Analyzing the causation of a railway accident based on a complex network*

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In this paper, a new model is constructed for the causation analysis of railway accident based on the complex network theory. In the model, the nodes are defined as various manifest or latent accident causal factors. By employing the complex network theory, especially its statistical indicators, the railway accident as well as its key causations can be analyzed from the overall perspective. As a case, the "7.23" China–Yongwen railway accident is illustrated based on this model. The results show that the inspection of signals and the checking of line conditions before trains run played an important role in this railway accident. In conclusion, the constructed model gives a theoretical clue for railway accident prediction and, hence, greatly reduces the occurrence of railway accidents.

Keywords: railway accident, complex network, accident network model

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1. Introduction

In recent years, China railway has stepped into a rapid development phase with an obvious increase in its transport capacity both for passengers and freights. Nevertheless, due to the enhancing of railway operation speed and the increasing of grid density, the railway security problems are quickly recognized. Especially after the 7.23 China–Yongwen railway accident, people are more and more worried about the railway safety. Henceforth, methods of analyzing railway accident become particularly urgent and important.

A railway accident is a special case of various accidents. It is now generally accepted that these accidents represent a complicated system phenomenon.[1,2] There are three traditional approaches to accident modeling: the sequential accident model, the epidemiological accident model, and the systemic accident model. The sequential accident model[3] explains accident causation as a result of a chain of discrete events occurring in a particular temporal order, and the cause-effect relation among consecutive events is assumed to be linear and deterministic. However, Qureshi[4] considered that this model cannot comprehensively explain the accident causations in modern socio-technical systems where multiple factors combine in complex ways, leading to system failure and accident. Epidemiological accident model regards events leading to accident as the spreading of a disease.[5] The main methods used in the systematic accident models are Accimap, HFACS, and STAMP.[6] Accimap is a method to identify and contact the errors among six social-technology levels based on the Rasmussen's risk management framework.[2,7] HFACS[8] adds some accident classification analysis methods to the Reason's Swiss cheese model.[9] STAMP uses the control theory and system dynamics methods to describe the errors which lead to the accident.[10] In order to know how each element influences each other, some accident safety analysis methods need to be introduced. With these methods, the causations can be analyzed deeply in a comprehensive and systemic way.

Three kinds of accident methods are frequently used in accident safety analysis: fault tree analysis, Petri nets, and Bayesian network.[11] Fault tree analysis is a deductive, structured methodology to determine the potential causes of an undesired event, referred to as the top event.[12] Petri nets can be described by sets of places and transitions, a valuation function, and an initial marking.[13] For analytical computations, Petri nets are defined by means of linear algebra where vectors represent markings and matrices flow relations.[14] A Bayesian network makes it easy to describe accident that involves many interdependent variables.[15] These methods are widely used in the accident safety analysis. However, these methods analyze the accident in the local view, focusing on point-to-point or part-to-part analysis, which is not enough for the complicated railway accident. In this paper, the complex network theory is used to analyze the railway accident. Here, we can obtain the global development process of accident and relationships among different factors from the perspective of the management, the physical process and the operations. Furthermore, the principal factors can be found out. And the possibility of railway accident will be reduced if we enhance the protection against those principle factors.

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The study of complex network emerged in the 1980s and made a breakthrough in a few years that followed.[16,17] As a very general abstraction and description for the complex system, the complex network highlights the structure of the topological characteristics. It has become one of the most important topics in the research of the complex systems,[18] such as diverse sexually transmitted disease,[19] the world wide web,[20] epidemiology,[21] scientific collaboration,[22] etc. Beyond that, Li and Gao[23] studied the modular structures of Chinese Northeast railway network. Latora and Marchiori's paper[24] has shown how the passage from abstract social networks to applied complex systems is present in nature. Through taking lessons from these papers and some research methods used in road traffic,[25,26] combing with some concrete problems in railway accident, we propose a new method to analyze the railway accident.

In this paper, a complex network relating to railway accident causes is constructed. Based on this accident network model, key factors in the accident are explored by employing complex network theory. By protecting those key causations, the possibility of railway accident occurrence can be greatly reduced. The rest of this paper is organized as follows. In Section 2 some fundamental concepts in complex network are recalled; in Section 3, a new model to analyze the causes of the railway accident is established; in Section 4, the 7.23 China–Yongwen railway accident is studied as a real case to test the proposed model. Some concluding remarks are represented in Section 5.

2. Basic concepts of complex network

A complex network is a graph with non-trivial topological features –features that do not occur in simple networks such as lattices or random graphs but often occur in real graphs. For the sequential analysis, some basic concepts of the complex network are introduced.

(i) Node degree and degree distributions

The degree k_i of a node i is the number of edges incident with this node, and is defined in terms of the $N \times N$ square adjacency matrix as[27]

$$k_i = \sum_{j \in N} a_{ij}, \tag{1}$$

where N is the number of the nodes, a_{ij} is the element in line i and column j of the matrix.

Here, k_i reflects the node importance in the network, the bigger the node's k_i, the more important the node is. The one with the largest degree is the Hub node, and it plays an important role in the network.

The degree distribution completely determines the statistical properties of uncorrelated networks, and can be described by $P(k)$. Here, $P(k)$ means the probability of a randomly selected node whose degree is k.

(ii) Shortest path length

The shortest path length is the least number of edges that connect two nodes together. It is useful to represent all the shortest path lengths of a graph G as a matrix D.[28] A measure of the typical separation between two nodes in the graph is given by the average shortest path length, defined as the mean of geodesic length over all nodes:

$$L = \frac{\sum\limits_{i,j \in N, i \neq j} d_{ij}}{N(N-1)}, \tag{2}$$

where d_{ij} is the length of the geodesic from node i to node j.

(iii) Clustering coefficient

The clustering coefficient C_i is used to describe the aggregation of nodes in the network, namely how intensive the network is, and defined as follows: in the network, a selected node i having k_i edges which connect it to other k_i nodes. If the nearest neighbors of the original node are all connected to each other, there will be $k_i(k_i-1)/2$ edges between them.[27] Define the ratio between E_i and the total number $k_i(k_i-1)/2$ as C_i

$$C_i = \frac{2E_i}{k_i(k_i-1)}, \tag{3}$$

where E_i is the number of edges that actually exist among these k_i nodes.

The clustering coefficient C of the graph is then given by the average of C_i over all nodes:

$$C = \frac{\sum\limits_i C_i}{N}. \tag{4}$$

(iv) The betweenness

The communication of two non-adjacent nodes, say j and k, depends on the nodes belonging to the paths connecting j and k. Consequently, a measure of the relevance of a given node can be obtained by counting the number of geodesics going through it, and defining the so-called node betweenness.[27] The betweenness is one of the standard measures of node centrality. More precisely, the betweenness b_i of a node i is defined as

$$b_i = \sum_{j,k \in N, j \neq k} \frac{n_{jk(i)}}{n_{jk}}, \tag{5}$$

where n_{jk} is the number of shortest paths connecting j and k, and $n_{jk(i)}$ is the number of shortest paths connecting j and k and passing through i.

3. Our accident causation model

To find out the key causation of a railway accident, we often analyze the accident from the view of the management,

the physical processes, and the operation. These aspects contain the ministry of railway, the railway bureau, train control center, train dispatcher, train drivers, driving environment including line environment and the natural environment. Based on the Rasmussen's risk management framework,[2] these causations can be put into the relevant levels. Rasmussen's risk management framework describes many system levels involved in the production and safety management. These levels are government, regulators, company, company management, staff, and work. According to Rasmussen's framework, every systemic level is involved in safety management via the control of hazardous processes through laws, rules, and instructions. For systems to function the safety decisions made at higher levels should promulgate down and be reflected in the decisions and actions occurring at lower levels of the system. On the contrary, information at the lower levels needs to inform the decisions and actions occurring at the higher levels.[29] Without this so-called 'vertical integration', systems will lose control of the processes that are designed to control. According to this theory, we analyze the causation of the railway accident and construct the complex network model in the following steps.

Step 1 According to the six levels referred in the Rasmussen's risk management framework, we summarize six levels associated with the specific railway accident. In general, these six levels can be defined as follows: 1) Ministry of Railways; 2) Department of Technologies, Foundation Department, Science and Technology Division; 3) Railway Bureaus; 4) The vehicle depot, electricity depot, engineering system; 5) The attendants' behaviors and process; 6) Equipment and environment.

Step 2 According to these six levels, in Step 1 we analyze the specific railway accident, find out the causation and put them into each level as nodes of the complex network. Then a correlation matrix is established for the accident where the element takes 1 if two nodes have the direct relationship, if they are unrelated, the element takes 0.

Step 3 We can construct the graph on the basis of the correlation matrix. If their relevant elements in the matrix are all 1, then there is a line which connects these two nodes together. The network model is constructed by the above steps.

On the basis of this model, the node degree, betweenness, clustering coefficient, and the shortest path length from each node to the end are calculated to compare each parameter value and find out the Hub node. Analyzing the Hub connecting with the specific railway accident, we identify that the Hub is a key factor that leads to the accident. Removing the Hub node, which means enhancing the protection of this element and stopping this cause from happening, and then we reconstruct the complex network compared with the original one, and make conclusions. There are many ways to strength the protection, such as increasing manpower investment, increasing the efforts and the frequency of inspection, etc. It is necessary to strengthen the inspection and protection of the Hub if there is a great influence when removing it. This means that the possibility of the accident will be reduced if some actions can be taken to protect the Hub.

4. A case study

The 7.23 China–Yongwen railway accident is taken for the real case to test the proposed model. On July 23, 2011, two high-speed trains (CRH train D3115 (CRH1-046B) and CRH train D301 (CRH2-139E)) traveling on the Yongwen railway line collided on a viaduct in the suburbs of Wenzhou, Zhejiang Province, China. The two trains both derailed, and four cars fell off the viaduct. 40 people were killed, at least 172 people were injured. The direct economic loss arrives at nearly 200 million RMB. To analyze this very grave accident with the model proposed in this paper, some elements need to be added. So, the China Railway Signal & Communition Corp (CRSC), the Signaling Design Institute, and the Train Control Institute will be added to levels B, C, and D respectively. The main factors at each level which lead to the accident are summarized in Table 1 according to the Accident Investigation Report.[30]

According to "The investigation report on the "7.23" Yongwen line major railway accident (2011)", we can find the relationships among these nodes, then construct the complex network as the model proposed in Section 3. The accident propagation paths can be represented as the paths from each node to the end E_{14}. Figure 1 shows the complex network about this accident.

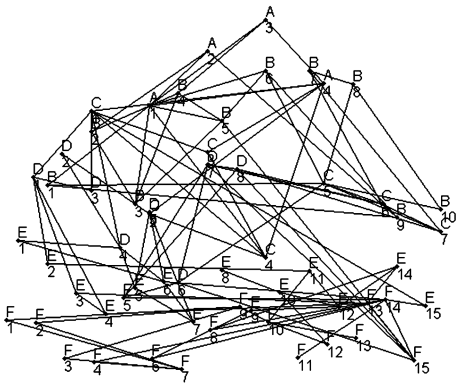


Fig. 1. Complex network of the 7.23 China Yongwen railway accident.

4.1. Analysis on the degree

Analyzing the complex network about the causations of the "7.23" China–Yongwen railway accident according to the methods in Section 2, we can calculate the node degree and the clustering coefficient, then analyze its degree distribution. Table 2 shows the node degrees.

Table 1. The list of causations of the accident.

A: Ministry of Railways	1) Seeking quick success and benefits, 2) weak management and incomplete rule standards, 3) unclear job responsibilities and functions, and 4) inadequate inspection and supervision for Shanghai railway bureau
B: Department of Technologies, Foundation Department, Science and Technology Division CRSC	1) Not carefully supervising the bidding of the equipment in Hening–Hewu Yongwen line train control center, 2) poor management of the operation of new products, 3) insufficient examination of the LKD2-T1, 4) no clear regulations on the technical review, 5) invalid and irregular technical pre-review on the equipment LKD2-T1 for train control center, 6) Science and Technology Division's illegal approval for the use of the LKD2-T1, 7) inadequate inspection and supervision of the quality management by CRSC, 8) CRSC fully transmit the project to the local design institute with little supervision or inspection, 9) cursory decision on the bidding for the Hening–Hewu line control equipment, and 10) finding no version of the train control center equipment in Hefei station that the signaling design institute has changed llegally
C: Shanghai Railway Bureau and the Signaling Design Institute	1) Insufficient safety education and training, 2) insufficient inspection and supervision, 3) neither sensitive safety awareness nor efficient measures to avoid or alleviate the accident, 4) no appropriate accident handling, 5) unwise decision on update of the LKD2-T1, 6) lack of the technical review on the development of the equipment for train control center, and 7) neither management responsibility for scientific research nor efficient control and supervision of the local companies on the product quality taken by the Signaling Design Institute.
D: Vehicle depot, electricity depot, engineering system, and Train Control Institute	1) Poor travel management and emergency handling, 2) not efficiently supervising the safety production management and training service work, lack of supervision to Wenzhou south station, 3) poor supervision to the dispatching institute and the vehicle depot system, 4) insufficient education and training for the staff, 5) no job responsibility taken by the electricity emergency management, 6) the equipment LKD2-T1 cursorily designed by the Train Control Institute, 7) poor equipment research and development management in the train control center, and 8) the equipment LKD2-T1 redesigned by the Train Control Institute.
E: The attendants' behaviors and process	1) not further following the situation of the red band by the dispatcher in Shanghai Railway Bureau, 2) not carefully monitoring the situation of D3115, 3) not reminding D301 driver of the emergency, 4) not contacting D301 driver in time, 5) not recording the circuit failure of the 5829AG, 6) not recording the replacement of some equipments of the track circuit except 5829AG, 7) not stopping the illegal behaviors, 8) not informing the D3115 driver to switch to the visual driving mode when the signal was red, 9) stopping D3115 by the ATP, 10) D3115 failing to drive in visual mode three times, 11) D3115 failing to report to the dispatcher, 12) D3115 switching to the visual driving mode but still in the 5829AG, 13) D301 leaving the Yongjia station, 14) D301 rear-ended D3115, and 15) illegally opening the protection net for work.
F: Equipment and environment	1) four sender boxes being damaged, 2) two receiver boxes being damaged, 3) one attenuator being damaged, 4) the fuse F2 in LKD2-T1 being broken, 5) the design flaws in PIO of LKD2-T1, 6) the ATP on the D3115 being activated, 7) thunder strike, 8) the ATP on D301 taking no actions, 9) the CAN total resistance being reduced, 10) the communication between 5829AG and the train control center being unavailable, 11) the displays on the terminal being wrong, 12) abnormal track circuit signal, 13) a red band, 14) the signal being wrong and keeping green for the faulted track section, and 15) unoccupied signal being sent to D301.

Table 2. Node degrees of constructed model.

Level \ Degree	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
A	8	3	3	6											
B	3	3	4	4	5	4	3	3	3	2					
C	7	4	3	5	7	5	4								
D	5	2	2	5	4	4	5	5							
E	2	2	3	3	3	5	3	1	2	3	3	4	5	3	2
F	2	2	2	2	4	2	4	2	4	4	1	2	1	9	6

The tables in this paper have some common features the level and the number in first line work together to represent the node, and the main parameters of the table are the nodes. For example, in Table 2 the degree of node A_1 is 8. Table 2 shows that the degrees of these nodes vary from 1 to 9, and most of them are around 3. The degree reflects the importance of the node in the network. So, the most important one in this table is F_{14}, which represents the cause element: the signal was wrong and kept green for the faulted track section from the train control center in Wenzhou South station.

The clustering coefficient (C) describes how the nodes gather together in the network: only in the whole network the C equals 1, and in other network it is less than 1. Table 3 shows the clustering coefficient of each node in this net, and based on it the C of the network can be calculated as

$$C = \frac{1}{N}\sum_i C_i = \frac{1}{59}36.7032 = 0.6221.$$

We can see that the net is compact since its C is high.

Table 3. Clustering coefficient of each node.

Level \ C_i	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
A	0.33	0.50	0.67	0.57											
B	0.50	0.67	0.70	0.60	0.53	0.50	0.67	0.67	0.50	1.00					
C	0.39	0.50	1.00	0.67	0.32	0.60	0.70								
D	0.47	0.67	1.00	0.40	0.60	0.60	0.67	0.60							
E	1.00	0.67	0.83	0.83	0.67	0.47	0.83	1.00	0.67	0.50	0.50	0.40	0.47	0.50	0.67
F	0.67	0.67	0.67	0.67	0.60	0.67	0.40	0.67	0.40	0.40	1.00	0.67	1.00	0.22	0.43

According to the node degree shown above, we analyze this network and obtain its degree distribution. Then we make the fitting and find this net to obey the Fourier distribution approximately, and the fitting function is described as follows.

In Fig. 2,

$$\begin{aligned} f(x) = & -12.55 + 11.25\cos\cos(0.1389x) \\ & + 13.29\sin(0.1389x) + 0.9556\cos\cos(2*0.1389x) \\ & - 4.718\sin\sin(2*0.1389x). \end{aligned} \tag{6}$$

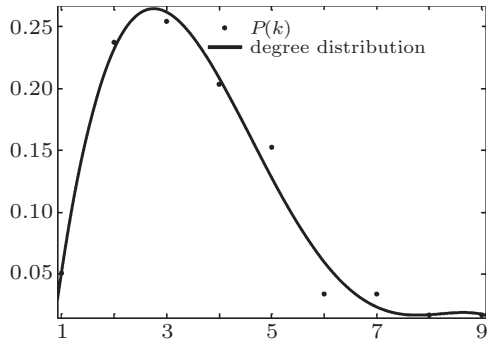


Fig. 2. Degree distribution of the constructed model.

Under the description of the degree, the degree distribution and the clustering coefficient of this network, we can find the causation of the railway accident, the degree distribution obeys the Fourier distribution approximately, and the C is high. This conforms to the clustering property of the complex network. Besides, we can find the Hub node F_{14}, which represents that the signal was wrong and kept green for the faulted track section from the train control center in Wenzhou south station. The result is consistent with the reported accident investigation, and this means the wrong of the passing signal in the train center plays an important role in the 7.23 China–Yongwen railway accident. With the development of electrification of China railway, the method to control the train is becoming more and more modenized. At present, the Chinese train control system (CTCS) is used to keep the trains from colliding. The CTRS installed on the Yongwen railway line is CTRS-2. (CTRS has four levels, and CTRS-2 is installed on Chinese trains with speeds ranging from 200 km/h to 250 km/h, there are two subsystems: a ground subsystem and an onboard subsystem. The onboard subsystem is the ATP, which controls the operation of train according to the signals provided by the ground system. When there is no signal or abnormal signal to the ATP, it will adopt automatic braking to stop the train. If the train needs to move at this time, it has to wait for 2 min, and turn ATP into visual driving mode to travel at less than 20 km/h. In the 7.23 accident, it is because of the wrong signal that makes the ATP on the D3115 adopt automatic braking and stop the train in the 5829 section. This is the main cause that led to this accident. The Chinese railway has become more and more automatic and intelligent, so the train center equipment and signal must be improved. If the inspection of signals can be strengthened in railway daily operation, the possibility of the accident will be largely reduced.

4.2. Analysis on the shortest path length

The shortest path length in the complex network is the least number of edges that link two nodes together. In the railway accident model, the shortest path length, that is, the distance from each node to the end, reflects the fastest way the accident spreads. In the real case mentioned in this paper, the end node is E_{14}, it represents D301 real-ended D3115. We calculate the shortest path length from each node to end and show the results in Table 4.

Table 4. The shortest path length L_1 from each node to E_{14}.

Level \ L_1	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
A	4	5	5	5											
B	5	5	4	4	3	4	5	5	5	5					
C	4	5	5	5	4	4	4								
D	3	5	4	4	4	3	3	3							
E	4	3	2	2	5	3	4	3	2	2	2	1	1	0	3
F	5	5	5	3	3	3	4	1	4	3	3	3	4	2	2

It is shown in this table that the shortest path length from each node to the E_{14} is less than 5. This means that each element can lead to the accident in less than 5 steps. The more steps one element needs to pass through before reaching the end, the lower probability this element can lead to the accident with. In order to reduce the possibility of the accident, some actions should be taken to increase the shortest path length from each node to the end.

According to all the above discussion, enhancing the protection of the Hub node F_{14} may be an effective way to reduce the possibility of the accident. This means that improving the quality of the train signal control equipment and enhancing the inspection of signals are able to prevent the accident from happening. This can be reflected in the network by removing F_{14}. The results are shown in Fig. 3.

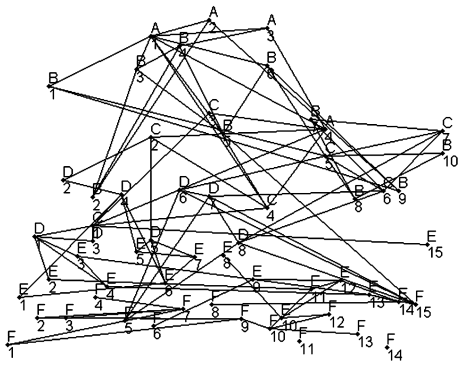


Fig. 3. Network after removing the Hub.

The shortest path length from each node to the end E_{14} after removing the Hub is shown in Table 5.

Table 5. Values of the shortest path length L2 after removing the Hub.

Level \ L_2	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
A	4	5	5	5											
B	5	5	4	4	3	4	5	5	5	5					
C	4	6	5	5	4	4	4								
D	3	6	4	5	7	3	3	3							
E	6	3	2	2	6	6	7	3	2	2	2	1	1	0	5
F	5	5	5	7	4	3	6	1	4	3	Inf	3	4	Inf	2

From Table 5 we can see that after removing the Hub F_{14} (namely strength supervision and management of the Wenzhou south railway train control center), the F_{11} cannot lead to the accident, and the shortest path length from C_2, D_2, D_4, D_5, E_1, E_5, E_6, E_7, F_4, F_5, and F_7 to the end E_{14} will increase. This means that even if there are some other failures, such as the thunder strike, the dispatcher does not do his work very well, etc., the possibility of the accident will be reduced a lot only when strengthening the inspection to the train signal control center.

4.3. Analysis on the betweenness

The betweeness, which has a strong real significance, reflects the effect and influence of the nodes in the whole network. From the view of reality, in the railway accident, the meaning of the betwenness needs to make a little change. In the railway accident, the main consideration is the influence of the individual node that leads to the accident. According to the definition of the betweenness mentioned in Section 2, we redefine the betweenness b_i of node i as follows: counting the number of the geodesics that is the shortest paths to the end E_{14} going through the node.

$$b_i = \Sigma_{j,k\in N, j\neq k} n_{jk(i)}/n_{jk}, \tag{7}$$

where n_{jk} is the number of the edges that connect the nodes j and k together, $n_{jk(i)}$ is the number of the edges that connect the nodes j and k together, and passing through the node i. k is E_{14}, which represents the crash.

According to the meaning of the betweenness mentioned above, the betweenness of this complex network is calculated and the results are shown in Table 6.

As can be seen from Table 6, the node E_{13} has the biggest betweenness in all the nodes. E_{13} means D301 left Yongjia station. Because of the Hub F_{14} that D301 left Yongjia, the ATP on the D301 did not work well and the driver on the D301 did not contact the dispatcher in time, and some other mistakes happened at the same time, all of these mistakes led to this accident. E_{13} has a great influence in the network since it has the biggest betweennness, if there were some actions to stop the D301 from leaving Yongjia, the accident would not happen. So, it is very necessary and important to check the line condition before trains leaving the station.

Table 6. Betweenness of the network.

b_i \ Level	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
A	0.04	0.00	0.00	0.00											
B	0.00	0.00	0.01	0.01	0.14	0.01	0.00	0.00	0.00	0.00					
C	0.08	0.00	0.00	0.00	0.04	0.02	0.00								
D	0.11	0.00	0.00	0.01	0.01	0.05	0.02	0.04							
E	0.00	0.00	0.07	0.07	0.00	0.10	0.01	0.00	0.01	0.02	0.10	0.19	0.53	0.00	0.04
F	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.24	0.04	0.07	0.00	0.00	0.00	0.24	0.33

5. Conclusions

In this paper, we introduce an accident network model to analyze a railway accident. By the complex network theory, key causations of railway accident have been explored via the proposed model. From a real case study, it can be seen that if the inspection of signals is stricter, the length of the shortest path for each node should increase a lot. In the meantime, adding some other active actions, such as checking the line condition before starting the train, the possibility of accident should be largely reduced.

It is worth mentioning that the characteristics of the complex network which have been mentioned in this paper are some simple ones, such as the degree, the betweenness, while the randomness and uncertainty of the network have not yet been considered. This will be one of our future research topics.

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