Safety Science 72 (2015) 83–96

Contents lists available at ScienceDirect

Safety Science

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

On the application of Valuation-Based Systems in the assessment of the probability bounds of Hazardous Material transportation accidents occurrence

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ARTICLE INFO

Article history:
Received 17 March 2014
Received in revised form 30 June 2014
Accepted 16 August 2014
Available online 16 September 2014

Keywords:
Hazardous Material (hazmat) transport
Valuation-Based System (VBS)
Theory of belief functions
Uncertainty

ABSTRACT

An important issue in Hazardous Material (hazmat) transportation risk assessment is to evaluate the probability bounds of accidents occurrence, whose values are difficult to be estimated due to its low frequency and the related lack of statistical data. This paper presents an original approach to integrate uncertainty in the quantitative analysis of hazmat transportation accidents. The proposed approach is based on the use of Valuation-Based Systems (VBSs) and belief functions theory. Furthermore, we propose to identify the factors for which the reduction of epistemic uncertainty (imprecision) gives the greatest impact on the uncertainty of the final results by using some proposed measures. The applicability and generality of the proposed approach is demonstrated on a case study.

1. Introduction

Hazardous Material (hazmat) transport represents about the 4% of road goods transport (Eurostat Statistical Books). Hazmat accidents involving dangerous goods can produce hazards such as fires, explosions, chemical leaks involving individuals, environmental systems and properties.

The classical approaches to define the hazmat transport risk introduce the probabilities of an accident. But in hazmat transport, this probability is very low and reported accident data are very scarce (Kazantzi et al., 2011): in 2011, in the European Union (27 countries), 46 accidents involving hazmat are reported, in 32 of which hazmat was released (Eurostat Statistical Books). The low frequency of such events and the high related consequences allow to classify this kind of risk under a specific category (Cha and Ellingwood, 2012), generally showing a risk averse decision making behavior. In addition to the low number of accidents making difficult the definition of a reliable statistic, other uncertain factors are represented by the exposure of risk. For example, the social risk generally depends on the number of individuals in a given area subject to the accident impact. However uncertainties are present in the true shape and coverage of this area, as well as on the expected number of individuals present in it. These aspects require decision making methodologies for the evaluation of the risk that go beyond traditional statistical approaches, taking into account the fuzziness of the information, its cause effect processes, and the expert experience.

In the literature, several methods were proposed to estimate hazmat transportation factors and occurrence. In Qiao et al. (2009), an integrated methodology to estimate hazmat transportation accident frequency by utilizing publicly available databases and expert knowledge has been implemented. The estimation process addresses route-dependent and route-independent variables. A multi-objective optimization model in hazmat transport has been studied in Bersani et al. (2010): here the Decision Maker (DM) has to plan, for each day, the hazmat deliveries from depots to several other destinations following a risk-averse routing approach. This model also takes into account the risk for domino effect arising from the simultaneous presence of one or more vehicles on the same link at the same time, with the purpose of improving the minimization of the overall maximum exposure. A different approach to hazmat transportation risk analysis was recently proposed by Clark and Besterfield-Sacre (2009), where the authors identified the most influential variables and countermeasures for two consequences of a hazmat accident: the economic cost and release quantity. This approach focuses on an exploratory data modeling based on hazmat accident data by the US Department of Transportation. The authors concluded that the most influential

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http://dx.doi.org/10.1016/j.ssci.2014.08.006
0925-7535/

variables are related to the failure of the container. Bayesian network (BN) can be considered as an interesting tool to find cause-effect relationships from hazardous factors. It is used both for graphically representing the relationships among a set of variables and for dealing with probabilistic variables. The underlying theory of BNs combines Bayesian probability theory and the notion of conditional independence to represent dependencies between variables (Pearl, 1988). During the last decades, the use of BN in risk analysis studies is increasing. Weber et al. (2012) presented a review on the application of BN to dependability, risk analysis and maintenance. In that paper, the authors have claimed that during the last few years, there is an increasing use of BN in dependability and risk analysis. They have also compared BN with three classical dependability and risk analysis methods: Fault Trees, Markov Chains and Petri Nets, to present the benefits of BN. Langseth and Portinale (2007) gave some arguments for the use of BNs in the reliability analysis (software reliability, fault finding systems, general reliability modeling, etc.). They also presented challenges and open problems when using BN such as building BNs from expert input or using continuous variables in BNs. Akhtar and Utne (2014) studied the human fatigue's effect on the risk of maritime ship accident using BN. Khakzad et al. (2013) developed a BN method to conduct quantitative risk analysis of drilling operations. BNs are used to develop accident scenarios. Zhang et al. (2013) estimated the navigational risk of the Yangtze River using the formal safety assessment and BN. BNs were used to model and evaluate accidents due to different factors. Leu and Chang (2013) developed a safety risk-assessment model for steel building construction projects using BN based on fault tree transformation. Song et al. (2013) proposed a BN approach to assess risks of service failures based on the dependent relationships among individual service failures. A case study of the outpatient consultation service was presented to show the feasibility of the method. Jia and Lu (2013) developed a mission-oriented risk assessment methodology based on BN. Naval vessel fire damage on warship was modeled and evaluated using BN. The methodology was applied on a hypothetical ship with five compartments. Sousa and Einstein (2012) presented a methodology to assess systematically and manage the risks associated with tunnel construction using BN. Goulding et al. (2012) proposed a BN model to assess the public health risk associated with wet weather sewer overflows. The uncertainty inherent in sewer overflow events and subsequent impacts were taken into account through the use of probabilities. Marsh and Bearfield (2004) proposed a method for modeling organisational causes of accidents in the UK railway systems using BN. An example from a model of the causes of Signals Passed at Danger (SPAD) incidents was also provided. Trucco et al. (2008) presented a BN applied to model the Maritime Transport System (MTS), by taking into account several factors: ship-owner, shipyard, port, etc., and their mutual influences. Particularly, Their model integrates human and organisational factors into a risk analysis. Zhao et al. (2012) proposed the use of BN to investigate the influence of a range of factors for hazmat transportation accidents in China. Note that the proposed BN structure was built based on expert knowledge.

Different architectures have been proposed to propagate probability functions in networks. First, Pearl (1988) concentrated on Bayesian causal trees to define BN. Shenoy and Shafer proposed a unified structure using local computation and having Pearl's scheme as a special case. This last work led some years later to the framework of Valuation-Based Systems (VBSs) (Shenoy, 1989), generalizing all the previous works on graphical structures. In order to model the causal factors in a hazmat transport accident we will use a VBS. The VBSs were introduced as a generic uncertainty calculus that allows one to represent various uncertainty calculi (Shenoy, 1989, 1992). The VBS consists of two parts: a static part that is concerned with representation of knowledge, and a dynamic part that is concerned with reasoning with knowledge. The knowledge about a set of variables is represented by a valuation for that set of variables. Two operations in VBS are proposed to perform inferences: combination and marginalization. The combination operation represents aggregation of knowledge whereas the marginalization operation represents coarsening of knowledge. The VBS framework is able to uniformly represent probability theory (Shenoy, 1992), belief functions theory (Shenoy, 1994; Smets and Kennes, 1994), possibility theory (Dubois and Prade, 1991), etc. Concerning the works related to the use of VBS in the framework of belief functions theory, Benavoli et al. (2007, 2009) proposed an information fusion system that aims at supporting a commander's decision making by providing an assessment of threat. Threat is modeled in the framework of VBSs by a network of entities and relationships between them. In Laâmari et al. (2010), Laâmari et al. compare two architectures for belief propagation in networks representing VBSs applied to reliability analysis under uncertainty. In Xu (1997), Xu uses a VBS in decision analysis to model a DM's degree of belief about which state of affairs will prevail. In this paper, we apply the combined VBS and belief functions theory to evaluate the probability of accidents occurrence.

In the literature, several theories are used to handle uncertainty in risk assessment. The ideal situation is when there is a good enough background knowledge about the occurrence of an event, i.e., the expert has representative samples of historical life data. Afterwards, by applying a frequentist probability approach and statistical analysis he/she can establish accurate probability distribution related to the occurrence of each event. In hazmat transportation problems, this ideal situation does not always happen, hence, a frequentist approach cannot always be applied. In such a case, Bayesians propose the use of a subjectivist probability approach. The subjective probabilities of an event were introduced by Finetti (1974) to indicate the degree to which the expert believes it. Kaplan and Garrick (1981) introduced the concept of probability of frequency to expand their definition of risk and to tacke into account all types of uncertainty. Pate-Cornell (1996) considered six levels of sophistication in the analysis of the uncertainties according to the circumstances. She also proposed an uncertainty analysis to obtain a family of risk curves in the presence of several levels of uncertainty. North (2010) argues that "It [standard probability theory] is the only way to reason consistently about uncertainties, both aleatory and epistemic". He then adds that it is a legitimate concern that subjective probabilities assessed by experts may be in error. In such a case, he recommends to minimize such error through careful assessment practices, rather than by replacing standard probability with other uncertainty theories. However, previous studies have shown that results can greatly differ depending on the assessment practices or the expert performing the assessment. Furthermore, there are some criticisms about representing epistemic uncertainties using subjective probabilities. These criticisms was exposed particularly by Walley (1991) and Caselton and Luo (1992). When there is sparse information about the value of a parameter β, the choice of probability distribution may not be appropriate. For example, there is a difference between saying that all that is known about the parameter β is that its value is located somewhere in an interval $[a, b]$ and saying that a uniform distribution on $[a, b]$ characterizes degrees of belief with respect to where the value of this parameter is located in the interval $[a, b]$ (Helton et al., 2007; Aven, 2011). Furthermore, in a situation of ignorance, a Bayesian approach must equally allocate subjective probabilities over the frame of discernment. Thus there is no distinction between uncertainty and ignorance. In such cases, different uncertainty theories than subjective probability theory deserve to be investigated.