Safety Science 79 (2015) 344–357

Contents lists available at ScienceDirect

Safety Science

journal homepage: www.elsevier.com/locate/ssci

Fault tree analysis combined with quantitative analysis for high-speed railway accidents

Pei Liu, Lixing Yang *, Ziyou Gao, Shukai Li, Yuan Gao

State Key Laboratory of Rail Traffic Control and Safety, Beijing Jiaotong University, Beijing 100044, China

ARTICLE INFO

Article history:
Received 10 August 2014
Received in revised form 10 April 2015
Accepted 23 June 2015

Keywords:
High speed railway accident
Fault tree analysis
Quantitative analysis
Intuitionistic trapezoidal fuzzy numbers

ABSTRACT

This paper focuses on employing the fault tree analysis method combined with quantitative analysis to investigate high-speed railway accidents. Specifically, by establishing a fault tree logic diagram based on a high-speed railway accident, an in-depth fault tree analysis combined with quantitative analysis is given to present a more comprehensive view of the accident. In quantitative analysis process, each basic event in the fault tree is endowed with uncertain characteristic due to the incompleteness of the prior information and the complexity of decision environments. With this concern, a novel method within the framework of intuitionistic fuzzy set theory is proposed to handle this problem, in which the failure possibilities of basic events are particularly treated as intuitionistic trapezoidal fuzzy numbers (ITFNs). In addition, a new ranking method for ITFNs is proposed by defining the expected values and compromise possibilities, and is efficiently employed to determine the importance degrees of all basic events. As an application, two numerical experiments are implemented to illustrate the effectiveness of the proposed fault tree analysis method, and some conclusions and suggestions are also given to decrease the occurrence possibilities of similar accidents.

1. Introduction

Nowadays, many countries begin to build high-speed railways to further satisfy the travel demands. The high-speed railway is a new railway transportation mode with the maximum speed of rolling stock, and superior to conventional trains in some characteristics, such as higher speed, time-saving, higher efficiency and lower pollution, etc. Therefore, developing high-speed railway will significantly reduce the transportation cost and finally result in considerable socioeconomic benefits.

In recent years, however, some serious high-speed railway accidents have happened and caused a lot of injuries, fatalities as well as economic losses. For instance, in July 2003, a Japanese express train derailed in Nagasaki which caused six carriages derailed and more than 60 people injured or dead. On July 23, 2011, the train D301 from Beijing South Station to Fuzhou Station rear-ended with the train D3115 from Hangzhou to Fuzhou South Station, leading to 40 fatalities, 172 injuries and 193.7165 million yuan direct economic loss (see reference Railway Accident, 2011). These accidents illustrate that improving the high technological innovations and operation management levels in transportation activities is urgent and important. Note that, compared to the past risk categories and levels which the high-speed railway faced, great changes need to implement to meet the high-requirements for the safety issues of high-speed railway. Hence, it is particularly important and urgent for railway system to fully implement security risk management. By analyzing the occurred accidents, effective solutions could be proposed to prevent or reduce similar accidents in the future.

Nowadays, accident analysis methods with the aid of qualitative analysis have attracted numerous researchers' attention. For example, Li (2011) discussed the train crash accident from a broader viewpoint, and the safety issues were addressed along with technological strategies and management suggestions. Song et al. (2012) employed the STAMP model to analyze the China-Yongwen railway accident and proposed some improvement measures. Besides of qualitative analysis, quantitative analysis is also a new approach to address some problems. Leveson (2004) pointed out that there were a number of quantified risk assessment techniques and tree-based methods, such as the event tree analysis, the fault tree analysis. However, a more detailed diagram of the contributing causes of an accident needs to be identified by the fault tree analysis. As an application, Shu et al. (2006) presented an algorithm of intuitionistic fuzzy fault tree analysis, and gave an application in printed circuit board assembly. Wang et al. (2010) investigated a novel incident tree methodology to characterize the information flow in quantified risk assessment,

* Corresponding author. Tel.: +86 13141299701.
E-mail addresses: 14114194@bjtu.edu.cn (P. Liu), lxyang@bjtu.edu.cn (L. Yang).

http://dx.doi.org/10.1016/j.ssci.2015.06.017
0925-7535/

in which an in-depth accident study in traffic operation was discussed to illustrate the effectiveness of the proposed methodology. Although fault tree analysis was successfully applied to handling and solving a variety of accidents, there were very few studies applied to the field of the high-speed railway accidents. For this reason, this paper will employ fault tree analysis combined with quantitative analysis to implement in-depth analysis for high-speed railway accidents. The following will focus on introducing the procedure of fault tree analysis method.

Fault tree analysis is a deductive and diagrammatic method to capture the failure possibility or probability of an accident. Starting from the top event (an accident occurred), we search and analyze all possible reasons level-by-level until all relevant basic events are found out. According to the relationships and interactions among basic events, a fault tree logic diagram can be easily established with the aid of symbols for the fault tree GB/T 4888-2009 (2009). Moreover, in conventional fault tree analysis method, the failure possibilities or probabilities of basic events were regarded as crisp values. However, it is difficult to capture the failure possibilities or probabilities of basic events from past experience due to the complexity and changeability of practical environment or the incompleteness of the prior information, and moreover, the basic events which have never occurred before are also needed to consider. Hence, some researchers employed the fuzzy set theory to avoid the potential shortcomings. For instance, Tanaka et al. (1983) analyzed the fault tree by employing fuzzy probability. That is, the failure probability of a basic event was defined as a fuzzy set on [0, 1] instead of a unique value. Kenarangui (1981) employed fuzzy sets logic to account for imprecision and uncertainty in data and a fuzzy event tree was established to analyze electric power protection system additionally. In addition, the fuzzy or stochastic optimization methods have been applied to a variety of real-world decision-making problems up to now (see Ni and Liu, 2011, 2013; Ni, 2012; Yang and Zhou, 2014; Yang et al., 2014, 2012, 2013). Motivated by these, the failure possibilities of basic events in this paper will be represented as intuitionistic trapezoidal fuzzy numbers to characterize the basic events' uncertain characteristics.

In this paper, some arithimetic operations of intuitionistic trapezoidal fuzzy numbers will be defined to calculate the failure possibility of the top event in the quantitative analysis procedure. In addition, investigating the importance degrees of all basic events is also important, because we can easily identify which basic event is the main reason for an accident. Therefore, we need to rank the intuitionistic trapezoidal fuzzy numbers to obtain the importance degrees for basic events. In some existing references, some ranking methods have been proposed. For example, Li (2010) developed a ratio ranking method based on the value index to the ambiguity index for ranking triangular intuitionistic fuzzy numbers. Mitchell (2004) interpreted an intuitionistic fuzzy number as an ensemble of fuzzy numbers and introduced a ranking method. However, both of those ranking method were not directly aim at intuitionistic trapezoidal fuzzy numbers (ITFNs). Hence, this paper will develop a new ranking method for ITFNs by calculating the corresponding expected value and compromise possibility.

The rest of this paper is organized as follows. In Section 2, after introducing fundamental concept of ITFNs, some arithmetic operations of ITFNs associated with some properties (like closure property, commutative law, associative law and distributive law) are formally presented. Moreover, the ranking criterion is proposed to give a sequence of the different ITFNs. Section 3 gives a description of the procedure of fault tree analysis combined with quantitative analysis. Then, two numerical examples are implemented in Section 4 to illustrate the application and effectiveness of the proposed approaches. Finally, some conclusions are made in Section 5.

2. Preliminaries

The concept of intuitionistic fuzzy sets was firstly introduced by Atanassov (1986), which is a generalization of fuzzy sets by adding an additional non-membership degree. By using the intuitionistic fuzzy sets, the incomplete information can be suitably described by two characteristic functions (membership and nonmembership). Typically, an intuitionistic fuzzy number (IFN) is a special case of the intuitionistic fuzzy set, and the most common IFNs are triangular intuitionistic fuzzy numbers and intuitionistic trapezoidal fuzzy numbers.

In order to describe the quantitative analysis in high-speed railway accidents under uncertain environment, this paper treats the failure possibility of a basic event as an intuitionistic trapezoidal fuzzy number to account for imprecision and uncertainty in data. The following contents are about some basic concepts related to intuitionistic trapezoidal fuzzy numbers.

2.1. Intuitionistic trapezoidal fuzzy numbers

Definition 2.1 Wang, 2008. Let $\tilde{a}$ be an intuitionistic trapezoidal fuzzy number in the set of real numbers. Its membership function is defined as

$$\mu_{\tilde{a}}(x) = \begin{cases} (x-a_1)\mu_{\tilde{a}}/(a_2-a_1), & \text{if } a_1 \leqslant x \leqslant a_2, \\ \mu_{\tilde{a}}, & \text{if } a_2 \leqslant x \leqslant a_3, \\ (a_4-x)\mu_{\tilde{a}}/(a_4-a_3), & \text{if } a_3 \leqslant x \leqslant a_4, \\ 0, & \text{otherwise}. \end{cases} \tag{1}$$

Its nonmembership function is defined as

$$\nu_{\tilde{a}}(x) = \begin{cases} ((a_2-x)+\nu_{\tilde{a}}(x-a_1'))/(a_2-a_1'), & \text{if } a_1' \leqslant x \leqslant a_2, \\ \nu_{\tilde{a}}, & \text{if } a_2 \leqslant x \leqslant a_3, \\ ((x-a_3)+\nu_{\tilde{a}}(a_4'-x))/(a_4'-a_3), & \text{if } a_3 \leqslant x \leqslant a_4', \\ 0, & \text{otherwise}, \end{cases} \tag{2}$$

where $0 \leqslant \mu_{\tilde{a}} \leqslant 1, 0 \leqslant \nu_{\tilde{a}} \leqslant 1, \mu_{\tilde{a}} + \nu_{\tilde{a}} \leqslant 1$, and $a_1', a_1, a_2, a_3, a_4, a_4'$ are real numbers. Then $\tilde{a} = \langle([a_1, a_2, a_3, a_4]; \mu_{\tilde{a}}), ([a_1', a_2, a_3, a_4']; \nu_{\tilde{a}})\rangle$ is called an intuitionistic trapezoidal fuzzy number.

Fig. 1 illustrates the geometric figure of an intuitionistic trapezoidal fuzzy number. Clearly, both the membership function $\mu_{\tilde{a}}$ and the complementary of nonmembership function $1-\nu_{\tilde{a}}$ are all trapezoidal shapes.

For simplicity, the following discussion only considers a special case of intuitionistic trapezoidal fuzzy numbers defined in Definition 2.1, i.e., $a_1 = a_1'$ and $a_4 = a_4'$. In this situation, an intuitionistic trapezoidal fuzzy number $\tilde{a} = \langle([a_1, a_2, a_3, a_4]; \mu_{\tilde{a}}), ([a_1', a_2, a_3, a_4']; \nu_{\tilde{a}})\rangle$ can be rewritten as the form of $\tilde{a} = \langle(a_1, a_2, a_3, a_4); \mu_{\tilde{a}}, \nu_{\tilde{a}}\rangle$. Typically, for any intuitionistic trapezoidal fuzzy number, if $\mu_{\tilde{a}} = 1$ and $\nu_{\tilde{a}} = 0$, an intuitionistic trapezoidal fuzzy number will degenerate to a trapezoidal fuzzy number. Thus, the concept of intuitionistic trapezoidal fuzzy number is actually a generalization of trapezoidal fuzzy number.

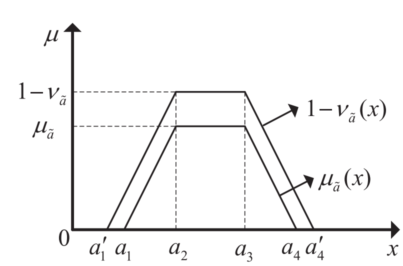

Fig. 1. A basic intuitionistic trapezoidal fuzzy number.