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Modeling urban hazmat transportation with road closure consideration

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ABSTRACT

Hazardous materials accidents during road transport have caused catastrophic losses to humans and the environment all over the world in recent years. Especially in an urban environment, heavy traffic congestion and road closures present serious and complex situations during hazmat transportation. The challenge of urban hazmat transportation is to determine the vehicle routes that minimize risk subject to cost considerations and road closures. This paper presents a bi-objective programming model and a heuristic algorithm to optimize the routing of hazardous materials transportation with road closure considerations. A model is formulated that minimizes hazmat risk and transportation cost subject to road closure constraints. A new heuristic algorithm is proposed to solve the bi-objective hazmat vehicle routing and it is applied to a realistic case study involving hazmat transportation in the highly populated metropolitan area of Shanghai, China.

Introduction

Hazardous materials (hazmat in short) are products which are flammable, explosive, poisonous, corrosive, infectious, or radioactive, such as gasoline, fuel oil, petroleum, and chemicals. Despite these dangerous characteristics, most hazmats are a fundamental part of both our daily lives and industrial development. It is estimated that approximately 4 billion tons of hazmat are transported annually at the worldwide level (Carotenuto et al., 2007). In the United States, the hazmat demand is between 3 and 4 billion tons each year, and these materials are widely used in manufacturing, farming, medicine, and other industrial areas (Glickman et al., 2007; Kara and Verter, 2004). Transport Canada estimates that nearly 80,000 shipments of hazmat are transported by road, rail, water and air in Canada (Erkut and Alp, 2007b). In China, approximately 95% of the hazmat is transported from producers to customers by trucks.

Although the incident rate of hazmat transportation is very small, accidents do happen and some consequences are very severe. An example is the November 2005 collision in Sinaloa, Mexico that involved an ammonia truck and caused 39 fatalities (Verter and Kara, 2008). According to statistics, over 92% of transportation related accidents in China happen during road transfer, and annually, there are 36 serious accidents on average involving hazmat road transport (Yang et al., 2010). On October 6, 2012, a truck carrying liquified gas crashed on a highway just before a tunnel and flipped over in Huaihai, Hunan province. The resulting explosion killed five people and injured two more, including three firefighters. In 2013, a truck

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carrying fireworks on the eve of the Chinese New Year celebrations exploded and destroyed part of an elevated highway in China's Henan Province, killing several people.

In fact, hazmat transportation in an urban area faces challenges which must be specially considered due to such critical factors, such as high population density, congestion and road closure. In China, Shanghai has an urban population of more than 24 million, and Beijing has more than 16 million. In Mexico, the metropolitan area of Mexico City has over 20 million inhabitants. Because of the high population density, urban hazmat transportation accidents can cause catastrophic human losses. On March 29, 2005, a truck carrying chlorine, collided with another vehicle in the urban area of Nanjing of China, the accident resulted in 29 deaths and over 10,000 people being evacuated.

Congestion and road closures are major concerns for hazmat transportation within an urban environment. In a metropolitan area, heavy traffic congestion is the most usual, serious and complex problem which can take hours to clear. Thus, some roads will be restricted from the hazmat transportation during that time. According to Decree No. 591 of the State Council of the People's Republic of China, some places, such as densely inhabited districts, stations, docks, and military control zones are also forbidden to transport Hazmat without being approved by the public security organizations. Moreover, when some important events are held, some roads must be closed during certain times and restricted from Hazmat transportation. During the 2010 Shanghai WorldExpo, hazmats were restricted to transport in urban areas from 10:00 am to 4:00 pm during the period from June 15 to October 15. In Beijing, when an important conference is held, hazmat transportation is forbidden on some roads from 6:00 pm to 6:00 am next day.

Facing the concerns of the public and restrictions of the government, the challenge in urban hazmat transportation is to determine the vehicle path that minimizes transportation cost and hazmat risk while satisfying road closure constraints. Therefore, how to optimize the routing options with consideration of cost, risk, and traffic control is an important area for research in order to enhance our understanding of this type of hazmat transport management. In this paper, we propose a bi-objective programming model to formulate this problem and investigate a new heuristic algorithm to solve the model with consideration of road closure constraints.

The rest of this paper is organized as follows. Section 'Previous work' provides a literature review on hazmat transportation and points out the differences between existing research and our contribution. The general model is presented in Section 'The path-based hazmat model'. In Section 'Case study', a case study in Shanghai is described together with a very efficient solution algorithm. Finally, Section 'Conclusions' presents the conclusion of the research.

Previous work

In this section, we review the existing research related to hazmat transportation risk assessment and routing optimization.

Hazmat transportation risk has been a popular research area (Alp, 1995; Chakrabarti and Parikh, 2011a, 2011b; Erkut and Verter, 1998; Kara et al., 2003; Van Raemdonck et al., 2013). Erkut and Verter (1998) explored different models of risk. Kara et al. (2003) then developed the accurate assessment risk approach which deals with link impedances that are path-dependent. Zhang et al. (2000) considered the risks imposed on populations by airborne contaminants using a Gaussian Plume model. Previous research treats the hazmat transportation risk as a measure of the probability and severity of harm to an exposed receptor due to potential undesired events involving hazmat transportation. The risk of hazmat transportation can be divided into two parts: (1) the probability of the occurrence of an accident and (2) the consequences of an accident if it has occurred (Alp, 1995; Van Raemdonck et al., 2013). Reniers et al. (2010) developed a risk assessment methodology for moving hazardous materials. They divided routes into smaller segments with multi-criteria analysis and likelihood scores of accidents in which hazmat vehicles were involved that caused fatalities. The consequences of an accident were computed according to the population exposed. However, they focused on several transport modes.

Many of the studies of hazmat transportation have focused primarily on routing optimization to balance risk and cost. For a review on this topic, we refer to the previous work of (Batta and Chiu, 1988; Erkut and Alp, 2007a; Erkut and Gzara, 2008; List and Mirchandani, 1991; Zhang et al., 2000). Gopalan et al. (1990) presented an integer programming model to minimize the total transportation risk and to balance the risks among the geographical regions with a single-trip case. Beroggi and Wallace (1995) assessed the risks and costs of four alternative models when a real time event occurs in the process of transportation. Kara and Verter (2004) proposed a bi-level programming function to design a hazmat transport network based on a link-based approach. The regulator's decision is the outer problem and the carrier's selection is the inner problem. Chang et al. (2005) developed an algorithm to find the shortest expected transfer time paths. Erkut and Ingolfsson (2000) established three risk-averse models to analyze the low probability but high consequence events in Hazmat transportation. These models reduce to optimal routing problems which do not pay attention to the regulations. Based on the shortest path algorithm, Bell (2006) developed a shared shipment to reduce the transport risks. Marcotte et al. (2009) used tolls to deter the hazmat transportation instead of road segment design. They presented a single-level mixed-integer programming formulation to solve the problem effectively. List and Mirchandani (1991) jointly analyzed the risk, cost, and risk equity by addressing a multi-objective framework. Verter and Kara (2008) jointly considered the transportation risk and shipment cost. They proposed a model to analyze the problem, followed by two case studies in the USA and Canada, respectively. The majority of this stream of research focuses on minimizing the total risk and cost (Erkut and Gzara, 2008; Glickman et al., 2007; Zografos and Androutsopoulos, 2004). Androutsopoulos and Zografos (2010) developed a bi-objective mathematical formulation of the routing of hazardous materials for the different case of less-than truckload distribution. A weighted sum method is