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RAMS analysis of railway network: model development and a case study in China

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Abstract

Purpose – This paper aims to investigate the reliability, availability, maintenance and safety analysis method for railway network operation.

Design/methodology/approach – The reliability of the railway network is proposed based on the accident frequency and the topology of the railway network. Network efficiency and capacity are proposed to evaluate the availability of the railway network. The maintenance of the railway network is analyzed from the perspective of accident recovery time. The safety index of the railway network is proposed to measure the safety of railway stations and sections and the K-means method is proposed to find the safety critical stations and sections. Finally, the effectiveness of the proposed method is illustrated through a real-world case study.

Findings – The case study shows that the proposed model can produce a big-picture averaged view of the network-wide safety level and help us identify the safety critical stations and sections by considering both the expected reduction of network efficiency and capacity.

Practical implications – The potential application of the proposed model is to help the safety managers determine the investments in safety management of each section and station and then increase the safety and robustness of railway network operation.

Originality/value – The safety analysis of the railway network should consider the reliability, availability and maintenance of the railway network. In this paper, the reliability of the railway network is proposed based on the accident frequency and the topology of the railway network. Network efficiency and capacity are proposed to evaluate the availability of the railway network. The maintenance of the railway network is analyzed from the perspective of recovery time. Finally, the safety index of the railway network is proposed to analyze the safety critical stations and sections.

Keywords RAMS, Safety level, Network efficiency, Network capacity, Railway network

Paper type Research paper

1. Introduction

Railway has become a popular transportation mode in our live. However, the operational accidents may break the normal railway operation. Therefore, the reliability, availability,



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maintenance and safety (RAMS) of railway network should be analyzed from the perspective of railway system operation.

RAMS analysis of railway networks can help managers find the key components such as safety critical sections and stations by analyzing the negative effect of a section or station failure on the safety of the network (Wang *et al.*, 2017). The interaction between RAMS of railway network should be defined to obtain a big-picture averaged view of the network-wide safety level. However, many researchers study the RAMS of railway networks separately. Fortunately, the railway company has collected many accident reports. For example, the Rail Accident Investigation Branch in the UK published many accident reports (Wang *et al.*, 2017). The accident data can help us to determine the operation reliability and the recovery time (maintenance) and we can analyze the effect of uncertain accidents on the availability of railway operation from the perspective of a complex network. Therefore, we can obtain the safety level of the railway network based on the reliability, availability and maintenance metrics.

Network reliability is an important aspect for ensuring network security. Researchers have proposed a good number of topological metrics applicable for analyzing network reliability including degree centrality, closeness centrality and betweenness centrality (Zhang *et al.*, 2011). Because these metrics only can be taken as the reliability influence factors, a comprehensive model which combines many reliability influence factors has been proposed (Gu and Li, 2019). However, these methods do not consider the effect of accident frequency on railway operation. Actually, the “reliability” describes the ability of a system or component to function under stated conditions for a specified period of time (O'Connor and A, 2012). The railway network is composed of sections and stations. Therefore, we should study the network reliability based on the section and station reliability analysis. There are many kinds of accidents such as signal failure and vehicle failure which can cause the breakdown of section lines and stations (Ouyang *et al.*, 2010). The collection of accident data can help us to determine the reliability of railway network components and then formulate the reliability of the railway network.

The network reliability in this paper is proposed based on a data-driven approach which is different from the complex network approach. We can express network availability using complex network metrics. The network efficiency and capacity has been used to represent the availability of railway network (Liu *et al.*, 2018). Because the managers of the railway network also put emphasis on accessibility, researchers also studied the effect of line and node failure on network connectivity and capacity (Nabian and Meidani, 2018; Chen *et al.*, 2002).

The railway operation can recover from the section or station failure quickly if the emergency dispatch is applied immediately (Narayanaswami and Rangaraj, 2013; Cheng and Yang, 2009). The emergency dispatch can be considered as the maintenance of the railway system and can help the railway operation recover after accidents. Therefore, the maintenance of the railway network should be proposed to evaluate the safety of the railway network. The ability of a railway network to resist disturbances and maintain predesigned functionality is referred to as robustness. However, emergency management was not considered in robustness assessment studies. For example, only the probability of hazard event and the impact have been considered to formulate the robustness index of the road network and subway system in ref (Yang *et al.*, 2015) and (Zhou *et al.*, 2017).

Therefore, the safety analysis of the railway network should consider the reliability, availability and maintenance of the railway network. In this paper, the reliability of the railway network is proposed based on the accident frequency and the topology of the railway network. The network efficiency and capacity are proposed to evaluate the

availability of the railway network. The maintenance of the railway network is analyzed from the perspective of recovery time. Finally, the safety index of the railway network is proposed to analyze the safety critical stations and sections.

The rest of the paper is organized as follows. Section 2 introduces the RAMS model of the railway network. Section 3 describes a real-world case study that was carried out to verify the effectiveness of the proposed RAMS model. Finally, conclusions and directions for future research are presented in Section 4.

2. Model development

In this section, the RAMS metrics of the railway network are proposed based on the railway network description.

2.1 Railway network description

The railway system can be described as a physical network $G = (N, E)$ in which the node $n \in N$ represents the railway station and the link $e \in E$ represent the railway lines connecting the stations. Let i, j denote the two adjacent railway stations, the railway line linking the station i and j can be represented by (i, j) .

2.2 Reliability analysis

The reliability of a railway network refers to the operation probability without accidents. Based on the accident reports, we can get the number of accidents. The accident may happen on the up or down line. Let P_{ij}^{up} and P_{ij}^{down} denote the accident probability of up line and down line linking the adjacent stations i and j , respectively. P_{ij}^{up} and P_{ij}^{down} can be described as:

$$P_{ij}^{up} = \frac{N_{ij}^{up}}{T}, P_{ij}^{down} = \frac{N_{ij}^{down}}{T} \quad (1)$$

where N_{ij}^{up} and N_{ij}^{down} are the number of accidents on the up and down line, respectively, T is the statistical time.

Therefore, the failure probability of railway section (i, j) can be described as:

$$P_{ij} = P_{ij}^{up} P_{ij}^{down} \quad (2)$$

The railway station has many tracks to dispatch the trains. Let P_i^k denote the accident probability of track k of station i . Therefore, the failure probability of railway station i can be described as:

$$P_i = \prod_{k=1}^K P_i^k \quad (3)$$

The reliability of railway network G can be describes as:

$$R_G = \prod_{i,j \in N} (1 - P_{ij}) \prod_{i \in N} (1 - P_i) \quad (4)$$

2.3 Availability analysis

The availability of railway network G can be analyzed from the perspective of a complex network. The network efficiency E and capacity C are used to represent the availability of railway network G in this paper.

2.3.1 Network efficiency. Considering the traffic flow between stations, the network efficiency of railway network G can be described as follows (Gutierrez et al., 1998):

$$E = \sum_{mn} \frac{u_{mn}}{d_{mn}} \quad (5)$$

where u_{mn} denote the number of trains from station m to station n and d_{mn} denote the minimum distance from station m to station n . Let E' denote the network efficiency when one station or section failed. The loss of network efficiency can be described as follows:

$$\Delta E = \frac{E - E'}{E} \quad (6)$$

2.3.2 Network capacity. The network capacity refers to the maximum number of trains that can be loaded on the network. The I-O method is used to measure the capacity of the railway network because it can measure the capacity of the directional and unidirectional network (15). Let x_j^i denote the number of trains between the adjacent railway stations i and j . Let X_j denote the number of trains from other stations to station j . The I-O matrix can be described as follows:

$$F_j^i = \frac{x_j^i}{X_j} \quad (7)$$

The number of trains entering the station j can be described as follows:

$$X_j = \sum_{i=1}^{N-1} F_j^i X_i + \sum_{s=1}^S x_j^s = \sum_{i=1}^{N-1} F_j^i X_i + U_j \quad (8)$$

where x_j^s denote the number of trains from the stations outside the railway network to the station j .

Equation (8) can be described as the following matrix form:

$$X = F^{(-i)} X + U \quad (9)$$

where X denotes the sum of trains going into all the stations in the network and U denotes the sum of trains from the stations outside the network. Therefore, the network capacity can be described as follows:

$$X = (1 - F^{(-n)})^{-1} U \quad (10)$$

If the section between stations u and v fail to run the trains, the network capacity will become:

$$X^{-(u,v)} = (1 - F^{(-i-(u,v))})^{-1} U \quad (11)$$

Therefore, the loss of network capacity ΔC can be described as follows:

$$\Delta C = \frac{\sum X - \sum X^{-(u,v)}}{\sum X} \quad (12)$$

However, the train traffic can recover if the dispatchers take emergency measures. Therefore, we should analyze the maintenance of railway network operation.

2.4 Maintenance analysis

The recovery time has been recorded in the accident reports. Let t_s and t_e denote the starting time and end time of accident. The maintenance M can be computed as the proportion of normal operation time in the operation time of railway network, that is:

$$M = 1 - \frac{t_r}{t_o} \quad (13)$$

where $t_r = t_e - t_s$ and t_o denotes the operation duration in each day.

2.5 Safety analysis

The safety or risk evaluation of railway network should consider the accident probability, loss of availability and maintenance (M) at the same time. The accident consequence S can be used to measure the safety level of railway network and thus can be described as follows:

$$S = (1 - R)\Delta A(1 - M) \quad (14)$$

Therefore, S denotes the accident consequence. $(1 - R)$ denotes the accident probability of railway network, ΔA denotes the loss of availability if there is no maintenance. $(1 - M)$ denotes the effect of maintenance on the operational safety.

However, the network-scale safety cannot reflect the safety importance of each section or station. Therefore, we formulate the [equation \(14\)](#) under the section failure and station failure, respectively. If the section (i, j) is broken by the operation accidents, the risk can be described as follows:

$$EL_{ij} = p_{ij}\Delta E(1 - M), CL_{ij} = p_{ij}\Delta C(1 - M) \quad (15)$$

where EL_{ij} denotes the expected loss of network efficiency and CL_{ij} denotes the expected loss of network capacity.

If the station i is broken by the operation accidents, the risk can be described as follows:

$$EL_i = p_{ij}\Delta E(1 - M), CL_i = p_{ij}\Delta C(1 - M). \quad (16)$$

where EL_i denotes the expected loss of network efficiency and CL_i denotes the expected loss of network capacity.

Because we can evaluate the safety of the same section based on [equations \(15\) and \(16\)](#), different evaluation results may be obtained. Therefore, we should evaluate the safety level or grade of each section or station based on the loss of network efficiency and capacity at the same time. The K-means method is a kind of clustering method and it can classify the data into different classes. Therefore, we used the K-means method to find the safety critical sections and stations.

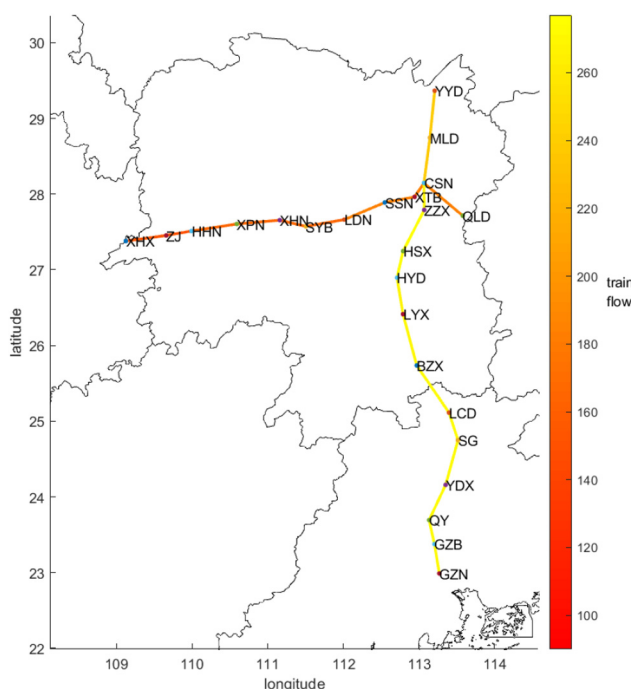


Figure 1.
Railway network and
section train flow

3. Case studies

The proposed model has been used to RAMS analysis of the railway network in China. All computational experiments were conducted on a PC with a 2.8GHz CPU running the Windows 10 operating system.

3.1 Data description

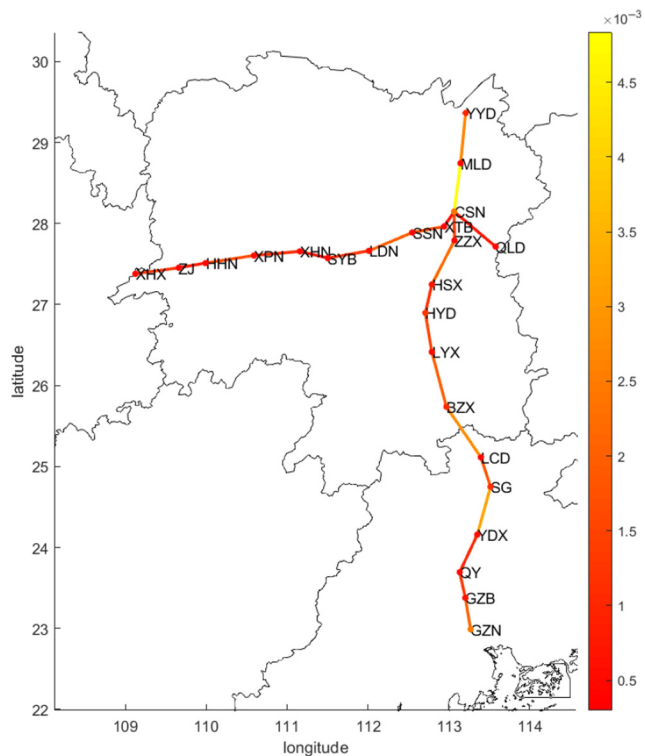
We collected the infrastructure and operation data about the railway network by field survey. The railway network contains two railway lines: Jing Guang (JG) Line (vertical direction) and Hu Kun (HK) Line (horizontal direction). The railway network and the train flow of each section have been depicted in Figure 1. As can be seen from Figure 1, the train flow in the JG line is larger than the HK Line.

Based on the reliability analysis in Section 2, we obtain the failure probability of sections and stations based on the accident data, as shown in Figure 2. As can be seen from Figure 2, the section between station Mi Luo Dong (MLD) and Chang Sha Nan (CSN) is broken much more easily than the other sections. The station Guang Zhou Nan (GZN) is broken much more easily than the other stations. Based on equation (4), the reliability of the railway network is 0.92 which indicates that the reliability of the railway network is very high.

3.2 Model results

The RAMS analysis results are plotted in Figure 3. Figure 3(a) shows the expected loss of network efficiency due to the section and station failure. With regard to the railway sections, as can be seen from Figure 3(a), the maximum network efficiency loss occurs when the section between station MLD and CSN is broken by accidents. With regard to the railway

Figure 2.
Failure probability of
sections and stations



stations, the maximum network efficiency loss also occurs when the station CSN is broken by accidents. Therefore, the risk increases largely from the perspective of network efficiency if the section between station MLD and CSN or the station CSN fails to run the trains.

Figure 3(b) shows the expected loss of network capacity due to the station and section failure. With regard to the railway sections, as can be seen from Figure 3(b), the maximum network capacity reduction occurs when the station CSN and GZN is broken by accidents. With regard to the railway stations, the maximum network capacity reduction occurs when the section between station MLD and CSN is broken by accidents. Therefore, the failure of station CSN and GZN can have a significant effect on the operation safety of the railway network. Much more risk control and safety management efforts should be made to protect the section between station MLD and CSN, the station CSN and GZN from the perspective of network capacity reservation.

The K-means method is proposed to find the safety critical sections and sections. We divide the sections and stations into four safety levels, such as high-risk, medium-risk, low-risk and lower-risk. The results are depicted in Figure 4. Figure 4(a) shows the evaluation results of railway stations and Figure 4(b) shows the evaluation results of railway sections. As can be seen from Figure 4(a), there are 1 high-risk railway station, 1 medium-risk railway station, 4 low-risk railway stations and 18 lower-risk railway stations. As seen from Figure 4(a), there are 1 high-risk section, 3 medium-risk section, 9 low-risk sections and 10 lower-risk sections. Therefore, the proposed model can identify the safety critical sections and railway stations from the perspective of network capacity and efficiency.

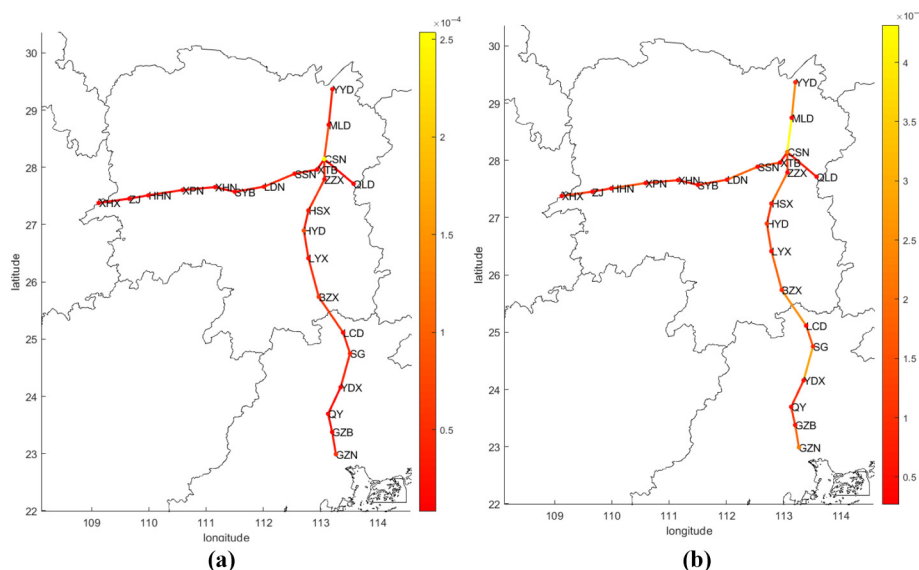


Figure 3.
Expected loss of
availability

Notes: (a) Expected loss of network efficiency due to section and station failure; (b) expected loss of network capacity due to section and station failure

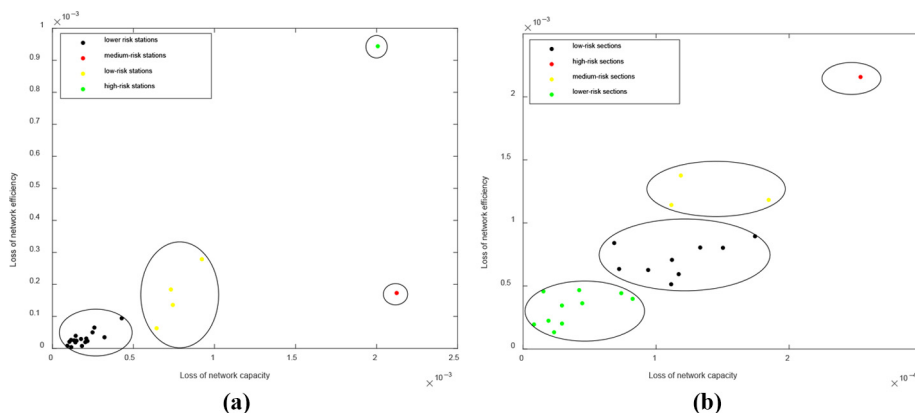


Figure 4.
Safety critical
stations and sections

4. Conclusion and extension

In this study, we present a model for RAMS analysis of railway network that is affected by various operation accidents. The proposed RAMS analysis method considers both the failure probability of stations and sections, the expected loss of network availability due to station and section failure. This method facilitates the identification of high-risk sections and high-risk stations from a more comprehensive perspective.

This proposed RAMS methodology was applied to the railway network in the real world. The case study results indicate that the safety importance of each section and railway station can be measured by the proposed safety index. Two risk maps of the

railway network were depicted based on network efficiency reduction and capacity loss. Based on the risk maps, we can evaluate the increase in transport cost due to detours by computing the expected network efficiency loss and evaluate the reduction of train flow due to propagation by computing the expected network capacity loss. Because different critical stations or sections can be obtained based on the network efficiency loss or the capacity loss, the K-means method is proposed to find the safety critical stations and sections by considering both the expected reduction of network efficiency and capacity.

The potential application of the proposed model is to help the safety managers determine the investments in safety management of each section and station and then increase the safety and robustness of railway network operation. In conclusion, the proposed RAMS analysis method can be used for both practical applications and theoretical investigations. In the future study, the proposed model may be improved by considering the varying failure probability of stations and sections. Therefore, the risk prediction model will be used to determine the failure probability in the following works and then we can obtain the changing safety state of the railway network.

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Further reading

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