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A network accident causation model for monitoring railway safety

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ABSTRACT

In railway systems, risk monitoring and accident causation analysis are important processes towards operational safety. This paper divides accident causal factors in a railway system into several error types, such as human and signal, and proposes a model based on a complex network for risk monitoring, where the risks of accident causal factors are quantified. This network accident causation model is used to identify accident causal factors and analyze how these factors affect each other, for example, how a signal error leads to a collision between two trains. The results of this case study show that in a complex environment, the proposed model can better identify the root causal factors by quantifying the accident causal factor risk, to find the causation chain based on the interactions among accident causal factors. Based on the analysis results, we can timely and correctly monitor the accident causal factors which have high possibility to raise faults or accidents, thereby protecting the railway system from these factors. The proposed network model provides an effective support for risk monitoring in a railway system.

1. Introduction

In a railway system, train operation safety is the prerequisite for applying new technologies and increasing operational efficiency. With the development of modern railway systems, the environment of train operation becomes more and more complex, and thus the demand to ensure train operation safety is constantly on the rise. In general, risk monitoring in a railway system is a critical step for ensuring train operation safety. Consequently, knowing how to monitor the risks associated with railway systems is increasingly important.

In general, an accident is raised by many system factors which affect one another. As discussed by Hollnagel (2014), an accident or an unsafe event is possibly raised by some elusive causes. In this regard, the system is unlikely to raise an accident with only one factor going wrong. Actually, in a railway traffic system, the occurrence of an accident is a burst result that is different from that of single system factor. Such a result is a collective event in which many system factors change or adjust themselves. These factors affecting each other construct a causation chain which leads to accident occurrence.

In each causation chain, there is one factor that can be considered as a root causal factor. If the root causal factor goes wrong, it would raise a series of errors. Therefore, we need to search for root causal factors, and make a proactive adjustment or management. Such a strategy is consistent with the discussion in Hollnagel (2014). Besides, these root causal factors are the most common daily factors, and their existence brings high risk for a railway system. Therefore, for a railway system with high risk, we need to decrease or adjust the influences of root causal factors by monitoring them.

In practice, the accident causation analysis in a railway system can be achieved by solving one key problem, i.e., how to identify the root causal factors? If the root causal factors are well identified, we can know which factors have high possibility to raise faults or accidents. Based on that analysis, we can direct risk reduction efforts in a timely manner with greater accuracy.

Finally, during the process of risk monitoring in a railway system, the system might be considered safe even if one factor goes wrong. In other words, the safety state of the system needs to be analyzed from a global view (Hollnagel, 2014; Qureshi et al., 2007). Recently, network models provide an effective way to analyze accidents from a system perspective. In the network model, all system factors are considered, including human, machine, environment and management.

2. Literature review

Theoretically, risk monitoring in a railway system is based on the accident causation analysis. In this field, a number 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

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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 upon 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.

Many other methods are frequently used to analyze the risk in a railway system, such as the BP (back propagation) neural network, the fault tree analysis, the Petri nets, and Bayesian network (Harms-Ringdahl, 2004). BP neural network is a multilayer feed forward neural network, which uses an error back propagation algorithm to train the neural network. For example, Bangalore and Tjernberg (2015) construct BP neural network to monitor the fault of the gearbox based on the system state data; and Shao et al. (2016) use BP neural network to predict railway accident based on the maximum information coefficient. Fault tree analysis is a deductive, structured method. Liu et al. (2015) apply the fault tree combined with quantitative analysis to analyze high-speed railway accidents, thereby giving suggestions to decrease the occurrence possibilities of accidents. Petri net is a model that accounts for the order of both logic and time, where the logic of the protocol is proved to be safe by means of state space analysis (Chen et al., 2012). A Bayesian network makes it easy to describe accidents with polymorphism and uncertainty. It has advantages in safety analysis because of its application in fault reasoning and diagnosis (Lacomme et al., 2004). In light of different importance degrees, the risk of transportation process can be assessed quantitatively, and the weakest link of transportation can be identified effectively (Yang et al., 2014). However, in a modern railway system, the number of accident causal factors is enormous and the relationships among them are more complex. Most methods discussed above are not designed for quantitative assessment, with which it would be very difficult to either identify the root causal factors well, or to correctly form the causation chain.

The accident causation model could extend the discussion on accident causation analysis. For example, Reason et al. (2006) developed a model based on the Swiss Cheese Metaphor that suggests multiple contributors must be aligned for an adverse event to occur. Barriers in a system are intended to prevent errors that result in these adverse events. Qureshi et al. (2007) propose that traditional accident modelling approaches are not adequate to analyze accidents that occur in a modern sociotechnical system. The study of modern complex systems requires an understanding of the interactions and interrelationships among the technical, human, social and organizational aspects of the system (Qureshi et al., 2007). Léger et al. (2009) put forward a methodology that aims to achieve the integration of the different methods and assess the risks' probabilities. The results can be used by decision makers to prioritize their actions when faced with potential or real risks. Macrae (2014) points out that the challenges of improving patient safety are knowing how to identify, interpret, integrate and act on the early warnings and weak signals of emerging risks before those risks contribute to a disastrous failure. They suggest three practical ways that healthcare organizations can improve patient safety and address emerging risks.

In addition, network analysis is a new method for modelling the complexity of real world. Large scale data sets, from biology to medicine, economic, and human endeavor, can be described by intricate networks. Based on those networks, the root causal factors can be analyzed from the system point of view, in which many complex factors are considered. Here, the nodes, edges and the structure of a network provide a rich source of information (Pržulj and Malod-Dognin, 2016). Meanwhile, lots of researches have shown that methods based on network analysis can explain the complex social and natural problem with more clarity (Valente, 2012). Thus, it becomes a valid method to represent system structure. Particularly, since the network-based traffic safety analysis has a good implementation prospect (Real Network Control, 2014).

In this paper, based on a network model, a new method is proposed to improve the identification of the root causal factors by quantifying the risk of accident causal factors, and form the causation chain. Such a method can effectively monitor the risk of the railway system for ensuring train operation safety. The rest of this paper is organized as follows. In Section 3, some fundamental concepts are introduced; in Section 4, a new model is proposed; in Section 5, the numerical results of accident database are analyzed. Some concluding remarks are presented in Section 6.

3. Some fundamental concepts

3.1. The evaluation indexes

The indexes for evaluating the railway system safety, among others, include casualties, service interruptions, delays, property and loss. These approaches have been developed for more than 20 years, and they all belong to multi criteria decision analysis. However, multi criteria decision analysis accounts for several indexes, whose diversity and complexity make it difficult for risk monitoring. Hence, it is helpful to convert these indexes into one.

In our method, based on the accident grading rules and accident conversion rules, the multiple consequence indexes are converted into a single index named equivalent damage, which is quantified with respect to the accident data. Equivalent damage is calculated by the following formula:

$$Ed = \sum_{i=1}^{3} u_i N_i \tag{1}$$

where u_i is the conversion factor, N_i is the measurement index considering evacuees, casualties and economic loss.

It should be noted that service interruptions and delays are not considered because of its absence in the chosen data. Table 1 shows the evaluation indexes in terms of railway system safety and their conversion factors. In this table, EL means the economic loss of one accident.

3.2. The quantification of risk

In order to quantify the risk in a railway system, two concepts are introduced in this paper, i.e., the severity and possibility. The severity of an accident is measured by the total number of passengers who are killed, injured and evacuated, as well as the total reportable damages for trains. The possibility that the damage occurs is measured by the frequency of the accident factor. Taking these concepts into account, the risk in a railway system can be quantified by the empirical formula.

Table 1
The evaluation index and the conversion factors.

index	Consequence severity	Conversion factor
Evacuees	People evacuated	0.1
Casualities	People injured or dead	0.3
Economic loss	10 thousand < EL < 1 million	0.3
	1 million < EL < 5 million	1
	5 million < EL < 10 million	3
	EL > 10million	10