ABSTRACT

HIGH-SPEED RAIL SAFETY ANALYSIS BASED ON DUAL-WEIGHTED COMPLEX NETWORK

by
Liu Lv

This study uses a complex network model to analyze the causes of accidents in High-Speed Rail operations. By identifying the key factors that led to High-Speed Rail accidents, hidden safety hazards were discovered. This will help improve the operational safety of the U.S. High-Speed Rail line under construction.

The analysis uses the regional High-Speed Rail network in Guangzhou, China as a case study, including the railway (including High-Speed Rail) accidents that occurred in the company's jurisdiction from 2013 to 2017. With comparative analysis between general railways and High-Speed Rail, the changes of High-Speed Rail safety factors are explored. Data analysis results show that the main accident causes of High-Speed Rail and general railways have no significant differences in categories, Equipment and human factors are the most important categories of factors leading to accidents. However, there are obvious differences in specific accident factors. Which include the significant impact of driver staff on the safety of High-Speed Rail, and the safety of High-Speed Rail is highly sensitive to incidents. Another key factor is the stability of the equipment, especially the performance of the signal system is critical to the operation of High-Speed Rail. The underlying reasons reflected by these safety defect factors include:

1. In the short term, a large number of equipment purchases and the construction of new railway lines will cause maintenance, driver, and mechanic pressures and staff shortages.

2. The weakness of the internal training system leads to insufficient professional quality of maintenance staff and driver.

The proposed strategy includes enhancing the training organization within the operating company, and adjusting the High-Speed Rail construction and equipment procurement policies should be gentler in order to reduce the pressure on the system and improve the level of safety.

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by
Liu Lv

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APPROVAL PAGE

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This dissertation is dedicated to my family:
Wife, Yijun
Son, Sherman
Daughter, Shirley

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CHAPTER 1

INTRODUCTION

1.1 Background

Safety is the most basic requirement of mankind, and ranks only second to physiological needs in Maslow's theory of needs. As a basic requirement of transportation in daily life, safety is not so easy to achieve: The statistics of the World Health Organization in 2016 show (as shown in Table 1.1). Traffic (road) injuries rank 5th among the causes of human death. The number of people killed in traffic accidents is as high as 82 thousand people per day.

Table 1.1 Cause of Death Around Worldwide

Rank	Cause	DALYs (000s)	% DALYs	DALYs per 100,000 population
0	**All Causes**	**2,668,476**	**100.0**	**35,761**
1	Ischaemic heart disease	203,700	7.6	2,730
2	Stroke	137,941	5.2	1,849
3	Lower respiratory infections	129,690	4.9	1,738
4	Preterm birth complications	101,397	3.8	1,359
5	Road injury	82,538	3.1	1,106
6	Diarrhoeal diseases	81,743	3.1	1,095
7	Chronic obstructive pulmonary disease	72,512	2.7	972
8	Diabetes mellitus	65,666	2.5	880
9	Birth asphyxia and birth trauma	63,928	2.4	857
10	Congenital anomalies	62,980	2.4	844

Source: WHO, 2016.

Road accidents bring not only the loss of lives and families, but also huge economic losses. According to the estimates of the United Nations, the global property damage caused by road accidents is as high as 518 billion US dollars each year. Road traffic injury losses in EU countries are 180 billion euros per year, which is twice the annual budget for all activities in these countries (European Transport Safety Council, 2003). US road traffic injury losses are approximately US $ 230.6 billion per year, or 2.3% of GNP. Some studies in the 1990s estimated that road traffic injury losses in the UK were 0.5% of gross domestic product (GDP), Sweden was 0.9%, and Italy was 2.8%; 11 high-income countries had road traffic injury losses averaged 1.4% of GDP (Elvik R, 2002). In 1999, China ’s road traffic injuries resulted in an estimated loss of US $ 12.5 billion, almost four times the country 's annual health budget. (Zhou Y et al. 2003)

It is the high and painful cost of traffic accidents that make safety research an eternal theme in transportation research. Countless talented scholars focus on traffic safety research, and the number of papers included in TRID alone exceeds 5,000 each year. Outside the university, NGOs and governments are driving improvements in traffic safety in various fields, including promoting the use of seat belts, controlling the use of illegal drugs or driving after alcohol, improving car safety, improving road signs, and recently starting to improve Problems with cell phone usage while driving. Countries 'financial investment in traffic safety is also huge: Safety research throughout all transportation programs remains US DOT's number one priority. The Fixing America's Surface Transportation Act (FAST Act). providing estimated average annual funding of $ 2.3172 billion for Highway Safety Improvement Program for lase five years.(FHWA, 2020) As a full-time federal agency responsible for highway safety in the United States, the National Highway Safety Administration NHTSA has a budget of 966.3 million US dollars (2019), The federal motor carrier safety administration FMCSA has a budget of 666.8 million US dollars. The federal Railway Administration FRA's has a budget of 221.7 million dollars. From 2004 to 2013, China invested 25.4 billion RMB in highway safety improvement, renovated 22,000 dangerous bridges, and spent 44 billion RMB. (Zhenglin Feng, 2013) Sweden proposed "Zero Vision" in 1997 (Trafikverket, 2015) extending the responsibility of road safety from road users to designers and engineers of road systems. Today, the vision expressed by "Zero Vision" to improve traffic safety regardless of cost has been adopted by many countries. It is these joint efforts that make travel more and more safe.

As another important mode of transportation, railway safety is also an area that transportation scholars cannot ignore. Despite the declining trend, railway transportation is still an important option of transportation, especially in Europe, India, China, and even parts of the United States. Even in the United States, railways still play an important role as commuting tools in local areas. NJ Transit, which operates in New Jersey, has 32% of its passengers, and about 140,000 people commute between New Jersey and New York City on the NJTRANSIT rail network on weekdays. (NJ Transit, 2019) The safety of the railway is related to millions of passengers and those high cost of infrastructure.

As an emerging transportation mode, the emergence of High-Speed Rail has greatly improved the transportation efficiency and increased economic value of the railway network. Passengers move on the rails between cities at unprecedented speeds, which can reach three to four times the speed of the highway. In some regions, the emergence of High-Speed Rail as a market competitor has reduced the market share of aviation. The extension of railroad tracks, the expansion of the network, the surge in passengers, the significant reduction in travel time, but the hidden safety risks are also rising at the same time. Ten years after the September 11th incident, in 2011, the high-speed developing High-Speed Rail in China encountered its own September 11th incident. The two high-speed trains collided due to the failure of the signal system. The accident killed 40 people and injured 200 people. The economic loss is estimated to be 193,716,500 (RMB). (State Council of China, 2011) The pause button of China's High-Speed Rail construction has been pressed because of this accident, and also the operating speed of entire High-Speed Rail national network has been reduced by 50km / h in the next few years. Subsequently, Spain and Taiwan had successive High-Speed Rail accidents in 2013 (Karl Penhaul, 2013) and 2018 (Taiwan Railways Administration, 2019), the number of casualties exceeded 200. High-Speed Rail safety research is already an urgent need, and few articles have been published in academia.

Accident research is an important step to improve safety. The investigator found the cause and process of the accident through post-event investigation and analysis, and explored the possibility of improving safety, hoping to avoid similar accidents in future operations. Statistics play an effective tool in exploring the law of accident occurrence. The time, place, trend, accident damage, and accident cause of the accident can be found in the statistics. But Railways, especially High-Speed Rail, are a technically complex transportation system. In modern socially complex railway systems, the cause of accidents cannot be isolated as single human error or technical function failure, but a mixture of personnel, technology, machinery, equipment, policies, management, and environmental factors. Therefore, statistical analysis in the traditional sense can no longer meet the needs of new situations. Various types of accidents propose models has been explored to explain the cause of the accident, and the most widely used model is called the system accident model. Recently, complex network model that has been born out of one of the branches of mathematics, "graph theory", has been applied to the analysis of accident causes after improved by scholars. The combination of the system accident model and the complex network model is to the great benefit for the in-depth study of the cause of the accident, and for providing specific and targeted safety improvement suggestions.

1.2 Problem Statement

Railway (especially High-Speed Rail) safety research has been ignored for a long time. Known research is focused on level-crossing, but it can also be seen as part of traffic safety. After all, car damage is more serious in this type of accident. The safety of the railway is much better than road since the total number of road accidents is far more than railway accidents. But compared to the "zero vision" plan for road safety, the number of deaths on the rails is unacceptable. The Figure 1.1 shows the number of railway accident deaths in China and UK. UK has 250 of deaths due to railway accidents each year. (RSSB, 2019) China's railway safety is improving year by year, but nearly 900 people still die from railway accidents every year. (National Railway Administration, 2011-2018)

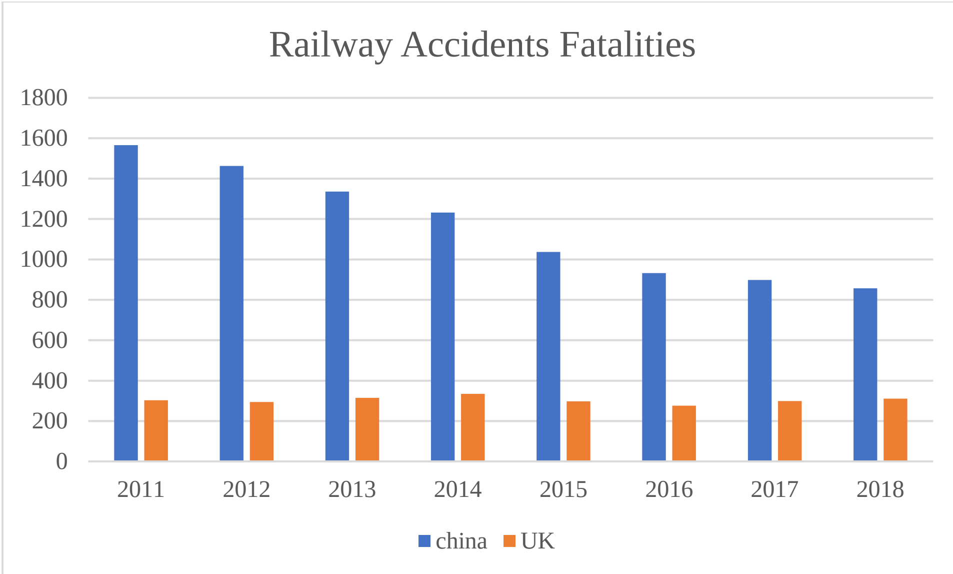


Figure 1.1 Statistics of railway deaths in China and U.K.

Source: China State Railway Group Company, Ltd. 2011-2018. UK National Railway Administration, 2011-2018.

The content of the chart shows that although the number of railway accidents is small, it does not mean that railway safety can be ignored. However, due to its nature of public transportation, a single accident may have profound impact on human lives, environment, and passenger perceptions. Especially with the development of High-Speed Rail, high-speed brings not only the reduction of travel time, but also the dangerous magnification. Table 1.2 lists the traffic accidents that have occurred since the operation of the High-Speed Rail. it is necessary to analyze accidents associated with High-Speed Rail operations, identify causing factors and reduce and eliminate any damage, if possible. This is what every country that operates High-Speed Rail and countries that want to develop this technology should be concerned about, and also transportation Security researchers cannot ignore the subject.

Table 1.2 High-Speed Rail Accident Cases

Year	Location	Accident	Fatalities	Injuries
1998	German-Eschede	Derailment	101	88
2011	China-Wenzhou	Collision	40	210
2013	Spanish-Santiago de Compostela	Derailment	79	140
2015	French-Eckwersheim	Derailment	11	42
2018	China-Taiwan	Derailment	18	215
2018	Turkey-Ankara	Collision	9	84

The rapid development of High-Speed Rail and the expanding network have led to an increasing number of stakeholders in safety research. As the latest development of railway technology, High-Speed Rail has become the mainstream development trend of the railway passenger transport market. Figure 1.2 summaries the High-Speed Rail develop plan around world. In continental Europe, the total length of High-Speed Rail in Spanish (ADIF, 2019) and France exceed 2500 kilometers, (Mengke Chen,2014) and the length of High-Speed Rail lines under planning / construction has reached thousands of kilometers. The United Kingdom is investing £ 56.6 billion in the construction of the High Speed 2 High-Speed Rail line, with a maximum speed of 400 kilometers per hour. The High-Speed Rail in Turkey, Thailand and India are all planned and are already under construction. (UIC, 2019) In addition to the Acela rapid train system, the United States is also building the first 800-mile High-Speed Rail to connect San Francisco and Los Angeles with an operating speed of 350 kilometers per hour. (California High-Speed Rail Authority, 2008)

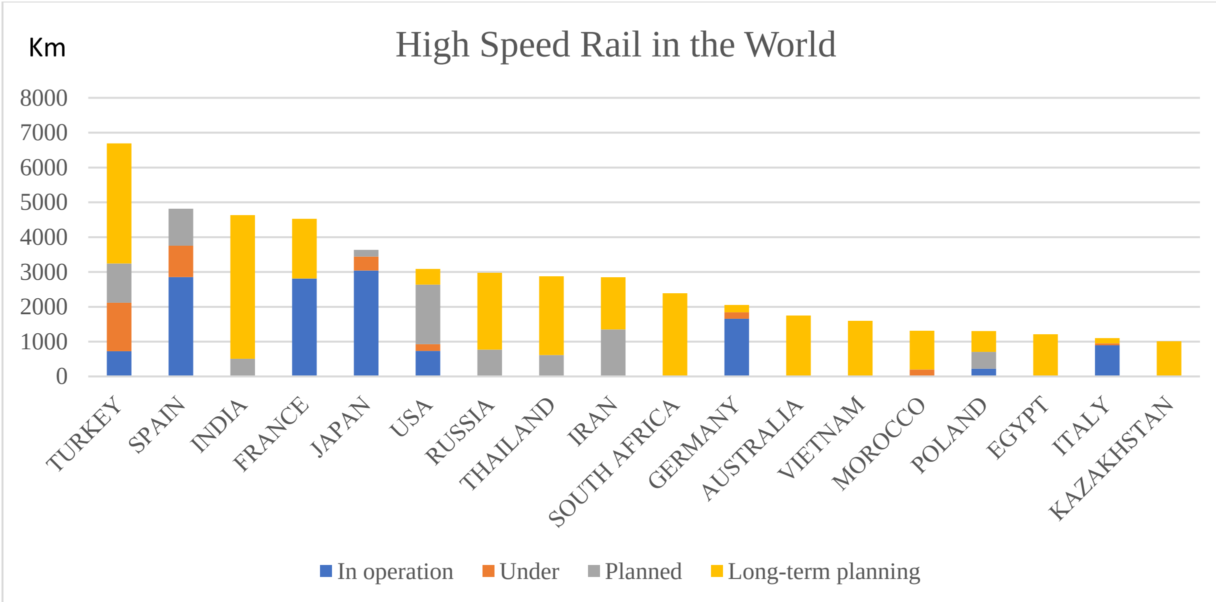


Figure 1.2 High-Speed Rail development and planning development in countries around the world.

In China, the country with the largest High-Speed Rail network in the world, more than half of the passenger capacity has been occupied by High-Speed Rail of the entire railway network. This shows the trend of China's High-Speed Rail mileage and passenger capacity from 2013 to 2018. (National Railway Administration, 2014-2019) The land on which thousands of kilometers of High-Speed Rail lines are located, fixed asset investments starting at tens of billions of dollars, are as safe stakeholders as the passengers on the train. Especially in the capital market, High-Speed Rail has become an important asset of listed companies. The Shinkansen of Japan completed the IPO as early as 1997. The Beijing-Shanghai High-Speed Rail, China's busiest High-Speed Rail line, completed the IPO in 2019 with a market value of more than 300 billion (RMB) (Figure 1.3). The success of the IPO indicates that the value of the High-Speed Rail has been recognized by the market, but it also means that the operator needs to minimize the accident rate of the railway operation, because any accident will affect the rights and interests of the operator directly.

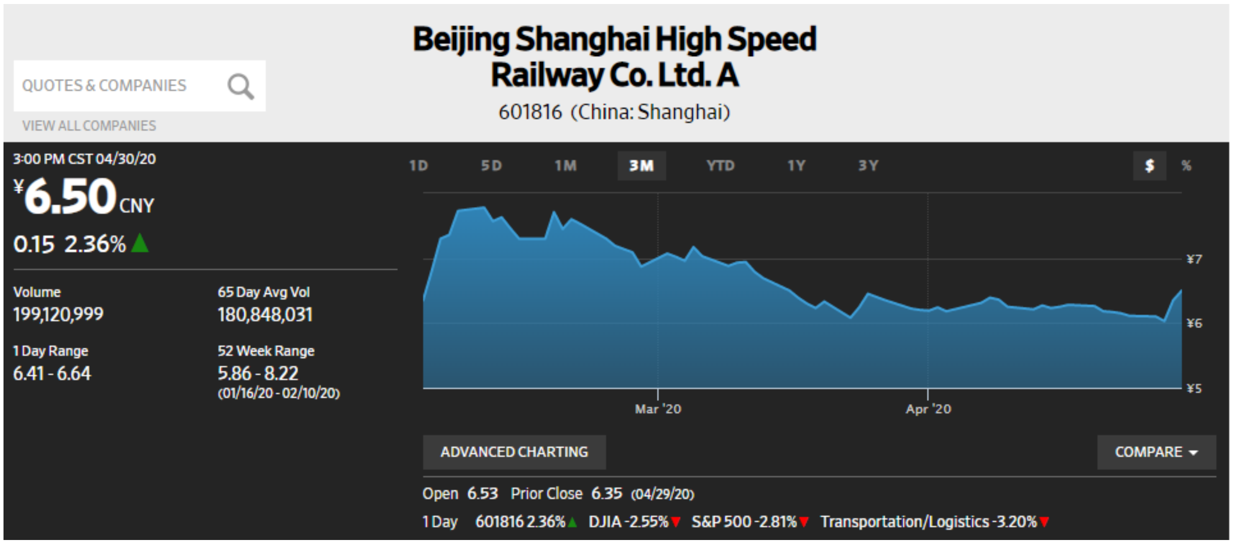
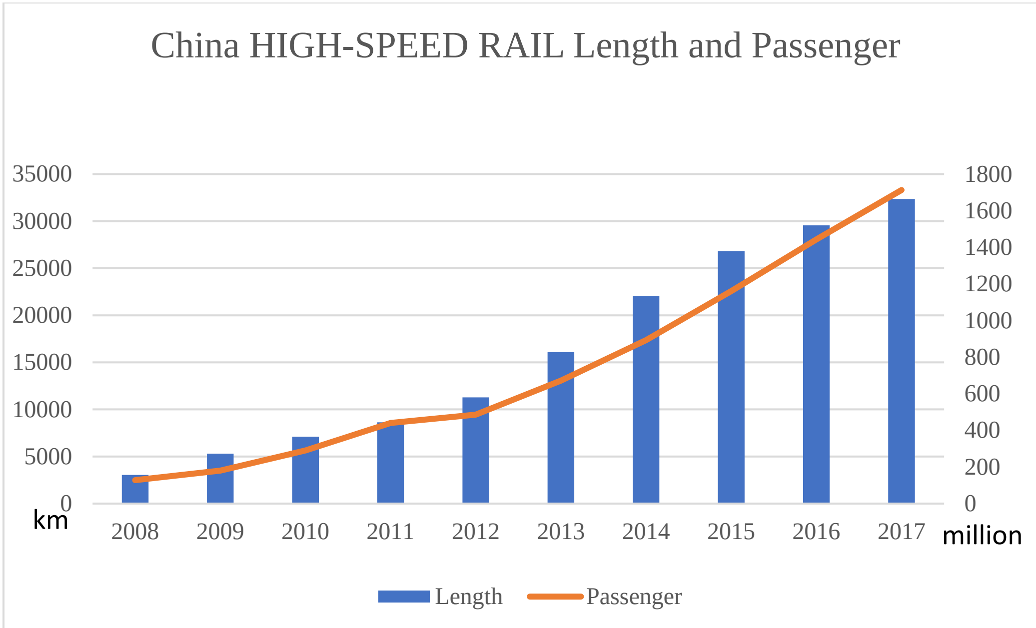


Figure 1.3 Beijing-Shanghai High-Speed Rail stock information.

Source: Wall Street Journal, 2020.

Although the development of High-Speed Rail is so rapid, the safety research around High-Speed Rail is still lacking. Some studies are directed at specific accidents, such as the 7.23 train collision accident in China, but there is little overall research on the safety characteristics of High-Speed Rail. In particular, there is no study comparing High-Speed Rail with traditional railways. We need to know what are the unique characteristics of High-Speed Rail accidents compared to traditional railways, and where are more accidents occurring? Is it a station or a line? Bridge or tunnel? What happened to the cause of the accident? Which factor is more important, human factors and machinery? Are the traditional management and risk control mechanisms still effective? Does the traditional maintenance policy need to be changed? These are the problems that researchers need to solve.

China is a good case to study the safety characteristics of traditional railways and High-Speed Rail. China's High-Speed Rail developed later compared to Japan and Germany. In 2008, China's first real High-Speed Rail began to operate before the opening of the Olympic Games. Today China has built the largest High-Speed Rail network with more than 32,000 kilometers of tracks and transported more than 1.73 billion passengers yearly during the past decade. (Figure 1.4) As a widely accepted human feat, the High-Speed Rail development has not only propelled China into the leadership position in railway transport but also state led technology transferring processes, not to mention the vast improvement to the travel conditions in China. At the same time, China also maintains the world's largest electrified railway network. There are 3.375 billion passengers per year, of which High-Speed Rail accounts for 2/3. As a large-scale network that has both conventional and High-Speed Rail, we can call it a hybrid network, and in a country with two modes of rapid transition, China can as an excellent case for observing the security features of a hybrid railway network.



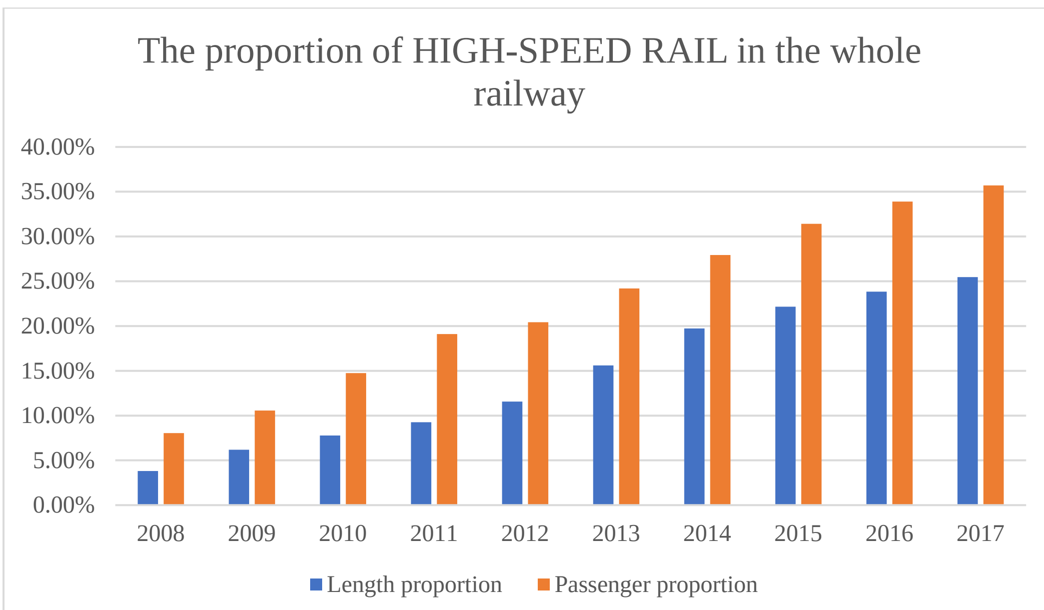


Figure 1.4 China High-Speed Rail development chronology.

Source: China State Railway Group Company, Ltd. 2019.

Knowledge in academia also needs to be reviewed under new conditions. Traditional statistical methods, system control theory, and other qualitative and quantitative analysis tools all require new case evidence. There have been scholars analyzing the medical complex network theory in railway accidents, but they are all analyzing regular railway accidents and lack of High-Speed Rail accidents. Moreover, the degree of accident injury is not taken into account by the original theoretical analysis tools, which is also the potential for the theoretical development of research tools.

1.3 Objective and Work Scope

The objective of the study is to use High-Speed Rail accidents in China as a case study, use complex network models to study the main causes of High-Speed Rail accidents, discover the safety risks in High-Speed Rail operations, and hope to help to improve the safety of High-Speed Rail, those operating worldwide Under construction and planning.

The scope of the study is mainly based on accidents in the Chinese railway network, and the geographical scope is limited to the three southern provinces: Guangdong, Hunan, and Hainan. The time frame of the accident is five years, 2013-2017.

1.4 Organization

The dissertation is divided into eight chapters. Chapter 1 emphasizes the importance of railway safety as background knowledge, and introduces the problems of railway (and High-Speed Rail) safety research. Chapter 2 summarizes the current research achievements of High-Speed Rail, especially safety research. The history of accident research and the application of complex network models in accident research are also introduced. Chapter 3 introduces the dual-weighted complex network model. Chapter 4 explains the reasons why the case study chooses Chinese railways, and gives an overall description of the data collected. Chapter 5 records the establishment process of DWCN. Chapter 6 analyzes the mathematical characteristics of the network. Chapter 7 discusses the major safety hazards of China Railways and High-Speed Rail. Chapter 8 summarizes the research results and future research.

CHAPTER 2

LITERATURE REVIEW

This chapter reviews the literature on High-Speed Rail and safety research. The first part reviews the main achievements of High-Speed Rail research, and the second part reviews the development of traffic safety research theory and mainstream analysis models. Then the development of complex network model theory and its application in traffic safety research have been reviewed.

2.1 Safety Research

As stated by USDOT, Safety is the Department of Transportation 's (DOT) highest priority. Similarly, security research is also the most important subject in academia. In the TRID database, more than 5000 articles about traffic safety are included every year. This figure only counts articles published in English. Research in the field of security has a long history, according to Zobair and KazuhikoAn (2017) who summarized the history of accident theory is classified into the following categories:

1. Statistical analysis and trends
2. Risk analysis
3. Domino theory
4. Epidemiologic theory
5. Control and system theoretic models

2.1.1 Statistical Analysis and Trends

Because of the nature of accident analysis, research is only possible after an accident has occurred. Data analysis, as the most basic scientific research method, exists throughout the history of accident research. From Vernon, who first applied statistical analysis to industrial accident analysis, to the latest complex network accident analysis model, statistical characteristics not only show the frequency of accidents under different time and space conditions, but also allow researchers to find out the occurrence of accidents depends on various factors such as internal and external factors (Vernon, 1918).

2.1.2 Risk Analysis

Through the development of statistical methods, Watson (1961) introduced the fault tree analysis (FTA) method to accident analysis. The so-called fault tree analysis method is to set certain risk control options (RCO) to quantify certain risk values. Through deductive analysis of known types of faults, understand how the system fails, determine the accident rate at different levels and find the best way to reduce risk. The emergence of fault tree analysis methods has made risk analysis popular in accident analysis. The main disadvantage of quantitative risk analysis is that it is impossible to predict how an accident will occur, so researchers in accident analysis have found another research method, domino theory.

2.1.3 Domino Theory

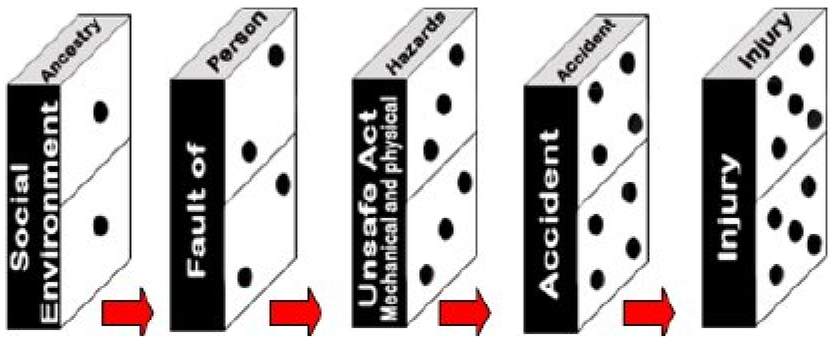


Figure 2.1 Accident development process at Domino Theory.

Source: Heinrich, 1931.

Domino's metaphor is very visual and intuitively points out that the accident is not isolated, but the result of a series of events. Heinrich (1931) likened the process of accidents to five categories: ancestry and social environment, personal fault, unsafe act, accident and injury. Dominoes metaphorically describes the logical relationship between social environment and personal factors in an accident. The diagram at Figure 2.1 clearly shows this relationship.

In the first version of this model, published in 1931, the five factors identified were:

1. Domino 1: ancestry and the worker’s social environment, which impact the worker’s skills, beliefs and “traits of character”, and thus the way in which they perform tasks
2. Domino 2: the worker’s carelessness or personal faults, which lead them to pay insufficient attention to the task (see box about “accident-proneness” theory)

3. Domino 3: an unsafe act or a mechanical/physical hazard, such as a worker error (standing under suspended loads, starting machinery without warning…) or a technical equipment failure or insufficiently protected machinery
4. Domino 4: the accident
5. Domino 5: injuries or loss, the consequences of the accident

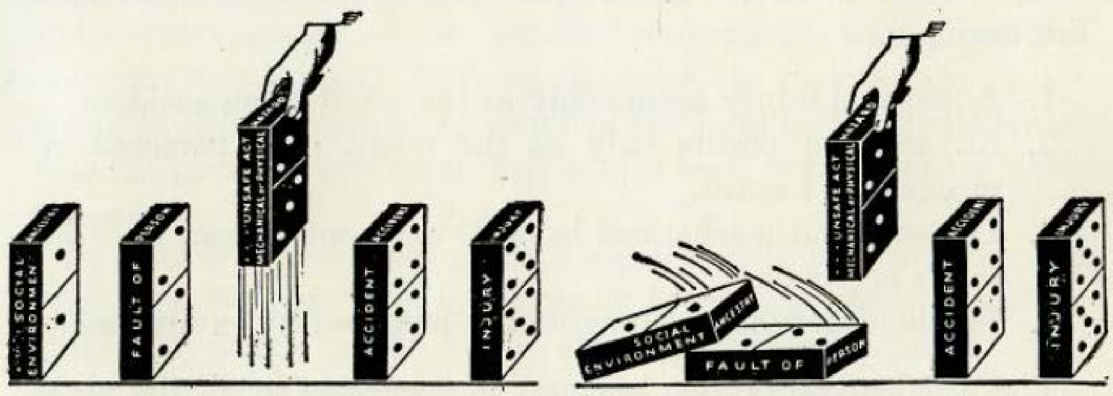


FIG. 4. The unsafe act and mechanical hazard constitute the central factor in the accident sequence.

FIG. 5. The removal of the central factor makes the action of preceding factors ineffective.

Figure 2.2 Accident prevention method based on Domino Theory.

Source: Heinrich, 1931.

Domino theory also intuitively provides a way to organize accidents: cut off the event transmission chain, as shown in the Figure 2.2.

The disadvantage of this model is that it is too simple for today's generally complex technology and organization to be a useful tool to help understand the cause of the accident. It uses a purely linear and mechanical model of causality, which is inappropriate in complex systems. In complex systems, accidents are usually caused by many interacting, partially competitive and unpredictable factors.

2.1.4 Epidemiologic Theory

Epidemiological theory is designed to explain infectious diseases and the environment, but has been extended to accident research. The theory focuses on causality between environmental factors and accidents. The theory assumes that if accidents are public health problem, safety issues can be addressed in ways and techniques that have proven useful for large-scale disease problems. The theory is that the cause of the accident was found to exist in agents, hosts and the environment. As show in the Figure 2.3. Haddon (1968) proposed a two-dimensional matrix in 1968 to determine the chronological order of hosts, pathogens, and environmental factors and to help determine preventive measures. (Table 2.1) The diagram shows the basic structure of the matrix: rows equivalent to the event phase and columns representing the epidemic triad of the host, pathogen, and environment. Pre-accident and accident units are full of factors contributing to the accident or potential factors of the expected accident. Controls that help prevent similar incidents are described in the cells after the incident. The matrix provides a tool that can be used to motivate people to think about the vulnerabilities and triggers that led to an event, or to develop a prevention strategy.

Table 2.1 Diagnostic Tool Based on Epidemiological Theory

	Host/personal factors	Agent/vector factors	Physical environment factors	Social environment factors
Pre-incident				
incident				
Post-incident				

Source: Haddon, 1972.

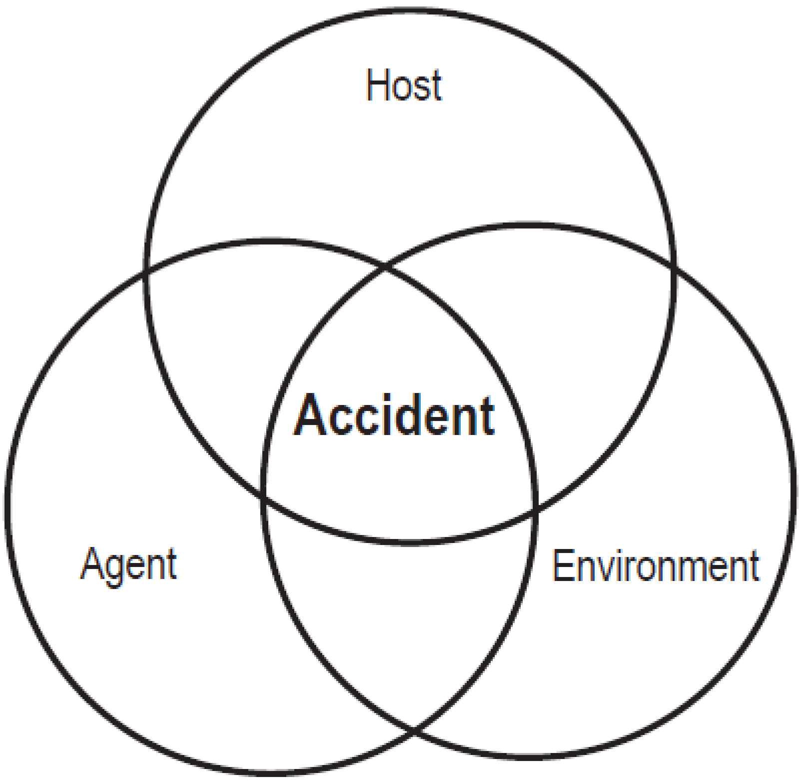


Figure 2.3 Relationship between host, agency and environment.

Source: Haddon, 1972.

2.1.5 Control and System Theoretic Models

Control theory is mainly used in complex dynamic systems. Because the external input of the system is in an unstable state, the system needs to process the input by controlling internal variables, so that the system output is stable and in line with expectations.

Since the Industrial Revolution, especially since the 1970s, the complexity of technology and organization has grown exponentially. Computers, CNC machine tools, and other large mechanical / electronic equipment have tens of thousands of parts. Large Stella organizations such as multinational companies have also reached the highest level of human knowledge in terms of business scope and geographical span. Taking into account the complex inside the system interactions (technical or organizational) and a large number of unavoidable accidents, Perrow (1984) proposed a term "normal accident" as a characteristic of the system.

2.1.6 FRAM Model

Through the study of complex systems, people began to think that failure and success have the same root cause. The functional resonance analysis method or FRAM (Hollnagel, 2004 and 2012) provides a method to describe the results. This method uses the concept of resonance: Unstable and gradually increasing resonance of performance. FRAM analysis includes five basic steps:

1. Identify and describe basic system functions.

2. Check the model for completeness or consistency.

3. Describe the potential variability of functions in the FRAM model.

4. Functional resonance is defined in terms of dependencies / couplings between functions and the possibility of mutation.
5. Identify methods for monitoring resonance development to control system development.

The spirit of FRAM is the following four basic principles:

1. The Principle of Equivalence of Successes and Failures

The theory believe that things go right and wrong in basically the same way. The fact that the outcomes are different does not mean that the underlying processes must be different.

2. The Principle of Approximate Adjustments

Many systems are complex, and the operating conditions will not always be stable in a state that perfectly meets the needs. Therefore, individuals and organizations usually adjust their performance to meet existing conditions. This adjustment makes performance and system conditions in a state of approximate adjustment, so the system will produce correct or wrong outputs.

3. The Principle of Emergence

The variability of normal performance is rarely enough to cause an accident, but the variability of different components may overlap in various ways leading to a sharp increase in non-linearity. Therefore, differences in system output cannot be predicted or explained by studying the performance of specific components.

4. The Principle of Functional Resonance

The variability of one function is affected and enhanced by another function, which is called resonance in machinery. The existence of resonance can abnormally increase the variability of a function, and this increase is not a simple causal relationship or a linear superposition relationship.

Overall, FRAM provides a comprehensive understanding of the system's work, emphasizing a more comprehensive perspective than previous research methods. But as a qualitative method, quantitative analysis cannot be performed, which is the disadvantage of this theory.

2.1.7 STAMP Model

The core of STAMP theory is the control and feedback loop composed of constraints. It believes that the occurrence of the accident is due to the loss of control (such as technology, engineering, management or organization, etc.) and the constraint failure in the feedback loop. As shown in the Figure 2. 4 is a basic control and feedback loop.

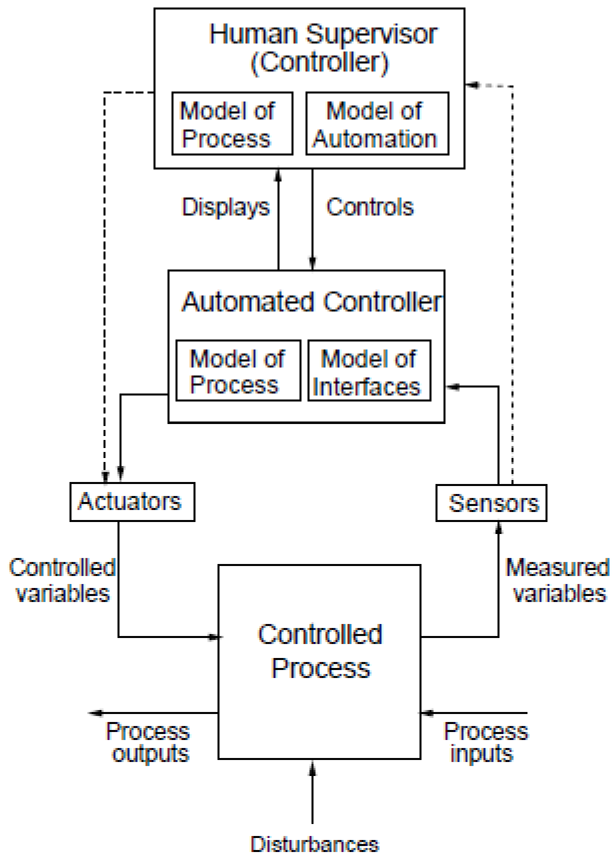


Figure 2.4 Control and feedback loop at STAMP Model.

Source: Leveson, 2011.

The basic concept of STAMP is to model the system structure, then identify the control and feedback loops related to safe operation, and then determine which controls and which constraints have failed to cause the accident, which means that the safe operation has lost control. As shown in the Figure 2.5, the control structure of STAMP is divided into two models at two levels, one for system development and one for operation. Constraints can be existing constraints (such as environmental or financial constraints) or external constraints (such as regulations) introduced.

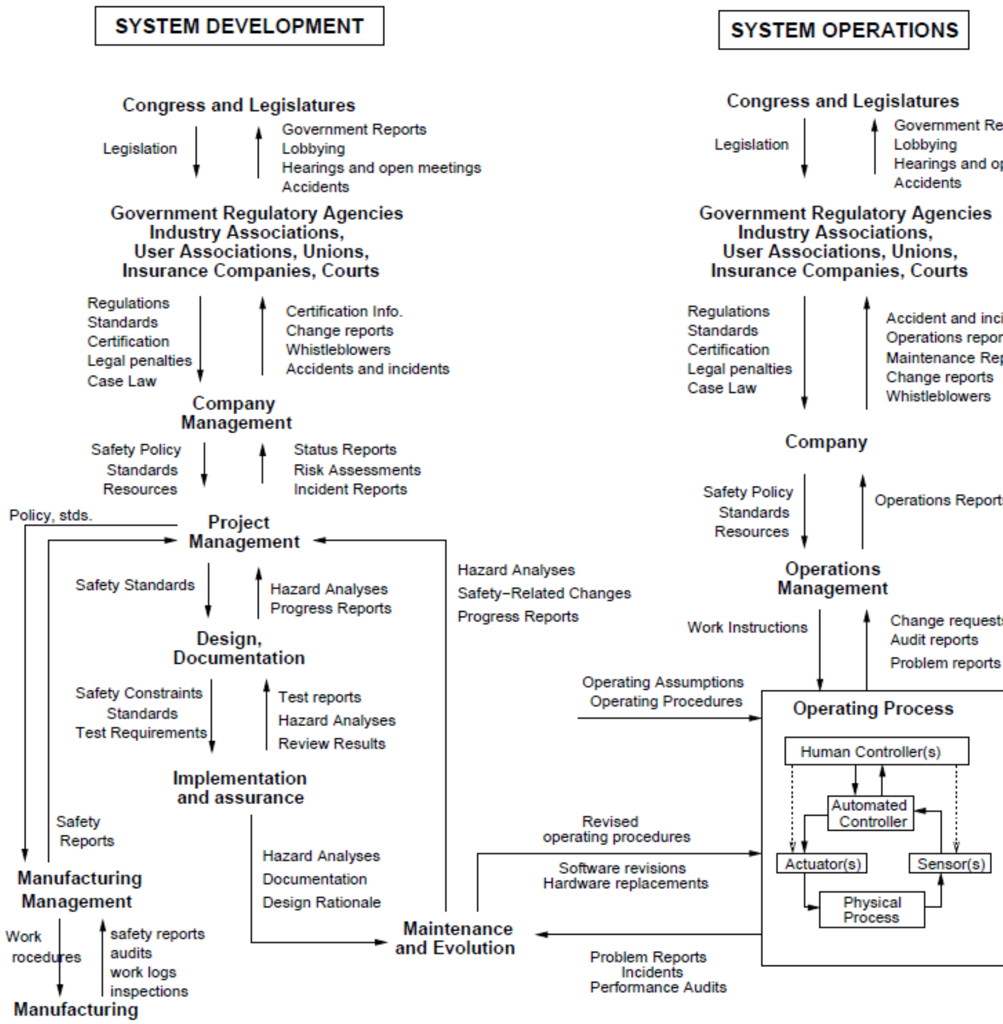


Figure 2.5 Two levels for STAMP Model.

Source: Leveson, 2011.

2.2 Complex Network Model

Complex network theory is a new and vital theory. The foundation of a complex network is the network topology in mathematics. Topology is the mathematical nature of a network that does not depend on the location of nodes and the specific shape of edges. It also means that topology only focuses on whether there are edges connected between nodes in the network, and ignores the position of nodes and the length, shape, and whether edges intersect with each other. Traditional mathematicians use the grid in Euclidean geometry to simulate the relationship of various factors in the system, and there are fixed connections between the nodes.

2.2.1 Random Network

The Erdős–Rényi model published in 1959 established the ER model. The model G (n, M) (Erdős and Rényi, 1959) or G (n, p) (Edgar Gilbert, 1959). The former indicates that n points and M edges form a network G, and the latter indicates that n points interact with each other with a probability of P. connection. The model simulates a random network structure, but the problem is that the connection probability of nodes in the actual network is not fixed. Moreover, the clustering coefficient in the ER model is low.

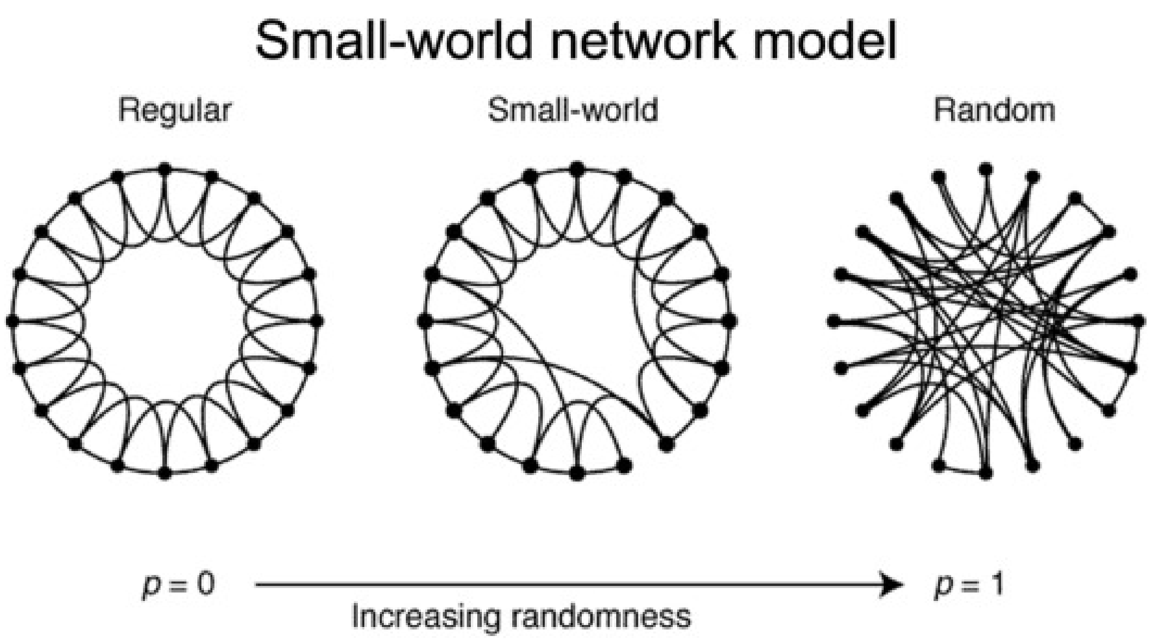


Figure 2.6 Different between regular and Random Network.

Source: Xuhong Liao, 2017.

2.2.2 Small World Network

In 1998, Watts and Strogatz established a small-world model, which also has a smaller average shortest path length and a high clustering coefficient. In reality, many networks conform to the characteristics of the small world model. For example, the WWW network can be regarded as a small world network composed of computers (nodes) and network cables (edges) (Watts D J, 1998). Similar networks include electric power network (Faloutsos M, 1997), social relationship network (Hofman J M, 2017), transportation network (Preston, 2015), neural network (Huang, 2019), etc.

Network	Size	$\langle k \rangle$	ℓ	ℓ_{rand}	C	C_{rand}	Reference	Nr.
WWW, site level, undir.	153,127	35.21	3.1	3.35	0.1078	0.00023	Adamic 1999	1
Internet, domain level	3015 - 6209	3.52 - 4.11	3.7 - 3.76	6.36 - 6.18	0.18 - 0.3	0.001	Yook *et al.* 2001a, Pastor-Satorras *et al.* 2001	2
Movie actors	225,226	61	3.65	2.99	0.79	0.00027	Watts, Strogatz 1998	3
LANL coauthorship	52,909	9.7	5.9	4.79	0.43	1.8×10^{-4}	Newman 2001a,b	4
MEDLINE coauthorship	1,520,251	18.1	4.6	4.91	0.066	1.1×10^{-5}	Newman 2001a,b	5
SPIRES coauthorship	56,627	173	4.0	2.12	0.726	0.003	Newman 2001a,b,c	6
NCSTRL coauthorship	11,994	3.59	9.7	7.34	0.496	3×10^{-4}	Newman 2001a,b	7
Math coauthorship	70,975	3.9	9.5	8.2	0.59	5.4×10^{-5}	Barabási *et al.* 2001	8
Neurosci. coauthorship	209,293	11.5	6	5.01	0.76	5.5×10^{-5}	Barabási *et al.* 2001	9
E. coli, substrate graph	282	7.35	2.9	3.04	0.32	0.026	Wagner, Fell 2000	10
E. coli, reaction graph	315	28.3	2.62	1.98	0.59	0.09	Wagner, Fell 2000	11
Ythan estuary food web	134	8.7	2.43	2.26	0.22	0.06	Montoya, Solé 2000	12
Silwood park food web	154	4.75	3.40	3.23	0.15	0.03	Montoya, Solé 2000	13
Words, cooccurence	460.902	70.13	2.67	3.03	0.437	0.0001	Cancho, Solé 2001	14
Words, synonyms	22,311	13.48	4.5	3.84	0.7	0.0006	Yook *et al.* 2001	15
Power grid	4,941	2.67	18.7	12.4	0.08	0.005	Watts, Strogatz 1998	16
C. Elegans	282	14	2.65	2.25	0.28	0.05	Watts, Strogatz 1998	17

Figure 2.7 Network sample for Small World Network.

Source: Reka Albert, Albert-Laszlo Barabasi, 2002.

Jon Kleinberg developed the W-S-K model based on the W-S model, and introduced the q coefficient (clustering exponent) to control the connection between nodes and the distance between nodes. The model is used to search for the shortest path, such as information transfer and message delivery in social networks.

2.2.3 Scale Free Network

Albert-László Barabási found that the degree distribution of the WWW network has a certain rule: as the degree increases, the probability of node degree is lower. In this regard, Barabási established the scale free model (Barabási, 2002), in which the degree of the network conforms to the power rate distribution. Epidemiology uses this theory to develop different immunization strategies. (Reuven Cohen, 2003) The scale free network actually provides a dynamic and complex network analysis method. Generally, the evolution of the network includes adding nodes, adding edges, reconnecting, reducing nodes, and reducing edges. Therefore, after considering the effect of time changes on the network structure, Krapivsky proposed a model to observe the changes of the network using the power exponent changes in the network. (P.L. Krapivsky, 2000)Albert and Barabási's second Scale Free network mechanism model (2000) considers three events: adding points, adding edges, and reconnecting. The research results show that both power rate distribution and exponential distribution can appear in the network.

Network	Size	$\langle k \rangle$	κ	γ_{out}	γ_{in}	ℓ_{real}	ℓ_{rand}	ℓ_{pow}	Reference	Nr.
WWW	$325,729$	4.51	900	2.45	2.1	11.2	8.32	4.77	Albert, Jeong, Barabási 1999	1
WWW	4×10^7	7		2.38	2.1				Kumar *et al.* 1999	2
WWW	2×10^8	7.5	$4,000$	2.72	2.1	16	8.85	7.61	Broder *et al.* 2000	3
WWW, site	$260,000$				1.94				Huberman, Adamic 2000	4
Internet, domain*	$3,015$ - $4,389$	3.42 - 3.76	$30 - 40$	2.1 - 2.2	2.1 - 2.2	4	6.3	5.2	Faloutsos 1999	5
Internet, router*	$3,888$	2.57	30	2.48	2.48	12.15	8.75	7.67	Faloutsos 1999	6
Internet, router*	$150,000$	2.66	60	2.4	2.4	11	12.8	7.47	Govindan 2000	7
Movie actors*	$212,250$	28.78	900	2.3	2.3	4.54	3.65	4.01	Barabási, Albert 1999	8
Coauthors, SPIRES*	$56,627$	173	$1,100$	1.2	1.2	4	2.12	1.95	Newman 2001b,c	9
Coauthors, neuro.*	$209,293$	11.54	400	2.1	2.1	6	5.01	3.86	Barabási *et al.* 2001	10
Coauthors, math*	$70,975$	3.9	120	2.5	2.5	9.5	8.2	6.53	Barabási *et al.* 2001	11
Sexual contacts*	2810			3.4	3.4				Liljeros *et al.* 2001	12
Metabolic, E. coli	778	7.4	110	2.2	2.2	3.2	3.32	2.89	Jeong *et al.* 2000	13
Protein, S. cerev.*	1870	2.39		2.4	2.4				Mason *et al.* 2000	14
Ythan estuary*	134	8.7	35	1.05	1.05	2.43	2.26	1.71	Montoya, Solé 2000	14
Silwood park*	154	4.75	27	1.13	1.13	3.4	3.23	2	Montoya, Solé 2000	16
Citation	$783,339$	8.57			3				Redner 1998	17
Phone-call	53×10^6	3.16		2.1	2.1				Aiello *et al.* 2000	18
Words, cooccurence*	$460,902$	70.13		2.7	2.7				Cancho, Solé 2001	19
Words, synonyms*	$22,311$	13.48		2.8	2.8				Yook *et al.* 2001	20

Figure 2.8 Network sample for Scale Free Network.

Source: Reka Albert, Albert-Laszlo Barabasi, 2002.

2.2.4 Application

Luo (2013) introduced the complex network model into the analysis of railway accidents. The original work is that the author provides a method to convert the railway accident into a network. As shown in the following figure, the levels include the organization (national level and local level), technology, staff and equipment of China's High-Speed Rail. The author analyzed the statistical characteristics of the network and found the key factors of the accident.

Table 1: Causation factors of the 7.23 China Yongwen railway accident [30].

Ministry of Railways	A1: seek quick success and benefits; A2: week management and incomplete rule standards; A3: unclear job responsibilities and functions; A4: inadequate inspection and supervision for Shanghai Railway Bureau.
Department of Technologies, Foundation Department, Science and Technology Division CRSC	B1: lack of careful supervision on the bidding of the equipment in Hening-Hewu Yongwen line train control center; B2: poor management of the operation on new products; B3: not enough examination of the LKD2-T1; B4: without clear regulations on the technical review; B5: no valid or regular technical prereview on the equipment LKD2-T1 for train control center; B6: illegal approval from the Science and Technology Division approved to use the LKD2-T1; B7: inadequate inspection and supervision of the quality management by CRSC; B8: little supervision or inspection from CRSC who fully transmit the project to the local design institute; B9: cursory decision on the bidding for the Hening-Hewu line control equipment; B10: unware of the illegal change of version of the train control center equipment in Hefei station.
Shanghai Railway Bureau and the signaling design institute	C1: not enough safety education and training; C2: not sufficient inspection and supervision; C3: not sensitive safety awareness; not efficient measures to avoid or alleviate the accident; C4: not appropriate accident handling; C5: unwise decision on update of the LKD2-T1; C6: lack of the technical review on the development of the equipment for train control center; C7: lack of responsibility on scientific research management and inefficient control and supervision of the local companies on the product quality.
Vehicle depot, electricity depot, engineering system and train control institute	D1: poor travel management and emergency handling; D2: not efficient supervision on the safety production management and train service work; lack of supervision to Wenzhou south station; D3: poor supervision on the dispatching institute and the vehicle depot system; D4: insufficient education and training for the staff; D5: lack of job responsibilities of the electricity emergency management; D6: cursory design of the equipment LKD2-T1; D7: poor equipment research and development management in the train control center; D8: the redesign of the equipment LKD2-T1 by the train control institute.
The attendants' behaviors and process	E1: failure of following further situation of red band by the dispatcher in Shanghai Railway Bureau ; E2: careless monitoring on the situation of D3115; E3: no reminder of the emergency to D301; E4: no in time contact with the D301 driver; E5: no record of the circuit failure of the 5829AG; E6: no record of the replacement of some equipments of the track circuit besides 5829AG; E7: illegal behaviors; E8: the mistake to inform D3115 to switch to the visual driving mode if the signal was red; E9: D3115 stopped by the ATP; E10: D3115 failed to drive in visual mode 3 times; E11: D3115 failed to report to the dispatcher; E12: D3115 switched to the visual driving mode but still in the 5829AG; E13: D301 left Yongjia station; E14: D301 rear-ended D3115; E15: illegal to open the protection net for work.
Equipment and environment	F1: the damage of 4 sender boxes; F2: the damage of 2 receiver boxes; F3: the damage of 1 attenuator; F4: the fuse of F2 in LKD2-T1; F5: the design flaw in PIO of LKD2-T1; F6: the activation of ATP on the D3115; F7: thunder strike; F8: failure of the ATP on D301 which did not take any action; F9: the reduction of CAN total resistance; F10: unavailable communication between 5829AG and the train control center; F11: wrong displays on the terminal; F12: abnormal track circuit signal; F13: a red band; F14: wrong signal which maintained green for the faulted track section; F15: the sending of the unoccupied signal to D301.

Figure 2.9 Coding method for causation network.

Source: Luo, 2013.

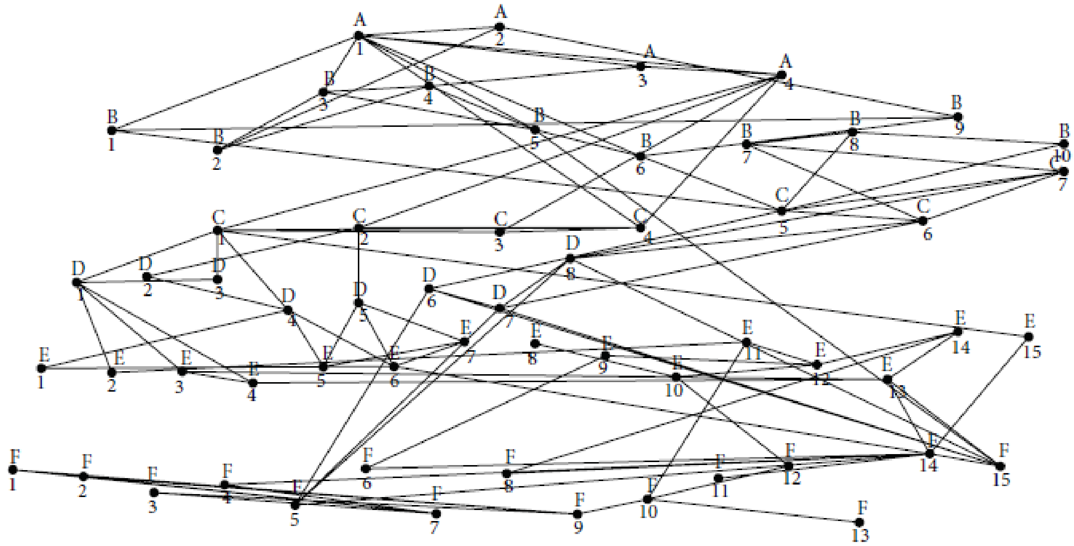


Figure 2.10 Coding method and undirected network based on “7.23 Railroad Accident”.

Source: Luo, 2013.

Compared to Luo, it uses an undirected network model, Liu established directed weighted accident causation network (DWACN) for the Rail Accident Investigation Branch (RAIB) in the UK, (Figure 2.10) which is based on complex network and using event chains of accidents. DWACN is composed of 109 nodes which denote causal factors and 260 directed weighted edges which represent complex interrelationships among factors. The statistical properties of directed weighted complex network are applied to reveal the critical factors, the key event chains and the important classes in DWACN. Analysis results demonstrate that DWACN has characteristics of small-world networks with short average path length and high weighted clustering coefficient, and display the properties of scale-free networks captured by that the cumulative degree distribution follows an exponential function. This modeling and analysis method can assist us to discover the latent rules of accidents and feature of faults propagation to reduce accidents.

This research is a further development of accident analysis methods using complex network.

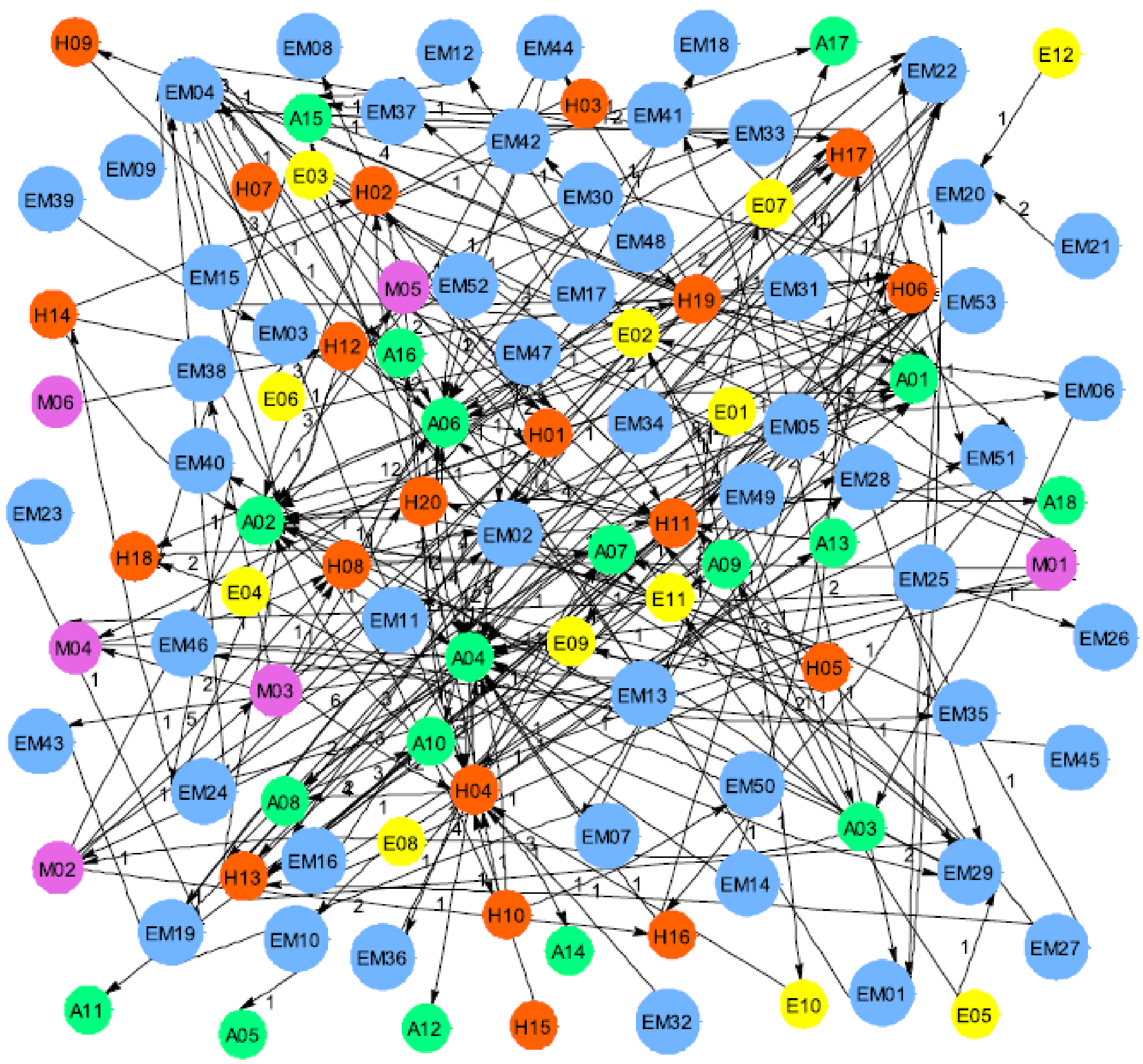


Figure 2.11 Directed causation network for accidents analytics.

Source: Zhou, 2015.

2.3 High-Speed Rail Study

2.3.1 General Study

Up to now, the research on High-Speed Rail has mainly focused on the economic field, such as the return on investment problem, competition with other travel modes, and the impact of High-Speed Rail on the regional economy.

Return of investment (ROI)

Return on investment is a concern of almost all countries and institutions, which is the key to the success of infrastructure. An important reason why most countries, including the United States, have not replaced traditional railways with High-Speed Rail is the high investment. According to the World Bank ’s research, the construction cost of High-Speed Rail per kilometer is as high as 145 million euros, even in China, which has the lowest cost, also reached 15.4-20.6 million US dollars per kilometer. (Osakar Herics, 2018) Risk analysis is necessary. For example, Thibaut LIMON, Yves CROZET, after evaluating different discount rates and risk factors in the evaluation of the South West High-Speed Rail project in France, the NPV value of the project changed from 735 million euros to -1.298 billion euros. This means that the economic value of the project needs to be reviewed. The research of Liu and Lv provides the ROI data of China ’s first High-Speed Rail, according to the research. Liu and Lv studies the investment-return of Beijing-Tianjin High-Speed Rail, and adopts a systematic analysis approach, which made connections between life cycle costs, revenues and ridership. After testing a number of life cycle scenarios, the authors have developed ridership potential and associated fare policies. The analysis results show that investments in High-Speed Rail will receive adequate returns when the investment recovery period and life expectancy of High-Speed Rail are linked and fare structures correspond to the demographic and social economic status of the travelers along the corridors.

Both Christian and Liu's research provide examples of the country's support for the development of High-Speed Rail. In Italy, the government provides support through massive public funding and special regulations, while in China, government-led technology transfer and the state-owned economy dominate the development of High-Speed Rail. This proves that safe and adequate financial support is the key to the success of the High-Speed Rail project.

Economic Impact

The economic impact of High-Speed Rail is mainly reflected in the tourism and aviation industries. Thanks to the European Structure and Investment Fund (ESIF), Spain has the world's second-highest railway construction plan after China. Even after experiencing its worst High-Speed Rail accident in 2014, Spain still plans to expand its High-Speed Rail network to 10,000 kilometers by 2020. It is the economic growth and the movement of people brought by High-Speed Rail driving the construction of Spain's High-Speed Rail network. Spain ’s tourism industry accounts for 16% of GDP. The impact of High-Speed Rail on tourism has attracted the attention of many scholars. B. Guirao take Spanish case study try to figure out the High-Speed Rail impact for tourism, author analysis 13 province via econometric model. For domestic travelers, the only provinces where there seems to be a relation between High-Speed Rail and the number of tourists is Guadalajara and Cuenca. The reason of few article is that there is only one data resource which from hotel, that maybe misleading the research finding: the main advantage for traveler take

High-Speed Rail is able to save money at overnight, that means part of travelers' number may be missed.

Francesca Pagliara developed a Revealed Preference survey at four famous tourist places at Madrid. Based on the survey data collected, authors calibrate two models via logistic regression approach to find out the relation between High-Speed Rail and tourists' destination choices. Depends on some characteristics of the Madrid tourism market and Spanish High-Speed Rail lacking contact with EURO railway network, the influence of High-Speed Rail is especially reflected in international tourists.

Table 2.2 High-Speed Rail Impact on Tourist Choice

High Speed Rail as a crucial factor influencing the choice of revisiting Madrid

YES	41.1%		
NO	58.9%		
MOTIVATIONS	1st CHOICE (%)	2nd CHOICE (%)	3nd CHOICE (%)
LESS TRAVEL TIME	65.8	12.5	7.4
ACCESSIBILITY OF THE DEPARTURE/ARRIVAL STATION	7.0	13.8	11.6
FREQUENCY OF SERVICE	0.5	9.4	8.3
LESS COSTLY	3.5	10.6	5.0
VISITING OTHER CITIES LINKED BY HSR	12.1	11.3	15.7
SAFETY	0.5	12.5	13.2
ENVIRONMENTALLY FRIENDLY	1.5	6.9	5.0
COMFORT	8.5	23.1	32.2
OTHER	0.5	0.0	1.7

Source: Francesca, 2017.

Table 2.2 shows the international tourists value aspects such as comfort and travel time reductions, and are generally less sensitive to ticket prices. The research has made it clear that other significant motivation for choosing High-Speed Rail is the possibility to visit nearby cities accessible by high-quality means of transport.

High-Speed Rail also have an impact on the aviation industry. This impact is confined to the region, cross-border and long-distance routes are less affected. The impact of the aviation industry also includes lower fares and fewer flight frequencies. The advantage is that the High-Speed Rail can also help the airline's network to cover more fringe markets. Wenyi Xia and Anming Zhang conducted a deeper study of the connecting market and found that the cooperation between High-Speed Rail and airlines increased the connecting market fare. Angela Stefania Bergantino, Leonardo Madio studied the impact of socio-economic factors on travelers ’choices between High-Speed Rail and aviation based on data from Italy, and found that High-Speed Rail customers increase with age, income, and education. And passengers for business travel are more inclined to take the High-Speed Rail.

2.3.2 High-Speed Rail Safety

In the railway safety research field, plenty of works have been published which can be divided into two aspects: causation modeling, and accident prediction. For example, Dong and Wan (2013) propose an accident causation model to examine the presence of significant correlations, and they find interesting relationships among accident causal factors. Baysari et al. (2008) adopt the Human Factors Analysis and Classification System (HFACS) framework to identify errors associated with rail accidents/ incidents in Australia. Ouyang et al. (2010) employ the Systems-Theoretical Accident Model and Processes

(STAMP) analysis technique to model the China–Jiaoji railway accident, and to discuss the accident spreading processes. Particularly, studies are carried out to evaluate the human factor in emergency situations during the Ladbroke Grove railroad accident (Stanton and Baber, 2008; Stanton and Walker, 2011). These studies also discuss how a driver passing a signal at danger would cause the Ladbroke Grove rail disaster. Here the root causal factor is the driver passing a signal, which is considered as a human factor. Oh et al. (2006) use various statistical models to examine the relationships between crossing accidents and features of crossings. Depending on the data of American Railway Safety Annual Report in 2005, Wang et al. (2009) build a railway accident prediction model with gray theory to predict the accident occurrence.

TRID is the largest database that combines the records from TRB's Transportation Research Information Services (TRIS) Database and the OECD's Joint Transport Research Centre's International Transport Research Documentation (ITRD) Database. Currently, TRID is able to provide research scholars in the field of transportation with more than 1.25 worldwide Millions of documents. However, only a very small amount of literature on High-Speed Rail safety research is currently available in the TRID database. The very limited literature focuses on the areas of mechanical design, Power System and traditional railway safety analysis: grade crossing.

Mechanical Safety

René Heyder, Gregor Girsch, studied different rail materials for rolling contact. The resistance of fatigue (RCF) has verified that head hardened rails have a better resistance against RCF defects than rails with as-rolled hardness. High-speed trains have extremely high requirements for the ballast of the railway track. The traditional ballast will cause the ballast to be dislocated when passing through the high-speed train, affecting safety. Jieyi Deng developed the Probabilistic Risk Analysis (PRA) model for evaluating the risk of flying ballast on High-Speed Rail. China, Japan and Germany have developed ballast less tracks for High-Speed Rail construction, providing better safety. Another focus is the impact of the environment on High-Speed Rail. Ma studied the fatigue crack growth and damage characteristics of High-Speed Rail rails under low temperature conditions. Xin Zhao's cracks on the rails are also low temperature. The damage to the rails deepens as the temperature decreases, and the form changes. Chongyi Chang et al. studied the wheel-rail adhesion of High-Speed Rail, and studied the changes of wheel-rail adhesion under different speed and temperature conditions, which is conducive to the design and improvement of train anti-skid control device. Ignacio Villalba Sanchis predicts that the probability of the occurrence of buckling events on the rails of the Spanish High-Speed Rail network will increase greatly in the context of global climate change. Liu conducted a similar study on wheel-rail contact and found that water has a positive effect on increasing the friction between the train wheel and the track.

Power System Safety

The most vulnerable part of the High-Speed Rail is the catenary system, which is easily damaged due to long-term exposure to air and the formation of complex electronic components. Xiao Wu developed an image recognition tool to detect the bird nest on the catenary system to eliminate the threat to train operation. He summarized the safety risk assessment research of the entire power supply system including catenary system. The article introduces the risk sources of the power supply system, including equipment performance degradation, environmental risks, and improper maintenance and repairs.

Grade Crossing Safety

The main areas that Federal Railroad Administration declared to enhance railway safety include:

1. Positive Train Control (PTC) Implementation
2. Rail Grade Crossing and Trespassing Prevention outreach
3. Human Factor / Workers Protection
4. Administering funding for rail infrastructure upgrades across the nation
5. Tank Cat Enhancements

The traditional railway safety theme, "grade crossing safety" is still the theme of American railway safety during the period of developing High-Speed Rail. Samantha G. introduced the safety challenges encountered by grade crossing on High-Speed Rail lines. The study mainly summarizes the current technical means, management methods and safety education that need to adapt to the changes brought about by the High-Speed Rail. For example, signal lights and reminders will not adapt to the speed of high-speed trains and cause potential safety hazards.

Accident Analysis

Research on High-Speed Rail accidents is even more limited. The only article is found in the analysis of the cause of a single accident. Ziyan Luo analyzed the cause of the 7.23 do EMU accident by establishing a causation network. In research, Luo regard the accident occurrence as a cascading failure and reveal key causation factors and key causation chains.

2.4 Summary

It can be concluded by reviewing the history of accident analysis theory that statistics is the most basic accident research method, and almost all accident analysis methods or models are based on statistics. The reason behind this fact is the importance of data in all analysis. Unfortunately, due to the lack of data, the current research on High-Speed Rail focuses on economic analysis and comparative analysis of various travel modes, and the research on safety topics is obviously insufficient. The only High-Speed Rail safety study is an analysis of isolated cases, and the results are not representative.

Most of the mature analysis tools in security research belong to qualitative analysis. By abstracting the system and logically inferring it, finding key nodes of the system and exploring ways to maintain security / normal operation. Quantitative analysis tools are inadequate. Complex network models are still statistical analysis in nature, but by adding directionality and weight to the network, it reflects the logical relationship of accidents.

In summary, the accident analysis of High-Speed Rail lacks macro analysis and research, and lacks a general description of the safety status of High-Speed Rail operations. The research on the difference between High-Speed Rail and regular railway accidents is still blank.

CHAPTER 3

METHODOLOGY

The research method of this paper is to use the network theory in graph theory to simulate the accident cause network in railway accidents. Network theory has applications in many disciplines, and a large number of network structures also exist in the field of transportation. Even the first widely recognized proof of the "Seven Bridges Problem" in network theory can be regarded as a traffic problem. The transportation lines we are familiar with (roads, railways, subways and air lines) have formed a complex transportation network, which is also the most common form of network. Traffic in the network provides network direction and weighting characteristics. For example, in a traffic network, the traffic volume of different traffic lines will affect the importance of the line in the network, and the difference in traffic flow in different driving directions also determines the characteristics of different networks or lines. The various characteristics of the network precisely reflect the complexity of the real world. The benefits provided by abstract networks are not only concise but also computable. The mathematical characteristics of the network, such as clustering coefficient, betweenness centrality, etc., provide an effective tool for analyzing the characteristics of the network in reality.

3.1 Overview

The structure of the methodology shown in Figure 3.1, identify the code of the cause, and then determine the direction between the factors through the sequence of events in the accident. Through weighting, the second weighting takes into account the importance of the event and the severity of the accident into the network to complete the network modeling. Calculate the mathematical characteristics of DWDN, including degree, strength, path length, etc.

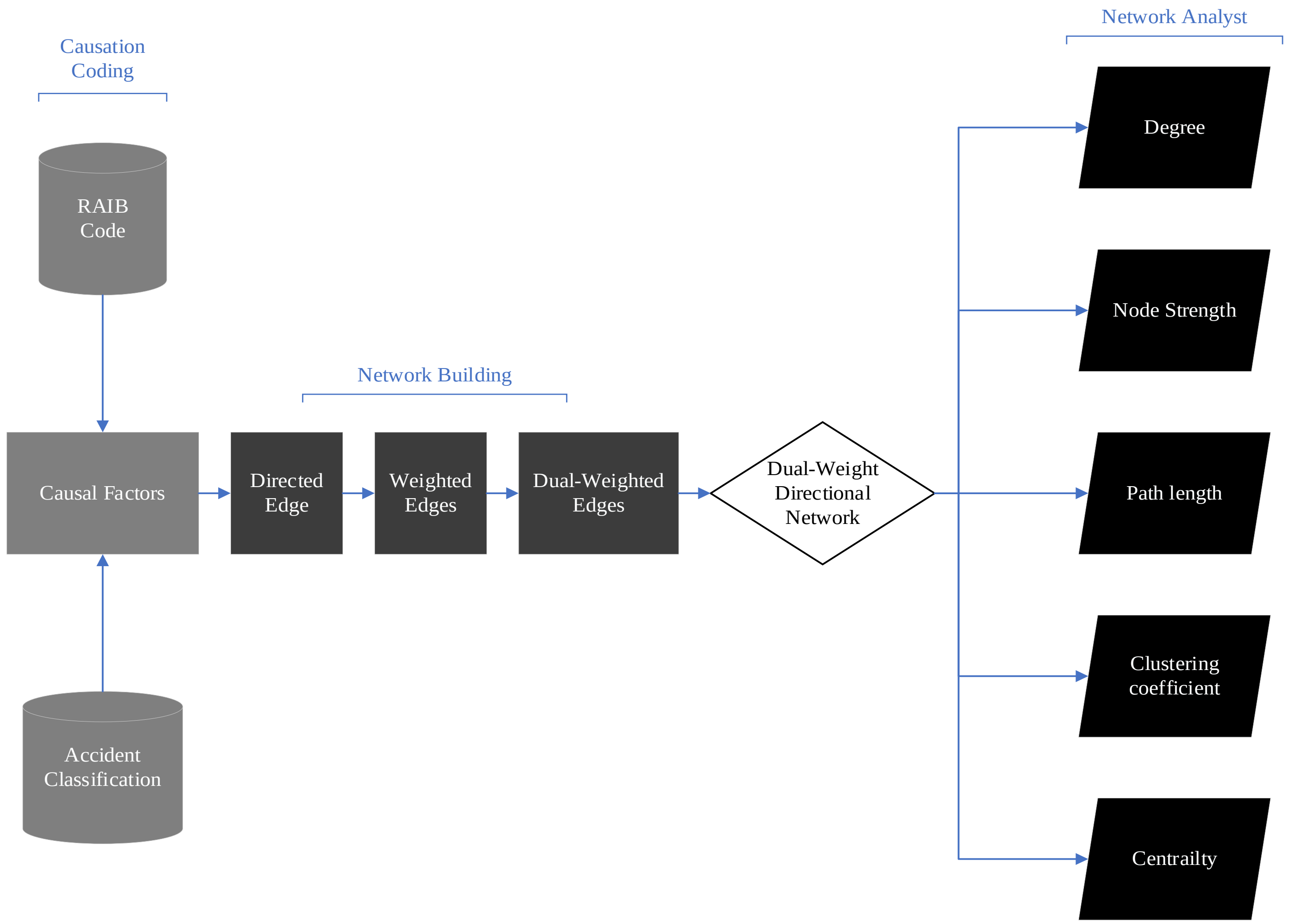


Figure 3.1 Methodology overview.

3.2 Complex Network Concepts

A complex network is a network structure composed of a huge number of nodes and edges connecting nodes. The mathematical definition of a complex network is a graph with a complex topology. Its structure is not completely regular or completely random. Figure 3.2 shows a typical complex network. The picture shows the aviation network in North America. The countless routes (edges) in the figure are connected to countless airports (nodes). The complexity of the network cannot be described in simple language. The analysis of complex networks must also rely on mathematical tools.

A directed weighted network G with N nodes can be represented mathematically by an N × N adjacency matrix A with elements.

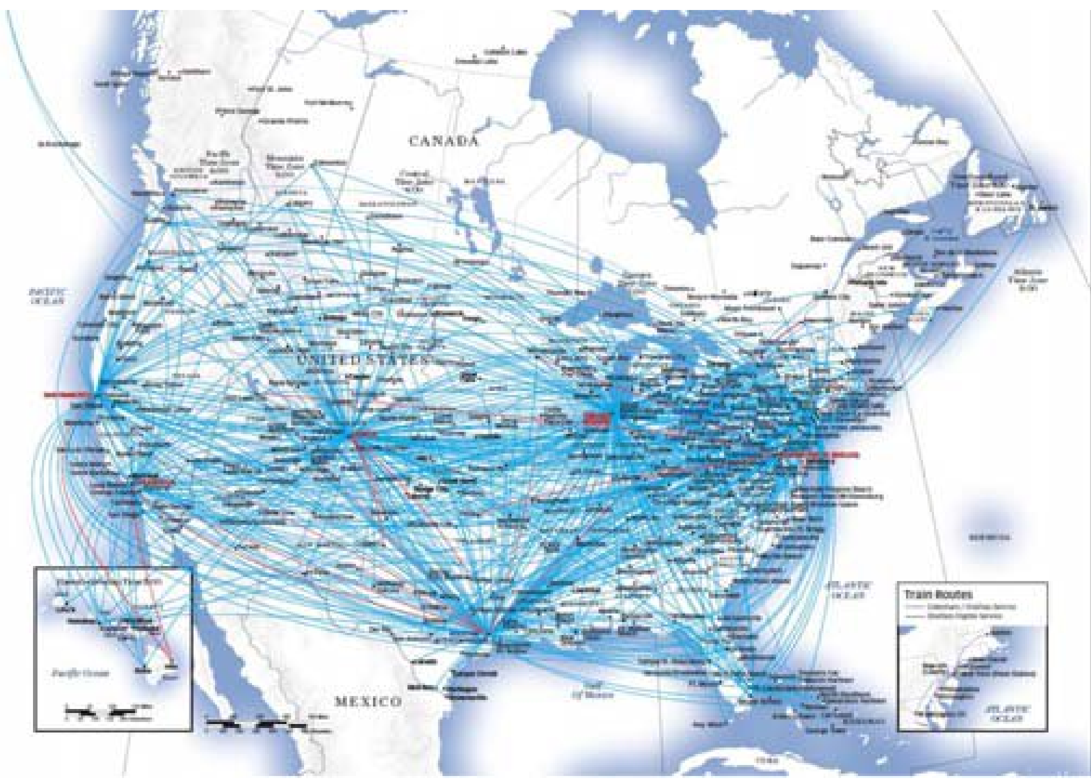


Figure 3.2 A conventional airline network in North America.

Source: Hidefumi Sawai, 2012.

3.2.1 Node

In network theory, nodes are one of the basic units of the network. The node and the edge connecting the two nodes together form a network. Nodes can represent different concepts in different networks. For example, nodes in a bus network can represent bus stations; nodes in a computer network can represent computers or routers. In this article, the nodes in the accident causation network represent the single events that occurred in the accident.

The mathematical features of node in the network are degree, weight, clustering coefficient, betweenness centrality, etc.

3.2.2 Edge

One of the basic units of the network, expressing the connection between two vertices. In an accident causation network, an edge indicates that there is a causal connection between two vertices (events). According to the directed nature of graphs, edges can be divided into two types: directed edges and undirected edges.

The mathematical features of edges in the network are weight, path length, etc.

3.3 Complex Network Features

3.3.1 Degree

One of the mathematical features of the node. The value of degree is equal to the number of all points connected by this node. It reflects the connectivity of vertices. The larger the value, the higher the connectivity. Note that the concept of degree does not consider the number of connections (strength) between two nodes.

As shown in Figure 3.3, the degrees of nodes A, B, C, and D are 2, 3, 1, and 4. That is, k_a = 2, k_b = 3, k_c = 1, k_d = 4.

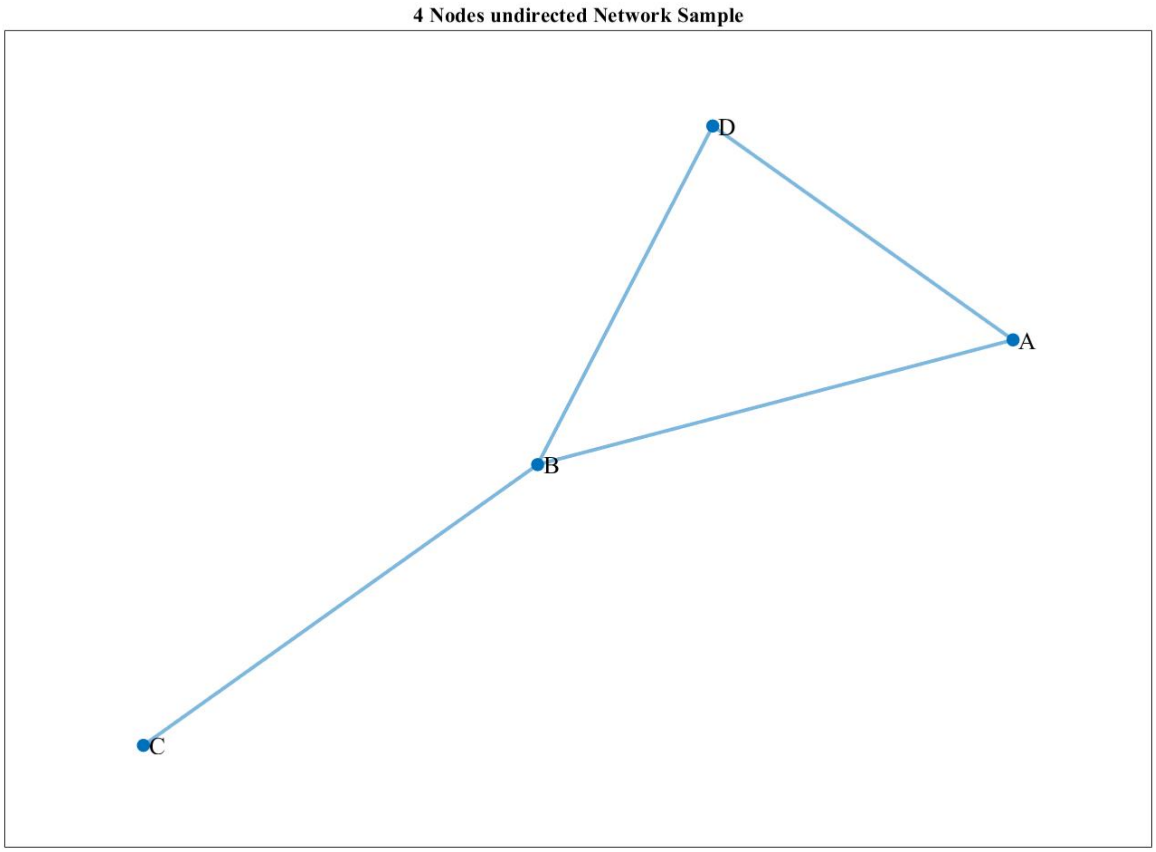


Figure 3.3 Undirected network sample.

In directed graphs, degrees are divided into in-degree and out-degree. In directed network (Figure 3.4) with almost the same structure as the above figure, the values of in-degree, out-degree and all-degree of node A, B, C, D are shown in Table 3.1

Table 3.1 Degree Calculation Sample

Node	In-degree	Out-degree	All-degree
A	0	2	2
B	1	2	3
C	1	0	1
D	2	0	2

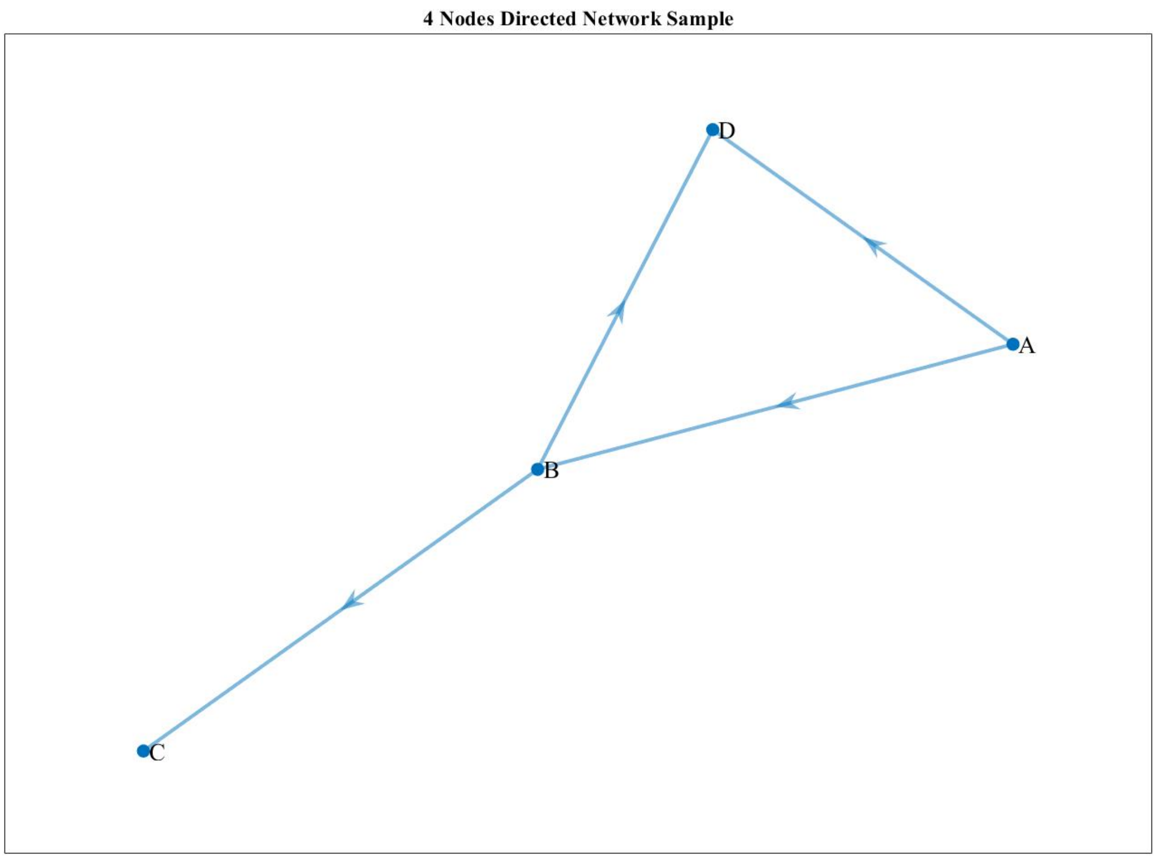


Figure 3.4 Directed network sample.

The equations for degree are as follows:

Degree: (Undirected Network)

$$\mathrm{k_i} = \sum_{\mathrm{j \in N}} a_{\mathrm{ij}} \tag{3.1}$$

Where:

i: node i in the network

j: any node except node i in the network

N: the number of nodes in the network

k_i: degree of node i

a_{ij}: equal to 1, when the node i is connected to the node j, otherwise is 0

In-Degree (Directed Network)

$$k_{i-in} = \sum_{j \in N} a_{ij} \tag{3.2}$$

Where

a_{ij}: equal to 1, when the i node points to the j node and is connected, otherwise is 0

Out-Degree (Directed Network)

$$k_{i-out} = \sum_{j \in N} a_{ji} \tag{3.3}$$

Where

a_{ji}: equal to 1, when the j node points to the i node and is connected, otherwise is 0

Total-Degree (Directed Network)

$$k_{i-all} = \sum_{j \in N} a_{ij} + \sum_{j \in N} a_{ji} = k_{i-in} + k_{i-out} \tag{3.4}$$

Degree distribution

$$P_k = \sum_{k'=k}^{\infty} p_{k'} \tag{3.5}$$

Where

P (k): refers to the sum of the probabilities that the degree is greater than or equal to k.

3.3.2 Strength

One of the mathematical characteristics of a node, the value of strength is equal to the number of all edges connected by this node. Strength can evaluate the importance of nodes in the network. The larger the value, the higher the importance. Note that the difference between strength and degree is that if you calculate two nodes connected multiple times. Degree ignores duplicate connections, and strength counts them. Also taking Figure 3.3 as an example, the strengths of nodes A, B, C, and D are exactly the same, because the connection state of the points is completely the same.

Same as degree, strength is also divided into in-strength and out-strength in the directed network. Similarly, because the network structure only adds directions, the in-strength, out-strength, and all-strength of the four nodes are exactly the same as the in-degree, out-degree, and all-degree values of node ABCD.

The strength equations are as follows:

Strength: (Undirected Network)

$$S_i = \sum_{j \in N} w_{ij} \tag{3.6}$$

Where:

i: node i in the network

j: any node except node i in the network

N: is the number of nodes in the network

S_i: strength of node i

w_{ij}: the weight of edge ij, which value equal to the number of connections from node i to node j

In-Strength (Directed Network)

$$S_{i-in} = \sum_{j \in N} w_{ij} \tag{3.7}$$

Where

w_{ij}: equal to the number of connections from node i to node j

Out-Strength (Directed Network)

$$S_{i-out} = \sum_{j \in N} w_{ji} \tag{3.8}$$

Where

w_{ij}: equal to the number of connections from node j to node i

Total-Strength (Directed Network)

$$S_{i-all} = \sum_{j \in N} w_{ij} + \sum_{j \in N} w_{ji} = S_{i-in} + S_{i-out} \tag{3.8}$$

Strength distribution

$$P_s = \sum_{s'=s}^{\infty} p_{s'} \tag{3.9}$$

Where

P (s): refers to the sum of the probabilities that the strength is greater than or equal to s.

3.3.3 Comparison of Degree and Strength

The calculation formula of degree and strength is similar, but the mathematical meaning is quite different. The difference can be clearly distinguished from Figure 3.5. Compared with Figure 3.4, a directional connection is added between the two nodes B and D, which can be regarded as a simple weighting of Figure 3.4. Table 3.2 shows the value of degree and strength after directional and weighted. The values in brackets come from the unweighted network (Figure 3.4)

Table 3.2 Degree and Strength Comparison (sample)

Node	Direction-in		Direction-out		All	
	degree	**strength**	**degree**	**strength**	**degree**	**strength**
A	0 (0)	0 (0)	2 (2)	2 (2)	2 (2)	2 (2)
B	1 (1)	1 (1)	2 (2)	3 (2)	3 (3)	4 (3)
C	1 (1)	1 (1)	0 (0)	0 (0)	1 (1)	1 (1)
D	2 (2)	3 (2)	0 (0)	0 (0)	2 (2)	3 (2)

The difference is reflected in nodes B and D. (Table 3.2) It can be seen that the increased connection has no effect on the degree value, but obviously the network is strengthened between these two nodes, and the degree value remains unchanged and the connectivity of the entire network has not changed. Such a comparison helps to understand the difference between degree and strength.

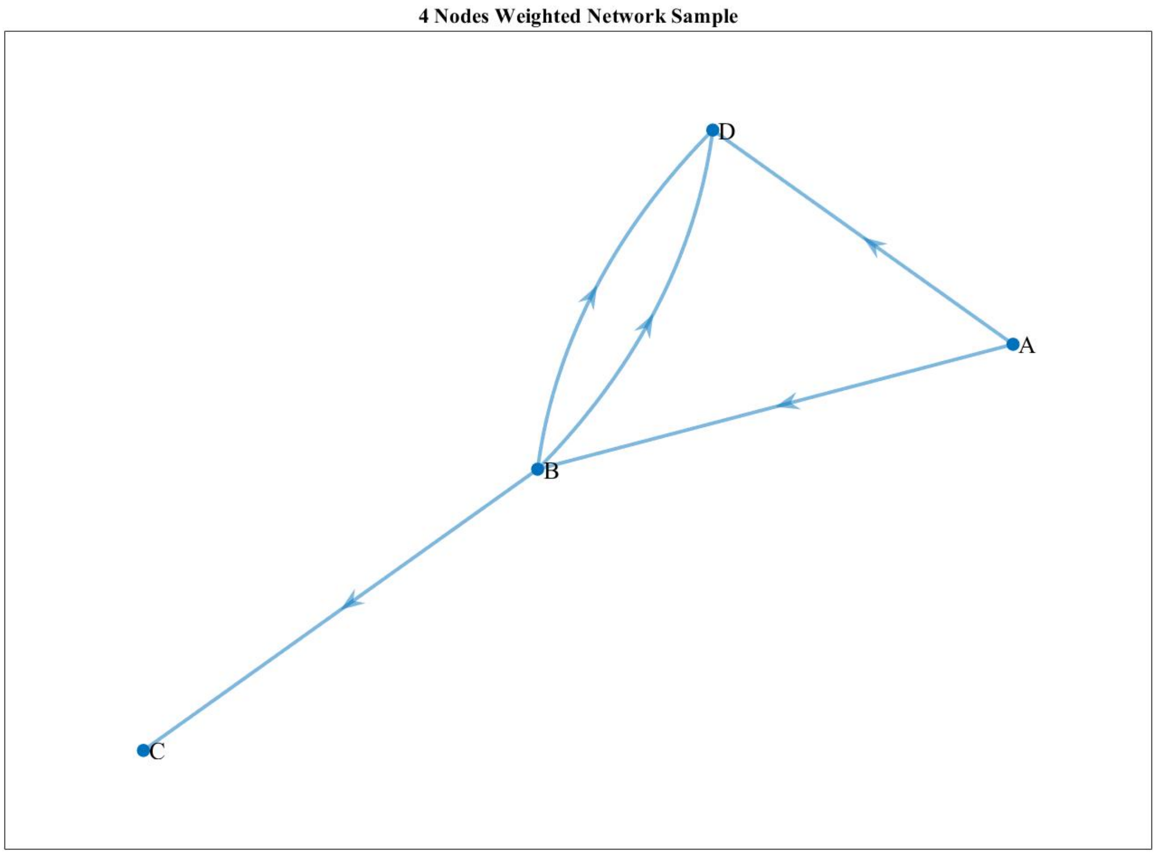


Figure 3.5 Directed network sample with weighted.

3.3.4 Dual Weighted

Double weighting means that while considering the strength of the network edge, the impact of the severity of the accident on the network structure is also considered. As mentioned above, railway traffic accidents are divided into four levels according to the time of casualties, property damage and traffic interruption. In the previous analysis methods and models, all attempts to use quantitative analysis methods for accidents are based on a unified standard to quantify the cause of the accident. model the accident, and then calculate the probability of the accident or the possible risk factors, the probability of causing an accident. For example, the causation network and complex network mentioned earlier. All causal factors are assigned a value of 1 (actually all factors in the model are assigned a value of 1). These methods are conducive to simplify modeling and calculation, but the degree of danger that ignores the cause of the accident varies with the severity of the consequences of the accident. For example, in the complex network model, both EM24 Signal Equipment failure and EM41 Train door detaching were assigned the same value “1”. However, EM24 caused the 7.23 accident and killed dozens of people, while EM41 only caused a minor accident without any casualties. This is actually that the model is too simplified in the modeling process, ignores the severity of the accident, and will mislead the system to improve safety. Perhaps for isolated accidents, the difference in the influence of factors is not as obvious as in this example. But when the sample size of the accident case is large enough, the cumulative difference will be sufficient to affect the safety improvement work.

Based on accident severity as shown in Table 3.3, the second weight details as follows:

Table 3.3 Weight Value for Accident Level

Accident Level	**Second Weight Factors (d)**
Level I	2.0
Level II	1.8
Level III	1.6
Level IV - A	1.4
Level IV - B	1.3
Level IV - C	1.1
Level IV - D	1.0

Weighting instructions

First, the factor d of the lowest-level general accident is determined, that is, the type D accident in level 4 is 1.0, and the upper limit of level 1 accident is 2.0.

Secondly, due to C in general accidents (level 4) accidents, D accidents do not involve casualties and small property losses. Type C accidents are only slightly more severe than Type D accidents, so the factor d for Type C accidents is set to 1.1.

Third, because the A and B accidents in the general accident (level 4) accidents involved casualties and more serious property losses, there was a clear difference from the C / D accidents, so there was a larger gap in weight, Set the factor d of the category B accident to 1.3. Accident A and accident B are both general accidents, and are higher than category B in various losses and injuries. Therefore, the factor d of the category A accident is set to 1.4.

Finally, according to level 1, level 2 and level 3, the difference in loss is very obvious, so the factor d of level 2 and level 3 accidents is set to 1.8 and 1.6 respectively.

3.3.5 (Shortest) Path Length

The path between two points is also called graph geodesic. In an undirected graph, the distance between two points is the length of the shortest path between the two points. If there is no path between two points, that is, they are not connected, then their distance is defined as infinity. There is a possibility that there are multiple shortest paths between two points.

In undirected graphs, the shortest path between two points is also directional, and the length of the shortest path in the two directions may not be equal. Note that there is a case where the shortest path from node A to node B exists, and the shortest path from node B to A does not exist.

The unweighted network defaults to a distance between two points of 1. Between two points in a weighted graph, that is, edges, can have their own lengths. The length of the edge is generally the weighted value of the edge.

The equation is as follows:

Shortest path length:

$$L = min\left(w_{ih} + \cdots + w_{hj}\right) \tag{3.10}$$

Where

L: the shortest path length

i, h, j: three different nodes in the network

3.3.6 Diameter / Radius / Average Path Length

The diameter of a network is defined as the largest value among the shortest path lengths present in the network.

The radius is defined as the smallest value of the shortest path length existing in the network.

The average path length is the average of the shortest path present in the network

The equation is as follows:

Average shortest path length:

The weights need to be reversed first, so the calculation include two steps.

Step 1

$$d_{ij}^{w} = min\left(\frac{1}{w_{ih}} + \cdots + \frac{1}{w_{hj}}\right) \tag{3.12}$$

Step 2

$$L_{mean} = \frac{1}{N(N-1)} \sum_{i,j \in N, i \neq j} d_{ij}^{w} \tag{3.13}$$

Where

i, h, j: are three different nodes in the network

L_{mean}: average shortest path length

3.3.7 Betweenness Centrality

The concept of betweenness centrality is a measure of network centrality based on (shortest) path length. It is obtained by calculating the ratio of the number of paths passing through the node in all the shortest paths to the total number of all shortest paths in the network. Betweenness centrality represents the degree of interaction between a node and other nodes, and also measures the importance of the node. The node with high betweenness centrality value is similar to a bridge on the river, and all cross-river traffic must pass through the bridge. The bridge acts like a central node in the city's transportation network. The importance of the bridge is expressed by the high value of betweenness centrality.

The equation is as follows:

betweenness centrality

$$C_h^B = \sum_{i,j,h \in N} \frac{n_h}{n'} \tag{3.14}$$

Where

C_h^B: the betweenness centrality of node h

i, h, j: three different nodes in the network

n_h: the number shortest path with node h

n': the total number of shortest path in the network N

3.3.8 Clustering Coefficient

In the network, if nodes A and B are connected and A and C are connected, then B and C are also likely to be connected, that is, your different friends may also be friends. The clustering coefficient is used to describe the degree of clustering between nodes in a network. The aggregation coefficient can measure a network or a node in the network.

The equation is as follows:

Node clustering coefficient:

$$C_i^w = \frac{1}{s_i(k_i - 1)} \sum_{j,h} \frac{(w'_{ij} + w'_{ih})}{2} a'_{ij} a'_{ih} a'_{jh} \qquad (3.15)$$

Where

a'_{ij}=1 if $a_{ij} = 1 \; or \; a_{ji} = 1$

$w'_{ij} = w_{ij} + w_{ji}$

k_i: degree of node i

Average clustering coefficient:

$$\overline{C^w} = \frac{1}{n} \sum_{i=1} C_i^w \qquad (3.16)$$

CHAPTER 4

DATA COLLECTION

4.1 Case Selection

Case studies require that the research object has sufficient data, and it can represent the field of research, have rich connotations, and more importantly, have value and ability for future development.

4.1.1 Country Selection

Since the successful operation of the first commercial railway in Leeds, England, the railway has been developed in human society for more than two hundred years. Almost all countries in the world have this mode of transportation. It has been sixty years since the Japanese started construction of the High-Speed Rail. Over 20 countries in the world have operated High-Speed Rail with a total mileage of more than 50,000 kilometers. At the same time, there are only a handful of countries that have developed outstandingly in these two fields. Japan is one of the most developed countries in railway transportation and the birthplace of High-Speed Rail. However, Japan's railway operation system is too complicated. In addition to the seven large railway companies evolved from the "National Railways" JR Group, there are 16 medium-sized railway companies operating in the metropolitan area and many small railway companies. This fragmented business model has hindered research. France is an outstanding representative of the European High-Speed Rail, with the highest passenger volume and top High-Speed Rail manufacturers like Alstom. However, the French high-speed trains use a hybrid mode, and high-speed trains can run on both regular railway networks and High-Speed Rail. This hybrid networking model makes it difficult to distinguish High-Speed Rail from traditional railways. The most direct impact is that the liability and loss of railway accidents are difficult to determine. The United States has the largest railway network in the world, but the passenger train business is shrinking year by year. And there is actually no real high-speed train running in the United States. The only Acela express train that meets the US DOT High-Speed Rail standard has an average operating speed of only 110 kilometers per hour. Britain is the hometown of railways, and has a sound railway management system and a professional accident analysis organization IRAB. However, the High-Speed Rail has only a 100-km line, and the data volume is too limited to support research.

Comprehensive comparison of major countries can be found China is the most suitable case study of railway (High-Speed Rail) safety. China has the world's largest railway passenger transportation network, and the number of passengers on China's railway network is high every year. During the “Spring Festival” period of railway transportation, the number of passengers traveling by train was as high as 100 billion people, with an average of 500 million people every day. There are 3,000 EMUs driving on the rails every day. There are more than 5,000 trains. Far more than Japan, Europe, let alone the gradually shrinking North American railway network.

China has the world's largest High-Speed Rail network. As mentioned earlier. China has built a 38,000-kilometer High-Speed Rail in just ten years, connecting all major metropolitan areas in China. The High-Speed Rail presents a multi-layer and multi-style network structure in China:

The first, the north-south arterial route that runs through the country, such as the Beijing-Hong Kong High-Speed Rail, has a total length of 2260 kilometers and a speed of

350 kilometers per hour, connecting Beijing and Hong Kong. This is also the world ’s longest High-Speed Rail.

The second, the High-Speed Rail along the river: a total length of 1900 kilometers and a speed of 350 kilometers per hour. A High-Speed Rail connecting the Yangtze River, the third longest river in the world, and all cities along the coast. Expanded Shanghai, the world's largest port is also China's economic center, economic hinterland to the Sichuan Basin.

The third, in the Pearl River Delta region, the express passenger transport channel between cities has formed a High-Speed Rail network centered on Guangzhou and radiating to surrounding small cities, forming an inter-city express passenger transport network in the urban area. In a sense, it played the role of commuter railway.

At last, the reconstructed fast railway. That is, after the original line is transformed, the operating speed reaches 200km / h or more. Although it is no longer classified as a High-Speed Rail according to China's latest official definition, it still meets the speed requirements of most countries in the world for High-Speed Rail. At present, this part of the railway has not yet achieved the separation of passengers and goods.

In summary, the huge number of passengers, the rich types of routes, plus the diverse geographical characteristics of China. This allows China's High-Speed Rail network to meet any analysis needs.

Of course, China is not a perfect case for research. The difficulty lies not in the lack of data but how to obtain it. There is a complete accident handling and information collection system in China, which is called the Ministry of Emergency Management of the

People ’s Republic of China (State Administration of Work Safety before 2018) at the national level. After the accident, the emergency management department reports it to local institutions at various levels. This is the only data most people see publicly. The annual report is published around April of each year, and the specific disclosure time may be advanced or delayed by about a month in different years. The information contained in the annual report is very limited. The data related to accidents are only the number of deaths, the number of particularly serious accidents and an indicator that links the traffic volume with the number of deaths: a death rate of 1 billion tons kilometers. Only a vague shadow can be obtained through the report, so the quantity and quality of the data are the only factors that restrict the research.

4.1.2 Operation and Accident Management in China

There are three levels in the current railway management systems: China Railway Corporation as the top level, the regional railway company as the middle tier and the segment or section as the third, or operating units of actual railway lines and stations. There are 18 railway companies, each with route segment and a local joint venture railway company. As independent legal entities, the regional railway companies operate all the railway services in its territories and their financial information are tallied independently. There are sub-bureaus in major cities, which are responsible for the daily supervision and management of railway operations and report to the regional railway companies.

Similar to the definitions used in the US, railway accident is defined as collision, derailment, fire, explosion, act of God, or other event involving the operation of on-track equipment, standing or moving, that results in total damages that are above certain threshold.

As documented in Table 4.1, railway accidents in China are generally placed in one of the four categories according to “Rules for Railway Traffic Accident Investigation and Handling”. The rail specific rules were developed by the Ministry of Railways in accordance with the “Regulations on Emergency Rescue and Investigation of Railway Traffic Accidents” formulated by the State Council of China. The placements are largely based on five different parameters: fatality, injury, property damage, derailment and delays. It is noted that the number of carts derailed for passenger and freight is different, which is logic as freight trains are generally longer and damages are assessed very different when human lives are involved, such as the case in passenger trains. Similarly, the operation stoppage or delay is generally measured by the number of hours the railroad is out of service and the delays along mainline operations are rated much higher than that of minor or branch lines.

Table 4.1 Railway Accident Classifications in China

Level	Fatalities (person)	Injuries (person)	Property Damage (Million RMB)	Derailment （Passenger/ Freight）	Operation stoppage (hours)
I	>30	>100	>￥100	>18 (P) or >60 (F)	>48
II	10-29	50-99	￥50 -100	2-17 (P) or 6-59 (F）	>24 (mainline) or >48 (Minor)
III	3-9	10-49	￥10 -50	2-17 （P） 6-59 （F）	>6 (Main) or >10 (Minor)
IV	<3	<10	<￥10	Other specific conditions	

Source: State Council of China, 2008.

There are four sub-categories: A, B, C and D, under the Level IV classification, which correspond to conditions that are more specific. For example, 4A specifies that two or less fatalities occurred, there are 5-10 serious injuries, property damage is between 5-10 million RMB, or the number of derailed carts and stoppage periods can vary depending on the type of trains and types of routes. In general, the type 4A is more severe than that of 4B, 4C, and 4D. The least severe category, 4D, may involve shunting conflict, wrong or not timely signal to cause the train to stop, mail loading and unloading operations delay the train, etc.

4.1.3 Study area Selection

Guangzhou Railway Group manages the longest High-Speed Rail line among the 18 regional companies. The region also has China ’s largest island, Hainan Island. Two of the four first-tier cities: Shenzhen and Guangzhou. Hong Kong, one of the world's financial centers, is also connected to China's railway network through Guangzhou Railway Group. The rich geographical characteristics and the multi-level economic development of the region have made Guangzhou Railway Group possess all the characteristics of China's High-Speed Rail. The following are the specific characteristics of this area:

Guangzhou Railway Group is located in the south-central part of China, and it has jurisdiction over some railways in Guangdong, Hunan and Hainan. It is located in Beijing-Guangzhou line, Jiaoliu line, Shanghai-Kunming line, Yuhuai line, Hengliu line, Xianggui line, Guangmao line and Beijing. The 9th line and the Guangzhou-Shenzhen, Shichang, Guangmei and other lines and the Guangdong, Hainan West Ring Line and Pingnan have a total of 4907.6 kilometers to operate the general-speed railway. The High-Speed Rail includes the Beijing-Guangzhou High-Speed Rail, the Guangzhou-Shenzhen-Hong Kong High-Speed Rail and the Xiamen-Shenzhen railway. Shanghai-Kunming Passenger Dedicated Line, Guiguang Passenger Dedicated Line, and Nanguang Railway.

The total length of the line is 10483.7 kilometers, the operating mileage is 4907.6 kilometers, the electrified operating mileage is 2005.554 kilometers, and the contact network is 72146.693 kilometers. There are 11785 group of Taoyuan, 2754 bridges, 301,637 meters, 964 tunnels, 435,043 meters, culverts, 19916, 527,074 meters. There are 1,291 locomotives, including 726 diesel locomotives and 565 electric locomotives; 4,322 passenger cars, with 11,12 vehicles in line. There are 456 jurisdiction stations, including 6 special stations, 15 first-class stations, 23 second-class stations, and 40 third-class stations. There are 6 marshalling stations. There are 477 interlocking stations, of which 294 are relay interlocking stations. The automatic blocking line is 2033 kilometers, and the semi-automatic blocking line is 3372.7 kilometers.

The study area of this article involves three provinces in China, including Hunan Province, Guangdong Province and Hainan Province from north to south. The hills in all three provinces accounted for a relatively high proportion, of which Hunan hills accounted for 70.2% of the total area of the province, and water areas accounted for 5.3%; Guangdong's hilly and mountainous terrain accounted for about 62% of the province's area, and the rest were plain. The main land part of Hainan Province is Hainan Island. The island takes mountainous terrain as the main terrain, and a high-speed ring railway is built around the island's central mountain range.

4.2 Data Collection

The data used in this research comes from the compilation of accidents prepared by Guangzhou Railway Group. This book has not been published and is only for internal use. The information includes 68 railway accidents with a time span of 2013-2017. According to the accident responsibility department, all accidents are divided into six chapters: Operation Department, Drive Department, Energy and Signal Department, Rolling Stock Department, Tracks and Structures Department and Subcontractors Department. Each accident includes the occurrence of the accident, time, location, route, repair or rescue treatment method and accident lost. Each accident record also comes with the judgment of the cause of the accident and the judgment of responsibility. The 68 accidents include 28

High-Speed Rail accidents and 40 regular railway accidents. Since there is currently no obvious distinction between High-Speed Rail and regular railways in management, the judgment criteria for High-Speed Rail accidents are as follows:

1. The accident happened on a High-Speed Rail line.
2. The accident vehicle is a high-speed train or EMU vehicle.
3. If the accident occurs at a station, it must be a newly built High-Speed Rail station on the High-Speed Rail line.
4. The accident involves damage to High-Speed Rail facilities, vehicles or employees, or the cause of the accident is related to the construction, maintenance and repair of High-Speed Rail.

4.3 Data Overview

4.3.1 National Level

According to limited data, the state of railway transportation safety in China can be observed at the national level. The total number of railroad accidents are generally tallied according to the classification presented above. As mentioned earlier, there is no separate report for High-Speed Rail operations and even the railway accident numbers were removed from the annual bulletin since 2013. The only available data are from 2011 and 2012. As shown in Figure 4. 1, there was only one “extremely serious” Level I accident in the two years combined and it belongs to the accident took place along the Fuzhou – Wenzhou Line on July 23, 2011.

The infamous “7.23” accident had claimed 40 lives, including three train crewmembers. The official statistics claimed that 172 people were injured and the railway segment was out of service for 32 hours and 35 minutes. Comparing to the serious Level I or II accidents, the total number of types 4D accidents/incident seem large at 1,997 and

2,318 for 2011 and 2012 respective. However, when putting in the contest of 93,000 route miles or 1.86 billion passengers transported annually, the incident rates per route mile or per passenger mile travelled (PMT) is much lower than that of US.

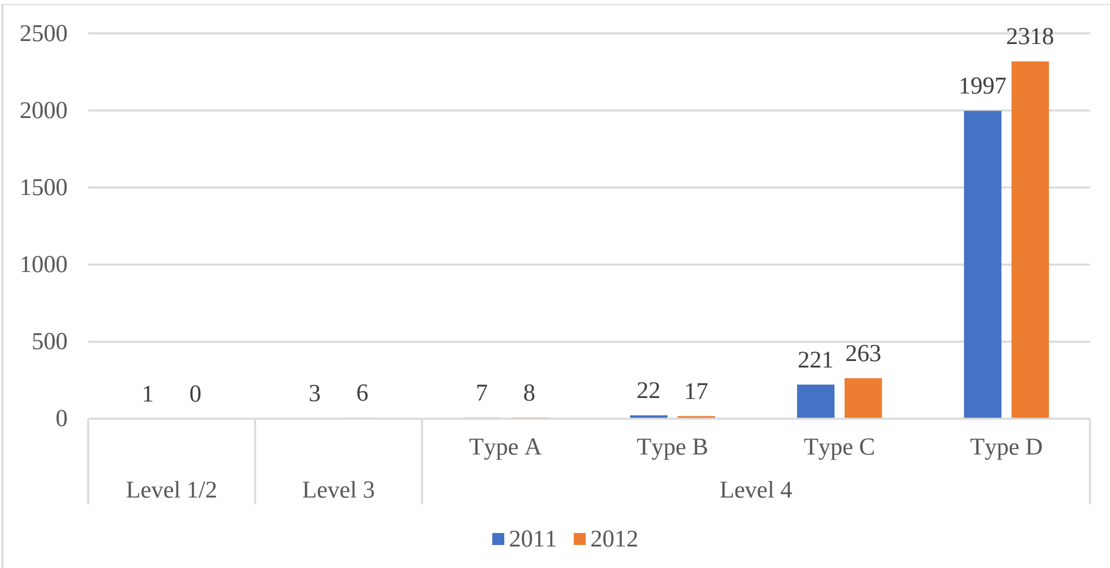


Figure 4.1 Railway accidents in China, 2011 and 2012.

Sources: Railway Statistical Bulletin, 2011, 2012.

On the other hand, one accident is too many. In 2011, the Chinese railway department interrupted the operation for a total of 119 hours and 6 minutes due to accidents, and the economic loss was 247,031,300 (RMB). In 2012, the railway operation was interrupted for 100 hours and 27 minutes, and the economic loss was 62.926 million (RMB). With the extension of the High-Speed Rail, the High-Speed Rail will soon cover all the large cities in China, and the railroad tracks will soon cross the border. More cities mean more complex networks, and the disruption of any node or line will have a huge impact on the network. Research and prevention of accidents will definitely be an important aspect of High-Speed Rail operations.

4.3.2 Accident Trending

According to accident statistics (Figure 4.2), the number of accidents of Guangzhou Railway Group has been stable since 2013-2014, and reached the most in 2015, but in 2016 The number of accidents has dropped significantly. It shows that the security situation has improved in 2016.

By observing the accident data and the operating line length together, we can find that the operating line length has increased significantly in 2015, and the number of accidents in the same period has increased correspondingly. It can be inferred that a large number of new lines were put into operation in a short period of time, which had an important impact on the daily operations of the enterprise. According to the STAMP model, the ability to control the safety constraints of the railway system is weakened. The constraints here can be management capabilities; the number of operating or maintaining employees, the level of training and experience; the reliability of the equipment, etc. During the period of 2016-2017, the length of operating lines changed relatively smoothly, and the number of accidents decreased significantly each year. This can prove the previous conclusion from the opposite direction: the system's constraint on safety is recovering, maybe the staff of different departments have gained enough experience, and maybe the reliability of the equipment is improving.

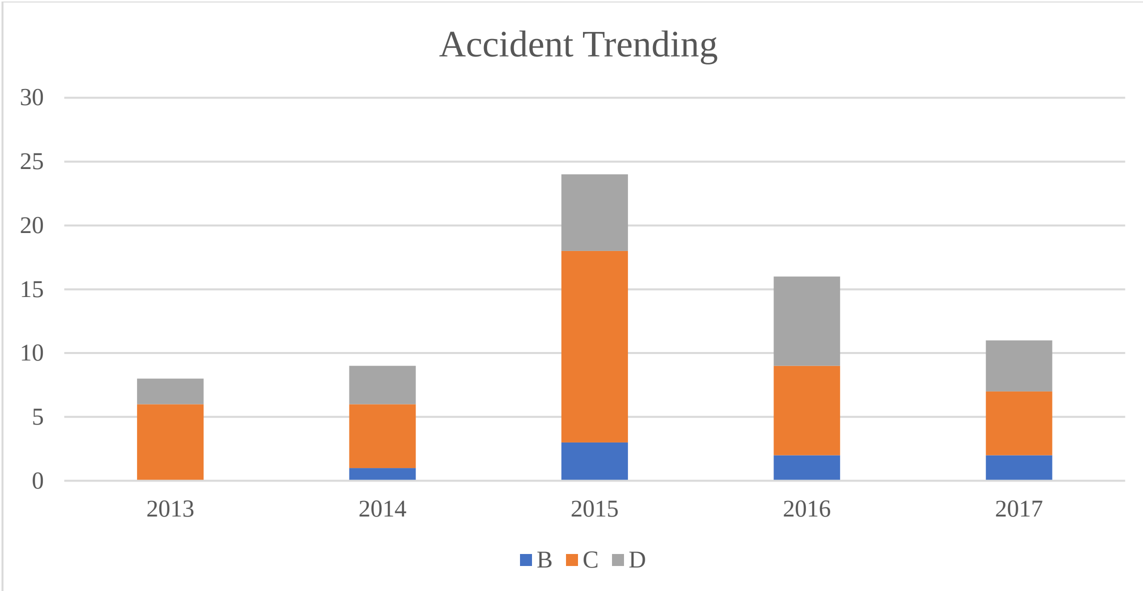


Figure 4.2 Accidents trending (Guangzhou, 2013-2017).

Regarding the proportion analysis of accident types, the proportion of B, C, and D accidents has been stable. Class C accidents accounted for the largest proportion between 2013 and 2017, and tripled in 2015 compared to the previous year. By querying the classification criteria for railway traffic accidents in the "Rules for Investigation and Handling of Railway Traffic Accidents", C and D-level accidents belong to the general category without causing casualties or obvious property losses (the judgment criterion is whether the property loss exceeds RMB 1 million) accident. C-level accidents are more serious and pose greater threats to operational safety. Although Class B accidents account for the smallest proportion, Class B accidents have higher hazards, or there are casualties, or property loss exceeds RMB 1 million, or the railway line is interrupted. Class B accidents also tripled in 2015 from the previous year, and together with Class C accidents marked a deterioration in railway safety in 2015.

4.3.3 Accident Location

Figure 4.3 shows the location of accident during 2013-2017. The first factor that affects the location of the accident should be geography. Due to the development of China's civil engineering and construction technology, the construction of High-Speed Rail has crossed the obstacles of the terrain. You can find that there are High-Speed Rail tracks on any terrain in China. Therefore, the location of the railway accident did not reflect very obvious geographical features, and only a few accidents that occurred in tunnels and bridges could be found.

During the study period, more than 90% (or even 100% in 2013 and 2013) of accidents occurred within the scope of open lines and stations, of course, this is also the main body of the railway. In most years (2013 and 2015-2017), the proportion of accidents that occurred at the station range was higher than on the line. The reason is that the station environment is more complicated. The station not only has the same track, signal, power, communication and other equipment as the line, but also more supplies, station maintenance, passenger and freight facilities and more types of workers. All of the above-mentioned complex conditions converge at the variability of the different parts of the station, organization, individual, equipment, etc., and cause resonance, causing the station to be less secure than the line.

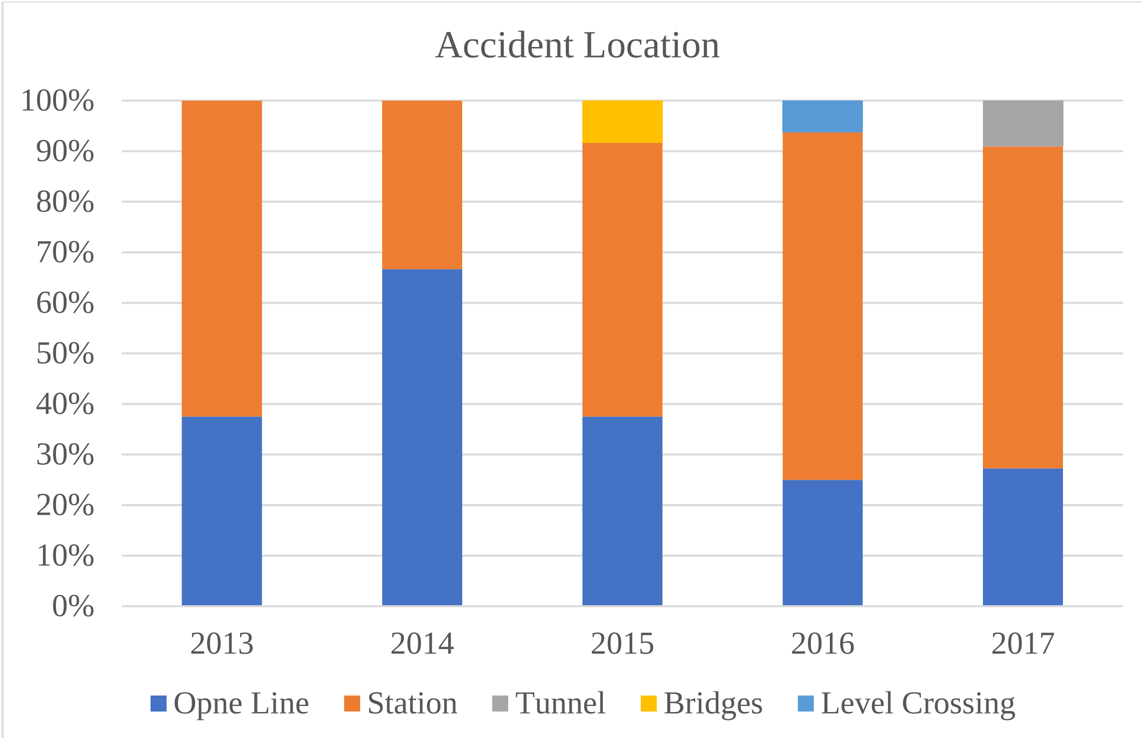


Figure 4.3 Accidents location (Guangzhou, 2013-2017).

4.3.4 Accident Department

Internal departments

The "accident department" appeared in the accident investigation report through investigation and study of the accident, and believed that the accident was caused by the mistake of this department. The division of departments is directly related to the Chinese railway management system. In the Chinese railway management system, the operating department is divided into five departments according to the work content:

1. Operating depot: In charge of train operation control and command, operation monitoring and management of passenger, freight and other services to ensure operating income.
2. Drive crew depot: In charge of the operation, maintenance and repair of railway locomotives.
3. Energy and signal depot: The supervisor manages and maintains railway line

signals, locomotive signals, and communication systems. It is also responsible for the power supply of railway lines and vehicles.

4. Rolling stock depot: Responsible for the operation, maintenance and repair of train vehicles (excluding locomotive). The depot is also the place where vehicles are operated, managed, parked, repaired, and maintained in the urban rail transit system (subway, urban light rail).
5. Tracks and structures: In charge of maintenance and repair of railway lines, bridges, tunnels and some equipment.
6. Subcontractors: an additional category. Subcontractors are responsible for railway engineering construction projects through outsourcing contracts. Because the work area is highly coincident with the railway operation area, the behavior of the subcontractor has a direct impact on railway safety.

Tracks and Structures Department

As shown in Figure 4.4, the highest percentage of accidents occurred in the rail and structural sectors since 2014, which proves that this is the most dangerous sector in the railway system. As mentioned in the previous paragraph, this department is responsible for the maintenance and repair of all infrastructure of the railway system. As the department's large working area has thousands of kilometers of railway tracks and bridges that need to be inspected daily to ensure traffic safety. The department has the most employees and the highest work intensity, which requires management, training and cooperation between departments to be skilled and effective. Mistakes in any detail are weakened security constraints and may lead to accidents.

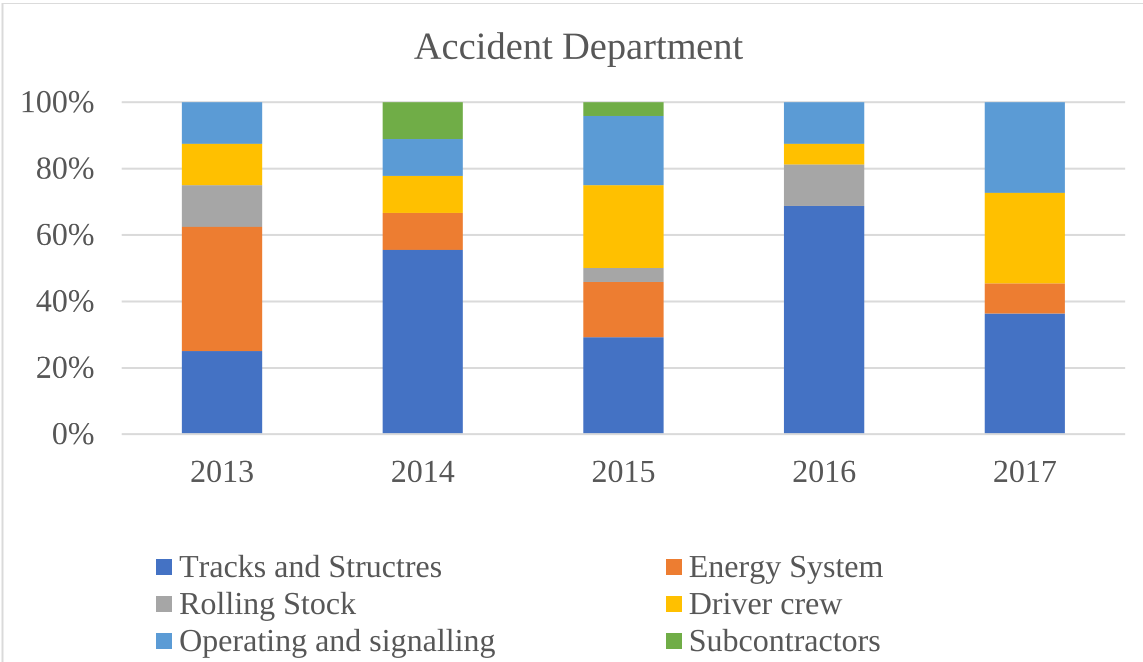


Figure 4.4 Accidents department (Guangzhou, 2013-2017).

Typical Year

Observing the distribution of the number of accidents in different years, it is found that the proportion of departments in 2015 is very representative. As mentioned above, the number of accidents in 2015 was the highest during the study period. Also, in 2015, the accidents in the four departments Track and structures, Energy, driver and operation were almost equal, and the sum accounted for 90% of the total accidents. This once again proves that the negative impact of a large number of new railway lines on operational safety in the short term is comprehensive, and each department has experienced challenges in the same period.

Drive Department

The proportion of drive depot accidents has been increasing from 2013 to 2015. China Railway Administration has admitted that the number and quality of EMUs system staff are very weak, and in 2017, it filled up 6,400 mechanics. Some figures show that at the end of 2016, employees under the age of 30 accounted for 80% of the total number of employees in the EMUs system. Age is directly related to experience. Young employees ’poor operational skills and emergency response capabilities are the biggest hidden dangers to EMUs’ operational safety. The High-Speed Rail accident that occurred in the Lion Ocean Tunnel in Guangdong Province in February 2018 was due to the inexperience and improper handling of the on-board mechanics, which caused the line to be interrupted for 8 hours, 19 train trips were cancelled or delayed and the journey of thousands of passengers Delayed or cancelled.

4.4 Data Quality

The essence of network analysis is statistical analysis with the help of some methods of graph theory. Regardless of degree or strength, it is the statistics of a certain aspect of the incident that develops into an accident. Therefore, the key to the success of network analysis is data. The data problems identified in the study included data availability and accuracy.

4.4.1 Accessibility

The access to accident data is limited. The 68 accident reports used in this study came from the internal training materials of a regional railway company in China. Because it is a safety training material, the basic information of the accident is retained, but the attachment materials for investigation reports such as testimonies, test reports, and schematic diagrams are deleted. This is not the most ideal data. But in a short period of time, this will be the best data available on China's railway safety research. Under the current Chinese management system, out of fear of the negative impact of public accident data on social stability and economic development has prevented the disclosure of accident reports in China. This makes accident data almost impossible to access. An exception is the 7.23 accident in 2011, because the losses caused by the accident were extremely large (forty people were killed and 172 injured), and the accident report was published in full.

The unavailability of accident information is also related to the accident investigation system. China has a complete accident reporting and investigation system and has been established in legal form. However, there are still some areas that need to be rethought in the details of this system. The first is the accident investigation agency. According to the “Regulations for Emergency Rescue, Investigation and Handling of Railway Traffic Accidents” that began in 2013, accident investigations are presided over by different agencies according to the accident level. The details are shown in the Table 4.2.

Table 4.2 Investigation Agency of Railroad Accident

Accident Level	**Investigation Agency**
Level I	State Council or an agency authorized by the State Council
Level II	Railway Administration
Level III & IV	Railway Operation Management Agency or State Council (if necessary)

Source: State Council of the People's Republic of China, 2007.

The main problem is that the railway operating unit and the railway supervisory unit are unified in China, namely the China National Railway Group (and its regional branches). The investigation organization of the accident is taken by the accident occurrence organization, which is a typical problem of integration of government administration with enterprise in the state-owned economy. In fact, this has changed from an independent accident investigation to an internal responsibility investigation. The "State Administration of Work Safety" (similar to the inter-departmental version of NTSB, later reorganized as the National Emergency Department) was almost excluded from the accident investigation and was only used as a data collection department. This cast doubt on the credibility and transparency of the accident investigation. In fact, after the 7.23 accident investigation report was published, there were voices questioning that the accident report masked the true cause of the accident. Accident liability tends to be borne by a commercial company that appears to have no contact with the government.

4.4.2 Accuracy

The content of the accident investigation report is also insufficient. As shown in the Table 4.3. China's railway accident report clearly lacks research on the cause and development chain of the accident. The vast majority of the report, about 3/4, is used to analyze accident responsibility and safety education of various departments in detail.

Table 4.3 Contents Requirement for Investigation Report

Index	Content
1	Accident profile.
2	Casualties and direct economic losses caused by the accident.
3	The cause and nature of the accident.
4	Identification of accident liability and suggestions for handling the person responsible for the accident.
5	Advice on accident prevention and rectification measures.
6	Certification materials related to the accident.

Source: State Council of the People's Republic of China, 2007.

The ideal investigation report comes from the British RAIB agency. The Railway Accident Investigation Service (RAIB) is the agency responsible for independent investigation of railway accidents in the UK and Channel Tunnel. Established in 2005. The RAIB report focuses on analyzing the cause of the accident rather than who is responsible. As shown in the Table 4.4, the accident report records the sequence of events in the accident and analyzes in detail the causes of the accident including immediate cause, underlaying cause and causal factors. In addition, a monthly summary and annual report of the railway accident can be found on the RAIB website.

Table 4.4 Content of RAIB Accident Report (sample)

Content

Source: UK RAIB, 2019.

The agencies involved in the investigation of train accidents in the United States are FRA and NTSB. FRA is an agency of the United States Department of Transportation that manages federal-wide railways. NTSB is an independent federal agency responsible for investigating traffic accidents. Three documents will be generated after a railroad accident in the United States. These are the accident brief issued by NTSB, the accident preliminary report and the investigation report issued by FRA. The difference between these three documents is that the preliminary report simply records the status of the accident and the composition and work plan of the accident investigation team, with the shortest length. The brief records in more detail the geographical information of the accident, the information of the rails and vehicles, and the results of various inspections. The obvious difference is that the brief finally guessed the cause of the accident. The length is slightly longer. The investigation report is located on the FRA website, and the report is more focused on record archiving, and the accidents are recorded in standardized forms. The main difference in the investigation report is that a formal conclusion has been made on the cause of the accident. Generally speaking, the survey report is the longest. The accident brief and preliminary report can be obtained on the NTSB website soon after the accident, and the full investigation report may be delayed on the FRA website for a few months.

CHAPTER 5

NETWORK ESTALISHMENT

This chapter introduces the steps and tools used in complete network construction. And a case has been used to demonstrate the structural characteristics of the network.

5.1 Causal Factors Coding and Directed

By reading the accident report, use the IRAB factor code to encode the accident. Coding manual used for coding, the author combined both accidents investigate methods from UK and China. In United Kingdom, there is an agency named Rail Accident Investigation Branch (RAIB) in charge of accident investigate. In these accident reports from RAIB, various factors can directly or indirectly result in accidents. To apply these causal factors for analysis, they are summarized and divided into 5 classes in a systemic way: ‘‘Human (H)’’, ‘‘Equipment & Machine (EM)’’, ‘‘Environment (E)’’ ‘‘Management (M)’’, and ‘‘Accident type (A, B, C, D)’’. These five classes can contain almost all of the causal factors which are generated by workers, managers, machinery, electrical equipment, external environment, construction establishment, management, etc. I take almost all the causal factors classification for study in my research, beside the category “accident type”. The reason is accident type is overlap with some other factors in RAIB’s system and more importation is there is a better choice.

As mentioned in previous chapter, China's railway administration has developed detailed accident classification regulation which called “Regulations on Emergency

Rescue and Investigation of Railway Traffic Accidents". The regulations stipulate complex and detailed accident classification rules. In addition to the classification of four different levels of accidents according to the severity of the accident, the regulations also specify the specific types of accidents under the fourth level (also named as general accidents). In the regulations, the fourth-level accident is subdivided into four sub-categories, named A, B, C, and D accident types. (Appendix B) Among them, the A/B type accidents are determined according to the severity of the accident, such as the number of casualties, economic losses and the interruption of railway operation time. The C/D type accident is classified into 46 accidents and has an accident code according to the form and cause of the accident.

In the study, the accident type code was included in the accident report from China, and more than 98% of the accidents belonged to the C/D category in the fourth-level accident, that is, the accident coded according to the accident pattern and cause. So, I only used the event code from RAIB in the cause of the accident, and I used the code from the Chinese railway administration when selecting the accident type code.

The following is an example of encoding:

Original accident record: (Originally in Chinese, translated)

"In the construction plan of the Guangzhou South High-Speed Rail Engineering Section, there is no clear responsibility for the lead driver. The lead driver is temporarily replaced before the start of construction. The leading driver did not perform his due responsibilities during the lead, and the location of the reverse pit stop signal at Guangzhou North Station was unclear. When the locomotive signal showed a red and

yellow light, the driver was not prompted to confirm the reverse pit stop signal. The display of the machine, especially when using the GSM handset to control with Guangzhou North Station, is not focused, mistakenly listening to "Parking outside Guangzhou North Station" as "Parking at Guangzhou North Station 4", and communicating the error to the driver Information and instructions are the main cause of accidents. Station supervisors are not aware of the critical safety risks, and the large-scale machine grinding in the interval and the maintenance of the electrical switch in the station are carried out at the same time. In particular, the key safety risks of the maintenance of the electrical switch on the running path of the polished vehicle back to the station are not under key prevention and control. There was no prompt for the duty officer to strengthen the joint control of the vehicle. In the end, when the driver showed a red light in the reverse direction and the red and yellow lights in the locomotive signal, the driver illegally pressed the [OK] key of the GYK device and entered the No. 4 turnout in the station at a speed of 14km / h. The vehicle squeezed out of the movable rail of the turnout in the reverse position and stopped, resulting in a C10 accident."

Step 1: Analyze the accident process and break down the accident into several consecutive events.

Sample:

Accident 60617 development process after abbreviation:

1. The management of the construction organization process is weak, the management staff have insufficient work plans, and the management staff temporarily changes the driver before the construction begins

2. The driver did not do his due diligence, wrong password and wrong operation

3. Failure of the supervision mechanism, failure to detect driver's operation errors, and failure of safety precautions

4. Under wrong operation, the train passes the red signal in a fault state

5. Mechanical impact of turnout caused by train impact

6. The train rushed into the signal light and accident C10 occurred

Step 2: Encode the event obtained in step one by IRAB code, refer to Appendix A.

Accident 60617: M03 H04 M05 EM34 EM16 C10

Repeat steps 1 and 2 to process all accident reports to obtain Table 5.1.

Table 5.1 Causal Factors for All Accident (Guangzhou, 2013-2017)

Accident ID	**Causal Factors**						
40106	H05	EM43	D10				
50401	M02	H05	EM43	EM26	D10		
50521	M03	H10	C10				
50702	H03	EM04	EM26	D05			
50729	H08	M05	H20	EM07	C24		
60322	M05	H08	H06	EM05	D01		
60514	M05	EM05	C16				
60518	H08	H06	EM05	C12			
60617	M03	H04	M05	EM34	EM16	C10	

Table 5.2 Causal Factors for All Accident (Guangzhou, 2013-2017) - continued

Accident ID	**Causal Factors**						
61010	M02	H04	EM48	C09			
61126	M06	H08	E04	EM02	H06	EM07	C25
61221	H08	H20	EM26	D09			
70113	H04	EM36	D15				
70128	H10	EM26	C09				
70602	M05	EM07	EM12	C13			
70713	H04	EM34	D15				
71011	H04	EM34	C10				
30115	H20	EM05	C13				
30416	M05	H20	EM28	EM43	D01		
30521	M03	M02	H03	EM03	EM25	C19	
30604	M03	H04	EM34	C10			
30607	H08	EM04	H10	EM07	C08		
30810	EM27	H04	EM26	D15			
31122	M05	EM17	EM25	EM26	C14		
40118	H06	EM44	EM26	C12			
40613	H05	EM07	EM22	C02			
40623	M05	H06	EM39	EM17	EM25	C14	
40803	H03	H04	EM01	D02			
40902	H19	EM14	EM26	C02			
41021	M01	M02	H03	H07	B01		
41213	M03	M02	H10	H07	H20	EM05	C13
41220	H20	M05	H06	EM07	EM26	D10	
50129	M01	H03	M05	H08	EM29	C15	
50226	H17	H03	EM36	D13			

Table 5.3 Causal Factors for All Accident (Guangzhou, 2013-2017) - continued

Accident ID	Causal Factors						
50425	M03	M05	H03	EM48	C13		
50518	M02	H07	B01				
50629	M01	H07	B01				
50711	H01	H03	EM28	D12			
50726	M05	H03	H17	EM25	D19		
50728	M03	M02	H08	EM39	EM25	EM26	C14
50824	M03	M02	H20	EM05	EM26	C13	
50826	M01	H01	EM34	C10			
50919	M03	H04	EM49	EM29	C23		
51004	H17	EM34	C10				
51007	H03	M05	H08	EM24	C24		
51009	M06	H13	EM10	EM26	C13		
51021	H04	EM24	C08				
51120	M01	H07	B01				
51130	M03	H08	M05	EM37	D09		
51212	M03	M02	E01	EM06	EM23	EM39	C14
51218	H01	EM34	C09				
51226	M03	H08	M05	H20	EM05	C13	
60229	M01	H08	B01				
60323	M06	H06	E07	EM23	EM05	C13	
60328	M01	H08	B01				
60728	H07	M05	EM46	EM22	D02		
60913	M03	H13	EM05	H04	EM16	C16	
60919	M03	H06	EM29	D10			
61006	M03	H06	EM07	H04	EM22	D02	

Table 5.4 Causal Factors for All Accident (Guangzhou, 2013-2017) - continued

Accident ID	**Causal Factors**						
61102	H06	EM05	D08				
61108	M03	H10	EM13	D10			
61122	H08	EM43	EM05	C13			
70303	M02	H20	EM05	C13			
70327	H10	EM29	EM16	D03			
70413	H06	EM02	B04				
70507	M01	H08	B01				
70528	H17	EM43	EM10	C08			
70901	M06	H20	EM26	D09			

Step 3, according to the sequence of events, add the direction of the accident. The direction directly reflects the causal connection during the accident. The development of some accidents is particularly complicated, which will disrupt the sequence of event development when performing the second step of encoding, so we must rearrange the causality of event development. This step is also giving direction to the network.

Sample:

Accident 60617: M03 → H04 → M05 → EM34 → EM16 → C10

By processing all data in the same way, the development chain of all accidents can be obtained, as shown in Table 5.2.

Table 5.5 Event Chains for All Accidents (Guangzhou, 2013-2017)

Accident ID	Event Chain
30810	EM27 → H04 → EM26 → D15
51218	H01 → EM34 → C09
50711	H01 → H03 → EM28 → D12
40803	H03 → H04 → EM01 → D02
50702	H03 → EM04 → EM26 → D05
51007	H03 → M05 → H08 → EM24 → C24
51021	H04 → EM24 → C08
71011	H04 → EM34 → C10
70113	H04 → EM36 → D15
70713	H04 → EM34 → D15
40106	H05 → EM43 → D10
40613	H05 → EM07 → EM22 → C02
61102	H06 → EM05 → D08
70413	H06 → EM02 → B04
40118	H06 → EM44 → EM26 → C12
60728	H07 → M05 → EM46 → EM22 → D02
61122	H08 → EM43 → EM05 → C13
61221	H08 → H20 → EM26 → D09
30607	H08 → EM04 → H10 → EM07 → C08
60518	H08 → H06 → EM05 → C12
50729	H08 → M05 → H20 → EM07 → C24
70128	H10 → EM26 → C09
70327	H10 → EM29 → EM16 → D03
51004	H17 → EM34 → C10
70528	H17 → EM43 → EM10 → C08

Table 5.6 Event Chains for All Accidents (Guangzhou, 2013-2017) - continued

Accident ID	**Event Chain**
50226	H17 → H03 → EM36 → D13
40902	H19 → EM14 → EM26 → C02
30115	H20 → EM05 → C13
41220	H20 → M05 → H06 → EM07 → EM26 → D10
50826	M01 → H01 → EM34 → C10
50129	M01 → H03 → M05 → H08 → EM29 → C15
41021	M01 → M02 → H03 → H07 → B01
50629	M01 → H07 → B01
51120	M01 → H07 → B01
60229	M01 → H08 → B01
60328	M01 → H08 → B01
70507	M01 → H08 → B01
50401	M02 → H05 → EM43 → EM26 → D10
61010	M02 → H04 → EM48 → C09
70303	M02 → H20 → EM05 → C13
50518	M02 → H07 → B01
30521	M03 → M02 → H03 → EM03 → EM25 → C19
50521	M03 → H10 → C10
60919	M03 → H06 → EM29 → D10
50919	M03 → H04 → EM49 → EM29 → C23
30604	M03 → H04 → EM34 → C10
51212	M03 → M02 → E01 → EM06 → EM23 → EM39 → C14
41213	M03 → M02 → H10 → H07 → H20 → EM05 → C13
50728	M03 → M02 → H08 → EM39 → EM25 → EM26 → C14
60617	M03 → H04 → M05 → EM34 → EM16 → C10

Table 5.7 Event Chains for All Accidents (Guangzhou, 2013-2017) - continued

Accident ID	Event Chain
60913	M03 → H13 → EM05 → H04 → EM16 → C16
50824	M03 → M02 → H20 → EM05 → EM26 → C13
61006	M03 → H06 → EM07 → H04 → EM22 → D02
61108	M03 → H10 → EM13 → D10
50425	M03 → M05 → H03 → EM48 → C13
51226	M03 → H08 → M05 → H20 → EM05 → C13
51130	M03 → H08 → M05 → EM37 → D09
50726	M05 → H03 → H17 → EM25 → D19
31122	M05 → EM17 → EM25 → EM26 → C14
40623	M05 → H06 → EM39 → EM17 → EM25 → C14
70602	M05 → EM07 → EM12 → C13
30416	M05 → H20 → EM28 → EM43 → D01
60322	M05 → H08 → H06 → EM05 → D01
60514	M05 → EM05 → C16
70901	M06 → H20 → EM26 → D09
60323	M06 → H06 → E07 → EM23 → EM05 → C13
61126	M06 → H08 → E04 → EM02 → H06 → EM07 → C25
51009	M06 → H13 → EM10 → EM26 → C13

5.2 Network Established

Combining the event chains of all accidents, different accidents may have the same events, such as driver errors, rainy weather, or the same mechanical failure. Combining all the incident chains of accidents, you can get a network. All the network diagrams in this article are generated by MATLAB. By converting the contents of Table 5.2 into a matrix, and then writing the code, you can quickly complete the drawing work. The results are shown in Figure 5.2.

The tool used for network construction and mathematical calculation in this study is MATLAB. The Figure 5.1 shows a screenshot of the software.

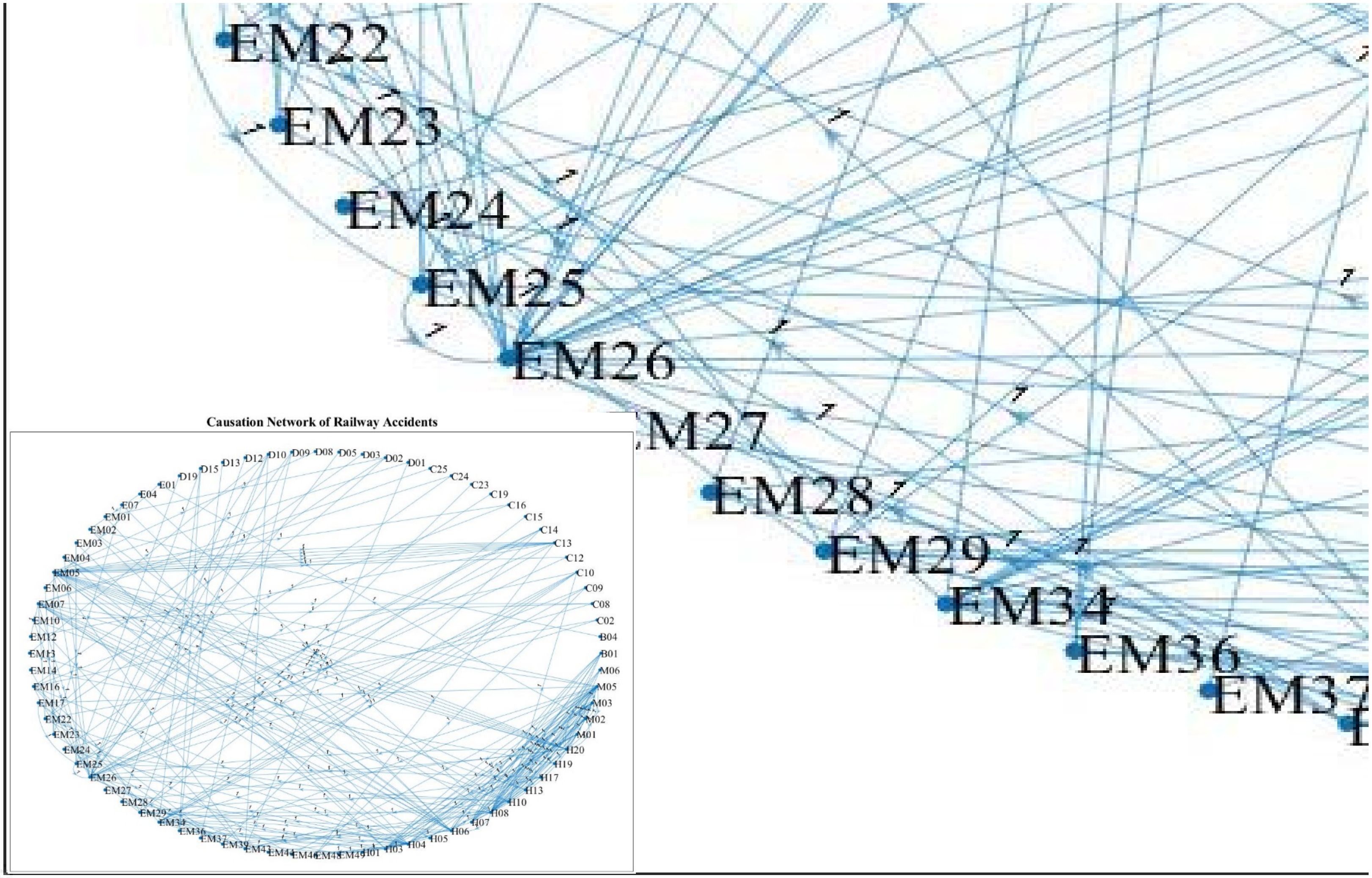


Figure 5.1 Network sample.

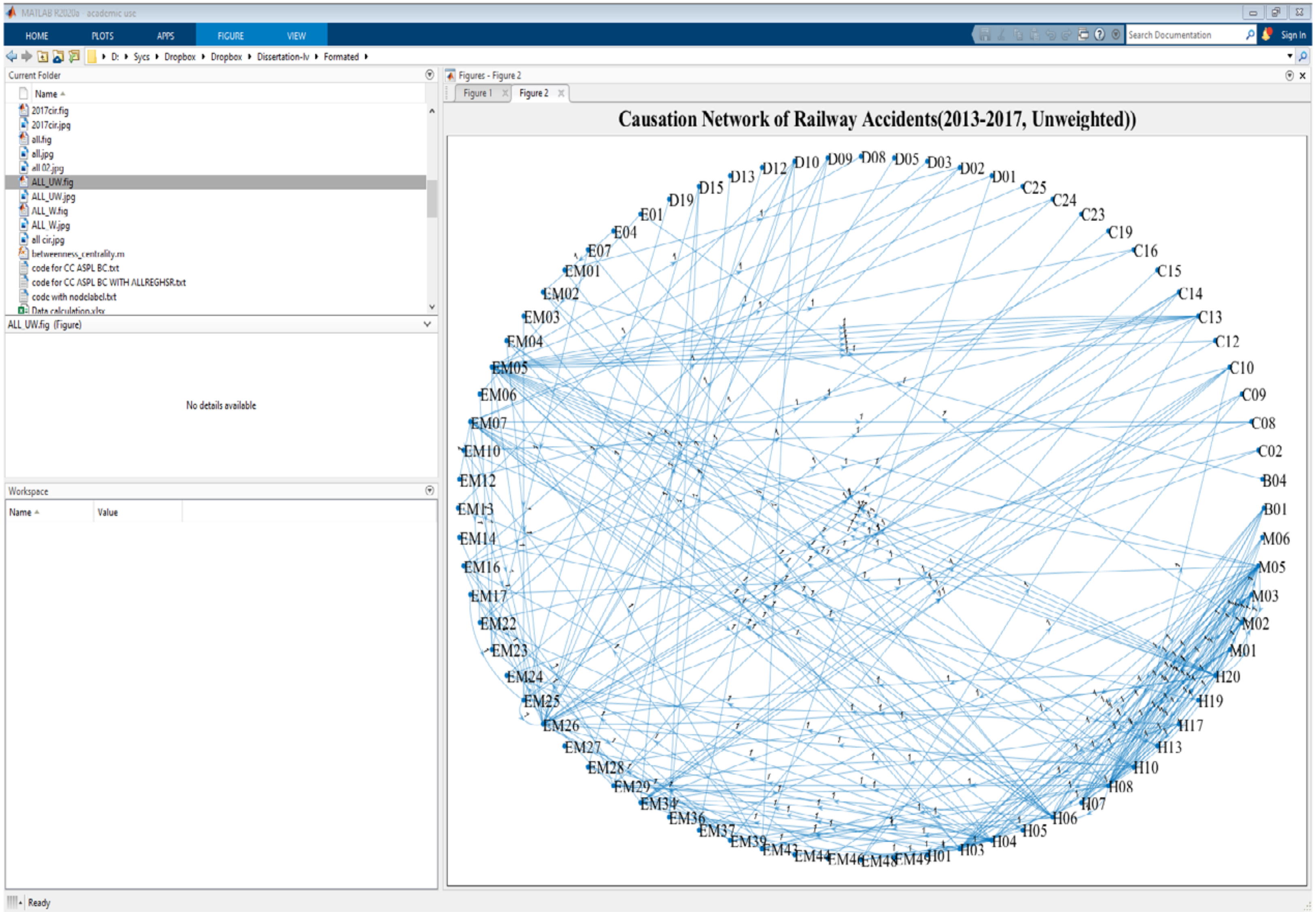


Figure 5.2 MATLAB UI screen.

Figure 5.2 is composed of two parts. The lower left corner is a full picture, which cannot be seen in detail due to space limitations. So, I took a part of it and enlarged it for explanation.

Node and Edge:

The so-called complex network is actually very simple. The entire network has only two parts: nodes and edges. The node is the event mentioned above, and the edge is the causal relationship between the events. The arrows on the lines indicate the direction of causality. The two ends of the arrows represent the cause and effect of a pair of causal relations.

Degree and Weight:

The number on the line represents the weight of the edge, because this picture has not been weighted, so the weight of the edge is 1. Each node has a line connected to other nodes, the number of lines represents the importance of this node, that is the weight of the node. And there may be many edges between two nodes, so how many nodes are connected to this node is the degree of this node.

Shortest path length and Diameter:

There may be no edge connection between the two nodes, but most points will be connected by other points, then the two nodes connected by the least edge are the shortest path length between the nodes. The length between the two longest points of the path is the diameter of the entire graph.

Clustering coefficient:

The clustering coefficient is used to measure the agglomeration between the surrounding nodes of a node. The more connections between other nodes connected to a node, the higher the clustering coefficient. But not all clustering coefficients can be calculated at all points in all graphs. For example, in some networks, the connectivity between nodes is not rich enough, it may not be possible to calculate this value.

Mean clustering coefficient is a parameter that measures the agglomeration of the entire network. It is obtained by calculating the average value of all clustering coefficients in the network.

Betweenness centrality

betweenness centrality is a parameter used to measure the position of a point. It means that the shortest path through this point accounts for the percentage of the entire network. Therefore, the maximum value of betweenness centrality is 1, and betweenness centrality equal to 1 means that the shortest path of any pair of nodes in this network passes through this point.

CHAPTER 6

DATA ANALYSIS

6.1 Overall Accident Analysis

Figure 6.1 is a causation network modeled on 68 railway accidents that occurred between 2013 and 2017 in Guangzhou Railway Group. The 68 accidents were decomposed into 76 nodes and 233 edges, which also means 76 events. In all accidents, they may have happened many times in different accidents. These events combined a total of 233 control-feedback loops. Obviously, all of these controls failed in these cases, which led to 68 accidents. It can be seen in the figure that there are multiple connecting lines with arrows between many nodes. The arrow means the direction, indicating that one event triggered another. The presence of multiple lines indicates that the same chain reaction has occurred many times, which means that the network in this picture has not been weighted.

The network is so complicated, so we analyze the characteristics of the network through the following sections: degree, strength, path length, clustering coefficient and betweenness centrality.

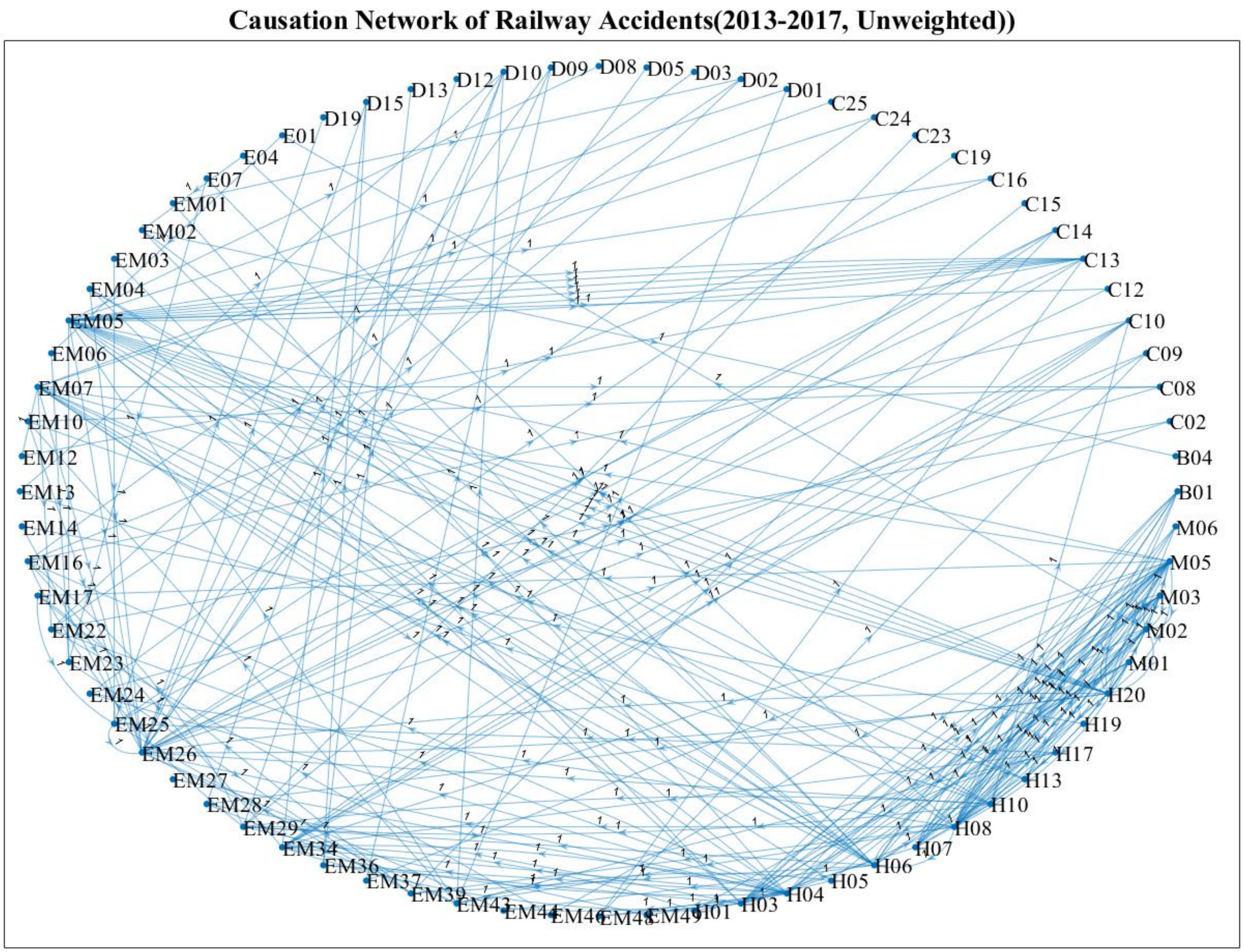


Figure 6.1 Causation network (2013-2017, unweighted).

6.1.1 Degree and Degree Distribution

Figure 6.2 shows the degree distribution of nodes (events) in all accidents. The highest degree is EM26 (Train delayed), which is far more than the degree value of other events, showing that EM26 (Train delayed) is very important in the network. It also shows that EM26 (Train delayed) appears very frequently in these five years of accidents: as an accident result, delay is the most common result of train accidents in these five years. As the cause of accidents, train delays are also the most likely to cause various accidents: delays can cause confusion in management, train dispatching, and the use of station lines, causing instability in the entire system and increasing requirements for other safety controls.

The other common second to fifth accident factors are: H04 (Driver’s operation mistake), M05 (Not sufficient inspection and Supervision), H08 (Track worker’s negligence), H03 (Conductor’s mistake). Three of the top five accident factors are staff factors. It can be seen that the quality of staff is the weakest factor in railway safety in these five years.

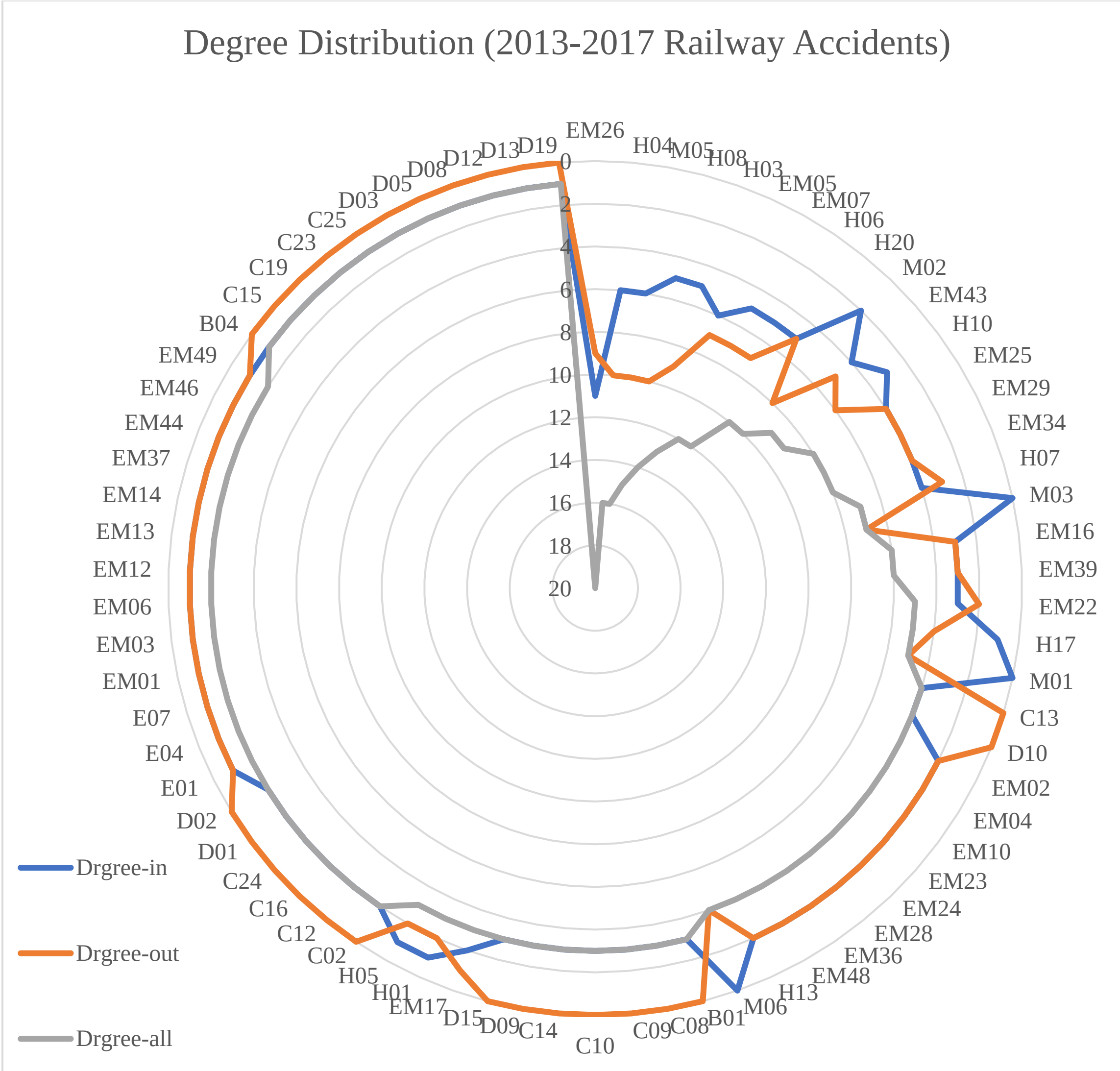


Figure 6.2 Degree distribution (2013-2017, all accidents).

Figure 6.3 illustrates that cumulative node degree distribution of Network follows an power law as $P(k) \sim 2.122x^{-1.318}$ ($R^2 = 0.8722$), The top 7.89% factors account for a majority (53.79%) of all causation relations, and the most (55.26 %) of factors occur only 1–3 times. The network has typical small-world model characteristics.

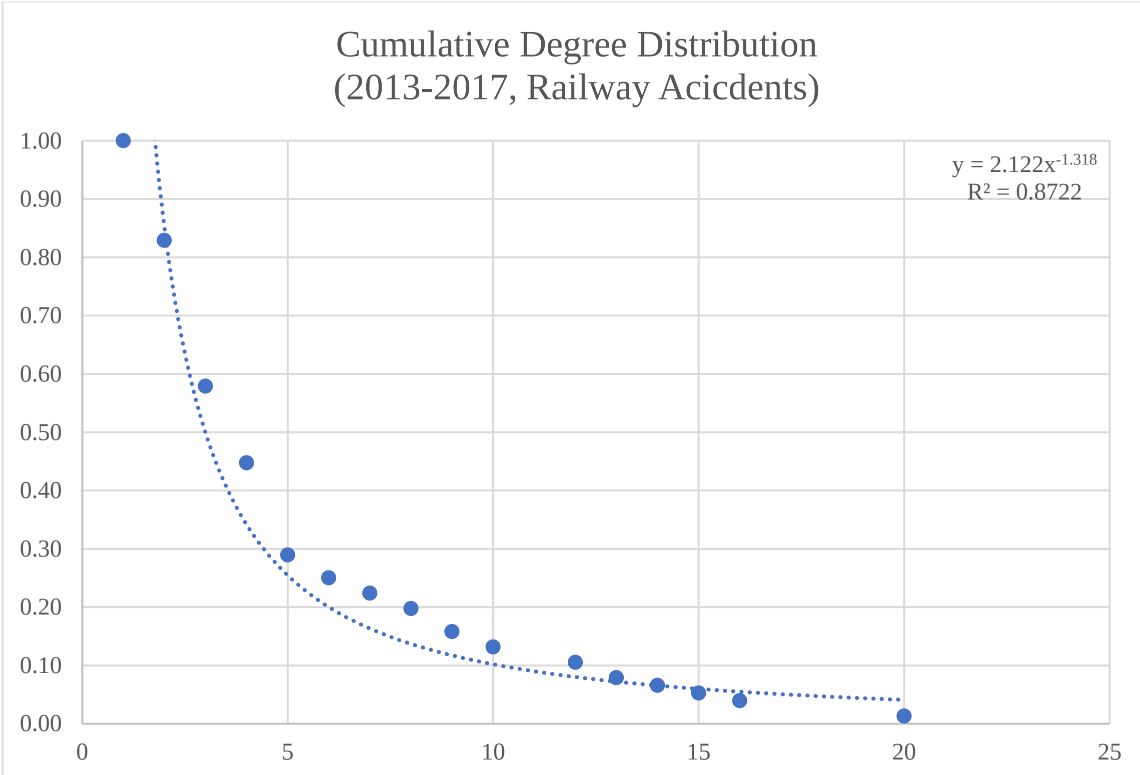


Figure 6.3 Cumulative degree distribution (2013-2017, all accidents).

6.1.2 Strength and Strength Distribution

Figure 6.4 shows the strength distribution of nodes (events) in all railway accidents over five years. The strength is weighted twice on the basis of the degree, not only considering the connectivity of the node in the network (the number of other points connected), but also considering the strength of the connection (the weight of the edge) and the size of the end node of the link (the severity of the accident). After weighting twice, it can be found that the importance of nodes in the network has changed significantly. EM26 (Train delayed) is no longer higher than other nodes, the most important node becomes H08(Track worker's negligence), and the second to fifth causal factors are: EM26 (Train delayed), M05 (Not sufficient inspection and supervision), EM05 (Train minor damaged), H04 (Driver's operation mistake). The human factor has occupied the same two positions as the equipment factor, and the management factor ranks third, showing the importance of management factors in the accident.

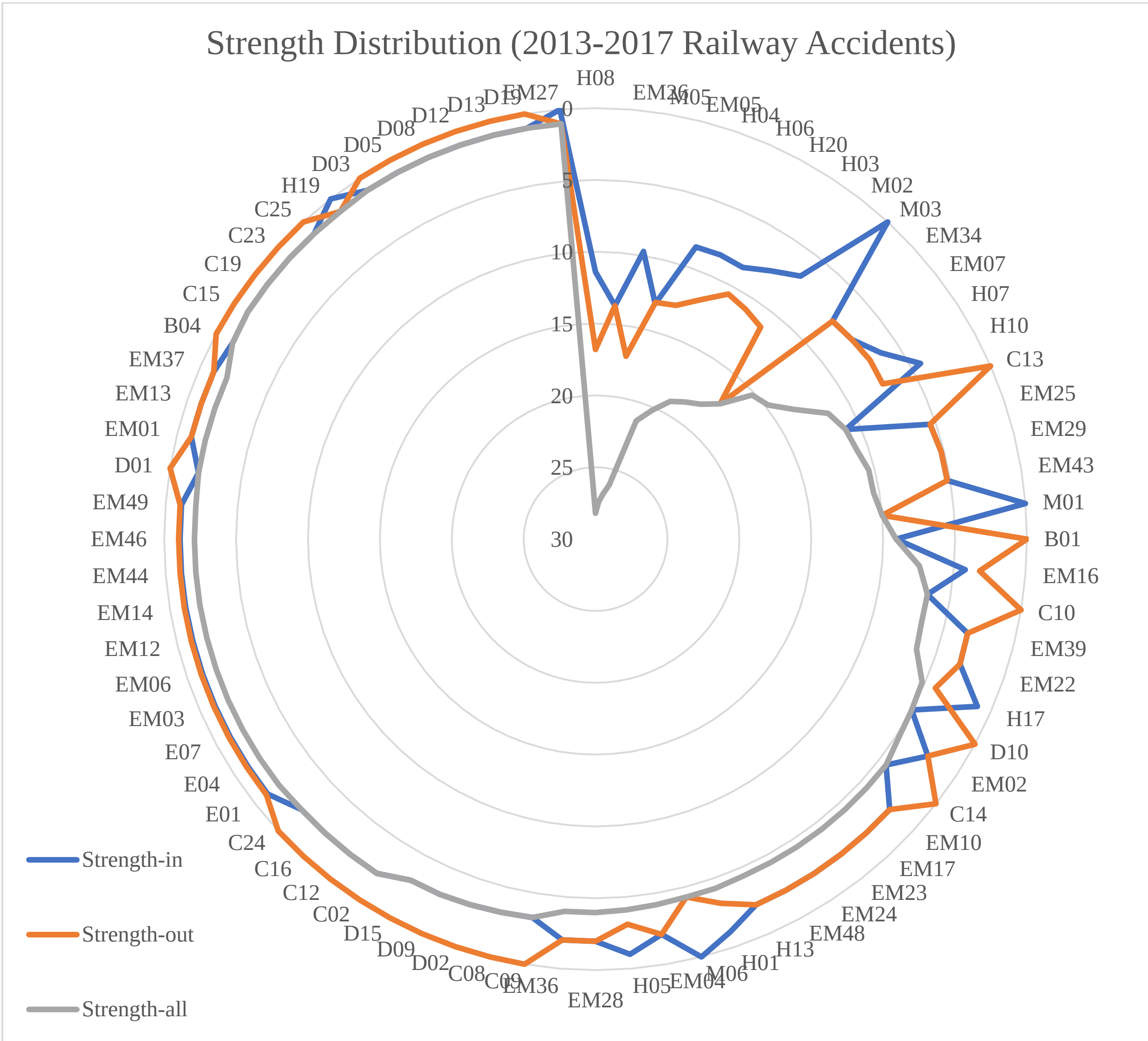


Figure 6.4 Strength distribution (2013-2017, all accidents).

Figure 6.5 illustrates that cumulative node strength distribution of weighted network follows an exponential function as $P(k) \sim 1.7164x^{-1.003} (R^2 = 0.8652)$. The top 13.16% factors account for a majority (54.07%) of all the times of occurrences, and the 50% of factors occur 1-4 times. The network has typical small-world model characteristics.

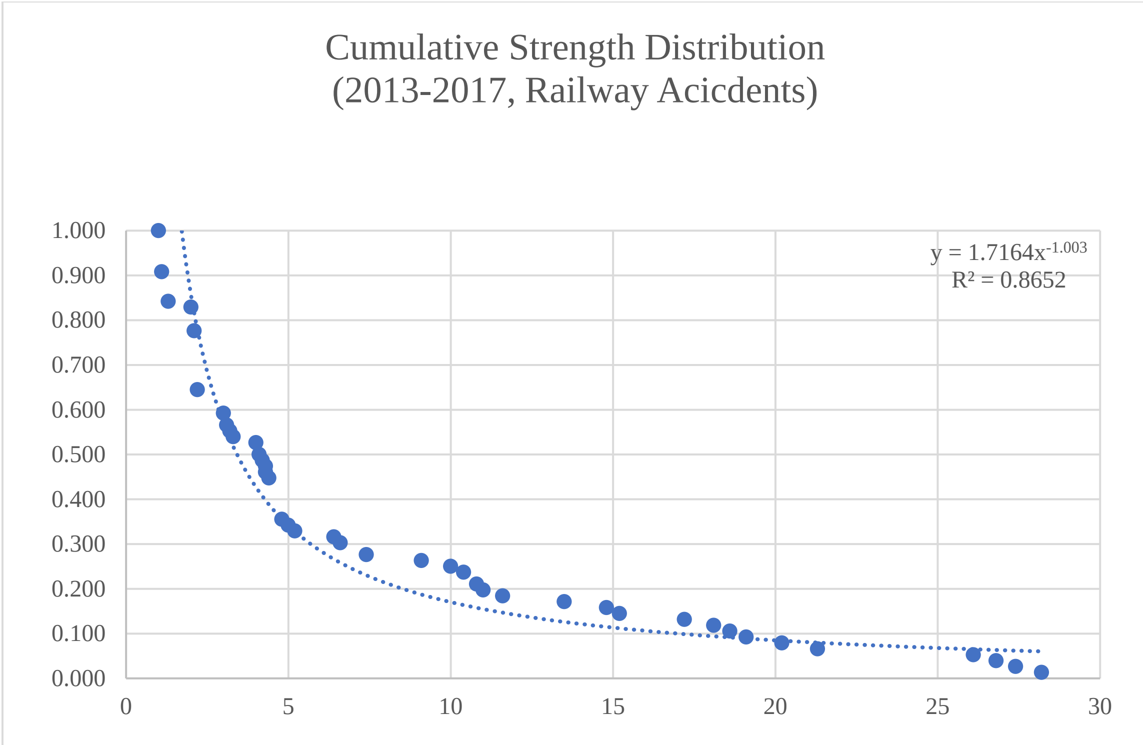


Figure 6.5 Cumulative strength distribution (2013-2017, all accidents).

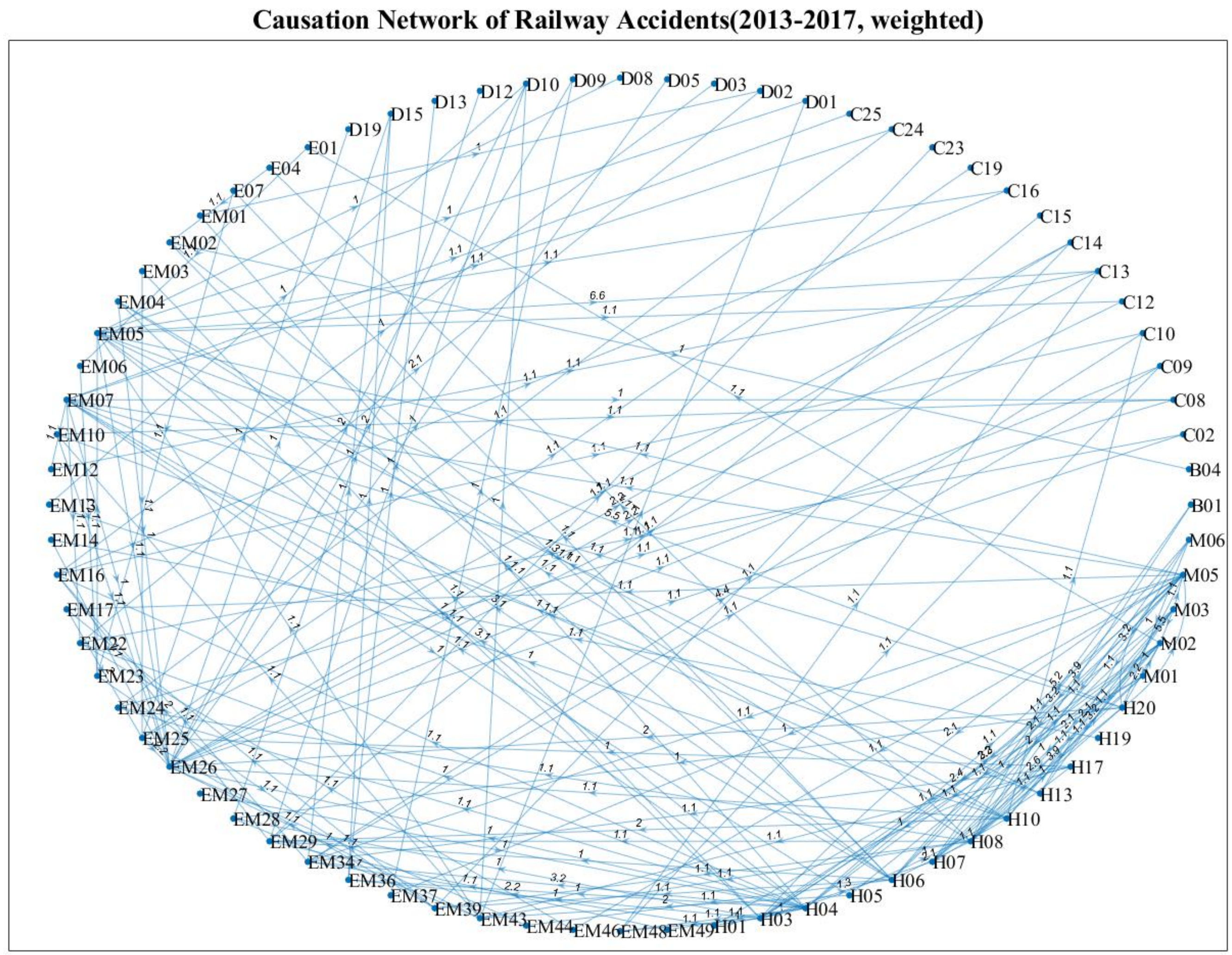


Figure 6.6 Causation network of railroad accidents (2013-2017, weighted).

6.1.3 Shortest Path and Diameter

In an unweighted causation network that mixes High-Speed Rail and regular railway accidents over a five-year period, the average path length is 3.11. This means that causality related to another factor requires approximately three steps in the network. The average path of the causality related to the accident is 3.09, which means that about 3 causal factors are needed to cause the accident. The diameter of the network is 9, and from E01 (Rainy condition) / 04 (Freezing temperatures) to EM13 (Wagon failure) are the two most distant nodes in the network. This indicates a possibility: the occurrence of harsh environment (Rainy condition / Freezing temperatures) can lead to the occurrence of Wagon failure through nine steps. At the same time, it means that if you want to avoid accidents, you can strengthen the control at any of the nine nodes.

6.1.4 Clustering Coefficient

Figure 6.7 shows the clustering coefficient in the causation network of all accidents. The clustering coefficient of the four nodes reaches 1, and two of them belong to the machine equipment category, showing that the machine equipment node tends to gather together. The overall clustering coefficient of the network is 0.4098, which shows that the aggregation between the nodes is high. Combining the average path of the network discussed in the previous paragraph is only 3.11, the combination of the two features makes the entire network very consistent with the characteristics of the small world network. This means that most factors can influence each other, and it is easy to produce the "resonance" phenomenon mentioned in the control theory. which means that the influences of the factors will overlap each other and enlarge, making the entire network particularly fragile.

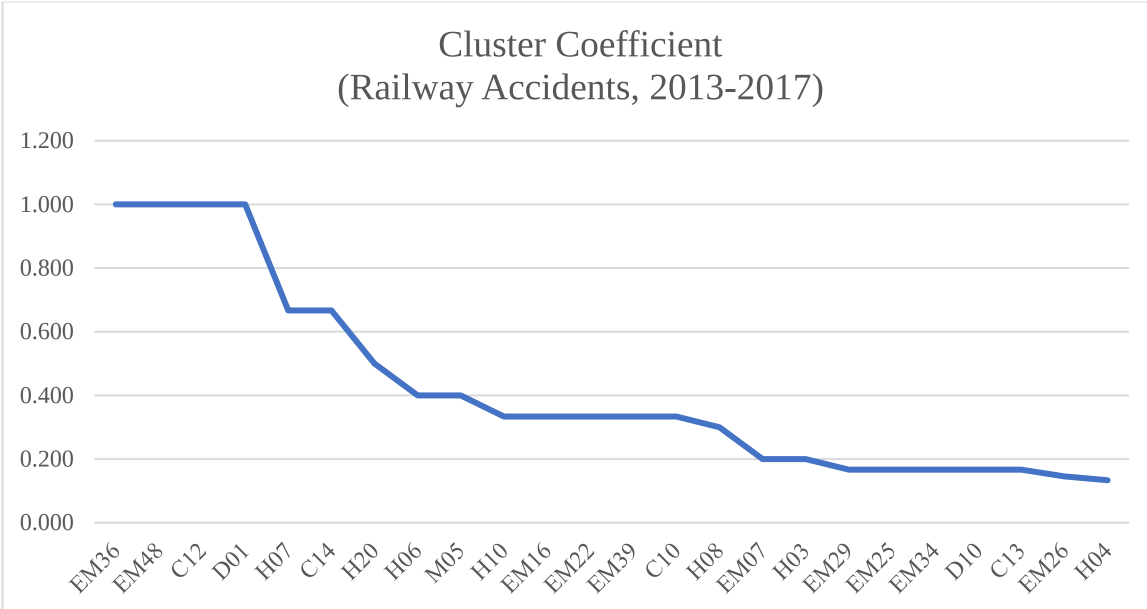


Figure 6.7 Clustering coefficient (2013-2017, all accidents).

6.1.5 Betweenness Centrality

Betweenness centrality indicates a possibility that the probability of this node on the shortest path connecting a pair of nodes. To a certain extent, Betweenness centrality is the advanced version of Degrees: Betweenness centrality selects the optimal solution (shortest path) on the basis of accessibility

Figure 6.8 shows the top 30% of the Betweenness centrality of all railway accident causation networks. Because weight and direction are considered, Betweenness centrality can reflect the historical trajectory and possible trajectory of accident development. The highest ranked EM26 (Train delayed), H06 reflects that a key chain, the untimely track inspection, is very likely to cause train delays.

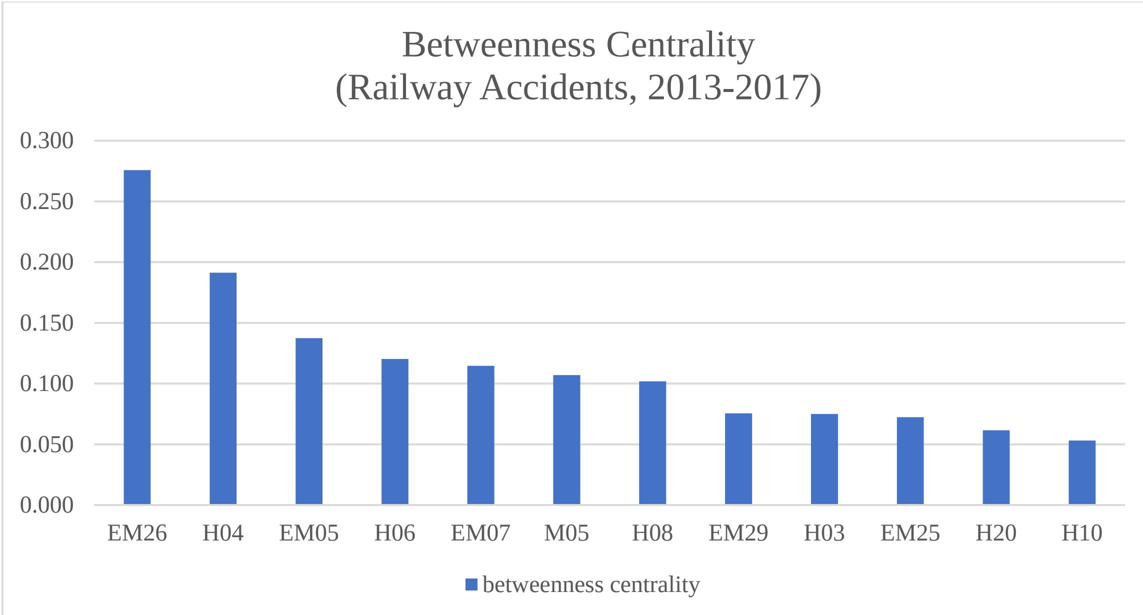
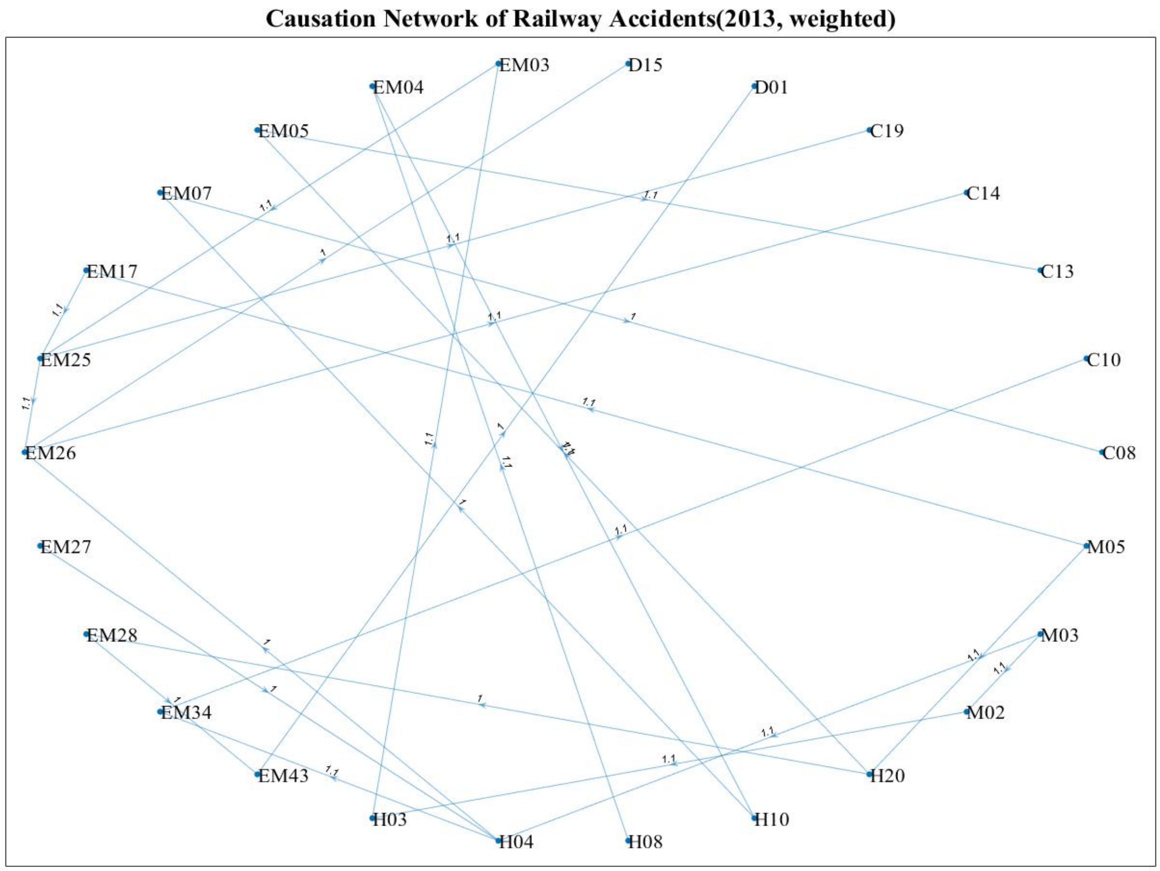


Figure 6.8 Betweenness centrality (2013-2017, all accidents).

6.2 Annual Accident Analysis

6.2.1 Annual data

According to the annual data report, the following networks were drawn. showing the causation network from 2013 to 2017. It can be observed that the spatial characteristics of the network are directly affected by the amount of data: 2013 with the least number of accidents is also the year with the simplest network structure. The network structure was also the most complicated in 2015 as the number of accidents increased. In fact, the limitations of methodology, the reasons why it is called a complex network depends on a huge number of nodes and edges connecting vertices. And when the network is no longer complicated, data analysis is impossible.



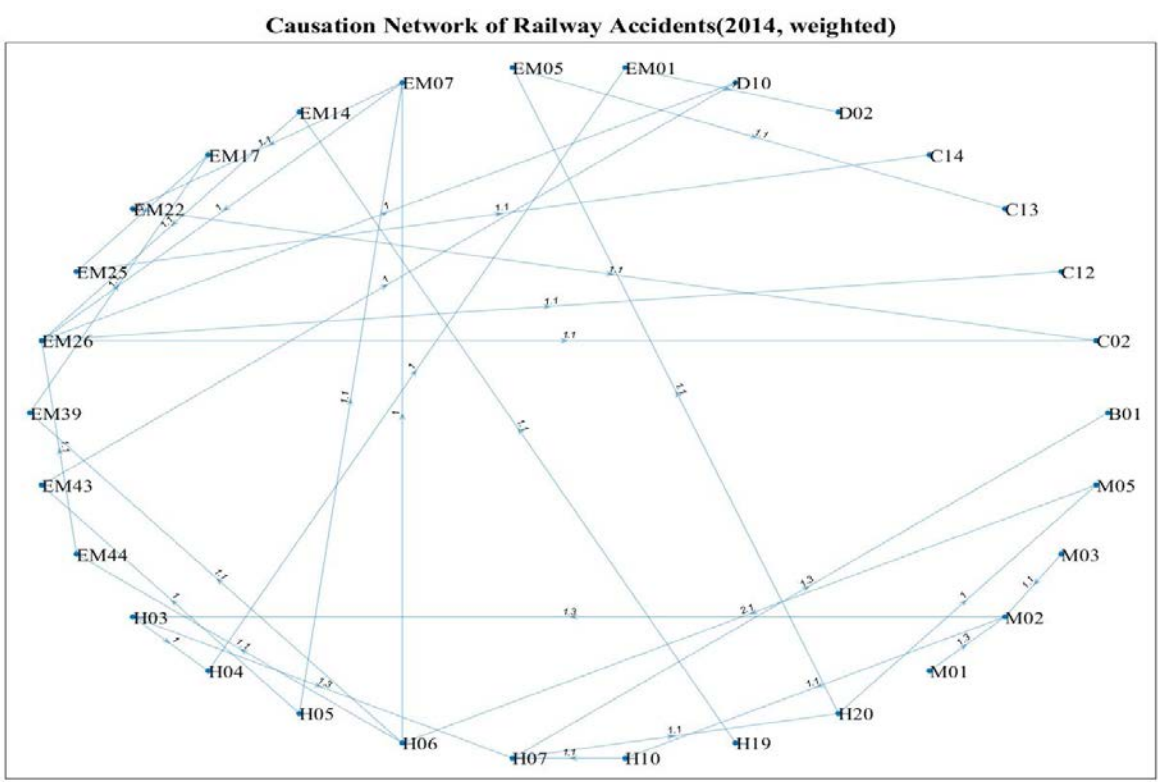


Figure 6.9 Causation network (2013-2014, all accidents).

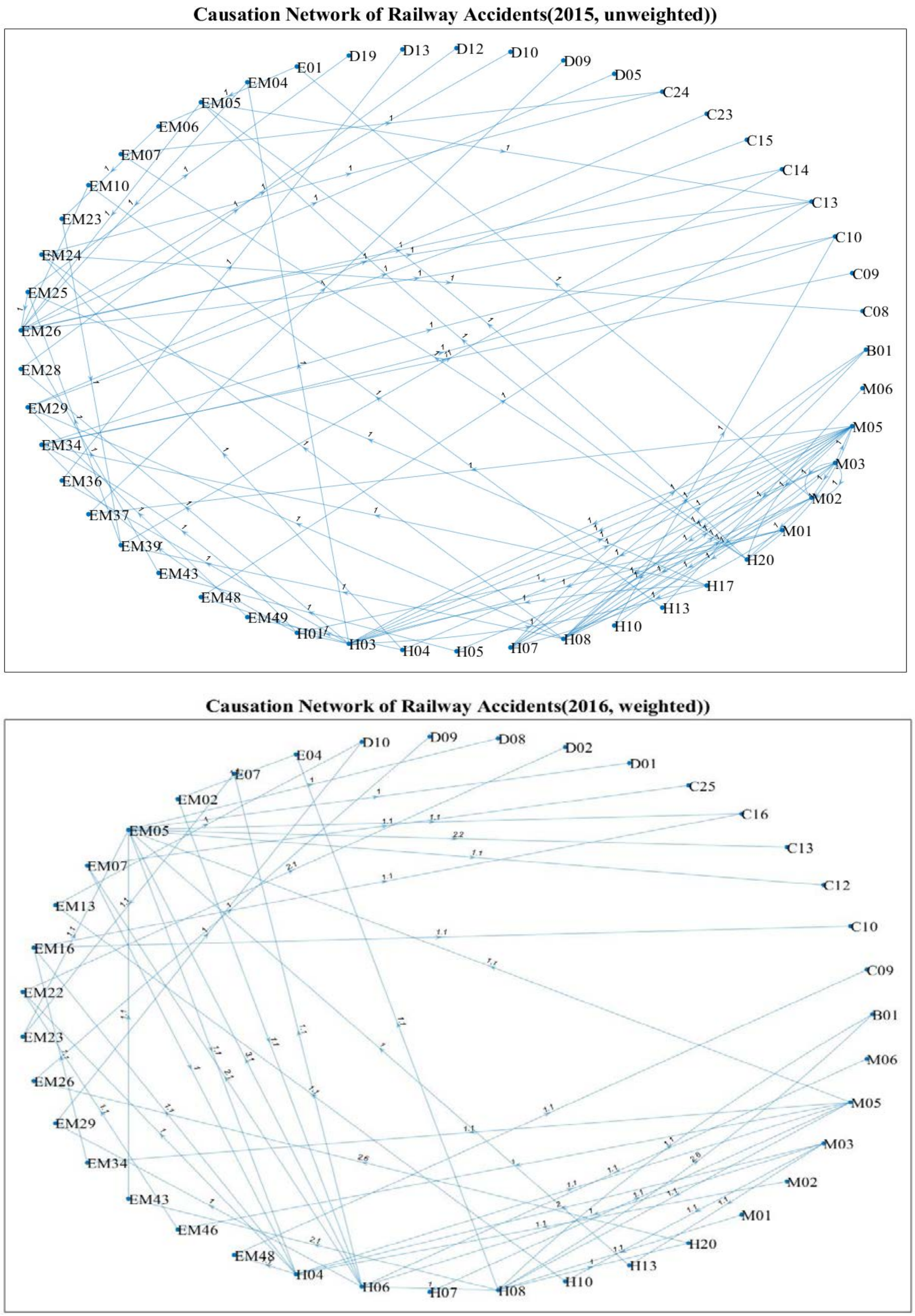


Figure 6.10 Causation network (2015-2016, all accidents).

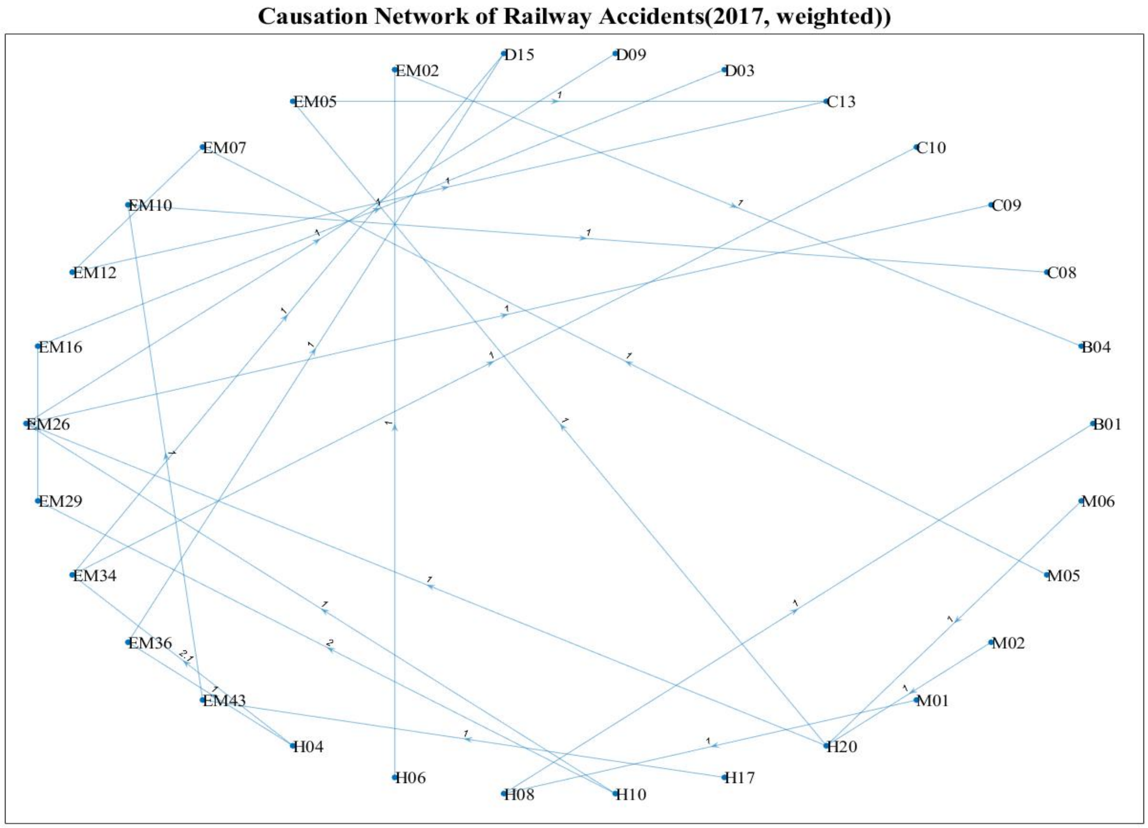


Figure 6.11 Causation network (2017, all accidents).

6.2.2 Annual Comparison

Degree and Strength distribution

Figure 6.12 is a summary chart of the top ten factors each year from 2013 to 2017. Each factor includes two values, degree-all and strength-all. Degree-all is the sum of degree-in and degree-out, strength-all is the sum of strength-in and strength-out. The abscissa includes five years, so through the continuous polyline in the figure, you can observe the change of several elements in five years: on the whole, the element is in the rising period from 2015 to 2016, which matches the annual change in the number of accidents. The most obvious changes are EM26 (Train delayed), M02 (Inadequate safety precautions) and H20

(Staff left machine/goods/material on the track), which maintained a continuous growth every year from 2013 to 2015. H03 maintained growth only in 2014-2015. H08 (Track worker's negligence) had a short-term growth in 2015-2016, and then fell sharply in 2017. Also falling are M01 (Inadequate safety education for workers) and M03 (Weak management), both of which have decreased in 2015-2016.

In 2015, two lines crossed on the graph, both of which are factors H07 (Worker was working in danger Conditions) and H08 (Track worker's negligence) belonging to the human factor category. After the two factors are weighted, the strength value has greatly increased from the degree value. The same thing happened with H03 in 2014. After weighting, the importance of H03 in the network has increased.

In addition to changes in railway safety, which can explain changes in element values, the distribution of accessibility and importance of each element is also directly related to the size of the network. In 2015-2016, when the network size is large (the amount of data is large), the line segment is on the ordinate the projection is more scattered. In 2013 and 2017, ten segments each year were concentrated in smaller areas.

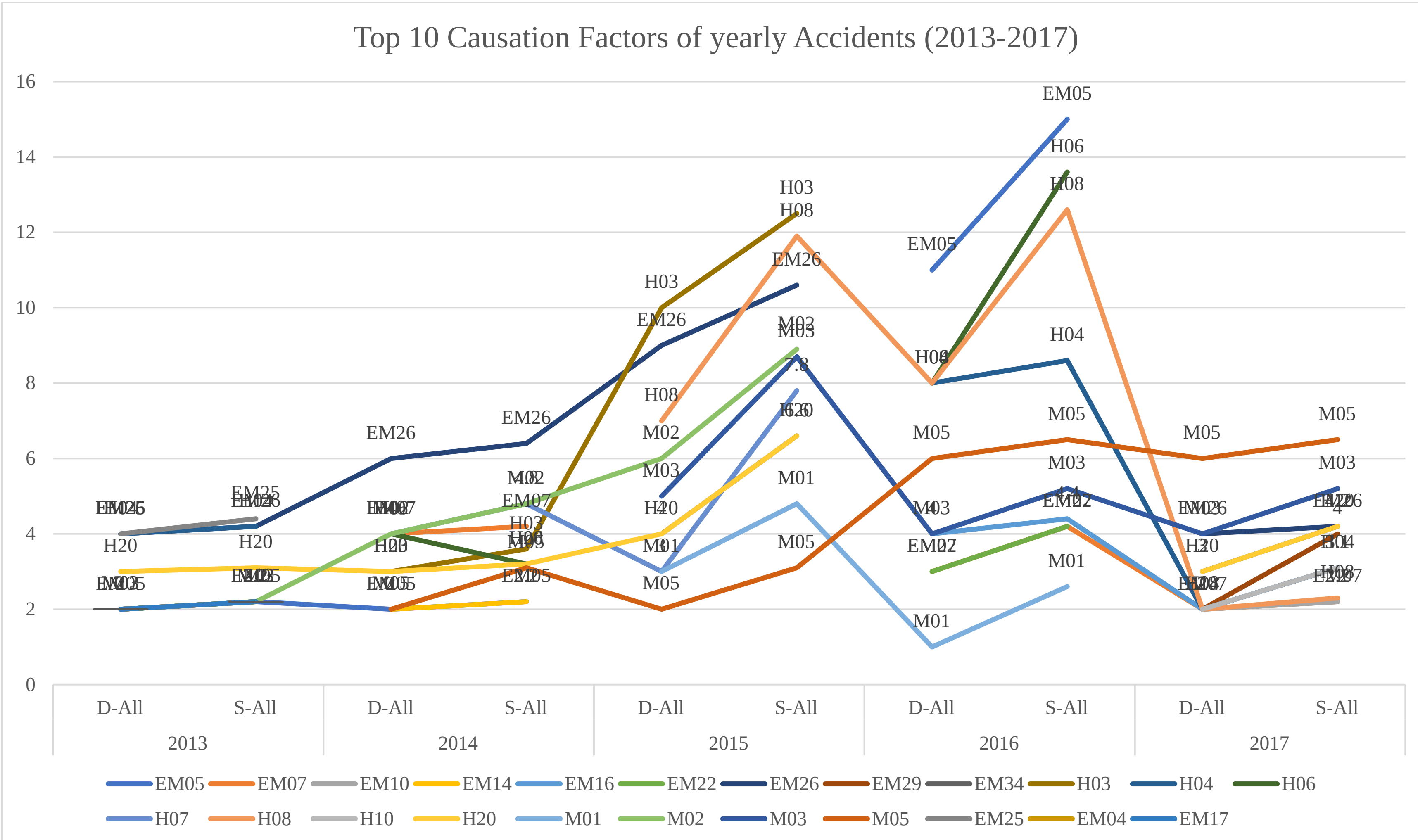


Figure 6.12 Top 10 Causation factors of annual accident (2013-2017, all accidents).

Path Length and Clustering Coefficient

Table 6.1 shows the geometric characteristics of the network, including the network diameter, the average shortest path length and the clustering coefficient. Depending on the size and structure of the network, the clustering coefficient is not available in most years. The average shortest path length is obviously related to the network diameter, and the larger the diameter, the larger the average shortest path length.

In 2015, due to abundant data and moderate network size, all network characteristics can be calculated. The average shortest path length and clustering coefficient can be combined to determine that the 2015 accident causation network conforms to the characteristics of the small world network. The various elements are closely connected, and the related influences are likely to cause the "resonance" phenomenon mentioned in the control theory. Managers need to strengthen the management of elements with a high clustering coefficient to eliminate security risks.

Table 6.1 Yearly Causation Network Characters Comparison (2013-2017, All Accidents)

<table>
<tr><th>Year</th><th>Diameter</th><th>Average Shortest Path Length</th><th colspan="5">Cluster Coefficient</th></tr>
<tr><td>2013</td><td>5</td><td>1.86</td><td colspan="5">N/A</td></tr>
<tr><td>2014</td><td>12</td><td>4.2</td><td colspan="5">N/A</td></tr>
<tr><td rowspan="2">2015</td><td rowspan="2">10</td><td rowspan="2">3.3</td><td>Average</td><td>C13</td><td>H03</td><td>H08</td><td>M05</td></tr>
<tr><td>0.370</td><td>0.333</td><td>0.167</td><td>0.667</td><td>0.333</td></tr>
<tr><td>2016</td><td>12</td><td>4.16</td><td colspan="5">N/A</td></tr>
<tr><td>2017</td><td>5</td><td>1.19</td><td colspan="5">N/A</td></tr>
</table>

Betweenness Centrality

Table 6.2 summarizes the value of Betweenness centrality ranked in the top nine each year for five years. The higher the element of Betweenness centrality, the more important it is in the causal chain of accident transmission. This is also where safety management should be reinforced.

Table 6.2 Top 9 Betweenness Centrality (2013-2017, All Accidents)

	2013		2014		2015		2016		2017	
Factors	EM25	0.390	H06	0.629	H08	0.320	H08	0.340	H20	0.148
	EM17	0.303	H20	0.552	H03	0.308	H04	0.335	EM26	0.140
	EM26	0.303	M05	0.512	EM26	0.288	EM05	0.322	EM05	0.099
	M05	0.280	H07	0.468	EM25	0.281	H06	0.303	C13	0.081
	H20	0.270	EM07	0.456	EM39	0.265	M05	0.273	H10	0.081
	H04	0.230	EM26	0.317	H17	0.173	M03	0.168	EM12	0.059
	EM28	0.120	EM39	0.192	M02	0.160	H20	0.102	EM29	0.059
	EM03	0.077	H03	0.192	M05	0.137	EM29	0.075	EM07	0.032
	EM05	0.063	H10	0.163	EM29	0.104	EM16	0.066	EM16	0.032

6.3 Regular Railway Accidents

Figure 6.13 shows an unweighted causation network for regular railway accidents, which contains 72 nodes(events) and 180 edges(causalities).

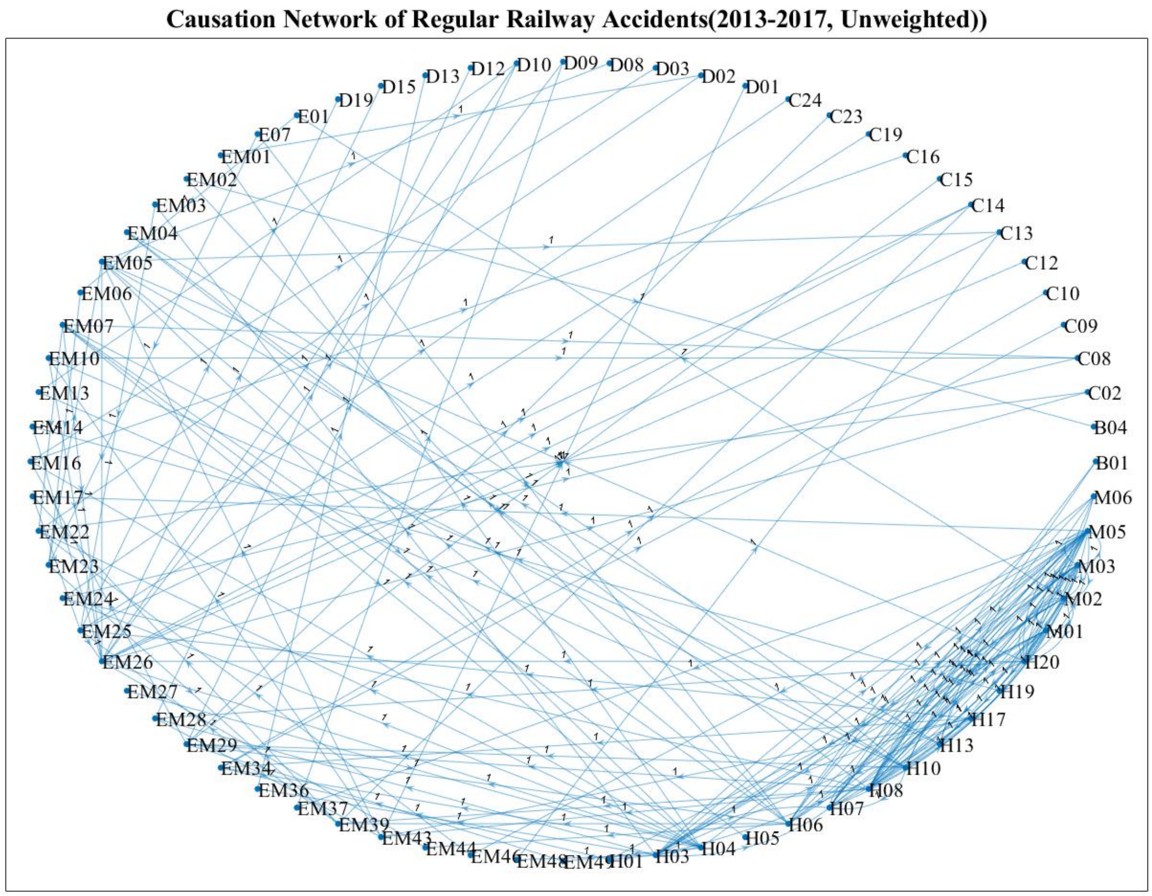


Figure 6.13 Causation network (2013-2017, regular accidents).

6.3.1 Degree and Degree Distribution

From the characteristics of the network, it can be found that the line density is significantly higher in the M (Management) and H (Human Factor) node areas than in other areas, reflecting that the intensity of causal connections related to M (Management) and H (Human Factor) is higher than in other areas. Statistics also prove this: Four of the top 6 nodes in the degree distribution (shown in Figure 6.14) are Human factors. In the statistical data by category, EM (Equipment and Machine)-related causal connections account for the highest proportion, 42.9%. However, the average number of connections on each node is only 4.06, which means that an average of 4.06 nodes are connected to EM (Equipment and Machine) nodes, only slightly higher than the network average level (3.81). The M (Management) and H (Human Factor) series nodes account for 29.8% and 12.7% of the causal connections, but the average number of connections is 6.83 and 7, which is much higher than the average level in the network.

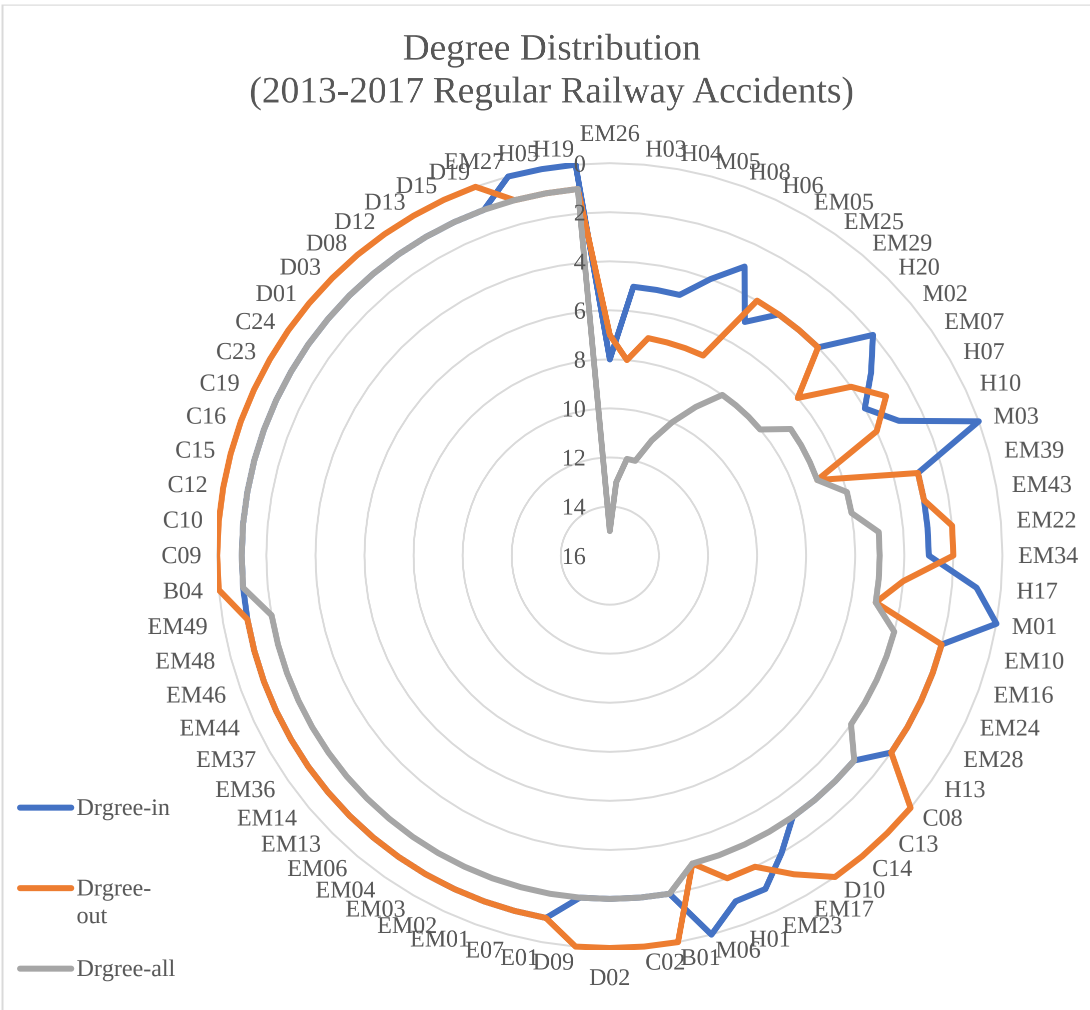


Figure 6.14 Degree distribution (2013-2017, regular accidents).

Figure 6.15 illustrates that cumulative node degree distribution of Network follows an power law as $P(k) \sim 2.0764x^{-1.451}$ ($R^2 = 0.8505$), The top 8.33% factors account for a majority (57.55%) of all causation relations, and the most (52.78 %) of factors occur only 1–2 times. The network has typical small-world model characteristics.

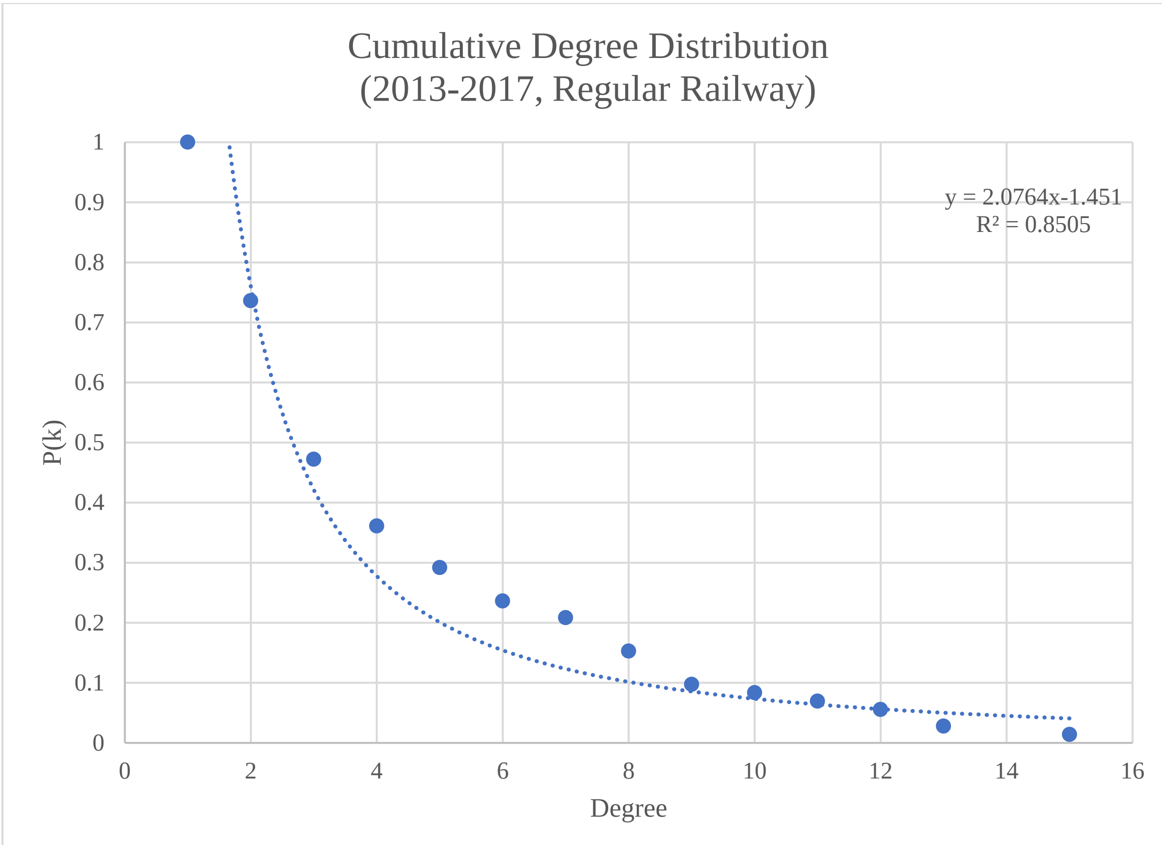


Figure 6.15 Cumulative degree distribution (2013-2017, regular accidents).

6.3.2 Strength and Strength Distribution

Figure 6.16 shows the dual-weighted network. Compared with the unweighted network, the number of edges in the weighted network (Figure 6.17) has been significantly reduced.

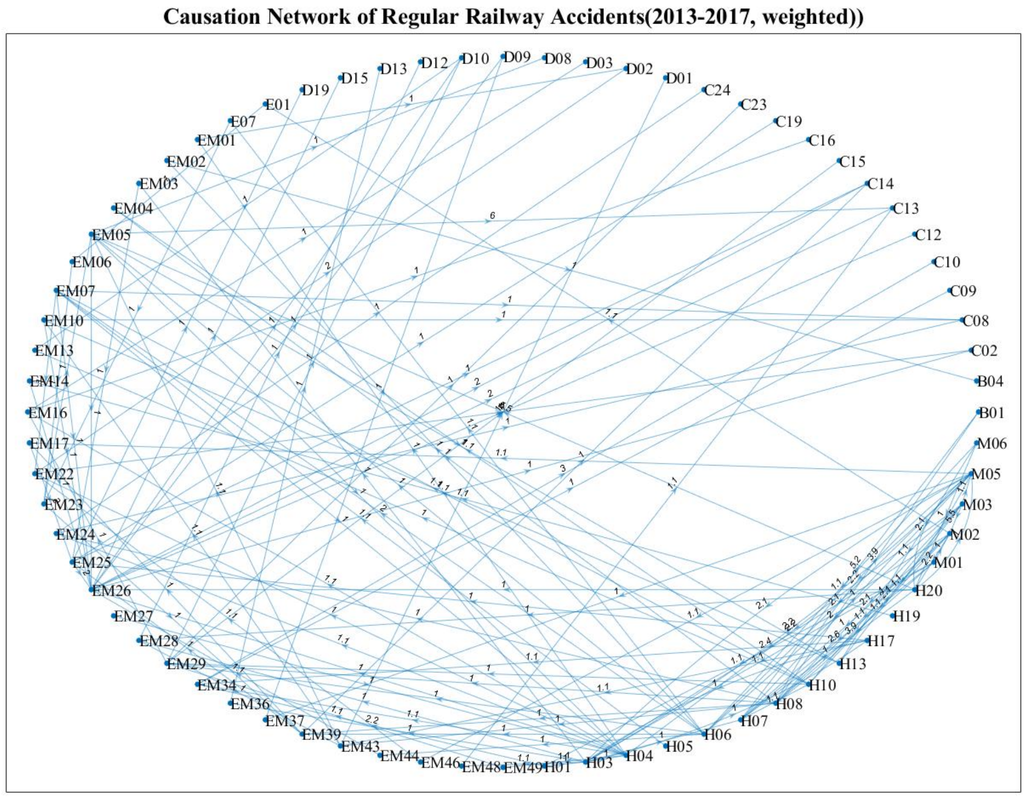


Figure 6.16 Causation network (2013-2017, regular accidents, weighted).

The numerical changes that are greatly affected by weighting are M02 (Inadequate safety precautions, 8 as degree, 16 as strength), M03 (Weak management, 7 as degree, 15 as strength), H08 (Track worker's negligence, 11 as degree, 20.8 as strength), EM05 (Train minor damaged, 9 as degree, 19.6 as strength). This proves once again that the frequency and severity of accidents need to be included in the analysis of the cause of the accident. It needs to be noted that M01 and M03, both of which have only Out-Strength values, show that the lack of training and weak management only affects other factors, but have not been affected by other factors. The average value of strength is 5.41, which means that on average each causal factor affects other factors 5.4 times.

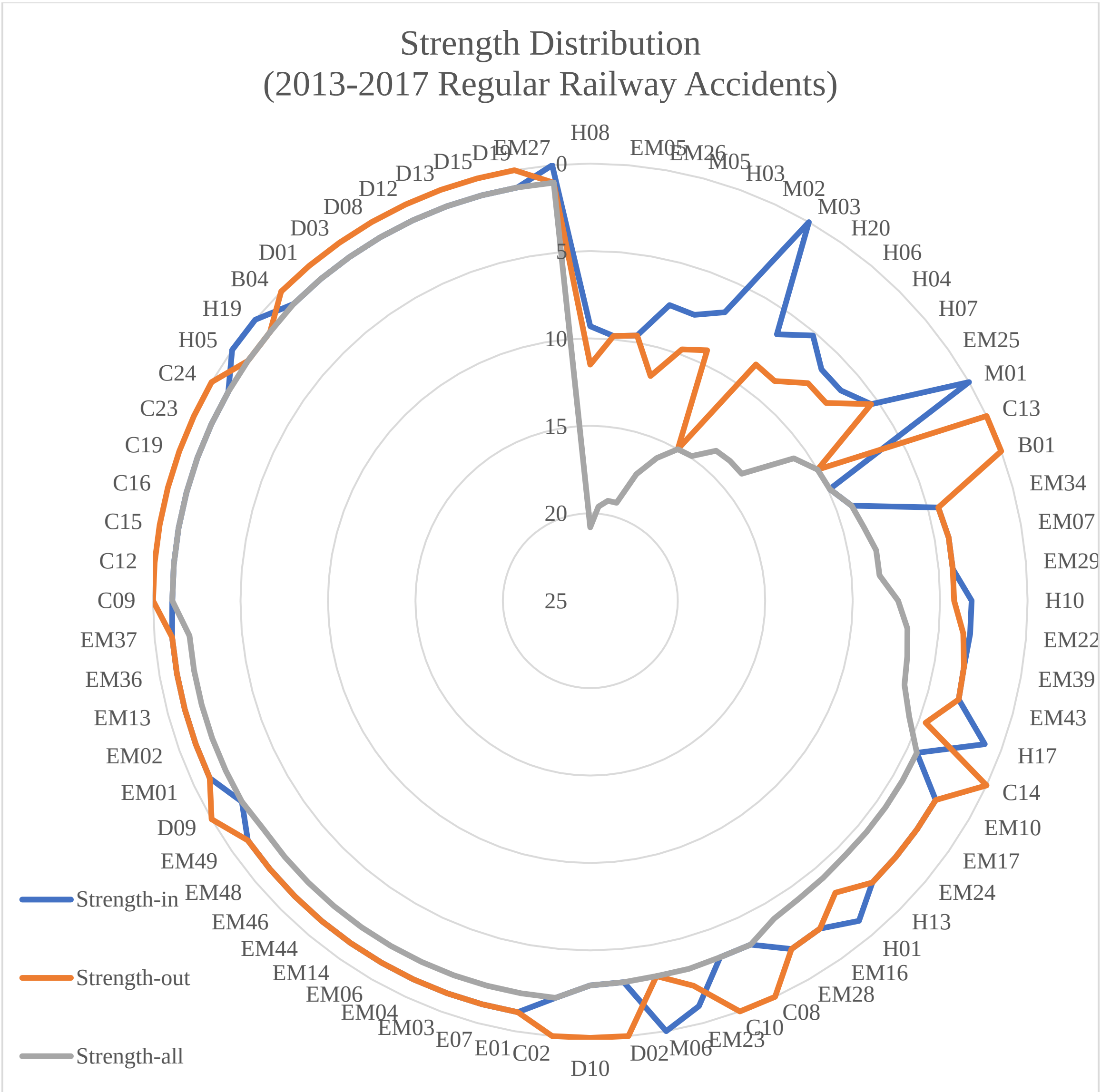


Figure 6.17 Strength distribution (2013-2017, regular accidents).

Figure 6.18 illustrates that cumulative node strength distribution of Network follows an power law as $P(k) \sim 1.6991x^{-1.072}(R^2 = 0.8274)$. The top 15.28% factors account for a majority (54.48%) of all the times of occurrences, and 33.33% of factors occur only 1–2 times. The network has typical small-world model characteristics.

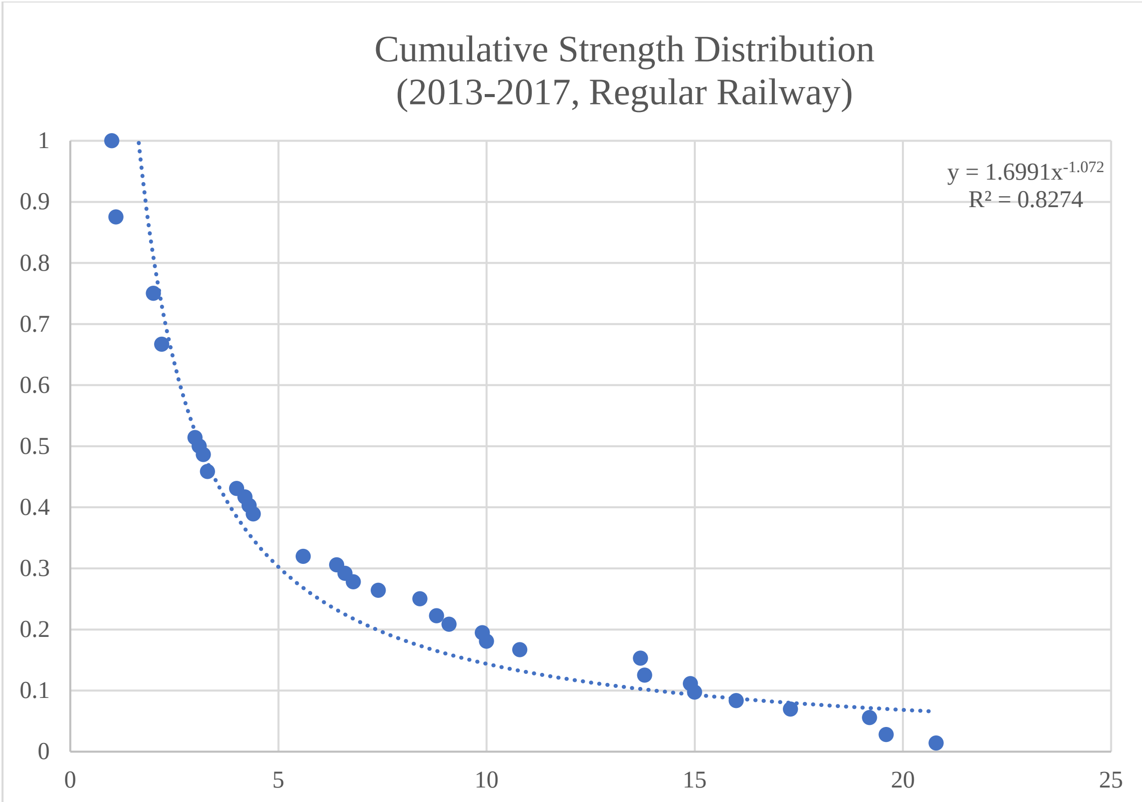


Figure 6.18 Cumulative strength distribution (2013-2017, regular accidents).

6.3.3 Shortest Path and Diameter

In the regular railway accident causation network, the average path length is 2.77. This means that the causality related to another factor is about three steps in the network. The average path of the causality related to the accident is 3.10, which means that about 3 causal factors are needed to cause the accident. The network diameter is 7, and from E01 (Rainy condition) to C10 (Train over signal or stop sign) / 13 (A collision occurred while the train was running) are the two furthest pairs of nodes in the network. This indicates a possibility: the rainy weather can lead to the accident C15 (Braking system malfunction) / 23 (Locomotive not tested) through 7 steps. At the same time, it means that if you want to avoid accidents, you can strengthen the control at any of the 7 nodes.

6.3.4 Clustering Coefficient

Figure 6.19 shows the clustering coefficient in the causation network of regular railway accidents. Four of the top six factors belong to human factors, and all of them are greater than 0.3, which indicates that the factors of human factors tend to be clustered together. The aggregation coefficient of the entire network is 0.3562, which is much larger than the random network of the same size. The aggregation coefficient higher than 0.3 and the average path length less than 3 indicate that this network conforms to the characteristics of a small-world network. This means that elements can easily affect each other, thereby breaking the normal operation of the system.

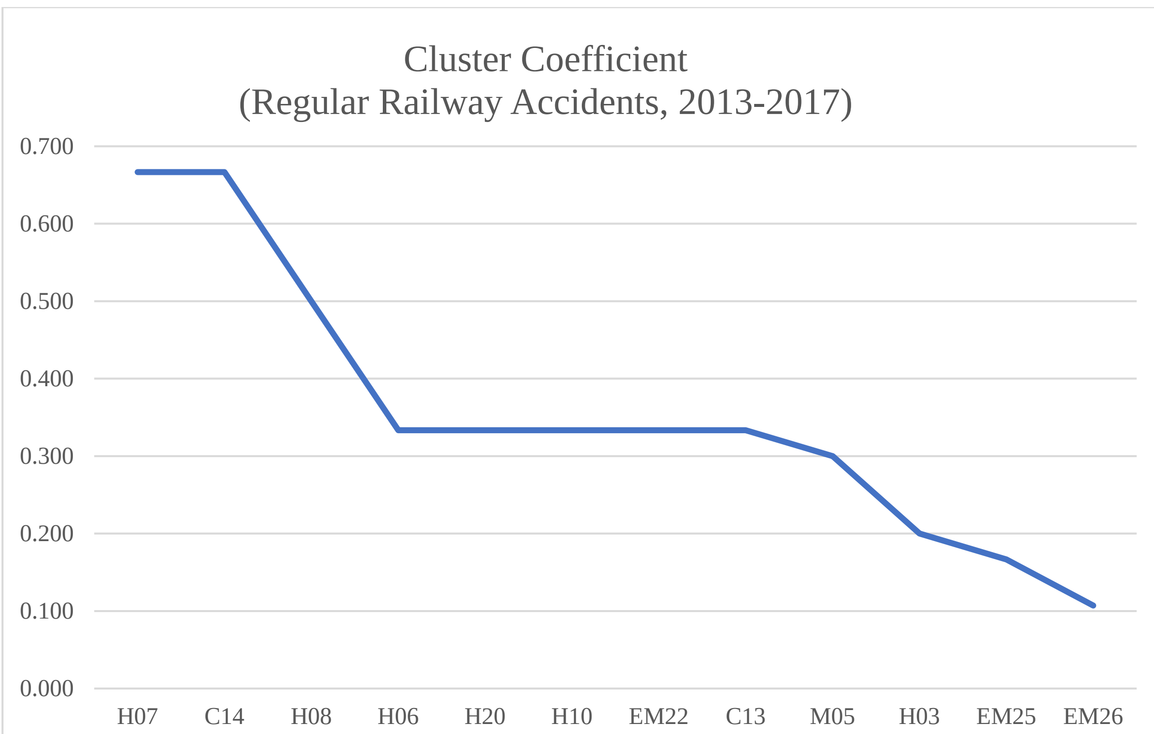


Figure 6.19 Clustering coefficient distribution (2013-2017, regular accidents).

6.3.5 Betweenness Centrality

Figure 6.20 shows the top 30% of the Betweenness centrality of regular railway accident causation networks. The highest ranked EM26 (Train delayed), H04 (Driver's operation mistake) reflects a critical chain that the mistake of the train driver is very likely to cause a delay in the train.

In addition, four of the top five Betweenness centralities are all human factors, showing the importance of human factors in regular railway accidents. Strengthening the management of human factors will more effectively improve railway safety.

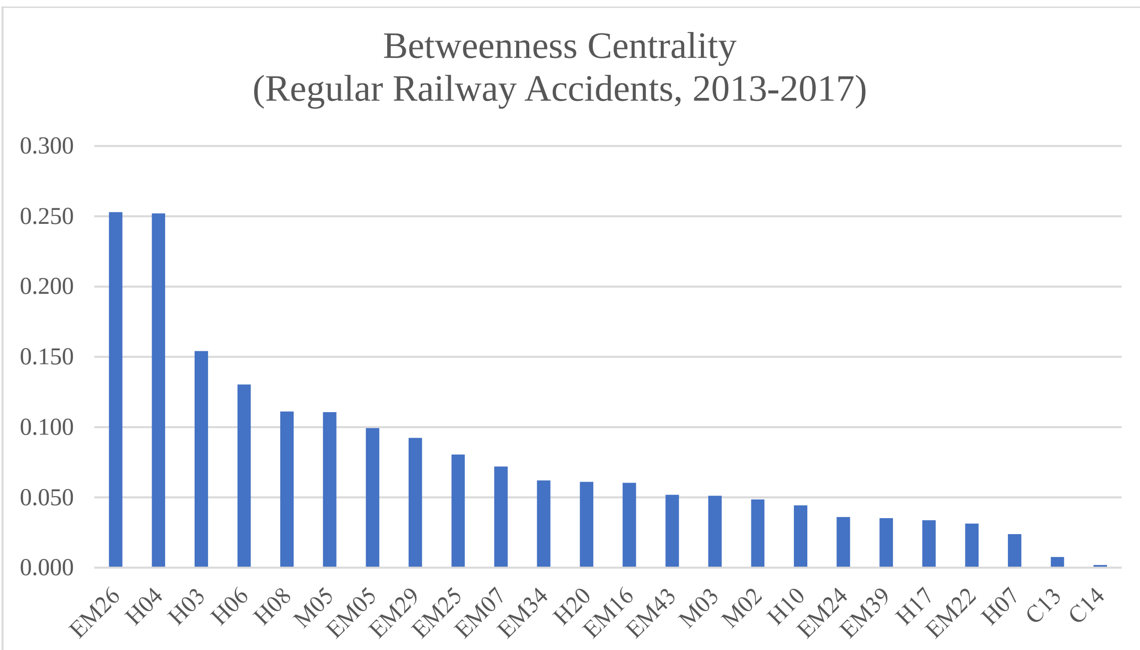


Figure 6.20 Betweenness centrality distribution (2013-2017, regular accidents).

6.4 High-Speed Rail Accidents Analysis

The High-Speed Rail accidents selected from all accident reports are broken down into 35 events and 80 causal links according to the method described in Chapter 4. It is then modeled into 35 nodes and 80 edges to form the network shown in Figure 6.21

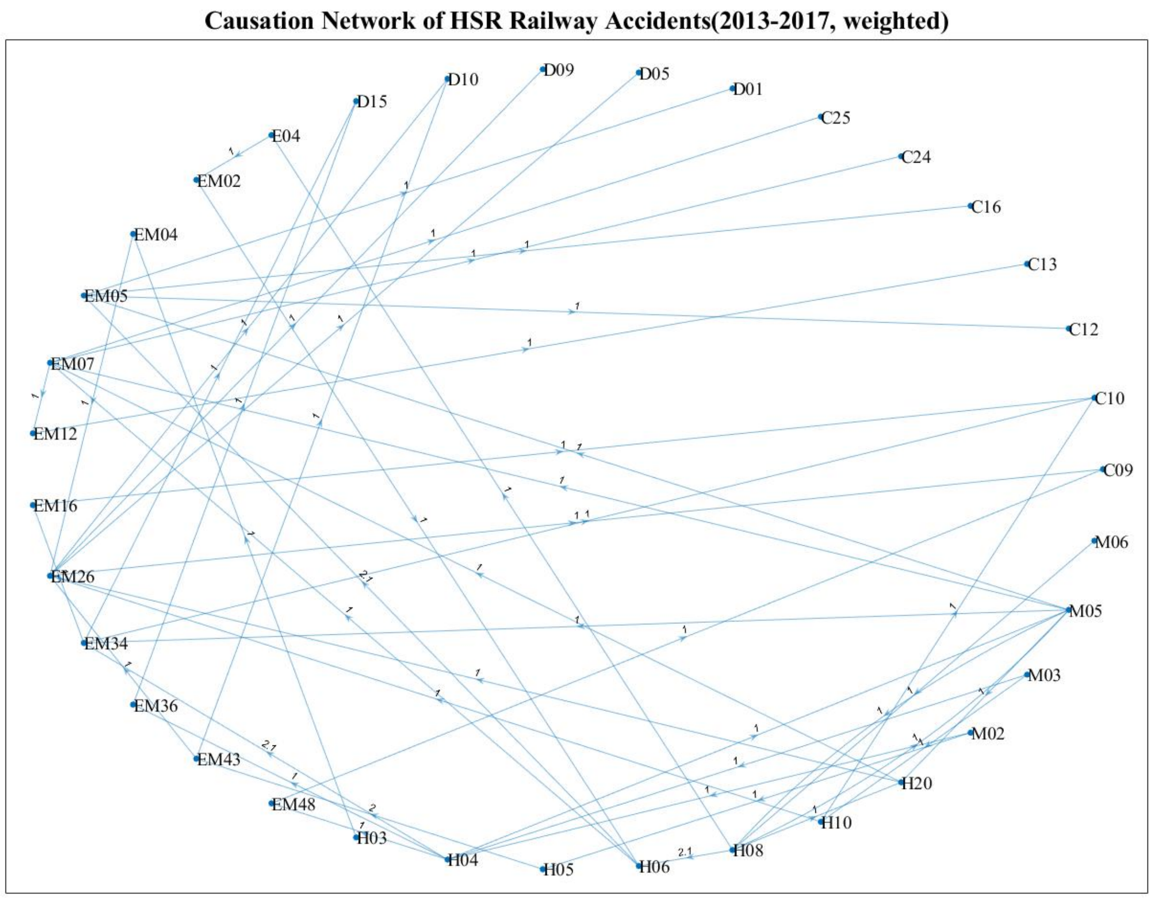


Figure 6.21 Causation network (2013-2017, High-Speed Rail accidents).

6.4.1 Degree and Degree Distribution

As shows in the Figure 6.22, the factors with the highest connectivity in the High-Speed Rail accident (top 10%) are EM26 (Train delayed) M05 (Not sufficient inspection and Supervision) EM07 (The risk of the line) H08 (Track worker's negligence) and H04 (Driver's operation mistake) (the last three have the same degree value), showing that train delay is still the main factor for High-Speed Rail accidents, driver errors and supervision the shortcomings reflect the internal management problems of High-Speed Rail and the impact of employees on safety. This confirms the previous assumption that the large number of newly purchased high-speed trains has a negative impact on operational safety.

In the equipment category, EM26 (Train delayed), EM07 (The risk of the line), EM05 (Train minor damaged), EM34 (Train passed red signal) are the most connected factors, which correspond to the slight loss in the accident (train delay and slight damage to the train), signal system and line safety.

Among the human factors, the biggest threats to safety are H04 (driver misuse), H08 (track worker negligence) and H20 (employee left items on the track).

The most frequent factor in the management process is M05 (Not sufficient inspection and Supervision), which means a lack of inspection and supervision. A large number of new lines and newly purchased vehicles have resulted in accidents due to insufficient management power.

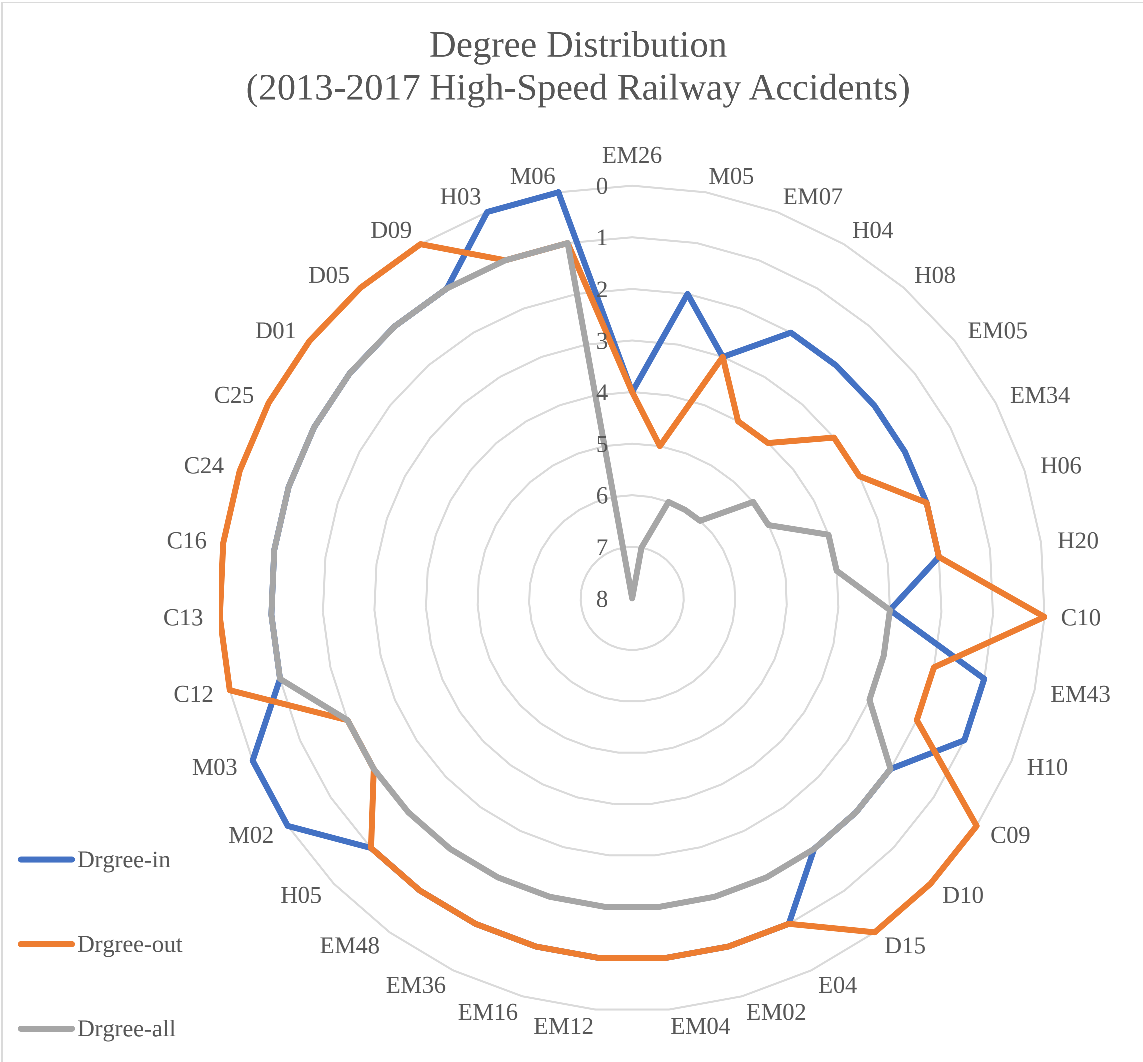


Figure 6.22 Degree distribution (2013-2017, High-Speed Rail accidents).

Figure 6.23 illustrates that cumulative node degree distribution of Network follows a power law as $P(k)\sim 1.6362x^{-1.573}(R^2 = 0.8539)$. The top 14.29% factors account for a majority (58.33%) of all causation relations, and the most (65.71%) of factors occur only 1–2 times. The network has typical small-world model characteristics.

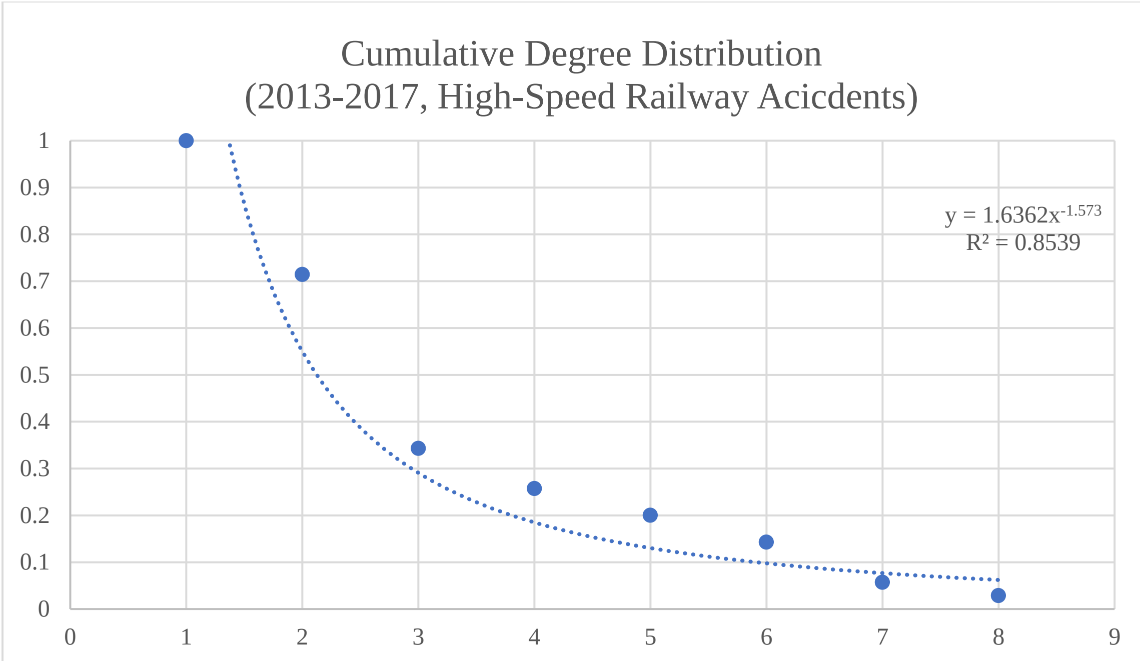


Figure 6.23 Cumulative degree distribution (2013-2017, High-Speed Rail accidents).

6.4.2 Strength and Strength Distribution

Through weighting (adding consideration to the network edge and the severity of the accident), the weighted network is obtained as shown in Figure 6.24. The most important point in the network (top 10%) is EM26 (Train delayed), M05 (Not sufficient inspection and Supervision), H04 (Driver's operation mistake)

In the equipment category, the strength value of EM34 (Train passed red signal) exceeds EM05 (Train minor damaged) after weighting, showing that line safety is more important for the safety of High-Speed Rail than line safety.

Among human factors, H06 (Rail line inspector did not check out problems in time) surpassed H20 (Staff left machine/goods/material on the track), becoming the third most important human factor affecting the safety of High-Speed Rail.

Among management factors, the most important factor is M05 (Not sufficient inspection and supervision), followed by M03 (Weak management), M02 (Inadequate safety precautions) and M06 (Weak maintenance system).

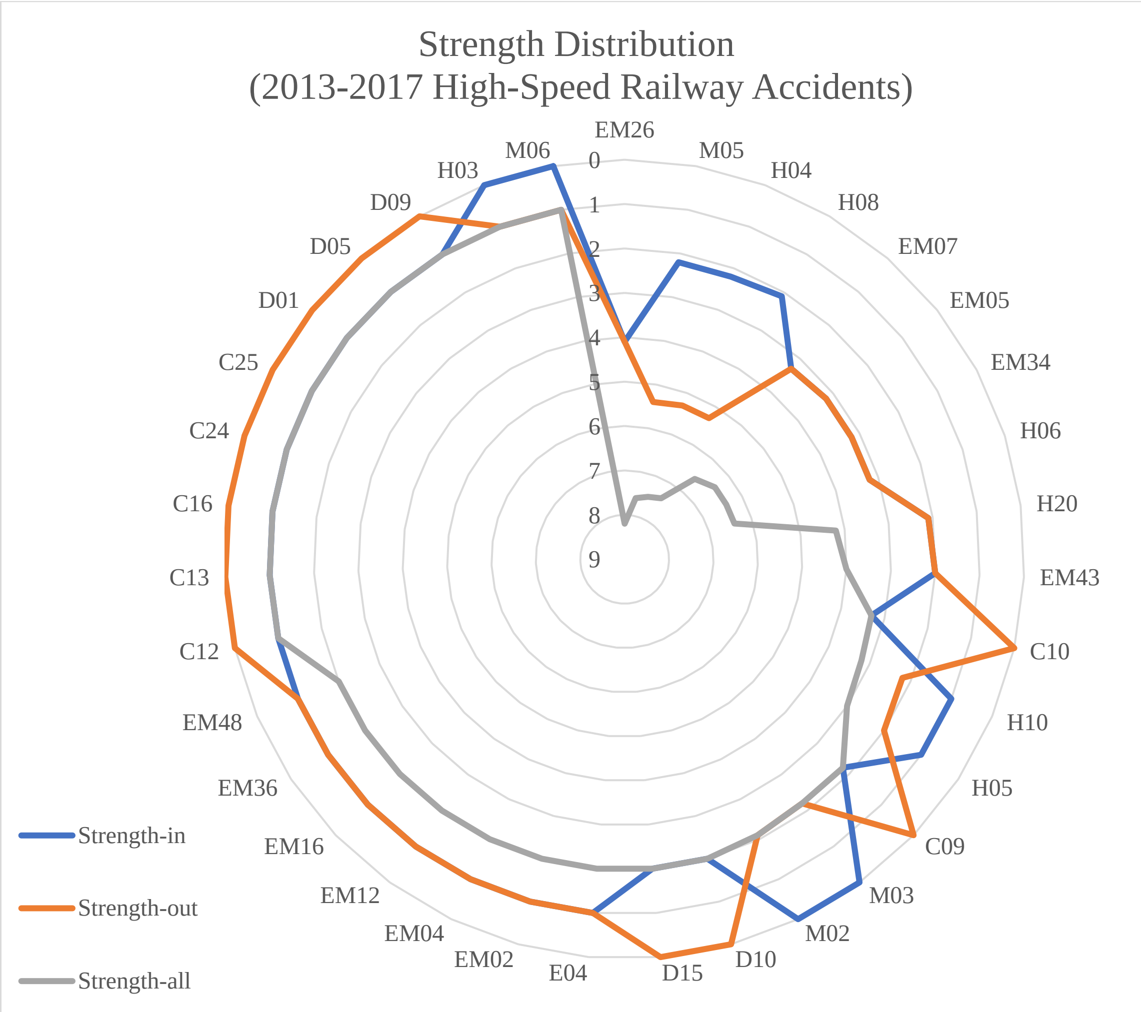


Figure 6.24 Strength distribution (2013-2017, High-Speed Rail accidents).

Figure 6.25 illustrates that cumulative node strength distribution of network follows an power law as $P(k) \sim 1.4823x^{-1.381}(R^2 = 0.8193)$. The top 14.29% factors account for a majority (54.29%) of all the times of occurrences, and the most (54.29%) of factors occur only 1–2 times. The network has typical small-world model characteristics.

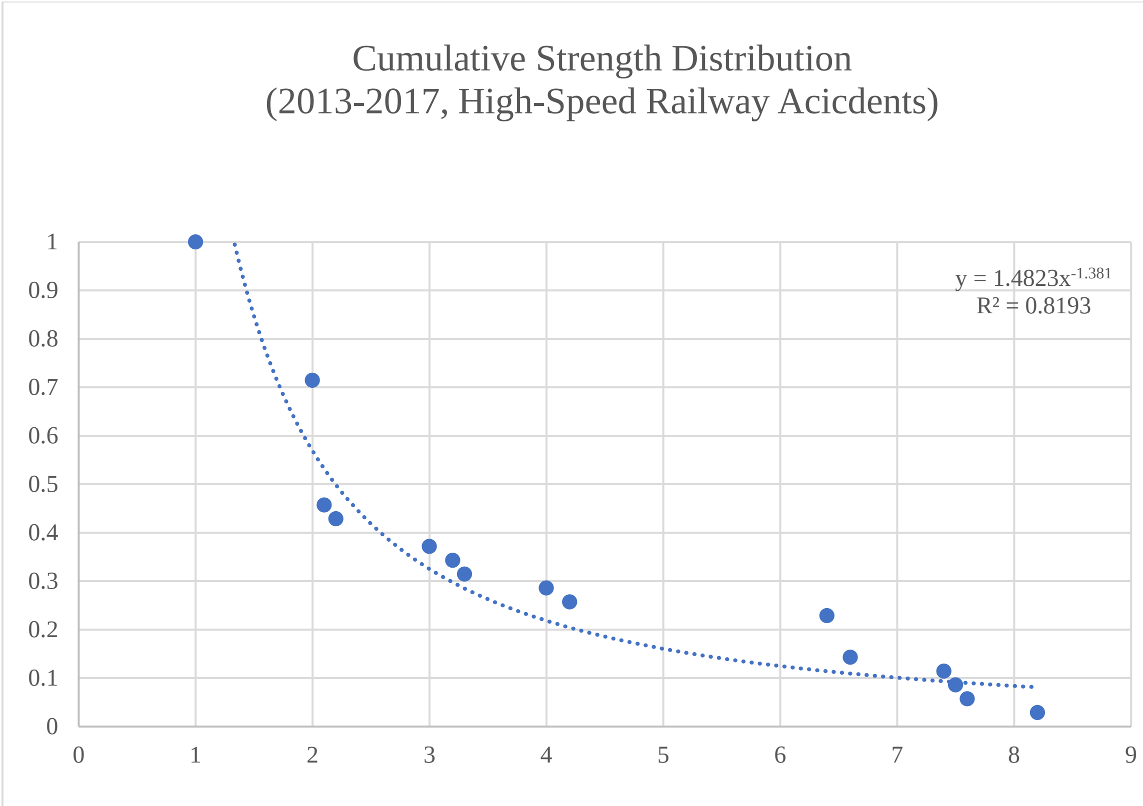


Figure 6.25 Cumulative strength distribution (2013-2017, High-Speed Rail accidents).

6.4.3 Shortest Path and Diameter

In the High-Speed Rail accident causation network, the average shortest path length is 2.21. This means that the causality related to another factor is about two steps in the network. The average path of the causality related to the accident is 2.56, which means that about 2-3 causal factors are needed to cause the accident. The network diameter is 5, from E04 (Freezing temperatures) to H20 (Staff left machine/goods/material on the track) / M02(Inadequate safety precautions) and M02 (Inadequate safety precautions) / M05 (Not sufficient inspection and supervision), H20 (Staff left machine/goods/material on the track) to C12 (Locomotive broken shaft, key components fall off) are the five furthest pairs of nodes in the network. This points to several possibilities: extreme cold weather can lead to the presence of remnants that affect safety on the rails in five steps or cause insufficient safety precautions. Inadequate management and inspection or misplaced items on the rails will lead to accident C13 (A collision occurred while the train was running) through the transmission of five factors.

6.4.4 Clustering Coefficient

Figure 6.26 shows the clustering coefficient in the causation network of the High-Speed Rail accident. The clustering coefficient of three of the five nodes reaches 1, and the other nodes are also greater than 0.3, showing that these five elements are highly clustered. The average aggregation coefficient of the network is as high as 0.73, and the average path of the network discussed in the previous paragraph is only 2.21. The combination of the two features makes the entire network very consistent with the characteristics of the small world network. This means that most factors easily interact with each other and need to be strictly controlled to eliminate the "resonance" phenomenon in system operation.

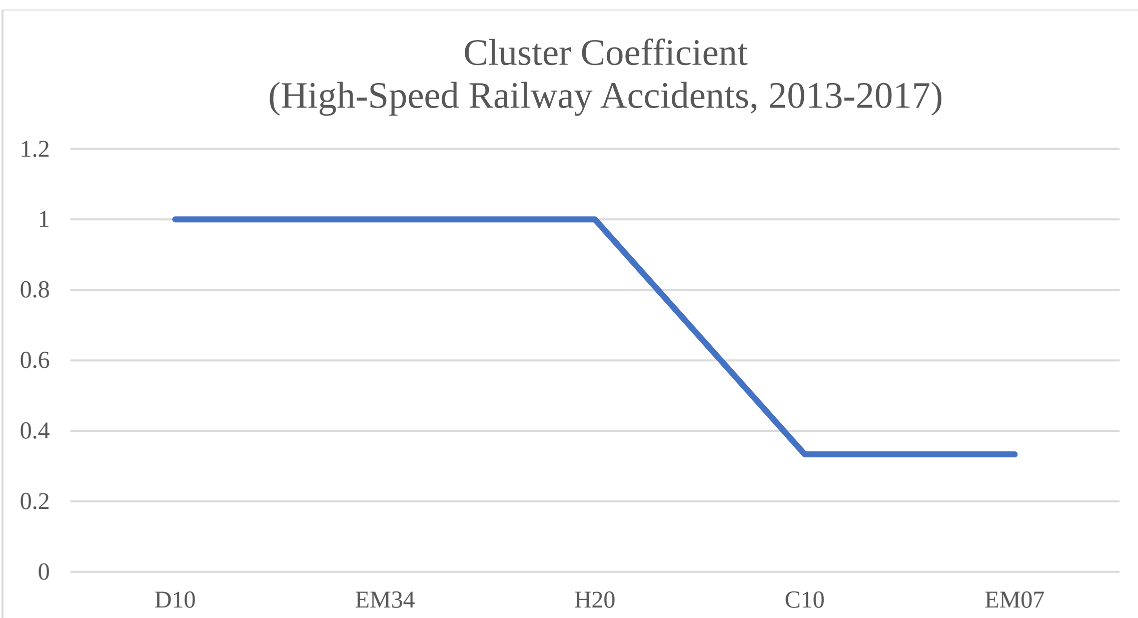


Figure 6.26 Clustering coefficient (2013-2017, High-Speed Rail accidents).

6.4.5 Betweenness Centrality

Compared with the networks in Sections 5.2 and 5.4, the causation network of the High-Speed Rail is smaller in scale and the path selection for accident development will be less, so the Betweenness centrality in the network is higher. The difference is that the highest value of Betweenness centrality in High-Speed Rail accidents is M05, which shows that daily maintenance and supervision are the key factors in High-Speed Rail accidents. Figure 6.27 describes a possible accident development chain: inadequate maintenance (M05) caused train delays (EM26), and railway line hazards (EM07) caused by employees leaving items on the rails (H20).

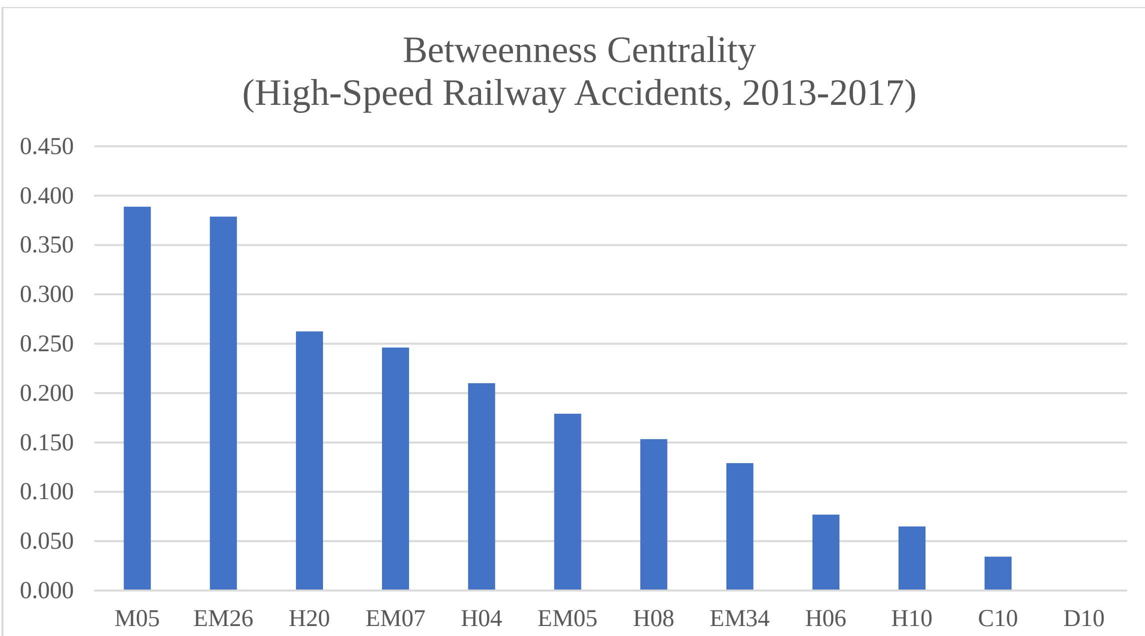


Figure 6.27 Betweenness centrality (2013-2017, High-Speed Rail accidents).

6.5 Comparison between Regular and High-Speed Rail Accident

This part is a comparison of the causes of accidents between regular railways and High-Speed Rail. Two network characteristics are used for comparison: node strength and betweenness centrality, all data comes from the previous chapters.

6.5.1 Overview

Strength is a measure of the frequency of node connections. Compared with the degree, it can better reflect the importance of nodes in the network. This also means that the intensity represents the influence of the incident on the accident. For each type of accident, three types of accident causal factors were selected: equipment and machinery, human factors, and management factors. The total strength of these three factors in the network is 84.52% (regular) and 82.06% (High-Speed Rail). The two types of factors that are not discussed here are the environment and the type of accident. The impact on the development of the accident is very small and can be ignored.

According to the comparison of categories, the proportion of High-Speed Rail equipment is 2.12% higher than that of general railway, the gap is very small, but the total proportion of management elements is lower than that of regular railway 4.38%. A reasonable explanation is that the use of automated systems, such as train control systems, is higher than regular railways, so the dependence of High-Speed Rail on management is reduced.

6.5.2 Equipment Factors

The table above (Table 6.3) lists the top five equipment factors in the High-speed Railroad and regular railroad accident network. The comparison found that the top five factors in the High-Speed Rail network accounted for 29.07% of the total, much higher than the regular railway's 17.12%. Shows a high concentration of equipment risk. Among them, the EM26 ranking rose to first, and the proportion has also increased significantly, showing the importance of High-Speed Rail for train delays for High-Speed Rail accidents. In the High-Speed Rail network, due to the application of the automatic driving control system, the minimum driving interval is 3 minutes (the design value of the CTCS-3 system, the minimum interval in practical application is 4 minutes, see the Beijing-Shanghai High-Speed Rail), while the regular line train interval For 7 minutes (CTCS-0 / 1 system), any delay of trains longer than three minutes is a huge security threat to the High-Speed Rail network.

Table 6.3 Equipment & Machine Node Strength Comparison Between High-speed Rail and Regular Railroad Accident

Rank	**Percentage of node strength (Equipment & machine)**					
	Regular			**High-Speed Rail**		
1	EM05	19.6	5.02%	EM26	8.2	7.54%
2	EM26	19.2	4.92%	EM07	6.6	6.07%
3	EM25	10.8	2.77%	EM05	6.4	5.89%
4	EM34	8.8	2.26%	EM34	6.4	5.89%
5	EM07	8.4	2.15%	EM43	4	3.68%
Summary			17.12%			29.07%
Category			37.99%			40.11%

The proportions of EM07 (risk of the line), EM34 (Train passed red line) and EM43 (infrastructure damaged) are significantly higher than those of regular railway, showing the high dependence of High-Speed Rail on infrastructure and signal system. As a complex technical system, High-Speed Rail highly depends on the cooperation of various parts of the system. Infrastructure, power system, signal system, train control system, and communication system are all important functional parts, which are crucial to the safety of High-Speed Rail.

6.5.3 Human Factor

Table 6.4 Human Factors Comparison Between High-speed Rail and Regular Railroad Accident

Rank	**Percentage of node strength (Human Factor)**					
	Regular			**High-Speed Rail**		
1	H08	20.8	5.33%	H04	7.5	6.90%
2	H03	17.3	4.43%	H08	7.4	6.81%
3	H20	14.9	3.82%	H06	6.4	5.89%
4	H06	13.8	3.54%	H20	4.2	3.86%
5	H04	13.7	3.51%	H10	3.2	2.94%
Summary			20.64%			26.40%
Category			30.27%			30.08%

Human factors and equipment show a similar pattern, and the top five High-Speed Rail are more concentrated. The biggest change is H04 (driver make mistake), which accounts for 3.38% more than regular railway. It shows that the wrong operation of the driver has the greatest threat to the safety of the High-Speed Rail, or that the professional level of the driver cannot fully meet the requirements of the High-Speed Rail. Factors that vary greatly in human factors are H06 (Rail line inspector did not check out problems in time) and H08 (Track worker 's negligence), which involves maintenance staff not meeting maintenance requirements. In general, human factors have the same impact on High-Speed Rail as regular railways, but the impact is more concentrated on each factor.

6.5.4 Management

The management factor data proves that there is no obvious defect in the management system and policies of High-Speed Rail. Compared with regular railways, the impact of overall management factors on safety is decreasing. The only increasement in M05 (Not sufficient inspection and supervision) can be regarded as the personal negligence of managers: the constraints (regulations) for protecting safety exist because the factors of arena do not play a role in safety management.

Table 6.5 Management Factors Comparison Between High-speed Rail and Regular Railroad Accident

Rank	**Percentage of node strength (Management)**					
	Regular			**High-Speed Rail**		
1	M05	19.2	4.92%	M05	7.6	6.99%
2	M02	16	4.10%	M03	2.2	2.02%
3	M03	15	3.85%	M02	2.1	1.93%
4	M01	10	2.56%	M06	1	0.92%
5	M06	3.2	0.82%			
Summary			16.25%			11.87%
Category			16.25%			11.87%

6.5.5 Regular Railroad Accidents

Observing the safety status of regular railway from another angle, the strength values of equipment factors are evenly dispersed in each equipment factor, showing that the overall safety level is low. The requirements for safety management are higher, because there is no key part to strengthen attention. This can be confirmed by the distribution of the value of betweenness centrality. Table 6.6 shows the top ten elements of the value of betweenness centrality among High-Speed Rail and regular railways. The highest value of betweenness centrality of High-Speed Rail is 0.388, while that part of regular railway is only 0.253. The value of clustering coefficient also shows the same characteristics: the clustering coefficient of the High-Speed Rail network is 0.7333, and the regular railway is only 0.3562. It shows that the causation network elements of the High-Speed Rail are more concentrated, while the causation network structure of the regular railway is more scattered.

Table 6.6 Betweenness Centrality (High- Speed Rail and Regular Rail)

Rank	**Betweenness Centrality**			
	HSR		**Regular**	
1	M05	0.389	EM26	0.253
2	EM26	0.379	H04	0.252
3	H20	0.262	H03	0.154
4	EM07	0.246	H06	0.130
5	H04	0.210	H08	0.111
6	EM05	0.179	M05	0.111
7	H08	0.153	EM05	0.099
8	EM34	0.129	EM29	0.092
9	H06	0.077	EM25	0.081

CHAPTER 7

CASE DISCUSSION

The previous network analysis has provided an overall description of the causes of different types of railway accidents. The following themes are aimed at analyzing the main problems found in network analysis. By combining specific cases, or comparing with the successful experience of other industries or countries, it is expected that strategic recommendations can be formed to help improve operational safety.

7.1 Training

In the network analysis in the last chapter, human factors show its great importance in High-Speed Rail accidents. Three of the top five High-Speed Rail accidents are caused by human factors (including management), and the proportion exceeds the equipment factor. These three factors are M05, not sufficient inspection and supervision, 6.99%) H04 (driver's operation mistake, 6.90%) and H08 (track worker's negligence, 6.81%). Moreover, betweenness' centrality value is also very high, ranking respectively the 1st, 5th and 3rd places of causation network. This means that by controlling these three factors, the loss of accidents on High-Speed Rail can be reduced by at least 20%.

7.1.1 Lion Ocean Tunnel Accident

The problem of weak human factors has been a symptom since the early stages of High-Speed Rail construction. In the 7.23 Wenzhou train collision accident that occurred in 2011, the illegal operation of maintenance staff and the negligence of the drivers of the accident EMU under abnormal operating conditions are the reasons for the accident. This situation continued at least until the “lion ocean tunnel accident” happened. At the beginning of 2018, a High-Speed Rail accident occurred within the jurisdiction of Guangzhou Railway Group. The direct cause of the accident was equipment failure of the power system. However, a large number of personnel factors have been exposed in emergency response such as maintenance and rescue after the accident.

Table 7.1 shows a record of an accident. (Liu, 2020) Accident happened on March 5, 2018, around 7 AM, a northbound High-Speed Rail train from Shenzhen to Guangzhou was stuck in the Lion Ocean tunnel when the power supply was cut off unexpectedly. According to the Accident Log, the catenary wire fell off and broken and/or damaged many pantographs and other equipment from the affected train. All High-Speed Rail trains along the Shen-Guang line are composed of Electric Multiple Units (EMU). With the power failure occurred in the tunnel, the entire segment of High-Speed Rail line is out of service, including the trains operating in the opposite direction. After emergency repairs, the line resumed operation eight hours after the accident.

Table 7.1 Accident Log of Lion Tunnel Accident

Time	Log
D (day) T (time)	Accident occurred in a tunnel near the sea. A short circuit caused by a failure of equipment that supplies power to the train and at the same time damage to the equipment on the roof of the affected vehicle;
1 min	The entire line stops running due to loss of power;
3 mins	**All railway network informed;**
10 mins	The maintenance technicians from the affected train inspected the vehicle and overhead wire;
20 mins	Reported pantograph damaged on affected train;
	A rescue train was arranged by the control center;
55 mins	Affected train request for rescue;
1 hour 15 mins	The rescue train departed;
1 hour 30 mins	The first maintenance team arrived;
1 hour 40 mins	The maintenance team reported that the accident was more serious than previously understood. The first repair plan developed;
1 hour 50 mins	The second maintenance team arrived;
1 hour 55 mins	**Maintenance team expected repair would be finished after 60 minutes;**
2 hours 30 mins	The maintenance team applied to board the train roof for repairs;
2 hours 35 mins	Rescue train stopped at the nearby station;
2 hours 50 mins	The maintenance team began to climb the train roof for repairs;
3 hours 35 mins	**The first repair plan failed as damages exceeded expectations; The second repair plan developed; repair time unpredictable;**
3 hours 40 mins	The control center arranged passenger train to transfer passengers from affected train;
4 hours 10 mins	**The second repair plan failed due to improper repair equipment. The third repair plan developed;**
4 hours 15 mins	The rescue train started again;
4 hours 45 mins	The passenger transferring train departure for the scene;
5 hours 15 mins	The passenger transferring train arrived at the scene;
5 hours 20 mins	The rescue train arrived;
5 hours 30 mins	**The third repair plan failed due to inappropriate repair process. The fourth repair plan developed;**
6 hours 15 mins	Passenger transfer finished;
6 hours 25 mins	Transfer train arrived station nearby;
7 hours 10 mins	The rescue train leaving with accident train;
7 hours 20 mins	The team completed the repair and started to supply power;
7 hours 50 mins	The first train passed the accident section at a lower speed;
D Day Night	The repairs to the damaged equipment and facilities continued;
D+1 Day Night	Repair finished; the line resumed normal operation.

Source: Lv and Liu, 2020

The maintenance technology and judgment of the on-board engineer exposed by the accident were not qualified. Even the emergency maintenance team, which was supposed to be the best engineering staff, failed to complete the maintenance task in time. The impact of the accident lasted until midnight the next day, and the line was restored to the state before the accident almost 48 hours later.

7.1.2 Operating Pressure

The human factor problem is caused by two reasons. First, the fast-growing High-Speed Rail network. The chart lists the procurement of new High-Speed Rail lines and vehicles from 2013 to 2017. Within five years, China has newly opened High-Speed Rail lines of 3,000 kilometers and purchased up to 1,300 High-Speed Rail EMUs (as shown in Figure 7.1 and Figure 7.2), each The EMU consists of 8 or 16 cars. EMUs purchased within three years have almost doubled the number of EMUs in China. This kind of complicated and sophisticated equipment purchased in a large amount of time is a huge challenge for drivers and maintenance. This directly aggravates the work intensity of the existing staff, and also causes a shortage of maintenance and operation staff. According to estimates by railway insiders in 2014, the shortage of mechanized mechanics is about 7,000.

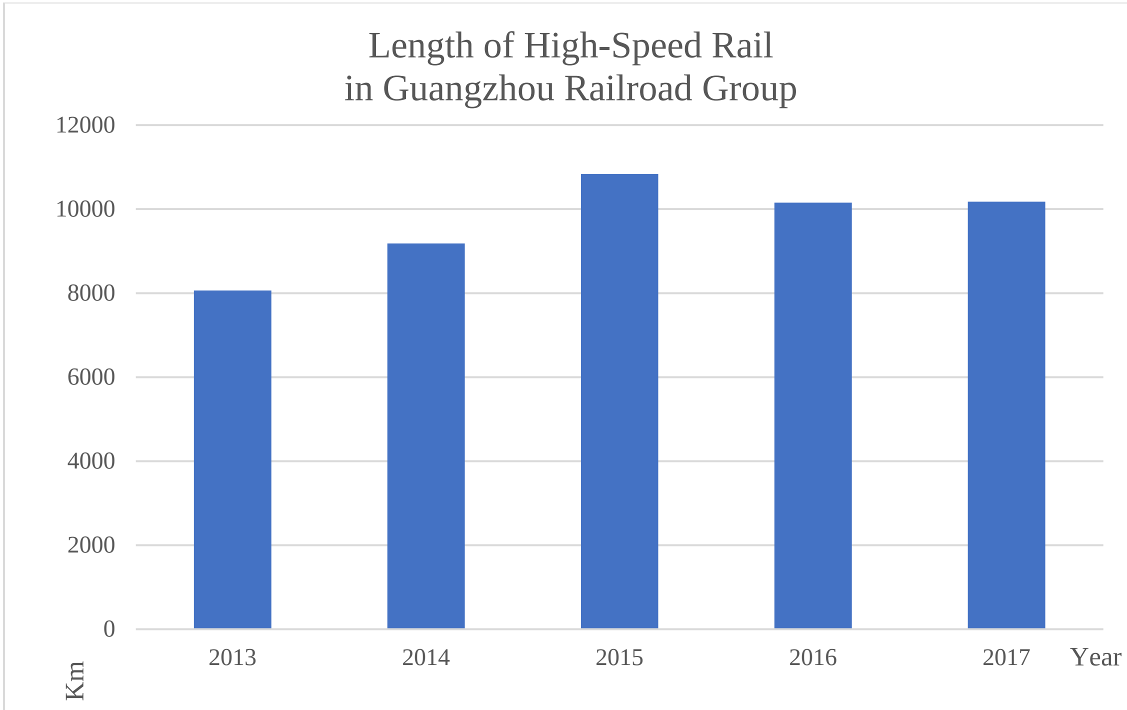


Figure 7.1 Length of High-Speed Rail in Guangzhou Railway Group.

Source: Guangdong Railway Group, 2015-2019.

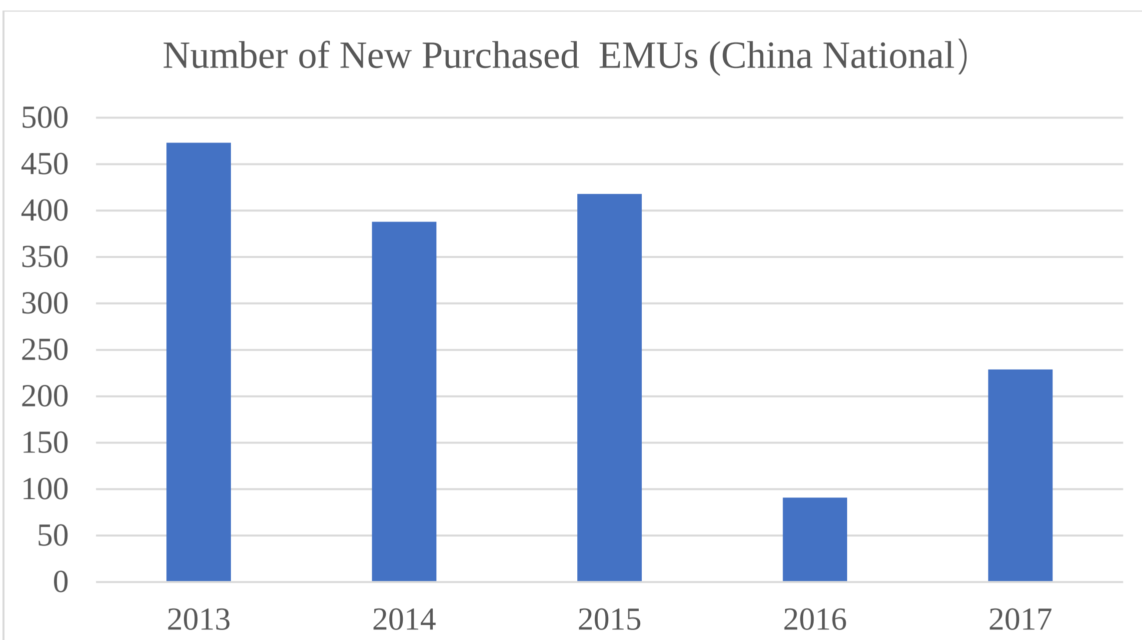


Figure 7.2 New purchase EMUs in China (2013-2017).

Source: China State Railway Group Company, Ltd., 2013-2017.

7.1.3 Absence of Internal Training System

In the management system of China's High-Speed Rail, training has not received the attention it deserves. In the structure of China Railway Corporation, there is no department responsible for staff training. The existing staff department is only responsible for the recruitment of management staff of the head office. In regional companies, the training situation has also undergone major changes: Since 2004, the training institutions under the Guangzhou Railway Group have been reformed in a market-oriented manner. The internal training institutions of the railway system managed by the former Ministry of Railways have been transformed into part of the national public education system. After the reform, 2,500 students graduated from an educational institution named "Guangzhou Railway Vocational and Technical College" at 2017. 40% of the 200 people leave the transportation industry, and another 60% of the trained staff are employed by more than ten subway companies in the Pearl River Delta region and railway companies in Hong Kong and Hainan. In 2015-2019, Guangzhou Railway Group recruited more than 2,000 people, and even more than 4,000 people at its peak. Most of them were college-level technical staff. (as shows in Figure 7. 3) Which does not include graduates who have signed a work contract for training in the above institutions since the start of school. There is a huge gap between the demand for technical staff and the graduates of professional training institutions. In order to supplement the redundancy of employees, Guangzhou Railway Group had to recruit people from the society. Although the number can meet the requirements, due to the lack of training of professional institutions, the staff will not be qualified for professional technical positions in the short term. After losing its own local training school, the daily training of all railway employees of Guangzhou Railway Group was organized by the national management agency "China Railway Corporation", but the efficiency and scale of the training decreased compared with before. The gap between training capacity and business needs should be planned for a long time to ensure that high-quality employees will greatly improve railway safety.

Figure 7.3 Recruitment in Guangzhou Railway Group (2015-2019).

Resource: Guangdong Railway Group, 2015-2019.

The negative impact of the absence of training institutions on employee quality is reflected in two aspects: qualification training and continue training. As one of 18 regional companies, Guangzhou Railway Company has about 147,000 employees and about 3,000-5,000 new employees each year. It is inferred that the annual recruitment of new employees of the national railway is about 41,600-69,300. Consider the difference between academic education and the actual situation of the industry. It is difficult to ensure that these new employees have the professional skills to engage in the railway industry, so the professional qualification training for new employees is a necessary part of ensuring the quality of employees. In the existing Chinese railway management system, the only professional training institution is located in Wuhan, Hubei Province, established in September 2014. The annual training capacity is 14,000. Compared with the total number of employees in the railway system of 2.04 million, this training capability is far from meeting the needs of employee training. At the same time, the technical system of High-Speed Rail is still evolving, the technology transfer phase is gradually ending, the proportion of localization is increasing, and the technology is constantly maturing. At the same time, new equipment (such as new traction power supply technology and new EMU vehicles) is continuously put into use. This requires that employees should be continuously trained to adapt their vocational skills to changing needs. And regional companies, such as Guangzhou Railway Company, have lost their own training institutions. The only training institutions in the country have very limited capacity. Therefore, the continuing education of employees cannot be guaranteed.

7.1.4 External Experience

Positive cases from the aviation industry may have inspired railway operators and policy makers. FAA statistics show that human causes account for 80% of accidents in the aviation industry. The aviation accident rate in China decreased from 5.42 per million flight hours between 1980 and 1985 to 0.19 per million flight hours between 2000 and 2005, and there was no flight accident for three consecutive years from 2005 to 2007. During this period, China established the Civil Aviation Safety Academy of China, a training institution dedicated to safety training. In addition, the Civil Aviation Administration of

China also invested 250 million (RMB) to establish flight training centers in major airlines such as Air China, China Eastern Airlines, China Southern Airlines, Hainan Airlines, and Civil Aviation University. At the same time, the Civil Aviation Administration actively promotes airlines, airports, air traffic control and other agencies to increase investment and establish their own training institutions and systems. It is these investments in human resources that have successfully improved the safety level of the aviation industry.

7.2 Equipment

The previous network analysis results show that the proportion of device factors in the network exceeds 40%. Especially in the causation network of High-Speed Rail, the out-degree ratio of equipment factors has reached 43.75%, indicating that equipment factors in High-Speed Rail accidents are the first major safety hazard.

7.2.1 Immature Technology

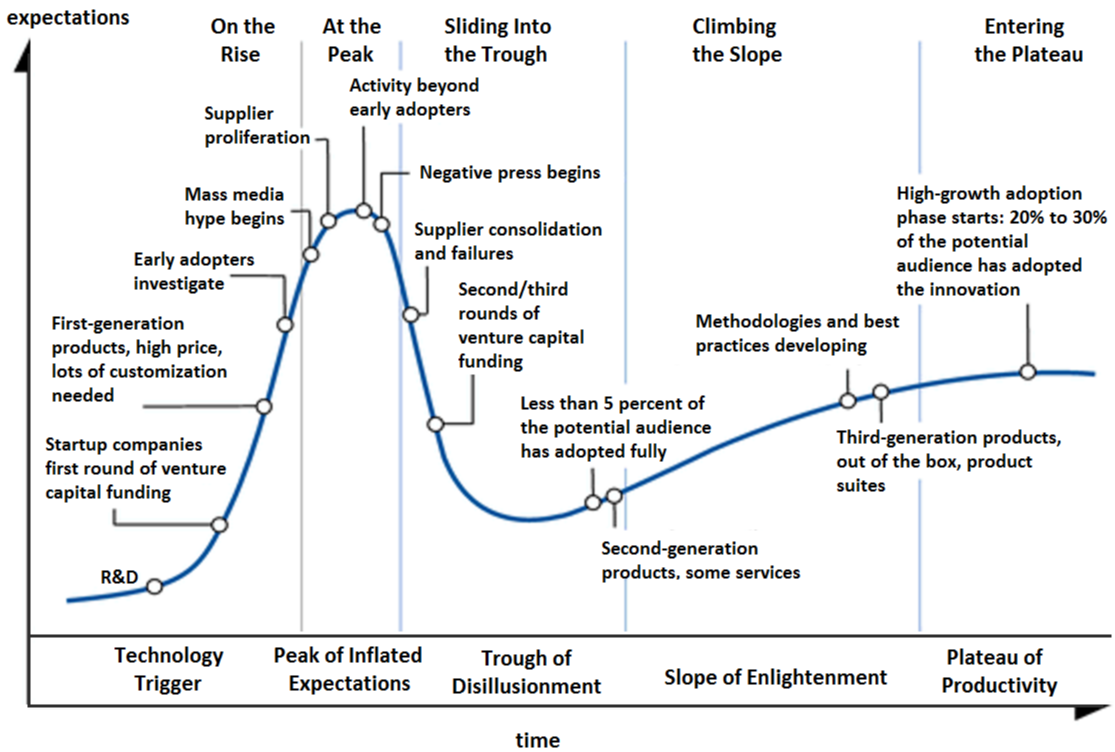


Figure 7.4 General Hype Cycle for technology.

Source: Gartner, 2019.

The hype cycle is a product cycle proposed by the business consulting company Gartner (Tarkovskiy., 2020), which describes the expected value change of a new technology at different stages. Although many critics point out that this model lacks data support, it still provides a way to describe technical products. As shown in Figure 7.4, new technologies are always expected to be high in the early stages of development and touted by the market. When the failure or performance of a technical product fails to meet market expectations, the attention and capital investment received by the product will decrease until the new technology gradually matures and is recognized by the people and the market. Observe the development of High-Speed Rail in China from the perspective of product maturity, the

High-Speed Rail experienced exactly this period of adaptation, development stage, many failures, and unstable performance, indicating the immaturity of the product.

7.2.2 Incomplete Transfer

According to widely accepted views, the development of High-Speed Rail technology in China is actually a government-led technology transfer. From 2004 to 2005, the first time China introduced High-Speed Rail technology from three countries to the period of this study (2013-2017), only ten years have passed. For China, the High-Speed Rail is a brand new, complex, and the fastest transportation vehicle ever on the ground. No matter how fast and how large this system is. Ten years is not enough to fully master such a brand-new technical product. As shown in the Table 7.2, although China announced in 2010 that it has successfully developed a new generation of EMU-CRH380 with independent intellectual property rights. But in fact, this model is still based on the imported model. Some key technologies in vehicles, such as bogies and train control systems, are still imported from abroad. To some extent, the EMU technology of this period is still a collection of multinational technologies and products in China. Until seven years after CRH380 was in operation, China once again declared that the fully-developed standard EMU "Fuxing" was officially put into operation. The High-Speed Rail technology transfer was not really completed until this moment.,

Table 7.2 Second Generation High-Speed Rail Models and Their Key Features

Series	CRH380A		CRH380B		CRH380C	CRH380D
Advanced Model	CRH380A	CRH380AL	CRH380B	CRH380BL	CRH380 CL	
Manufactory	CSR Qingdao Sifang		CNR Changchun		CNR Changchun	BST
Original model	CRH2C Phase2		CRH3		CRH3C & CRH380BL	ZEFIRO 380
Manufactured time	2010-1011	2010-2013	2012	2010-2013	2011-2013	2012-2014
Running time	2010.9.30	2011.6.30	2012.10.9	2011.1.13	2011	2013
Format	6M2T	14M2T	4M4T	8M8T	8M8T	4M4T
Capacity	480	1028/1061	450	1043	1053	
Power	9600kW	20440kW	9600kW	18400kW	19200kW	
Speed	350/380 km/h		350/380 km/h		350/380 km/h	350/380 km/h
Running count	41	95	41	102	25	70

Source: Liu and Lv, 2014.

7.2.3 Radical Development Plan

The policy did not match the development of the High-Speed Rail well. On the contrary, the aggressive policy amplified the potential safety hazards of the equipment.

At a time when the product was not mature enough, China did not adopt a reliable small-scale experimental operation to discover equipment and operational vulnerabilities. Instead, it was built quickly under the direction of a strong manager. The Table 7.3 shows the main points of China's long-term railway development plan. It can be said that policy makers launched railway development plans in 2004, 2008 and 2016 respectively. The target time points of the three plans are all in 2020, but the planning targets of the railways change greatly. The planned railway scale is getting bigger and bigger. The average annual construction length is gradually increasing. According to the 2004 plan, an average of 400 kilometers of High-Speed Rail are constructed each year, and according to the revised plan in 2008, this number has increased to 1,200 kilometers, and it has doubled in 2016, almost four times the 2004 plan.

Table 7.3 Railway Network Planning For 2020 In Different Years

Plan Year	**2004 Plan**	**2004 Plan (2008 Revision)**	**2016 Plan**
High-Speed Rail Grid	4+4	4+4	8+8
Intercity Passenger Railway (Center City)	3 metropolitan areas Beijing; Shanghai; Guangzhou	8 metropolitan areas Beijing, Shanghai, Guangzhou, Changsha, Chengdu, Zhengzhou, Wuhan, Xi'an, Xiamen	All City with population over 0.5M
Network Length(km)	100000	120000	150000
High-Speed Rail Length(km)	12000	16000	30000
Current Length (Network)	75000	86000	19000
Current Length (High-Speed Rail)	405	1396	121000

Source: State Council of the People's Republic of China, 2004, 2008, 2016.

Bold is not just a plan, the Figure 7.5 shows the progress of the construction every year, you can see the "Chinese speed" in the construction of High-Speed Rail. As mentioned in the previous section, 1600 high-speed trains were added in three years, and the tracks of High-Speed Rail were extended by 10,000 kilometers. Excessive pursuit of construction speed compresses the development and testing time of various supporting products, which in turn causes hidden safety hazards. There have been examples of accidents caused by tight construction schedules. The official 7.23 accident investigation report believes that the main reason for the accident is the serious design flaws in the train control equipment. The investigation team believes that the management department (the Ministry of Railways at that time) "rushed the schedule and progress in the railway construction and unilaterally pursued the construction speed of the project. Insufficient attention to security ". The technical department of the Ministry of Railways, which is responsible for the review of train control equipment, did not comply with the specifications when reviewing the equipment. In the case of "urgent line construction schedule requirements, urged by relevant departments", the equipment was irregularly reviewed. These factors caused the non-compliant design and installation of train control equipment, resulting in the 7.23 accident.

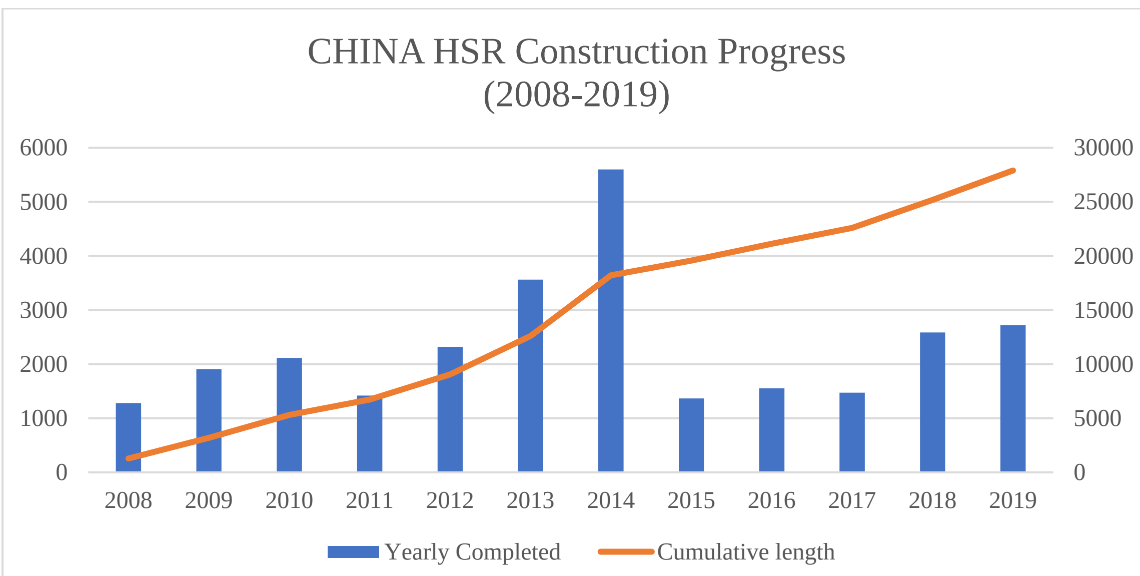


Figure 7.5 High-speed Rail yearly construction progress (2008-2019).

7.2.4 Imperfect Maintenance

Poor maintenance of equipment is another important factor that affects equipment safety. Part of the problem comes from the maintenance staff, which has been discussed before. The important changes in the maintenance policy during this period also caused potential safety hazards to the equipment.

Lu Chunfang, as the deputy director of the Ministry of Railways of China, introduces the maintenance system of the China EMU, which is divided into five levels of maintenance according to the running time or running journey. The specific requirements are as follows table.

Table 7.4 High-speed Rail Maintain System in CHINA

China EMU Maintenance Classes	
Level	Condition
I	Every running 4000km or 48 hours
II	Monthly Maintenance
III	Running 0.6 million km or 1.5 years
IV	Running 1.2 million km or 3 years
V	Running 2.4 million km or 6 years

Source: Lu, 2015.

The maintenance cost of a series of EMUs (8-car group) is 15 million RMB per year, accounting for 10% of the purchase price of EMUs. The annual maintenance cost of EMUs trains in the entire system is 39 billion RMB, while the total liabilities of China Railway Corporation in 2016 were 4.3 trillion RMB, and the corporate debt ratio was 64%. Due to the pressure of operating costs, China Railway Corporation has extended the high-level repair cycle interval of EMUs from 600,000 kilometers to 1.2 million kilometers in 2015, while compressing the maintenance time of various levels by 30% -40%. The operation time of routine rapid maintenance (level 1 maintenance) is required to be controlled within 2 hours, and the maintenance content has also been reduced. In addition, not only the maintenance policy of EMU, the maintenance frequency of ordinary passenger cars and trucks has been reduced by 10% -30%. The maintenance location is also changing from the manufacturer to the maintenance department of the railway system. The maintenance location of EMUs used to be at the manufacturer, and now the Railway Group Corporation is constructing multiple facilities nationwide for maintenance. The relocation of maintenance sites brings financial benefits, but for railway systems with weaker maintenance capabilities than manufacturers, the maintenance and repair pressure of more than 2,600 EMUs, 50,000 ordinary passenger cars, and 900,000 trucks is definitely a challenge.

Another hidden danger of maintenance lies in maintenance technology. The aforementioned Lion Ocean Tunnel accident exposed the threat of equipment maintenance by maintenance technology. The cause of the accident was the accelerated aging of the High-Speed Rail power source "catenary" in the high-salt environment in the coastal tunnel. The accident train damaged catenary when passing the line and lost power. Catenary's maintenance and daily inspection found no problems. In the daily operation of China's High-Speed Rail, there is a "no-load inspection vehicle run" before the revenue trains running. The problem is that this kind of routine maintenance is done at low speed through the railway line. This kind of train operation itself will use line equipment, which creates a paradox: Is there any way to check and maintain the line after the maintenance vehicle passes?

7.2.5 Social Factors

In addition to the natural environment, social factors are also important factors affecting the safety of High-Speed Rail equipment. As more and more cities are connected by High-Speed Rail, the length of inevitable lines built in urban areas is also increasing. The complexity of the urban environment and the impact of human activities have also affected the safety of High-Speed Rail. The most fragile part of the High-Speed Rail is its power system. The catenary is composed of electrical components and has a complex structure that must be exposed to the air. It is easily affected by the activities of urban residents. Within two days in 2017, February 20 and 21, the High-Speed Rail in the Zhengzhou area had 16 incidents caused by light objects hanging on the catenary, causing a total of seven trains to be delayed and the railway interrupted running for up to 1 hour 23 minutes.

CHAPTER 8

CONCLUSION AND FUTURE RESEARCH

This chapter summarizes the results of this research, including theoretical contributions, railway (High-Speed Rail) safety features and strategic recommendations. In the future research, the methodology and scope of research will be discussed.

8.1 Conclusion

8.1.1 Railway & High-Speed Rail Safety

Data analysis shows that the annual change of railway accidents (including High-Speed Rail) is obvious, and it is mainly affected by equipment reliability and staff factors. The main accident causes of High-Speed Rail and general railways have no significant differences in categories, with equipment factors accounting for approximately 40% and human factors accounting for approximately 30%. However, there are obvious differences in specific accident factors. The main reasons include negligence of staff (including drivers and maintenance staff), and the reliability of the equipment is not high. Compared with traditional railway accidents, the impact of Conductor on safety has been greatly weakened, but the impact of driver errors has increased, and the frequency of failure to receive timely maintenance is also higher than traditional railways. The delay of trains has shown a higher impact on the safe operation of High-Speed Rail, while the impact of minor damage has declined. Overall, the safety of high-speed trains is more sensitive to the schedule (time), the requirements for maintenance are higher, and the requirements for the quality and maintenance of drivers are higher. It shows the characteristics of the High-Speed Rail as a complex advanced technical complex.

8.1.2 Strategy Recommendation

1. The frequency of policy changes should be more moderate, including construction and procurement plans.

Chinese policymakers have a preference for eagerly accomplishing some iconic, compelling achievements to enhance their reputation and promotion opportunities. Meanwhile, building a large amount of infrastructure or purchasing equipment in a short period of time will definitely impact the maintenance system and management system. The impact includes an increase in failure rate, an increase in safety accidents, and a decline in service levels.

2. Enhance training system and improve staff quality.

Enhance the company's own training institutions, including the establishment of supervisors in the company's management and the establishment of training centers in the region and the formation of routine employee training arrangements. The frequency and depth of staff training should be increased in daily operations and long-term planning.

3. Improve data quality

Both the accuracy and accessibility of accident information need to be improved, including improving the content of accident reports and publishing accident information to the public. The disclosure of accident information does not spread panic among the public. On the contrary, timely and accurate provision of accident information is beneficial to improving safety. And timely update of train operation information is an important content of customer service.

8.1.3 Theoretical Contribution

First of all, the study verified that the complex network can be applied to the analysis of High-Speed Rail accidents. By decomposing High-Speed Rail accidents into event chains, a directed network is modeled. Then to use the mathematical characteristics of the network, such as degree, strength, average shortest path length and clustering coefficient, to analyze the accident, describe the logical relationship between the accident factors, and find out the key accident factors. The basic analysis steps of the above complex network models have been verified in the High-Speed Rail safety research in this paper, and succeeded.

Furthermore, the damage degree of the accident is included in the analysis framework. The weighted directional network is upgraded to dual-weighted directional network, by adding a second weight. This makes the description and analysis of the accident by the complex network more comprehensive.

Additionally, it has been proved during the research that the success of the analysis method of complex network systems depends on sufficient data. In the study, some network features could not be calculated due to the lack of sufficient data. For example, we tried to compare the clustering coefficient of different years, but failed because the data in most years was insufficient to support the calculation.

Last of all, five years of accident cases have added a large number of empirical cases to complex network analysis models. Through case analysis, especially the case analysis by year, we have a more comprehensive understanding of the limitations of complex network models. Complex network models also rely on adequate data support like other models. In the case of insufficient data, the mathematical characteristics of complex networks cannot be fully utilized, which will affect the final analysis results. This is proved by the analysis of the clustering coefficient in this paper.

8.2 Future Research

8.2.1 Methodology

1. Dual-Weighted Method

The parameters shown in Table 3.1.3 for weighting according to the severity of the accident are my assumptions. Whether these values are reasonable requires further study.

2. Modeling Method.

The first step of causation network modeling is to extract the cause of the accident. The extraction process does not have a unified standard, and it completely depends on the researcher's experience and knowledge. How to make the extraction of accident causes universally accepted is a potential research topic.

8.2.2 Research Topic

1. Extensive research

This study only selected one of the eighteen regional management agencies in the Chinese railway network for analysis. China has the world's largest High-Speed Rail network, and great geographical characteristics, economic and cultural characteristics diversity of these 18 regions. These all affect the construction and operation of High-Speed Rail. It is hoped that the follow-up study can extend the scope of the study to other regions, or the nationwide High-Speed Rail system. To make the safety situation of China's High-

Speed Rail more comprehensively studied, this not only has important academic achievements, but also is inestimable for the value of life and economy.

2. Mining data

The data of current research is still limited, and some research results are not complete. For example, the analysis of clustering coefficient in some years is lack of sufficient data support. Continuous data mining is required by subsequent research.

Appendix A

CASUSAL FACTORS (RAIB)

The causal factors in this appendix are extracted from the research results of RAIB railway accidents. The factors in the original text include human factors, equipment factors, environmental factors, management factors and accident factors. In addition to accident factors, the other four types of factors are directly cited in this doctoral dissertation to analyze the accident and construct the accident causal network in Chapter 5.

Table A.1 Human Factors

Factor	Code
Shunter’s operation Mistake	H01
Driver failed to Apply Emergency brake	H02
Conductor’s Mistake	H03
Driver’s operation Mistake	H04
Track Maintainer’s inadequate Maintenance	H05
Rail line inspector did not check out problems in time	H06
Worker was working in danger conditions	H07
Track worker’s negligence	H08
Passenger fell from platform	H09
Dispatcher’s Mistake	H10
Train driver unable to stop the train	H11
Level crossing watchman’s Mistake	H12
Train Maintainer’s inadequate Maintenance	H13
Pedestrians/car on the line in danger	H14
Train driver drove when tired	H15
Train driver drove Higher than the permitted speed	H16
Signaler’s wrong command	H17
Staff insufficient braked the train	H18
Staff’s negligence	H19
Staff left Machine/goods/material on the track	H20

Source: Zhou, 2015.

Table A.2 Equipment and Machine Factors

Factor	Code	Factor	Code
Locomotive failure	EM01	Train started with door open	EM28
Track damaged	EM02	Train braking system failure	EM29
Power supply failure	EM03	Container train failure	EM30
Signal displayed false	EM04	Design defect of locomotive component	EM31
Train Minor damaged	EM05	A system fault on the set of train door	EM32
Ineffective drainage	EM06	Crossing operating failure	EM33
The risk of the line	EM07	Train passed red signal	EM34
Train seriously damaged	EM08	Ineffective handbrakes on the wagon	EM35
Risk of signal system	EM09	Train’s unbraked condition	EM36
Train’s signal system failure	EM10	Bridge failure	EM37
The Automatic operation of the crossing failure	EM11	Control center system failure	EM38
Railway tunnel was unsafe	EM12	Overhead line failure	EM39
Wagon failure	EM13	Container fell	EM40
Uneven loading of the wagon	EM14	Train door detaching	EM41
Track circuit failure	EM15	Container door open	EM42
Turnout failure	EM16	Infrastructure damaged	EM43
Pantograph fell	EM17	Goods Moved out from wagon/train	EM44
Train’s window broken	EM18	Design defect of the track	EM45
Railway bed failure	EM19	Track gauge out of tolerance	EM46
Train fire	EM20	The wagon overloaded	EM47
Electrical failure	EM21	Unauthorized train Movement	EM48
Train wheel failure	EM22	Draw hook broken	EM49
Collapsing of soil	EM23	Point was operated into wrong situation	EM50
Signal Equipment failure	EM24	Information transmission failure	EM51
Losing traction power	EM25	Hand points Mechanism failure	EM52
Train delayed	EM26	Parts of train failure	EM53
Train technical failure	EM27		

Source: Zhou, 2015.

Table A.3 Weather Factors

Factor	Code
Rainy condition	E01
Water (flood water)	E02
Wind	E03
Freezing temperatures	E04
Snowy condition	E05
Fallen trees on the line	E06
Fallen big stone	E07
Fallen ice	E08
Fallen rubble	E09
Low Adhesion condition	E10
Fallen concrete debris	E11
Fire	E12

Source: Zhou, 2015.

Table A.4 Management Factors

Factor	Code
Inadequate safety Education for workers	M01
Inadequate safety precautions	M02
Weak Management	M03
Poor travel Management and Emergency handling	M04
Not sufficient inspection and supervision	M05
Weak Maintenance system	M06

Source: Zhou, 2015.

Appendix B

CHINA GENERAL ACCIDENT CLASSIFICATION (2007)

The accident classification in this appendix is the source of the accident type code in Chapter 5. The following content is excerpted from "Railway traffic accident investigation and handling rules":

Article 12. In the case of one of the following circumstances, if it does not constitute a major accident, it is a general Class A accident:

A1. Two people were killed.

A2. Serious injuries of 5 or more and 10 or less.

A3. Cause direct economic losses of more than 5 million yuan and less than 10 million yuan.

A4. Conflicts, derailments, fires, explosions, and collisions in trains and shunting operations, resulting in one of the following consequences:

A4.1 One line of busy trunk line or single line train is interrupted for 3 hours or more and 6 hours or less, and the double line train is interrupted for 2 hours or more and 6 hours or less.

A4.2 One line of other lines or single line breaks for more than 6 hours and 10 hours, and the double line train is interrupted for 3 hours or more and 10 hours or less.

A4.3 Passenger trains are delayed for more than 4 hours.

A4.4 Passenger train derailed 1 vehicle.

A4.5 passenger train picks up more than 2 vehicles in the middle.

A4.6 passenger car scrapped 1 vehicle or broke more than 2 vehicles.

A4.7 locomotive broke more than one.

A4.8 More than one vehicle was broken in the EMU.

A4.9 freight train derailed more than 4 vehicles and less than 6 vehicles.

Article 13. In the case of one of the following circumstances, if it does not constitute a general Class A accident, it is a general Class B accident:

B1. Caused one death.

B2. Serious injury to 5 people or less.

B3. Direct economic losses of more than 1 million yuan and 5 million yuan.

B4. Conflicts, derailments, fires, explosions, and collisions in trains and shunting operations, resulting in one of the following consequences:

B4.1 The busy trunk line was interrupted for more than 1 hour.

B4.2 Other lines are interrupted for more than 2 hours.

B4.3 Passenger trains are delayed for more than one hour.

B4.4 Passenger train picks up one vehicle in the middle.

B4.5 passenger car broke 1 vehicle.

B4.6 locomotives broke.

B4.7 freight train derailed more than 2 vehicles and less than 4 vehicles.

Article 14 In the case of one of the following circumstances, if it does not constitute a general Class B accident, it is a general Class C accident:

C1. Train conflict.

C2. Freight train derailment.

C3. Train fires.

C4. Train explosion.

C5. The train collided.

C6. Issue the train to the occupied area.

C7. Connect to the train to the occupied line.

C8. Not ready to connect and send trains.

C9. Unsuccessful or wrongly occluded to send trains.

C10. The train rushes into the signal or crosses the police.

C11. The rolling stock slips into the section or station.

C12. The locomotive and vehicle in the train are broken, the wheels are cracked, and the brake beam, the pull-down lever, the crossbar and other components fall off.

C13. Collision of light vehicles, trolleys, construction machinery, machinery, protective fences and other equipment and facilities, or road materials, carcasses, falling rocks.

C14. Contact wire contact wire is broken, rebared or collapsed.

C15. Close the angled plug door to release the train or close the angled plug door during operation.

C16. Damage to driving equipment during train operation.

C17. During the operation of the train, the equipment and facilities, loading of goods (including bag, mail), loading of reinforcement materials (or equipment) exceed the limit (including exceeding the approved size of the telegraph by the over-limit cargo) or falling.

C18. Vehicles loaded with over-contained goods are classified into trains by vehicles carrying regular cargo.

C19. Electric locomotives and EMUs are electrified to enter the power outage area.

C20. Error supply power to the catenary of the power outage section.

C21. The electrified section climbs the roof and delays the train.

C22. Passenger train separation.

C23. Locomotive vehicles that have collided or derailed are not inspected and certified into trains.

C24. No dispatching order construction, over-range construction, over-range maintenance operations.

C25. Missing, wrong, leaking, misdirected dispatch commands cause the train to run at over speed.

Article 15 In the case of one of the following circumstances, if it does not constitute a general Class C accident, it is a general Class D accident:

D1. Shunting conflict.

D2. Shutdown and derailment.

D3. Squeeze turnout

D4. Shutdown and collision.

D5. Wrong or not timely signal to cause the train to stop.

D6. Wrong driving certificate or departure train.

D7. The shunting operation touches the derailer, the protection signal, or the unprotected signal.

D8. Freight train separation.

D9. Construction, overhaul, and cleaning equipment delay trains.

D10. The operator violates labor discipline and work discipline to delay the train.

D11. Abuse of the emergency brake valve to delay the train.

D12. Unauthorized departure, driving, parking, wrong passage or passing in the interval.

D13. Train pull iron shoes to drive.

D14. Missing, wrong, leaking, misdirected dispatching commands delay trains.

D15. Mishandling, using the driving equipment to delay the train.

D16. Use light vehicles, trolleys and construction machinery to delay trains.

D17. The train tail device shall be installed and the train shall not be installed.

D18. The train and mail loading and unloading operations delay the train.

D19. Electric locomotives and EMUs enter the contactless network line incorrectly.

D20. Workers on the train throwing objects outside to cause personal injury or equipment damage.

D21. The failure of the driving equipment is delayed by more than one hour for the passenger trains in this column, or the freight trains of this train are delayed for more than 2 hours; the delay of fixed equipment affects the normal driving for more than 2 hours (only on the main line).

REFERENCES

[1] A.L. Barabási, R. Albert, Emergence of scaling in random networks, Science, 286(1999), 509-512.

[2] Adif - Líneas de alta velocidad. www.adifaltavelocidad.es. 17 August 2019.

[3] A. S. Bergantino, L. Madio, Intermodal competition and substitution. High-Speed Rail versus air transport: Understanding the socio-economic determinants of modal choice, Research in Transportation Economics, Volume 79,2020,100823, ISSN 0739-8859

[4] M. B. Barrat, R. Pastor-Satorras, et al. (2004). The architecture of complex weighted networks. Proceedings of the National Academy of Sciences of the United States of America, 101 (11), 3747–3752.

[5] C.A. Ericson, Fault tree analysis A history, Proceedings of the 17th International System Safety Conference, Florida, USA, 1999, pp. 1-9.

[6] California High-Speed Rail Authority. "Implementation Plan" (PDF). July 17, 2008.

[7] C. Jiang, A. Zhang, Airline network choice and market coverage under High-Speed Rail competition, Transportation Research Part A: Policy and Practice, Volume 92,2016, Pages 248-260, ISSN 0965-8564

[8] M. Chen, "Impacts of French High-Speed Rail Investment on Urban Agglomeration Economies" (2014). Publicly Accessible Penn Dissertations. 1234.

[9] C. Chang, B. Chen, Y. Cai, J. Wang, An experimental study of high speed wheel-rail adhesion characteristics in wet condition on full scale roller rig,Wear,Volumes 440–441,2019,203092

[10] C. Desmaris, F. Croccolo, The High-Speed Rail competition in Italy: How are the regulatory design and practices concerned? Research in Transportation Economics, Volume 69,2018, Pages 290-299, ISSN 0739-8859,

[11] D.J. Watts and S.H. Strogatz, Collective dynamics of 'small-world' Networks, Nature, 393(1998), 440-442.

[12] E. Hollnagel, and O. Goteman, The functional resonance accident model. Proceedings of Cognitive System Engineering in Process Plant, 2004, pp.155-161.

[13] E.A. Suchman, Accidents and social deviance. Journal of Health and Social Behavior. Vol. 11 (1970), No. 1, pp. 4-15.

[14] E.N. Gilbert (1959). "Random Graphs". Annals of Mathematical Statistics 30 (4): 1141–1144.

[15] P.Erdős,; . Rényi, (1959). "On Random Graphs. I". Publications Mathematica 6: 290–297.

[16] Z. Feng, China Road Traffic Safety Forum, Beijing, China, 2013

[17] F. Pagliara, F. Mauriello, A. Garofalo, Exploring the interdependences between High Speed Rail systems and tourism: Some evidence from Italy, Transportation Research Part A: Policy and Practice, Volume 106,2017,Pages 300-308,

[18] Global Health Estimates 2016: Disease burden by Cause, Age, Sex, by Country and by Region, 2000-2016. Geneva, World Health Organization; 2018.

[19] H. M. Vernon, An investigation of the factors concerned in the causation of industrial accidents, Health and Munition Workers Committee, Ministry of Munitions, Memorandum No. 21, His Majesty's Stationery Office, London, 1918.

[20] H.A. Watson, Launch Control Safety Study, Bell Labs, Murray Hill, NJ, 1961.

[21] H.W. Heinrich, Industrial Accident Prevention: A Scientific Approach, McGraw-Hill, 1931.

[22] Haddon W Jr. A logical framework for categorizing highway safety phenomena and activity. J Trauma 1972;12(3):193-207.

[23] Haddon W, On the escape of tigers: an ecologic note. (Strategy options in reducing losses in energy-damaged people and property). Technology Review (MIT), Vol. 72 (1970), pp. 44-53.

[24] I. V. Sanchis, R. I. Franco, P. M. Fernández, P. S. Zuriaga, J. B. Font Torres, Risk of increasing temperature due to climate change on High-Speed Rail network in Spain, Transportation Research Part D: Transport and Environment, Volume 82,2020,102312, ISSN 1361-9209,

[25] J.U. Schrder-Hinrichs, E. Hollnagel, and M. Baldauf, From Titanic to Costa Concordia-a century of lessons not learned. WMU Journal of Maritime Affairs, Vol. 11 (2012), No. 2, pp. 151-167.

[26] J. Deng, X. Liu, G. Jing, Z. Bian, Probabilistic risk analysis of flying ballast hazard on High-Speed Rail lines, Transportation Research Part C: Emerging Technologies, Volume 93,2018, Pages 396-409, ISSN 0968-090X,

[27] J. Zhou, W. Xu, X. Guo, J. Ding, A method for modeling and analysis of directed weighted accident causation network (DWACN), Physica A: Statistical Mechanics and its Applications, Volume 437, 2015, 263-277,

[28] K. Penhaul, L. P. Maestro and L. Smith-Spark. Spanish train driver charged in deadly crash. CNN https://www.cnn.com/2013/07/28/world/europe/spain-train-crash/index.html, July 28, 2013

[29] L. Ma, J. Guo, Q.Y. Liu, W.J. Wang, Fatigue crack growth and damage characteristics of High-Speed Rail at low ambient temperature, Engineering Failure Analysis, Volume 82,2017, Pages 802-815, ISSN 1350-6307

[30] R. Liu, L. Lv, and Z. Huang. High Speed Rail Development in China – A Case Study of State Guided Technology Transfer. China as an Innovation Nation? Oxford University Press, United Kingdom. 2015. 26.

[31] C. Lu. (2015). Highlights of China high speed railway[J]. Science & Technology review, 33(18), 13-19

[32] M. Barthélemy, A. Barrat, R. Pastor-Satorras, et al. (2005). Characterization and modeling of weighted networks. Physica, A 346 (1), 34–43.

[33] M.T. Hossain, Z.I. Awal, and S. Das, A Study on the accidents of inland water transport in Bangladesh: The transportation system and contact type accidents, Journal of Transport System Engineering, Vol. 1 (2014), No. 1, 23-32.

[34] N. Leveson, A new accident model for engineering safer systems, Safety Science, Vol. 42 (2004), No. 4, pp. 237-270.

[35] N. Schwartz, R. Cohen, D. ben-Avraham, A.-L. Barabási ans S. Havlin, Percolation in directed scale-free networks, Phys. Rev. E, 66(2002), 015104(R).

[36] National Railway Administration, "Statistical Bulletin of Railways 2011", Beijing, China, 2011

[37] National Railway Administration, "Statistical Bulletin of Railways 2012", Beijing, China, 2012

[38] National Railway Administration, "Statistical Bulletin of Railways 2013", Beijing, China, 2013

[39] National Railway Administration, "Statistical Bulletin of Railways 2014", Beijing, China, 2014

[40] National Railway Administration, "Statistical Bulletin of Railways 2015", Beijing, China, 2015

[41] National Railway Administration, "Statistical Bulletin of Railways 2016", Beijing, China, 2016

[42] National Railway Administration, "Statistical Bulletin of Railways 2017", Beijing, China, 2017

[43] National Railway Administration, "Statistical Bulletin of Railways 2018", Beijing, China, 2018

[44] National Railway Administration, Railway Statistical Bulletin 2013, Beijing, China, 2014

[45] National Railway Administration, Railway Statistical Bulletin 2014, Beijing, China, 2015

[46] National Railway Administration, Railway Statistical Bulletin 2015, Beijing, China, 2016

[47] National Railway Administration, Railway Statistical Bulletin 2016, Beijing, China, 2017

[48] National Railway Administration, Railway Statistical Bulletin 2017, Beijing, China, 2018

[49] National Railway Administration, Railway Statistical Bulletin 2018, Beijing, China, 2019

[50] NJ TRANSIT. 2019 ANNUAL REPORT. 2019

[51] O. Herics, A European High-Speed Rail network: not a reality but an ineffective patchwork， European Court of Auditors 2018 19

[52] P.L. Krapivsky, S. Redner and F. Leyvraz, Connectivity of Growing Random Networks, Phys. Rev. Lett., 85(2000), 4629-4632.

[53] Perrow, Normal Accidents - Living with High Risk Technologies, Basic Books: New York, 1984.

[54] P. R. Aldrich, J. El-Zabet, S. Hassan, J. Briguglio, E. Aliaj, M. Radcliffe, Monte Carlo tests of small-world architecture for coarse-grained networks of the United States railroad and highway transportation systems, Physica A: Statistical Mechanics and its Applications, Volume 438, 2015, Pages 32-39, ISSN 0378-4371

[55] R. Albert and A.-L. Barabási, Topology of evolving networks: local even and universality, Phys. Rev. Lett., 85(2000), 5234-5237.

[56] R. Elvik How much do road accidents cost the national economy? Accident Analysis and Prevention, 2002, 32:849−851.

[57] Rail Safety and Standards Board (RSSB) "RAI0501: Railway accidents: casualties by type of accident" Department for Transport and Office of Rail and Road, 17 December 2019

[58] R. Heyder, G. Girsch, Testing of HSH® rails in high-speed tracks to minimize rail damage, Wear, Volume 258, Issues 7–8, 2005, Pages 1014-1021, ISSN 0043-1648

[59] R. Cohen， S. Havlin, D. ben-Avraham, Efficient Immunization Strategies for Computer Networks and Populations, American Physical Society, 91, 2003

[60] Risk assessment and target setting in EU transport programmers. Brussels, European Transport Safety Council, 2003.

[61] R. Zhang, D. Johnson, W. Zhao, C. Nash, Competition of airline and High-Speed Rail in terms of price and frequency: Empirical study from China, Transport Policy, Volume 78,2019, Pages 8-18, ISSN 0967-070X

[62] S. Boccaletti, V. Latora, Y. Moreno, et al. (2006). Complex networks: Structure and dynamics. Physics Reports, 424 (4), 175–308.

[63] Safety Fact Sheet, U.S. Department of Transportation Federal Railroad Administration, December 2016

[64] S. G. Chadwick, N. Zhou, M. Saat, Highway-rail grade crossing safety challenges for shared operations of high-speed passenger and heavy freight rail in the U.S., Safety Science, Volume 68, 2014, Pages 128-137

[65] T. Opsahl, F. Agneessens, J. Skvoretz. (2010). Node centrality in weighted networks: Generalizing degree and shortest paths. Social Networks, 32 (3), 245–251.

[66] The Investigation of TRA Puyuma Derailment Case Has Been Concluded by the Yilan Prosecutors Office's Task Force. Taiwan Railways Administration (TRA). 15 November 2019.

[67] The State Council's "July 23" Yongwen Line Extraordinary Major Railway Traffic Accident Investigation Group "7 · 23" Yongwen Line Special Major Railway Traffic Accident Investigation Report, State Administration of Work Safety, 2011

[68] T. Limon, Y. Crozet. (2017). Risk analysis and High-Speed Rail projects in France: introducing economic slowdown into appraisal methodologies, Transportation Research Procedia, Volume 25,2017, 2824-2842.

[69] Trafikverket, Road Safety: Vision Zero on the move, Sweden Transport Administration, 2015

[70] Transport accident costs and the value of safety. Brussels, European Transport Safety Council, 1997.

[71] W. Haddon. The changing approach to the epidemiology, prevention, and amelioration of trauma: the transition to approaches etiologically rather than descriptively based. American Journal of Public Health and the Nation's Health, Vol. 58 (1968), No. 8, pp. 1431-1438W.

[72] W. Xia, A. Zhang, High-speed rail and air transport competition and cooperation: A vertical differentiation approach, Transportation Research Part B: Methodological, Volume 94, 2016, Pages 456-481, ISSN 0191-2615

[73] X. Liu, C. Xiao, P. A. Meehan, The effect of rolling speed on lateral adhesion at wheel/rail interface under dry and wet condition, Wear, Volumes 438–439, 2019

[74] X. Zhao, X. Zhao, C. Liu, Z. Wen, X. Jin, A study on dynamic stress intensity factors of rail cracks at high speeds by a 3D explicit finite element model of rolling contact, Wear, Volumes 366–367,2016, Pages 60-70, ISSN 0043-1648

[75] Y. Huang, Y. Liu, D. Zhao, B. Liu, H. Zhang, Z. Huang, Small-world properties of the whole-brain functional networks in patients with obstructive sleep apnea-hypopnea syndrome, Sleep Medicine, Volume 62, 2019, Pages 53-58, ISSN 1389-9457,

[76] Z. Luo, K. Li, X. Ma, J. Zhou, A New Accident Analysis Method Based on Complex Network and Cascading Failure, Discrete Dynamics in Nature and Society, vol. 2013

[77] Z. He, T. Feng, S. Lin, X. Sun, Review of Research on Safety Risk Assessment of High-Speed Rail Traction Power Supply System, Journal of Southwest Jiaotong University, 2016, 51(3), Pages 419-429

[78] Z. Yang et al. (2015). Productivity loses from injury in China. Injury Prevention, 2003, 9:124−127.

[79] Z. I. Awal, K. Hasegawa, A Study on Accident Theories and Application to Maritime Accidents, Procedia Engineering, Volume 194,2017, Pages 298-306, ISSN 1877-7058,