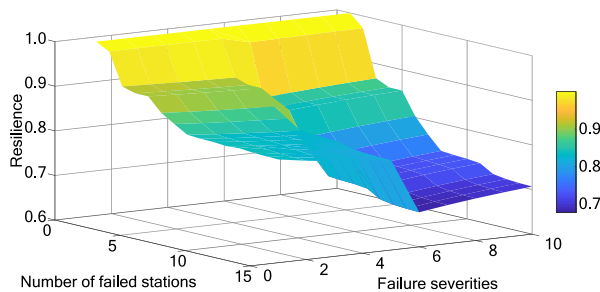


Fig. 11. Relation among resilience, number of failed stations, and failure severities.

Table 6

The values of failure severities should not be exceeded to guarantee that $R > 0.9$ when the number of failed stations is different.

Number of failed stations	Values of failure severities should not exceed	Number of failed stations	Values of failure severities should not exceed
1	10	9	0
2	10	10	0
3	5	11	0
4	1	12	0
5	1	13	0
6	0	14	0
7	0	15	0
8	0	-	-

4.3.3. Sensitivity on parameters on Chengdu subway network's resilience

In this subsection, we shall discuss the influences of the parameters on the resilience of the Chengdu subway network using the control variate method. By considering station failure in the Chengdu subway caused by malicious disturbances as an example, its resilience under a different number of failed stations with different failure severities is depicted in Fig. 11.

As illustrated in Fig. 11 ($t_r = 120$ s, $\tau = 300$ s, and $\vartheta = 1$), the network's resilience is inversely proportional to the number of failed stations when the values of failure severities are fixed. More failed stations imply a smaller value of resilience. When the number of failed stations is fixed, greater failure severities lead to lower resilience. The Chengdu subway network has higher resilience when the failure severity is less than 5 (i.e., the disturbance duration is 5 min).

To maintain the high resilience of the Chengdu subway network, i.e., to guarantee that $R > 0.9$, the values of failure severities that should not exceed are listed in Table 6, when the number of failed stations is different. To guarantee $R > 0.9$, the number of failed stations that should not be exceeded is listed in Table 7, when the values of failure severities are different. Tables 6 and 7 provide a monitoring failure severity and a monitoring number of failure stations, respectively, to ensure the high resilience of the Chengdu subway network when station failure occurs, which helps operators monitor the operations of the network to maintain its high resilience.

The effects of parameters t_r , τ , and ϑ on the Chengdu subway network's resilience are displayed in Fig. 12. Fig. 12(a) ($\tau = 300$ s, and $\vartheta = 1$) depicts that the network's resilience is inversely proportional to t_r . The fitting equation between R and t_r is $R = -0.009t_r + 0.858$. This indicates that the network's resilience can be improved effectively by shortening the emergency response time, and a 1 s reduction in emergency response time can increase the network's resilience by

Table 7

The numbers of failed stations should not be exceeded to guarantee that $R > 0.9$ when the values of failure severities are different.

Values of failure severities	Number of failed stations should not exceed	Values of failure severities	Number of failed stations should not exceed
1	5	6	2
2	5	7	2
3	3	8	2
4	3	9	2
5	2	10	2

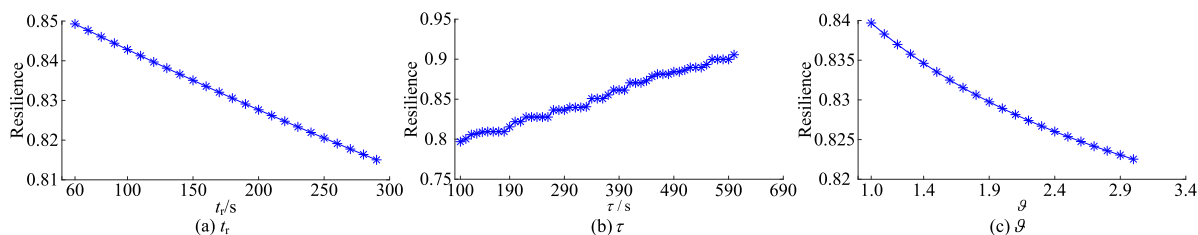


Fig. 12. Effects of parameters t_r , τ , and ϑ on network resilience.

0.009. To reduce the emergency response time, an information-sharing platform that integrates governments, operators, passengers, and public safety agencies should be established in the Chengdu subway system. This platform conveys information efficiently and thus promotes operators to make correct decisions in a shorter time.

Fig. 12(b) ($t_r = 120$ s, and $\vartheta = 1$) indicates that the network’s resilience increases with an increase in passengers’ tolerance time. When $\tau = 100$ s, the network’s resilience is 0.797, whereas its resilience is 0.906 when $\tau = 600$ s. Therefore, the operators can take the following measures to enhance the network’s resilience. At first, they need to provide high-quality transportation services (e.g., clean train carriages and friendly passenger inquiry services) to passengers. Secondly, the travel guidance information should be announced promptly through broadcasting and smartphone applications, which help passengers to choose reasonable paths when they need to detour. Finally, operators can temporarily change the train routes to evacuate trapped passengers.

Fig. 12(c) ($t_r = 120$ s, $\tau = 300$ s) illustrates that a greater ϑ implies a smaller value of resilience, and the relation between R and ϑ is $R = -0.008\vartheta + 0.847$. This implies that improving a system’s emergency rescue ability can effectively enhance the resilience of the network. For instance, building professional repair teams in the Chengdu subway system to efficiently carry out repair work. The skills of repair teams can be improved by organizing regular emergency rescue drills. Furthermore, operators can seek help from public safety agencies (e.g., the fire and rescue department) when the disturbances are serious.

5. Conclusion

In this study, the resilience of a URT network is assessed. Considering the efficiency of a URT network in transporting passengers, an indicator called the DI indicator is proposed to evaluate the performance of a URT network. By considering a URT network’s ETPs and passengers’ path choice behavior, a node centrality called EPB is proposed to measure the importance of stations. The performance curve of a URT network during the attack and repair processes has been depicted using the DI indicator, and a modified resilience metric has been formulated based on the performance curve and resilience triangle. Finally, the proposed model and metrics are implemented in the Chengdu subway network. The correlation coefficient between the stations’ EPB and BC is 0.901 on the Chengdu subway network. EPB provides a more effective assessment of stations’ importance when compared to BC, by considering the importance of stations for transporting passengers and the effect of the stations’ failure on a URT network’s performance. The DI indicator is considered more suitable for evaluating the network’s performance than network efficiency because it can effectively reflect the effect of passenger trips among stations on the network’s performance. The proposed performance curve is more consistent with the real operation of the Chengdu subway system during disturbances, and it comprehensively assesses the resilience of the network. The Chengdu subway network possesses greater resilience under random disturbances than under malicious disturbances. Based on the sensitivity analysis of the network’s resilience assessment, several practical suggestions involving the management of disturbances, shortening emergency response time, providing passenger services, and improving emergency rescue ability are provided for the management of the Chengdu subway system under disturbances.

Although the model and metric are only verified with the Chengdu subway network, they can be applied to other URT networks worldwide. In future works, we will further modify the resilience metric and propose a weighted resilience metric by considering the importance of different phases (disturbance, response, and recovery phases).

CRediT authorship contribution statement

Jinqu Chen: Methodology, Investigation, Software, Writing – original draft. **Jie Liu:** Software, Data curation, Visualization. **Qiyuan Peng:** Conceptualization, Project administration, Writing – review & editing. **Yong Yin:** Funding acquisition, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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