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# Evaluation and reduction of vulnerability of subway equipment: An integrated framework

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ABSTRACT

Subway system, consisted of a variety of equipment, is a fundamental and critical infrastructure providing basic transportation service for promoting social development. According to statistics, it is discovered that equipment fault is the main reason for interruptions or accidents in subway operation. Due to the serious results of equipment fault, equipment safety management should be proactive and effective. At first, an integrated framework is put forward for evaluation and reduction of vulnerability of subway equipment. Then, case study is implemented for demonstrating feasibility and effectiveness of the proposed framework in evaluating vulnerability in vehicle and assessing running status of wheel set. It is discovered that the two kinds of most vulnerable equipment in vehicle are train door and train control and management system. The running status of 24 detected wheel sets are identified based on variable weight theory. Finally, recommendations are proposed for reducing the vulnerability and promoting equipment safety management from two perspectives. The warning threshold is set as blue warning, yellow warning and red warning. The logic diagram of maintenance modes is presented in consideration of vulnerability, technology, economy and fault feature. The proposed framework has the potential for a better understanding of vulnerability of subway equipment, and this study may be beneficial to offer suggestions related to equipment safety management for reducing accident caused by equipment fault.

## 1. Introduction

In 1863, the world's first subway system was opened to public in the British capital London. Subsequently, Chicago, Budapest, Paris, Berlin, New York, Tokyo, Moscow and other cities in many regions (including America, Europe, Asia, North Africa and the Middle East) have begun to build their own urban subways. Since then, subway has become an important part of the urban public transportation system in the world. Exactly due to the advantages of larger capacity, higher speed, lower noise and less pollution, it plays an increasingly important role in alleviating urban traffic pressure and promoting the rapid development of big cities.

In view of historical experience, development and utilization of underground space in residential areas is a solution for the problems related to the deficiency of land and environment deterioration during urban construction. For this reason, it can be said that subway are more likely to be invested and constructed when a city developed to a certain phase. With the development of the world economy, cities are springing up and getting bigger and bigger after World War II. It is expected that more and more urban subways will emerge around the world, especially in developing countries, such as China (Li et al., 2011). According to China Statistical Yearbook 2015, there are 143 cities in China have populations exceeding one million in 2014, of which 52 cities with a population of more than two million and 17 cities with a population of more than four million, whereas these three figures are only 133, 47 and 14 in 2013, respectively. By the end of 2015, 39 cities in total have been approved to construct subway system by China's central government, of which 27 cities have put their subway systems into operation with a total length of approximately 3376 km. In addition, several other cities have submitted their application to the central government.

Subway is a kind of typical transportation system with crowed passengers and complex technology. It is a typical complex system, including vehicle system, signal system, power system, communication system and rail system. Its complexity mainly stems from various and complex functions, endogenous functional dependencies, and exogenous physical dependencies (Wang et al., 2012). Interfered by various kinds of factors in operation, it is argued that ensuring the equipment to work safely for long time is very difficult. A statistics analysis on the causes of subway operation accident in Beijing is depicted in Fig. 1. It is

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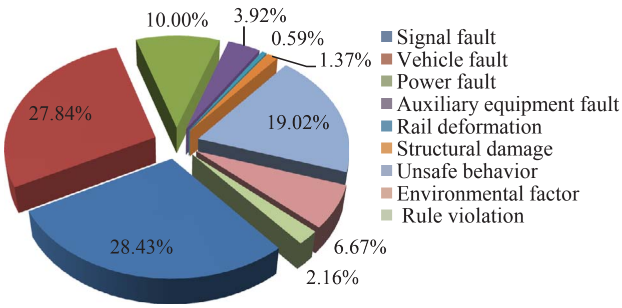


**Fig. 1.** A statistics of the accident causes in Beijing subway from 2008 to 2011.

indicated that approximately 71% accidents are caused by various kind of equipment fault (Deng et al., 2015). In another recent study, it is discovered that about 79% subway operation incidents in Shanghai are caused by the occurrence of equipment fault, of which the vehicle fault accounts for 29.32% and signal fault accounts for 21.29% (Zhang et al., 2016). A number of other statistics in different cities also show the similar results. Therefore, it can be said that equipment fault is the main reason for interruptions or accidents in subway operation. Indeed, equipment fault may result in subway operation interruption or accident and lead to tremendous personnel casualties, equipment disruption and economic loss. For instance, the subway collision caused by power fault on 27 September 2011 in Shanghai, resulting in 284 citizen injured and severe social influence.

Equipment fault can be defined as the equipment is in a state that the specified function cannot be performed. It seriously influences normal operation of subway system. Vehicle is an essential subway equipment, and its fault occurs frequently. A recent research shows that 482 vehicle faults occurred during operation in Line 1 (including 20 trains) of Nanjing subway from January 2011 to December 2012 (Deng et al., 2015). Hence, it can be said that vehicle is vulnerable in subway system. As is known to all, each component may affect the vehicle safety. For example, as a key part of vehicle, the stress condition of wheel set is dynamic and complex during the operation of vehicle, making it prone to abnormal wear and fatigue cracks.

Due to the complexity of vehicle and particularity of its running circumstance, the fault rate is high and its harm is big. Furthermore, the fault rate of equipment increases with working hours. The fault rate curve is an important basis for establishing the scheme of the technical support in routine maintenance. It is argued that decreasing fault rate is the most effective approach to reduce vulnerability and reduce the related accidents. According to the current application, maintenance is the best way to reduce the equipment fault and promote the operation efficiency in subway system. Safety as being the first goal in subway operation, it brings forward strict requirements for equipment maintenance.

The aim of this study is to evaluate the vulnerability of subway equipment and identify its running status with the purpose of promoting the equipment safety management in subway operation. To do this, an integrated framework is proposed at first. Then, a vulnerability evaluation model is established based on grey relational analysis (GCA) and technique for order preference by similarity to ideal solution (TOPSIS), and a variable weight comprehensive evaluation model is established for identifying running status of equipment. Vehicle is selected as example for vulnerability evaluation, and wheel set is selected as example for running status evaluation. Based on the result, recommendations are proposed and discussed for reducing the vulnerability and promoting equipment safety management. This paper aspires to expand knowledge on evaluation and reduction of vulnerability of subway equipment.

After this introduction, the rest of paper is organized as follows. In Section 2, a detailed literature review is summarized on the theme of vulnerability study and maintenance strategy. Then, Section 3 describes the methodology in this study, including the research framework, fuzzy theory, method of determining weight, vulnerability evaluation model and variable weight comprehensive evaluation model. Next, case study is implemented in which the vulnerable equipment in vehicle is identified and the running status of equipment is identified in Section 4. Section 5 provides recommendations to reduce the vulnerability and promote equipment safety management. In the end, conclusions and discussions concerning possible application issues and future research are offered in Section 6.

## 2. Literature review

### 2.1. Content of vulnerability study

The study of vulnerability began in the field of natural sciences, such as ecosystems, disaster science, groundwater, and water resources in the 1970s. With the deepening of research, the study of vulnerability had slowly extended into the field of social systems and engineering systems. Vulnerability is mainly used to represent the property of system that its components are susceptible to interference and can be influenced and destructed easily (Deng et al., 2015). Perhaps the most striking example of vulnerability is Achilles heel. Recent literature reviews indicates that vulnerability is attracting more and more attention in current research, contributions are produced in many different fields and applied in various disciplines (Matisziw et al., 2012). Because of the difference of research perspectives, backgrounds, and objects, the definitions of vulnerability are usually different and seem ambiguous, especially between social science and natural science (Jönsson et al., 2008).

With the development of research, two interpretations are widely acknowledged and accepted. One is that vulnerability is regarded as a system property which means the severity of consequences under the occurrence of a specific hazardous event (Dilley and Boudreau, 2001; Brooks et al., 2005). For example, Tsakiris et al. (2013) considered drought as a natural hazard and proposed an innovative system-based approach for decreasing system vulnerability towards drought. The other is that vulnerability applies to express a critical system component, a geographical location, or an aspect of a system (Apostolakis and Lemon, 2005; Johansson and Hassel, 2010). For instance, Jenelius and Mattsson (2012) proposed a method for analyzing vulnerability of road network and discovered that the vulnerability shows an obviously different geographical distribution. Based on these two common concepts, three kinds of vulnerability analysis are widely applied in specific research, including global vulnerability (Johansson et al., 2007), crucial geographical locations (Patterson and Apostolakis, 2007), and crucial component (Jönsson et al., 2008). They are widely used in various vulnerability studies (Armaş, 2012; Wallnerstrom and Hilber, 2012; Correa and Yusta, 2013; Neshat et al., 2014; LaRocca et al., 2015;). In this study, the third kind of vulnerability analysis is selected to do research on vulnerability of subway equipment.

### 2.2. Maintenance strategy

The running status of equipment deteriorates along with the using time increasing due to man-made factors and outside nature factors, such as uncertain stress or load in the real environment and random event (Jardine et al., 2006). It is a progressive and irresistible process of degradation (Song et al., 2016). In various industries, with the increase of equipment investment, maintenance and repair of equipment is becoming a more and more important part in daily production. In reality, the running status of equipment undergo a normal, degradation and fault cycle, as shown in Fig. 2.

Generally speaking, the maintenance can be described as managerial and technical actions taken during usage period to maintain or restore the required functionality of a product or an asset (Shen et al., 2012). Maintenance management aims at lengthening the useful life of