# Spatiotemporal vulnerability analysis of railway system

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ABSTRACT: This paper aims to develop a comprehensive framework to analyze the spatiotemporal vulnerability of railway systems assessed by passengers delay under disruptions and the framework integrates the time-related attributes of disruptions, railway system, and heterogeneous train flows. In the framework, the modeling of the railway system involves a two-layer network structure consisting of physical layer and service layer. The proposed framework introduces the concept of component damage scenario to represent the post-disruption state of railway component. Combination of the component damage scenarios can represent the system damage status under any kinds of disruptions. This study applies the proposed framework to the Chinese high-speed railway system and analyzes its spatiotemporal vulnerability under two types of disruptions: individual station failure and spatially localized failures. The finding of this study facilitate the design of system maintenance strategies to mitigate system vulnerability under various disruptions.

Railway is one of the most important transportation modes all over the world. However, railway systems are 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 [1]. Hence, the problems on how to better protect railway systems have attracted growing attentions from governments and researchers in recent years.

These problems relate to a variety of measures, such as risk, vulnerability, reliability, robustness, flexibility, survivability, and resilience, addressed for the three stages mentioned above. Among these measures, vulnerability, robustness and resilience are frequently used to analyze, evaluate, and mitigate the disruption impacts in the context of railway systems [2]. Although the definitions of these measures vary in the literature, many researchers agree that, vulnerability and robustness mainly concern the first two stages in the disaster management process, while resilience deals with the whole three stages and emphasizes the last one - recovery.

System recovery problems emphasize the time-related attributes from the system and disruption perspectives [3]. For example, resilience-focused studies facilitate the system “to recover quickly after a shock" or "to recover within an acceptable time" that acquires time-related attributes involved in the modeling [4]. Time-related attributes are also important to the first two stages, as well as to system vulnerability or robustness analysis. For the railway system, the time-related attributes, such as disruption occurrence time and duration, the trains' timetable are all important factors for system disaster management, which are seldom discussed in previous studies [5]. Hence, as an initial step to integrate time-related attributes into consideration, this paper aims at developing a framework to analyze the spatiotemporal vulnerability of railway system, in which the system vulnerability is assessed by total passengers delay under disruptions. Not only the time-related attributes of disruptions (occurrence time and duration), but also of railway system and passengers, are integrated into the framework.

## 1. LITERATURE REVIEW

System vulnerability assessment depends on two essential factors: the system performance metric and the disruption mode. Different performance metrics and disruption modes may lead to diverse results of vulnerability analysis.

We divide the performance metrics of railway system into two categories: the metrics based on the characteristics of railway system and the metrics based on the service of railway system that provided to the passengers. Many scholars modeled the railway system as a network of nodes connected by links to better represent the topological and geographical information of railway physical infrastructures [6]. Then, the network topological metrics are naturally used to measure the performance of railway system, such as average degree and betweenness, shortest path length, network efficiency, size of the giant components and connectivity. But, the research results based on topological metrics may be difficult to be implemented in reality and provide useful recommendations to the stakeholders or governments [7]. Other scholars used flow-based metrics to assess railway system performance. Sun et al. [8] considered passenger flow redistribution in the vulnerability analysis of a rail transit network. Jiang et al. [9] proposed a station-based accessibility to measure the performance of a rail transit network, in which the accessibility metric addressed the passenger flow and land use characteristics simultaneously.

Instead of using the characteristics of railway systems, other studies analyze the service quality of railway systems to assess systems' performance from the perspective of passengers, for instance, the number of canceled trains or delay of passengers. Pieter et al. used the number of canceled trains as the performance metric to analyze the railway systems' vulnerability caused by planned maintenance interventions [10]. Fikar et al. used the average disruption delay time (ADDT) and the total disruption delay time (TDDT) [11].

In system vulnerability assessment, the other essential prerequisite is disruption modes. Different kinds of disruptive events can lead to diverse vulnerability analysis results. Railway systems can be affected by many kinds of disruptions caused by technical failures and man-made faults, terroristic attacks, extreme weather events, natural disasters, failure of climate-change mitigation, and cyberattacks. Zhang et al. analyzed the vulnerability of high speed railway systems in three counties and the Shanghai subway system under random failures and degree- and betweenness-based intentional attacks [12]. Chang and Nojima [13] introduced a method to analyze the post-disaster performance of the railway system under earthquake scenarios. Hong et al. analyzed the vulnerability of the Chinese railway system under floods [14] and earthquakes [15]. From the above discussion, we find that many spatial features of disruptions are included in the vulnerability analysis of railway system, such as the locations of railway components and disruptions, the distribution intensity distribution; however, little attention has been paid to the time-related attributes of disruptions, such as occurrence time and duration. The time-related attributes of disruptions, railway system and passengers should be integrate into the passenger delay calculation and further the vulnerability analysis of railway system.

To address these issues, this study seeks to assess the railway system vulnerability by taking into account time-related attributes of disruptions, railway system and passengers. The overall objective is to develop a more comprehensive framework to analyze the vulnerability of railway system, not only in the dimension of space but also in the dimension of time.

## 2. METHODOLOGY

### 2.1. *The two-layer network model*

$G = \{(V,E),(V,L),T,M\}$ is used to represent a railway system. A directed network $(V,E)$ represents the physical layer of railway system, where the node set $V = \{v^i\}_{i=1}^{k^v}$ denotes the railway stations, the edge set $E = \{e^i\}_{i=1}^{k^e}$ denotes the railway tracks, and $k^v$ and $k^e$ represent the number of stations and tracks in $G$, respectively. Each edge in $E$ connects two stations in $V$. Two railway tracks with different directions connecting the same station pair are represented as two different edges in $E$. A directed network $(V,L)$ represents the service layer of railway system, the link set $L = \{l^i\}_{i=1}^{k^l}$, $k^l$ represents the number of links in $G$. If two stations in $V$ are served by a train without stops in between, there will be a link in $L$ to connect these two stations in the service layer, and the link has the same direction of the train. $T = \{t^i\}_{i=1}^{k^t}$ denotes the train set, and $k^t$ represents the number of trains in $G$. The route of a train can be specified by a sequence of adjacent links in $L$ from the origin station to the destination station in the service layer, or a sequence of adjacent edges in the physical layer. Hence, a train is represented as $t^i = \{V_i, E_i, L_i, S_i, P_i\}$, $V_i$, $E_i$, and $L_i$ denote the station set, the edge set and the link set in the route of train $t^i$. $E_i = \{e_i^j\}_{j=1}^{k_i^e}$, $E_i \subset E$, $e_i^j$ denotes the $j$th edge in the route of train $t^i$, $k_i^e$ denotes the total number of edges in the route of train $t^i$. $L_i = \{l_i^j\}_{j=1}^{k_i^l}$, $L_i \subset L$, $l_i^j$ denotes the $j$th link in the route of train $t^i$, $k_i^l$ denotes the total number of links in the route of train $t^i$, $k_i^e \geq k_i^l$, the equality holds when train $t^i$ stops at all the stations in its route in the physical layer. $S_i = \{(s_i^{j1}, s_i^{j2})\}_{j=1}^{k_i^e}$ denotes the arrival and departure time set of train $t^i$ on its edges in $E_i$ , where $s_i^{j1}$ and $s_i^{j2}$ denote the departure time and the arrival time on edge $e_i^j$ of train $t^i$ respectively, $s_i^{j1} < s_i^{j2} \leq s_i^{(j+1)1}$ , the equality holds when train $t^i$ doesn't stop at the station between edge $e_i^j$ and $e_i^{j+1}$. $P_i$ is used to record the passengers flow in each station in the route of train $t^i$, $P_i = \{(p_i^{j1}, p_i^{j2})\}_{j=1}^{k_i^l}$, where $p_i^{j1}$ and $p_i^{j2}$ denote the number of boarding passengers on at the origin station and the number of alighting passengers at the destination station on link $l_i^j$ of train $t^i$, respectively. In the train model $t^i = \{V_i, E_i, L_i, S_i, P_i\}$, $V_i$ and $E_i$ is used to determine whether train $t^i$ is affected by a disruption, $S_i$ is used to identify the location of train $t^i$ when a disruption occurs, $L_i$ and $P_i$ is used to calculate the number of delayed passengers of train $t^i$ after a disruption. $M$ is used to record the relationships among railway stations, edges, links, $M = \{((v^x, e^{\mathrm{y}}), (v^x, l^{\mathrm{z}}), (e^{\mathrm{y}}, l^{\mathrm{z}}))\}$, where $v^x \in V$, $e^{\mathrm{y}} \in E$, $l^{\mathrm{z}} \in L$, $x \in \{1,2,3, \ldots, k^v\}$, $\mathrm{y} \in \{1,2,3, \ldots, k^e\}$, $\mathrm{z} \in \{1,2,3, \ldots, k^l\}$. If $v^x$ is the origin station of railway track $e^{\mathrm{y}}$, $(v^x, e^{\mathrm{y}}) = 1$; if $v^x$ is the destination station of $e^{\mathrm{y}}$, $(v^x, e^{\mathrm{y}}) = 2$; otherwise, $(v^x, e^{\mathrm{y}}) = 0$. If $v^x$ is the origin station of link $l^{\mathrm{z}}$, $(v^x, l^{\mathrm{z}}) = 1$; if $v^x$ is the destination station of $l^{\mathrm{z}}$, $(v^x, l^{\mathrm{z}}) = 2$; otherwise, $(v^x, l^{\mathrm{z}}) = 0$. If a railway track $e^{\mathrm{y}}$ is a part of $l^{\mathrm{z}}$ (with the same direction), $(e^y, l^{\mathrm{z}}) = 1$ ; otherwise, $(e^y, l^{\mathrm{z}}) = 0$.

### 2.2. *Component damage scenarios*

Studies on vulnerability analysis of railway system have seldom involved the time-related attributes of disruptions, such as the disruption occurrence time and duration. To incorporate the time-related attributes of disruptions into vulnerability analysis of railway system, this section introduces a concept of component damage scenario, which is used to record the damage to railway components caused by disruptions, including component damage level, component damage occurrence time and component damage duration. The damage statuses of railway infrastructure caused by different disruptions can all be represented by the combinations of component damage scenarios.

The component damage scenarios set under a disruption is denoted as $C_\eta = \{c_\eta^j = (q_\eta^j, x_\eta^j, y_\eta^j)\}$, where $\eta$ denote the disruption; $c_\eta^j$ denotes a component damage scenario of component $j$ due to disruption $\eta$, $j \in [1, k^v + k^e]$ is the index of railway components, when $j \in [1, k^v]$ , the damaged component is a railway station in $V$, and when $j \in [k^v + 1, k^v + k^e]$ , the damaged component is a railway track in $E$; $q_\eta^j$ denotes the damage level of component $j$ under disruption $\eta$, and the value of $q_\eta^j$ can have binary value {0, 1}, or be a function of disruption $\eta$, $q_\eta^j = f(\eta)$; $x_\eta^j$ denotes the component damage occurrence time; $y_\eta^j$ denotes the damage duration.

### 2.3. *Spatiotemporal vulnerability analysis*

#### 2.3.1. *Delay of affected trains under disruption*

The delay of an affected train under a disruption is calculated based on the delay of this train under each corresponding component damage scenario caused by the disruption. Let $D_\eta^T = \{d_\eta^i\}$ represent the delay time set of all affected trains under disruption $\eta$, $d_\eta^i$ denote the delay of an affected train $t^i$. The three steps listed below investigate whether train $t^i$ is affected by disruption $\eta$ and how long it will be delayed.

**Step 1**: Identify affected trains;

Step 1.1: Choose a train $t^i$ in $T$.

Step 1.2: Choose a component damage scenario $c_\eta^j$ in $C_\eta$. If component $j$ belongs to $\{E_i \cup V_i\}$, then this damaged component is in the route of train $t^i$ and train $t^i$ may be affected by scenario $c_\eta^j$.

Step 1.3: Repeat Step 1.2 for all the component damage scenarios in $C_\eta$ . Let $C_\eta^i$ denote the component damage scenario set which may affect train $t^i$.

Step 1.4: Repeat Step 1.1 to Step 1.3 for all trains in $T$. Let $T_\eta$ denote the train set which may be affected by disruption $\eta$, $T_\eta \subseteq T$.

**Step 2**: Determine the delay of all affected trains in $T_\eta$ under disruption $\eta$.

Step 2.1: Choose an train $t^i$ in $T_\eta$.

Step 2.2: Choose a scenario $c_\eta^j$ in $C_\eta^i$.

Here, we use $e_i^\delta$, $\delta \in [1, k_i^e]$ to locate the damaged component, and $e_i^\gamma$ , $\gamma \in [1, k_i^e]$ to locate the position of the affected train when the disruption occurs. $e_i^\delta$ is determined by scenario $c_\eta^j$ , while $e_i^\gamma$ is determined based on the component damage occurrence time $x_\eta^j$ and the departure and arrival time of train $t^i$ in each edge (track) stored in $S_i$: if $x_\eta^j \in (s_i^{\gamma 1}, s_i^{\gamma 2})$ means train $t^i$ is in an edge $e_i^\gamma$ when component damage occurs; if $x_\eta^j \in [s_i^{\gamma 2}, s_i^{(\gamma+1)1}]$, then train $t^i$ is in a station which is the destination station of edge $e_i^\gamma$ when component damage occurs.

According to the locations of an affected train $t^i$ and the damaged component, there are six different situations, and the delay under each of these situations are calculated respectively:

(1)The damaged component is a station (a node in $V_i$) and train $t^i$ is exactly in that station when component damage occurs. This means $\gamma = \delta$, we have $s_i^{\delta 2} \leq x_\eta^j < s_i^{(\delta+1)1}$ , the delay of train $t^i$ under scenario $c_\eta^j$ is $d_{c_\eta^j}^i = y_\eta^j$.

(2) The damaged component is a station and it is in front of train $t^i$ when the damage occurs, and when train $t^i$ arrives at this damaged station it hasn't been recovered yet. The location of the damaged station is identified by the destination

station of edge $e_i^{\delta}$. Then, we have $\delta > \gamma$, $x_\eta^j < s_i^{\delta 2} < x_\eta^j + y_\eta^j$, $d_{c_\eta^j}^i = x_\eta^j + y_\eta^j - s_i^{\delta 2}$.

(3) There are two cases that train $t^i$ will not be affected: I. $\delta > \gamma$, $x_\eta^j + y_\eta^j \le s_i^{\delta 2}$, which means the damaged station will be recovered before train $t^i$ arrives; II. $\gamma > \delta$, $s_i^{(\delta+1)1} \le x_\eta^j$, which means that when the station damage occurs, train $t^i$ has already passed it. In these two cases, $d_{c_\eta^j}^i = 0$.

(4) The damaged component is a track (an edge in $E_i$) and train $t^i$ is exactly in that damaged track when the damage occurs. This means $\gamma = \delta$, and $s_i^{\delta 1} \le x_\eta^j < s_i^{\delta 2}$, $d_{c_\eta^j}^i = y_\eta^j$.

(5) The damaged component is a track and it is in front of train $t^i$ when the damage occurs, and when train $t^i$ arrives at this damaged track it hasn't been recovered yet. This means $\delta > \gamma$, $x_\eta^j < s_i^{\delta 1} < x_\eta^j + y_\eta^j$, $d_{c_\eta^j}^i = x_\eta^j + y_\eta^j - s_i^{\delta 1}$.

(6) There are two cases that train $t^i$ will not be affected: I. $\delta > \gamma$, $x_\eta^j + y_\eta^j \le s_i^{\delta 1}$, which means the damaged track will be recovered before train $t^i$ arrives; II. $\gamma > \delta$, $s_i^{\delta 2} \le x_\eta^j$, which means when the track damage occurs, train $t^i$ has already passed it. In these two cases, $d_{c_\eta^j}^i = 0$.

Step 2.3: Repeat Step 2.2, and determine the delay of train $t^i$ under each of those related component damage scenarios in $C_\eta^i$.

Step 2.4: Repeat Step 2.1 - Step 2.3 for all the trains in $T_\eta$, and determine the delay of all affected trains under all the related component damage scenarios.

**Step 3**: Determine the delay of all affected trains under disruption $\eta$.

The delay of a train $t^i$ under a disruption $\eta$ equals to the maxima of its delay under all related component damage scenarios in $C_\eta^i$, $d_\eta^i = \max\{d_{c_\eta^j}^i\}$, and the maxima delay corresponding component damaged scenario for train $t^i$ is denoted as $c_\eta^{i^*} = (q_\eta^{i^*}, x_\eta^{i^*}, y_\eta^{i^*})$, $c_\eta^{i^*} \in C_\eta^i$.

Then the delay of all affected trains $D_\eta^T$ can be abtained by checking the delay of all the affect trains under all related component damage scenarios.

### *2.3.2. Delayed passenger flows*

The number of delayed passengers of an affected train will be calculated in three different situations.

(1) The train $t^i$ is exactly in a railway component (a station or a track) which is damaged under scenario $c_\eta^{i^*}$, this means $\gamma = \delta$. According to the relationship of railway tracks (in $E$) and links (in $L$) stored in the matrix $M$, the corresponding link to edge $e_i^\delta$ is denoted as $l_i^{\delta'}$, where $\left(e_i^\delta, l_i^{\delta'}\right) = 1$ in $M$, $\delta' \in \{1,2,3,\dots,k_i^l\}$, $e_i^\delta \in E_i$, $l_i^{\delta'} \in L_i$. The total number of delayed passengers of train $t^i$ equals to the number of all passengers who will alight at the following stations in the remained route of train $t^i$ after disruption $\eta$, and can be calculated as $\sum_{\beta=\delta'}^{k_i^l} p_i^{\beta 2}$, where $p_i^{\beta 2}$ is the number of passengers who will alight at the destination station of link $l_i^\beta$, $\beta \in \{\delta', \delta'+1, \dots, k_i^l\}$, $p_i^{\beta 2} \in P_i$.

(2) The damaged railway station is in front of train $t^i$ when the component damage scenario $c_\eta^{i^*}$ occurs. This means $\delta > \gamma$, $x_\eta^j < s_i^{\delta 2} < x_\eta^j + y_\eta^j$. The number of delayed passengers of train $t^i$ is $\sum_{\beta=\delta'}^{k_i^l} p_i^{\beta 2}$, where $\left(e_i^\delta, l_i^{\delta'}\right) = 1$ in $M$.

(3) The damage railway track is in front of train $t^i$ when the component damage scenario $c_\eta^{i^*}$ occurs. This means $\delta > \gamma$, $x_\eta^j + y_\eta^j > s_i^{\delta 1} > x_\eta^j$, the number of delayed passengers is $\sum_{\beta=\delta'}^{k_i^l} p_i^{\beta 2}$. Hence, in all the above three situations, the number of delayed passenger of train $t^i$ can be represented as $\sum_{\beta=\delta'}^{k_i^l} p_i^{\beta 2}$.

### *2.3.3. Vulnerability analysis*

The passenger delay of an affected train $t^i$ under disruption $\eta$ can be calculated based on the delay of each affected train and the number of delayed passengers in these trains:

$$d_\eta^i * \sum_{\beta=\delta'}^{k_i^l} p_i^{\beta 2} =$$

$$\begin{cases} \boldsymbol{y_\eta^{i^*} * \sum_{\beta=\delta'}^{k_i^l} p_i^{\beta 2}}, \\ (when\ \delta = \gamma, s_i^{\delta 2} \leq x_\eta^{i^*} < s_i^{(\delta+1)1}, \\ destination\ station\ of\ edge\ e_i^\delta\ is\ damaged; \\ or\ \delta = \gamma, s_i^{\delta 1} \leq x_\eta^{i^*} < s_i^{\delta 2}, \\ the\ edge\ e_i^\delta\ is\ damaged.) \\ \boldsymbol{\left(x_\eta^{i^*} + y_\eta^{i^*} - s_i^{\delta 2}\right) * \sum_{\beta=\delta'}^{k_i^l} p_i^{\beta 2}}, \\ (when\ \delta > \gamma, x_\eta^{i^*} < s_i^{\delta 2} < x_\eta^{i^*} + y_\eta^{i^*}, \\ destination\ station\ of\ edge\ e_i^\delta\ is\ damaged.) \\ \boldsymbol{\left(x_\eta^{i^*} + y_\eta^{i^*} - s_i^{\delta 1}\right) * \sum_{\beta=\delta'}^{k_i^l} p_i^{\beta 2}}, \\ (when\ \delta > \gamma, x_\eta^{i^*} < s_i^{\delta 1} < x_\eta^{i^*} + y_\eta^{i^*}, \\ the\ edge\ e_i^\delta\ is\ damaged.) \\ \boldsymbol{0}, (otherwise) \end{cases}$$

Then, the spatiotemporal vulnerability of railway system under disruption $\eta$, which is assessed by the total delay of passengers in all affected trains, is calculated as:

$$Vul_\eta = \sum_{i \in [1, k^t]} \left(d_\eta^i * \sum_{\beta=\delta'}^{k_i^l} p_i^{\beta 2}\right)$$

This paper considers two kinds of disruptions: the individual railway station failure and the worst-case spatially localized failures. For the individual station failure, each time a railway station is chosen as the damaged component, then the total passengers' delay under disruption scenarios with different disruption occurrence time and durations will be calculated respectively. The railway system spatiotemporal vulnerability caused by this station failure is assessed by the average passengers' delay under all these disruption scenarios with different disruption occurrence time and durations. Further, this paper analyzes the spatiotemporal vulnerability of railway system under spatially localized failures (SLFs). The vulnerability of the Chinese railway system under three kinds of SLFs have been studied in the authors' previous study [16], and this paper will analyze the railway system spatiotemporal vulnerability under one of SLFs, circle-shaped spatially localized failures (CSSLFs), with the consideration of disruption occurrence time and duration.

## 3. CASE STUDY

This section applies the proposed spatiotemporal vulnerability analysis framework to the Chinese high-speed railway system (CHRS) that is the most popular long-distance travel mode in China. In CHRS, $k^v = 337$, $k^e = 370$, $k^l = 30117$, $k^t = 5694$.

For each individual station failure, we categorize 24 disruption occurrence time from 1 o'clock to 24 o'clock and 12 disruption durations {0.25, 0.5, 0.75, 1, 1.25, 1.5, 1.75, 2, 2.25, 2.5, 2.75 and 3} hours. This means, there are 288 scenarios for each individual station failure, and the system vulnerability caused by a damaged station is the average vulnerability under all these 288 scenarios.

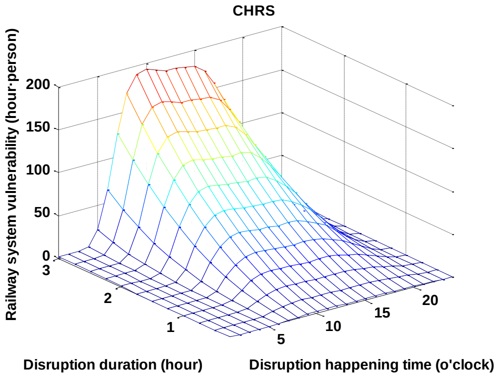

*Fig. 1 the spatiotemporal vulnerability of CHRS under individual station failure with different disruption occurrence time and duration.*

Fig. 1 shows the vulnerability of CHRS caused by the individual station failure at different disruption occurrence time and durations, where the system vulnerability is the average value of each individual railway station failure with a certain damage occurrence time and duration. For the CHRS, if the disruption occurrence time is between 8 o'clock to 17 o'clock, the disruption can cause larger system vulnerability than other time points. This result can be shown more clearly in Fig. 2, which shows the average system vulnerability at each of 24 time points. Fig. 6 shows that when the disruption duration is small, the vulnerability of CHRS are all very small, and with the increasing of disruption duration, the system vulnerability increase sharply.

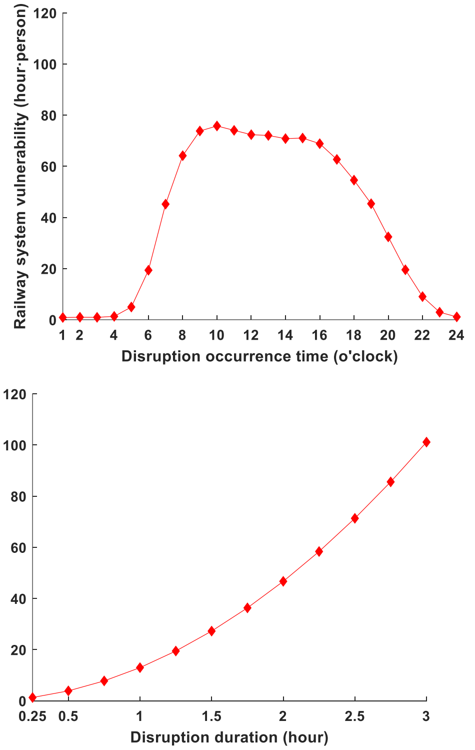

*Fig. 2 The railway system vulnerability under individual station failure: (a) based on disruption occurrence time; (b) based on disruption duration.*

For the CSSLFs, the circle radii of CSSLFs range from 25 to 300 km with a step of 25 km. Similar, the spatiotemporal vulnerability of railway system under a certain disruption radius of CSSLF is the average system vulnerability under these 288 scenarios.

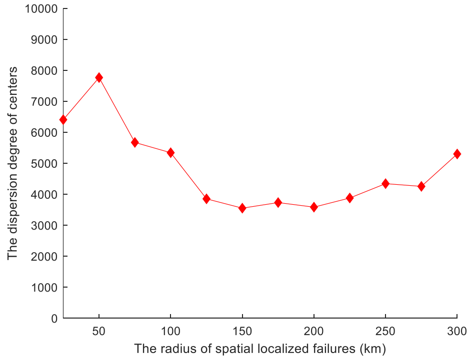

*Fig. 3 The dispersion degree of centers under different radii of CSSLFs*

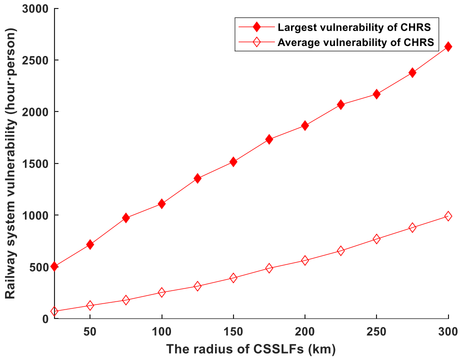

*Fig. 4 The railway system vulnerability under CSSLFs*

For each of the 288 scenarios with certain disruption occurrence time and duration, there will be a critical center for each radius. This means, there are 288 critical centers for each disruption radius with different disruption occurrence time and duration, in each of the three railway systems. We find that with the increase of disruption radius, the distances between these critical centers become smaller and smaller. We call the sum of the distances between these critical centers for each disruption radius as the dispersion degree of these centers. Fig. 3 shows that with the increase of disruption radius, the dispersion degree of centers in CHRS merely changes.

Fig. 4 shows the largest and average spatiotemporal vulnerability of CHRS under different radius of CSSLF. With the increase of radius, the largest and average vulnerability both increase smoothly. Note that the results in Fig. 4 are different with our previous work in [57], where the largest vulnerability has a sharp increase when the radius of CSSLF changes from 100 km to 140 km.

## 4. CONCLUSIONS

This paper proposes a comprehensive framework to analyze the spatiotemporal vulnerability of railway systems with the consideration of time-related attributes of disruption, railway system, and heterogeneous train flows. The framework includes a two-layer network model of railway system, a new concept called component damage scenario to capture the damage results in the physical infrastructure of railway system, the methods to calculate the delay of affected trains and the number of delayed passengers in each of the affected trains. This study proposes a method consisting of three steps to calculate the delay of the affect trains under related component damage scenarios. Based on the method, the spatiotemporal vulnerability of railway system is assessed by the total passengers' delay under disruptions. The spatiotemporal vulnerbility analysis results is helpful to identify the critical railway stations, design valuable system maintenance strategies and mitigate system vulnerability under disruptions. Meanwhile, the proposed framework can be easily adapted to analyze other schedule-based transportation systems' vulnerability, such as subway, bus, airline, shipping and so on.

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