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Time-varied Accessibility and Vulnerability Analysis of High-speed Railway System in China

Lei Wang[1], Min Ouyang[1,2,—], Min Xu[3,4]

1. School of Artificial Intelligence and Automation, Huazhong University of Science and Technology, Wuhan, Hubei, 611731, P.R. China
2. Key Laboratory of Image Information Processing and Intelligent Control, Huazhong University of Science and Technology, Ministry of Education, Wuhan, Hubei, 611731, P.R. China
3. College of Public Administration, Huazhong University of Science and Technology, Wuhan, Hubei, 611731, P.R. China
4. Innovation Institute, Huazhong University of Science and Technology, Wuhan, Hubei, 611731, P.R. China

— Corresponding Author: min.ouyang@hust.edu.cn
Tel: 18071749645

ABSTRACT

At present in China, the emergence of high-speed railway technology makes the high-speed rail system widely developed, with a total length extended up to 50, 000km by the end of 2020. As the high-speed rail system can provide fast, safe, comfortable and very punctual services, this system has been extensively chosen by citizens for inter-city travelling. The accessibility via the high-speed rail system time-varied depends on the departure time at the origin railway station. The accessibility metric applied in this paper is the travel time based accessibility (TTA) which provides the minimal travel time from departure railway station to another destination railway station at a given departure time. Based on this accessibility metric, the vulnerability of the high-speed rail system under single high-speed train station failures and an extreme weather event has been also analyzed. The findings provide insightful suggestions to plan the high-speed rail system.

KEYWORDS: high-speed rail system, accessibility, time-varied, departure time, vulnerability

1 INTRODUCTION

High-speed railway system, which can provide fast, safe, comfortable and very punctual services for citizens, plays an important role in inter-city travelling. By the end of 2020, the total length of high-speed railway system will extend up to 50, 000km. However, high-speed railway system is often affected by various disruptions which cause great loss to welfare of the modern societies, not only damaging the railway physical infrastructures, but also compromising the system service level for the passengers. These problems have attracted growing attentions from governments and researchers in recent years, and great efforts have been made from different perspective, such as accessibility, vulnerability and resilience.

This paper investigates the time varied accessibility via the high-speed railway system in China, where the accessibility metric is quantified based on the travel time as is known to be a predictive metric in various research domains [1]. The time-varied characteristics originate from the operation frequencies of the high-speed railway system and also from various departure time expected by passengers. In addition, as the high-speed railway system is widely distributed in a country and is then subject to many hazards (floods, rainstorms, typhoons, earthquakes, etc.), this paper will also investigate the vulnerability of the high-speed railway system based on the proposed accessibility metrics.

In the literature, high-speed railway system has been extensively investigated. Some researchers quantified the accessibility of a station (or a city) by its average travel time to all other stations (cities), and then analyzed the change of accessibility brought by the high-speed railway system, such as the impact of the Qinghai-Tibet Railway on the accessibility of major cities in mid-eastern China (Li et al., 2018). Some researchers quantified the accessibility of a city by population or GDP based weighted average travel time to all other cities, and then analyzed the impact of high-speed rail systems on the national economy [3-5]. Some researchers used the number of job opportunities which passengers can obtain to measure the accessibility [7] and analyze the accessibility change due to the future Madrid-Barcelona-French high-speed line. Some researchers considered the economic attraction and the distance between two stations to quantify the accessibility of a station [6]. Besides the above accessibility analysis, some researchers have analyzed the vulnerability of high-speed rail systems or national railway systems under disruptions. Sen et al. analyzed the vulnerability of the Indian railway system under random failures and targeted attacks [8]. Similar works have been done by Zhang et al. [9] for the high-speed rail system in China. Ouyang et al. studied the vulnerability of the Chinese railway system under worst-case attacks [10]. Hong et al. analyzed the vulnerability of the Chinese railway system under floods [11]. Chang and Nojima analyzed the vulnerability of the U.S high-speed rail system under earthquake scenarios [12]; Sa'adin et al. analyzed the vulnerability of the Singapore-Malaysia high-speed rail system under heavy rainfall [13].

This paper will conduct a comprehensive time-varied accessibility and vulnerability analysis of the high-speed railway system in China. The rest of this paper is organized as follows: Section 2 introduces the network-based description of high-speed railway system and the algorithm for calculating the minimum travel time from one railway station to another railway station. Section 3 introduces the methods for accessibility and vulnerability analysis. Section 4 analyzes the results. Section 5 discusses the findings and provides conclusions and directions for future research.

2 FORMULATION AND ALGORITHM

This paper models the high-speed railway system as a two-layer network, including physical layer and service layer, where the physical layer models the railway infrastructure (including stations and tracks) and the service layer captures the time-related attributes of trains, such as the departure time and arrival time. Hence, a high-speed railway system can be modelled by a network $G = \{(N^H, E^H), (N^H, L^H), M\}$, where N^H is the set of high-speed train stations and E^H is the set of high-speed rail segments between stations; L^H describes scheduling timetable information for all high-speed trains, including the rail route, the arrival and departure time at each stop station of each train; M describes the relationship between nodes, tracks and high-speed trains and records the travel path of each train.

This paper focuses on the transport accessibility from an origin railway station in a city to a destination railway station in another city via the high-speed railway system, and other transport modes are not considered. However, if one city has several railway stations and these stations are accessible via the local metro rail system, passengers can take this kind of transport mode and the travel times between them are obtained from the Baidu Map. The reason that this paper considers the local metro rail system due to it can also provide the punctual services. Here, the transport accessibility is measured by the travel time. Due to the punctual characteristic of the high-speed rail systems, this paper investigates the accessibility at the minute scale. In addition, as the high-speed trains are not frequent as much as the metro trains and they are operated according to a scheduling timetable, the departure time from the origin railway station largely affect the travel time of the trip, which means the minimum travel time based accessibility $\tau_{mn}^{ab}(t)$ from a railway station *m* in a city *a* to another railway station *n* in a city *b* has the time-varied characteristic, depending on the departure time *t* at railway station *m*.

To compute the minimum travel time $t_{mn}^{ab}(t)$, this paper applies the Dijkstra's algorithm, and the algorithm is implemented as follows:

(1) Set $t_{mm}^{ab}(t) = 0$, and $t_{mn}^{ab}(t) = \infty$ for all $m \neq n$. At departure time *t* from *m*, according to the high-speed train scheduling timetable, identify all those trains with the departure time from station *m* later than time *t* to compute the earliest arrival time at any station *n*, which then produces the minimum travel time $\Omega_m(n)$ (the earlist arrival time at station *n* minus *t*) from *m* to *n* via only one train; if there is no train from station *m* to station *n*, set the least travel time $\Omega_m(n)$ as ∞; note that $\Omega_m(m)$ is not included in $\{\Omega_m(n)\}$.

(2) Update the minimum travel time vector $\{\Omega_m(n)\}$ if the city with high-speed train station *m* has other high-speed train stations. For each of those high-speed stations *n* together with *m* in the same city, if *m* and *n* are accessible via the local metro rail system, update $\Omega_m(n)$ with minimal time between the travel time by the local metro rail system and the travel time $\Omega_m(n)$.

(3) Based on $\{\Omega_m(n)\}$, identify the high-speed train station n^* with the least minimum travel time from high-speed train station *m*, set $t_{mn^*}^{ab}(t) = \Omega_m(n^*)$, and remove $\Omega_m(n^*)$ from $\{\Omega_m(n)\}$.

(4) For each of those high-speed train stations *n* together with n^*in the same city, if *n* and *n** are accessible via the local metro rail system, update $\Omega_m(n)$ with the minimal time between the travel time by the local metro rail system and the travel time $\Omega_m(n)$.

(5) According to the high-speed train scheduling timetable, identify all those trains with the departure time at station n^* later than time $t_{mn^*}^{ab}(t) + t_{n*}^{H\mapsto H}$, where $t_{n*}^{H\mapsto H}$ is the transfer time between different high-speed trains at station *n**, and then use those trains' timetable to compute the minimum travel time η_{n^*n} (the earliest arrival time at station *n* minus $t_{mn^*}^{ab}(t) + t_{n*}^{H\mapsto H}$) from n^* to any other high-speed train station *n* with $t_{mn}^{ab}(t) = \infty$ via only one train; if there is no train from station *y** to station *y*, set the minimum travel time η_{n^*n} as ∞; Update $\Omega_m(n) \leftarrow \min(\Omega_m(n), t_{mn^*}^{ab}(t) + t_{n*}^{H\mapsto H} + \tau_{n^*n}(t))$.

(6) Repeat steps (3)-(5) until $\{\Omega_m(n)\}$ is empty or all elements in $\{\Omega_m(n)\}$ are ∞.

By implementing these six steps, the minimum travel time $t_{mn}^{ab}(t)$ from one destination station to all of other railway station at the departure time *t* can be obtained. Moreover, this algorithm can be also applied to compute the minimum travel time $t_{mn}^{ab}(t)$ when several railway trains have been canceled due to the natural hazards, such as typhoon and heavy snow.

3 ACCESSIBILITY METRICS AND VULNERABILITY ANALYSIS METHOD

The minimum travel time $\tau_{mn}^{ab}(t)$ provides minute-scale accurate travel time information for inter-city trips, and this information is particularly useful for those trips with origins and destinations both served by railway stations. Based on $\tau_{mn}^{ab}(t)$ for any combination of *m* and *n* in cities *a* and *b*, this section first introduces accessibility metric, and then illustrate the accessibility-based vulnerability analysis method.

This paper introduces the travel time based accessibility (TTA), and the TTA of railway station m in city *a* at the departure time *t* is computed as follows:

$$TTA_m^a(t) = \sum_{b \neq a} \sum_n \frac{w_{mn}^{ab}}{\sum_{b \neq a} \sum_j w_{mn}^{ab}} \tau_{mn}^{ab}(t) \qquad (1)$$

where w_{mn}^{ab} is the weighted coefficient for the trip from *m* to *n* and can be interpreted as the possibility that a randomly selected trip via the integrated rail system starts from metro station *m* and ends at metro station *n*. This paper sets w_{mn}^{ab} identical for any pair of *m* and *n*, i.e., $w_{mn}^{ab} = 1/\sum_a \sum_{b \neq a} n_a^M n_b^M$, then $TTA_m^a(t)$ is simply the average travel time from metro station *m* in city *a* to any other railway stations in other cities. Furthermore, the travel time accessibility $TTA^{ab}(t)$ from city *a* to city *b* via the high-speed railway system is measured by Equation (2), and the travel time accessibility $TTA^a(t)$ of city *a* via the high-speed railway system is measured by Equation (3).

$$TTA^{ab}(t) = \sum_m \sum_n \frac{w_{mn}^{ab}}{\sum_n \sum_m w_{mn}^{ab}} \tau_{mn}^{ab}(t) \qquad (2)$$

$$TTA^a(t) = \sum_m \sum_{b \neq a} \sum_n \frac{w_{mn}^{ab}}{\sum_m \sum_{b \neq a} \sum_n w_{mn}^{ab}} \tau_{mn}^{ab}(t) \qquad (3)$$

This paper quantifies the vulnerability under a disruption event as the system-level performance change, where the system performance is measured based on the time based accessibility (TTA). The *TTA* based performance of the high-speed railway system is quantified as the average TTA^a of each city. But note that the larger the average TTA^a is, the worse the system performance is, and then in this case, the *TTA*-based system vulnerability under a disruptive event ξ is quantified as follows:

$$V_{\xi}^{TTA} = \frac{\sum_a TTA_{\xi}^a}{Q} - \frac{\sum_a TTA^a}{Q} \tag{4}$$

where TTA_{ξ}^a is the travel time based accessibility of city a under the disruption event ξ.

This paper considers two types of disruptions for vulnerability analysis. The first type of disruptions is single high-speed train station failure, which causes all high-speed trains passing through the failed train station cancelled. Considering this type of disruptions can identify the most critical high-speed train station. The second type of disruptions is a real extreme weather events, which is the typhoon event occurred on September 16, 2018, resulting many high-speed trains passing through Guangdong province cancelled. The information for those cancelled trains in these events are obtained from the official website of China Railway Corporation (www.12306.cn).

4 CASE STUDY

This section first analyzes the accessibility via the high-speed railway system in China and then investigates its vulnerability under different disruptions. For the high-speed rail system, according to its definition by the National Railway Administration of the People's Republic of China (2018), it mainly includes rail lines served by G, C, and D trains, with the operation speeds around 200~350 km/h. By the end of 2020, the total length of the high-speed rail system in China will be over 50,000km. This system serves around 290 cities in mainland China, and the cities with population more than 500,000 are almost all served. The physical layout of the high-speed rail system in mainland China is shown in Fig. 1. The high-speed railway system in China contains 898 railway station and 7464 trains.

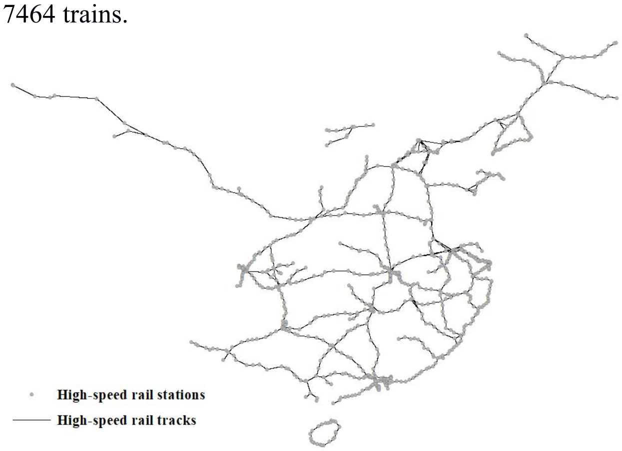
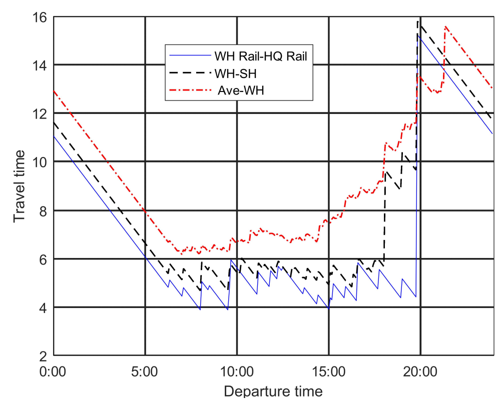


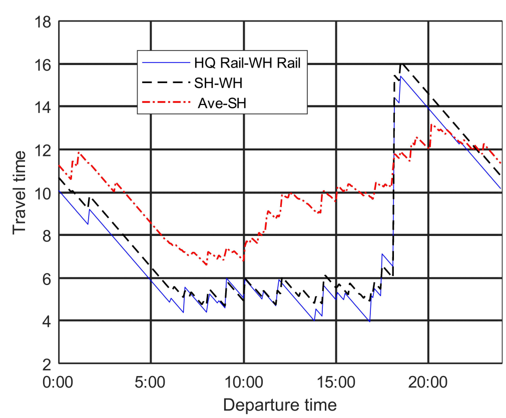
Fig. 1 The physical layout of the high-speed rail system in mainland China

4.1 Accessibility Analysis under Normal Operation

To demonstrate how the departure time affects the accessibility via the integrated rail system (IRS), Fig. 2 shows the results by taking two typical railway stations in two different cities as an example (Wuhan Railway Station in the city of Wuhan and Hongqiao Railway Station in the city of Shanghai). For comparison purposes, the minimal travel time from Wuhan to Shanghai and the average travel time from Wuhan to all other high-speed railway station are also shown in the figure. The minimum travel time linearly decreases with the departure time gradually approaching to the earliest available high-speed trains; if the last high-speed train for that day is not caught up, the minimum travel time has a sudden increase as the passengers need to wait for the earliest high-speed train in the next day.



(a)



(b)

Fig. 2: Travel time based accessibility curves as a function of the departure time: (*a*) accessibility from Wuhan Railway station to Shanghai Hongqiao Railway Station via high-speed rail system (HRS), accessibility of city Wuhan to city Shanghai via the HRS, accessibility curve of city Wuhan via the Wuhan; (b) accessibility from Shanghai Hongqiao Railway station to Wuhan Railway Station via high-speed rail system (HRS), accessibility of city Shanghai to city Wuhan via the HRS, accessibility curve of city Shanghai via the high-speed railway system.

Fig. 3 shows the distribution of the travel time based accessibility for each city. From the figure, 40% cities have the travel-time based accessibility less than 8 hours if departing at 6:00, and this fraction becomes 43.3%% if departing at 9:00, 20% if departing at 12:00. Table 1 shows the travel time-based accessibility rankings of cities for high-speed rail system when the departure time is varied. From the table, the accessibility rankings of cities are different when the departure time is varied f. For example, the city with the largest accessibility is Nanjing if departing at 9:00am, Zhengzhou if departing at 12:00am, and Wuhan if departing at 15:00pm.

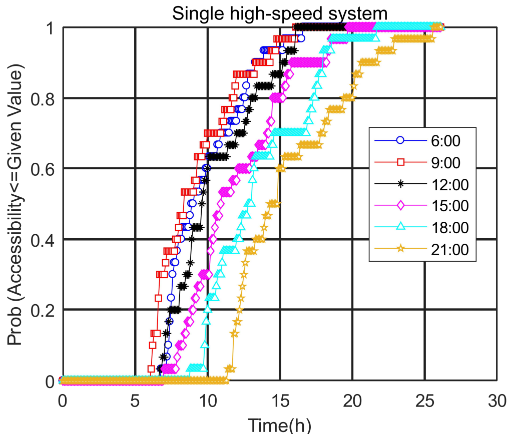


Fig.3 The distribution of the travel time based accessibility of each city at different departure time

Table 1 City rankings in terms of the travel time based accessibility for high-speed rail system if the departure time is varied

Rank	High-speed rail system		
	9:00	12:00	15:00
1	Nanjing	Zhengzhou	Wuhan
2	Changsha	Wuhan	Changsha
3	Wuhan	Nanjing	Zhengzhou
4	Shanghai	Changsha	Hangzhou
5	Hefei	Hefei	Nanjing
6	Hangzhou	Shanghai	Shanghai
7	Beijing	Shijiazhuang	Nanchang
8	Zhengzhou	Beijing	Beijing
9	Shijiazhuang	Hangzhou	Hefei
10	Wuxi	Nanchang	Tianjin

4.2 Vulnerability analysis under disruptions

Vulnerability analysis is associated with the disruptions. This paper considers two types of disruptions: single high-speed train station failures and two real extreme weather events. Figure 4 shows how the TTA-based vulnerability of the system is changed under different disruptions when the departure time is varied. The "worst-case" means the damage of the most critical station which causes the largest vulnerability at that departure time. Note that when the departure time is varied, the most critical high-speed train station is also changed. For example, if the departure time is earlier than 14:00, the most critical station is Nanchangxi train station; if the departure time is at 15:00, the most critical station is Xi'anbei train station. For the single high-speed train station failures, the failure of Nanchangxi station causes the largest vulnerability (0.98 hours) if the departure time is 2:00.

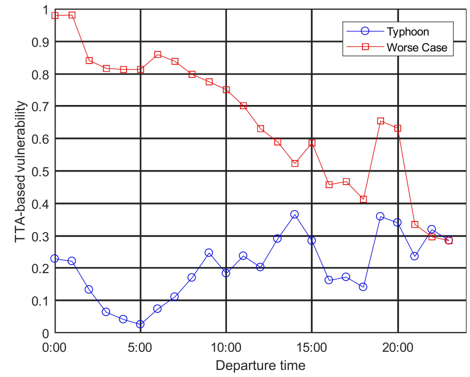


Fig. 4 TTA-based vulnerability of high-speed rail system under the worst-case high-speed train station failure, the typhoon event.

5 CONCLUSIONS

This paper develops an approach to assess travel time based accessibility via high-speed rail transport system. Based on the accessibility metric, this paper also introduces the vulnerability analysis method for high-speed rail system. The proposed approach has been applied to analyze the accessibility and vulnerability of the high-speed rail system in China.

This paper analyzes the accessibility based on the identical weighted coefficient for each railway station to railway station trip. Despite this assumption can capture the heterogeneous flow among different cities, considering more realistic weighted coefficients for accessibility analysis is a direction of the future research. For the vulnerability analysis, this paper assumes the disruption lasts for a whole day and recovers in the next day, but in practice, many frequent daily events only last for several hours with uncertainties, modeling those frequent daily events for vulnerability analysis is also an interesting direction for future research. In addition, this paper does not consider post-disruption recovery, then analyzing the integrated system from the resilience perspective is another direction for future research.

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