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An innovative gravity-based approach to assess vulnerability of a Hazmat road transportation network: A case study of Guangzhou, China

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ABSTRACT

The transportation of hazardous material (hereinafter referred to as Hazmat) is different from general cargo. If a Hazmat road transportation accident occurs, it will not only cause significant casualties and road network damage but also threaten the safety of the lives and property of the residents near the road. Therefore, a quantitative vulnerability analysis of the Hazmat road transportation network is developed to assess the vulnerability of each link, which can help improve the road transportation risk management level. First, we propose an indicator to measure the relevance between two links based on comprehensive analysis of the road transportation network topology and Hazmat road transportation risk characteristics. Second, we discover that we cannot identify road vulnerability using only topology and risk characteristics alone. Thus, an Impact Strength model is developed to assess Hazmat road transportation vulnerability. This model is based on the classical Gravity model and considers both topology and risk characteristics. Relevant algorithms are proposed accordingly. Third, we use Guangzhou's Hazmat highway transportation as a case study to verify our Impact Strength model. The related statistics data are collected, and ArcGIS software is employed. By using this model, we can calculate the Impact Strength of each link in the whole transportation network. The empirical results verify that this innovative Impact Strength model can help to identify the links with significant vulnerabilities, which can thus help to reduce road transportation risk in advance and build the road transportation risk early-warning mechanism. This innovative model can also be used to support the relevant decision-making process for further analysis.

1. Introduction

The United Nations defines hazardous materials (Hazmats) as those substances that have physical and chemical properties that are potentially harmful to human life and to the environment (UNECE, 2011). With the development of the world economy and the increasing growth of the population, Hazmats have become indispensable materials in industry, agriculture, national defence and citizen's daily lives. It is estimated that more than 4 billion tons of Hazmats were shipped at the worldwide level in the first half of the current decade (Zografos and Androutsopoulos, 2004). In the United States, approximately 3.2 billion tons of Hazmats are transported each year (Kara and Verter, 2004), which explains why Hazmat shipment network planning has been a very popular research

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area in the United States. However, an increasing number of scholars are beginning to pay attention to Hazmat transportation problems all over the world. For example, Bianco et al. (2009) built a bi-level flow model for Hazmat road transportation network design that considers both total risk minimization and risk equity together, using an Italian regional network as a case study. Huang et al. (2004), from Singapore, combined Geographic Information System (GIS) and the Genetic Algorithm to improve Hazmat road route planning using Singapore's populated area to test the method. In China, more than 1 million tons of Hazmats are transported every day, and the annual Hazmat transportation burden is over 400 million tons (Zhang and Zhao, 2007). With the rapid expansion of the Chinese chemical industry, the number of enterprises related to Hazmats reaches more than 300 thousand. In most cases, the regions where Hazmats are consumed and produced are different and far apart. More than 95% of Hazmats, in terms of tons, are transported between different regions, with more than 80% of Hazmat transportation depending on road transportation (Wu and Sun, 2006; Fan et al., 2015). In recent years, many road accidents involving Hazmats have resulted in catastrophic losses to human beings and to the environment in China (Wu and Lin, 2015). Meanwhile, the damaged road transportation networks are heavily blocked or even paralyzed. According to historical statistics, over 92% of transportation-related accidents occur during road transfer in China, with an annual average of 36 serious, social-impact accidents involving Hazmat road transportation. One example is the March 2005 collision in Nanjing that involved a truck carrying chlorine, which caused 29 fatalities, and over 10,000 people had to be evacuated. These Hazmat road accidents have attracted great attention from the Chinese public, the Chinese government at all levels, and various non-governmental organizations/communities (Yang et al., 2010; Fan et al., 2015).

In an attempt to ensure public and environmental safety and to reduce the occurrence of Hazmat accidents, the Chinese government at all levels has created rules and regulations for Hazmat transportation. There are many ways in which governments can regulate Hazmat transportation, such as by setting standards for the vehicles that are used in carrying Hazmats, or by designating which roads are used for Hazmat transportation. Both technology and management instruments are applied simultaneously (Erkut and Verter, 1995).

Despite the increasing demands and significance of Hazmat transportation, upon review of a comprehensive literature review of Hazmat transportation by Erkut et al. (2007), it is clear that the vulnerability of Hazmat transportation networks has not yet been thoroughly studied. This paper develops an innovative model to effectively identify road vulnerability in Hazmat transportation networks. It will help transport authorities recognize the most vulnerable links in the traffic network, build early-warning mechanisms and otherwise elevate their management capabilities. It can also assist governments at all levels in creating related policies in various forms (e.g., regulations and rules) for Hazmat transportation. From the users' perspectives, it can help a driver to make a relatively more reasonable decision with less risk on road routing planning when he or she can obtain the road vulnerability information in advance.

The remainder of this paper is organized as follows. In Section 2, a literature review on Hazmat road transportation is provided. Section 3 presents the innovative vulnerability assessment model and related explanations. Section 4 proposes the algorithms according to the model in Section 3. Section 5 addresses a case study of Guangzhou's Hazmat highway road transportation. Finally, Section 6 is dedicated to conclusions and implications.

2. Related literature

After reviewing two classical and state-of-the-art literature reviews by List et al. (1991) and Centrone et al. (2008), it is clear that Hazmat transportation literature can be classified into three major branches as follows: risk analysis, routing/scheduling, facility location, and a combination of the three. As early as 1985, Saccomanno and Chan (1985) proposed a model that could realistically represent the effects of an accident occurring in a crowded population. The model employs two criteria as follows: a minimum risk criterion and a minimum accident likelihood. Beroggi and Wallace (1995) considered a situation in which a dispatcher receives real-time information, such as weather and traffic reports, and can use that information to judge the risk for road transportation of Hazmat and re-direct the shipments. With regard to the transportation risks themselves, there does not seem to be any consensus on how to define transportation risks and how to model the associated transportation risks. Erkut and Verter's (1998) empirical analysis of the U.S. road network, indicates that different risk models usually select different optimal paths (routing) for Hazmat transportation between a given origin–destination pair. Therefore, selection of the road transportation risk model is crucial and tricky. As early as 1995, Alp (1995) proposed the Traditional Risk (TR) model, which is a non-linear binary integer programme, to minimize the expected consequences of Hazmat road transportation. In 1997, Jin and Batta (1997) simplified and approximated Alp (1995)'s Traditional Risk model to the Approximated Traditional Risk (ATR) model as follows:

$$R^r = \sum_{(i,j)\in L^r} P_{ij} C_{ij} \tag{1}$$

In this model, Hazmat road transportation risk on link (i,j) is the product of accident probability (P_{ij}) on link (i,j) and accident consequence (C_{ij}) on link (i,j). Thus, the following two approaches exist to minimize Hazmat road transportation risk: minimizing accident probability, minimizing accident consequence and a combination of these two factors. This Approximated Traditional Risk (ATR) model is easier to optimize than Alp (1995)'s Traditional Risk (TR) model. That is why several other risk models have been developed based on the ATR model from different perspectives over the past years. For example, Kara et al. (2003) defined the transportation risk as the product of incident probability and the affected population, and use "affected population" to represent the "accident consequence".

As early as 1994, Laurentius (1994) defined vulnerability as "a susceptibility for rare, though big, risks, while the victims can hardly change the course of events and contribute little or nothing to recovery". Unfortunately, to date there is still no internationally