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Equity and social acceptability in multiple hazardous materials routing through urban areas

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ABSTRACT

In this article we study the problem of routing hazardous materials (hazmat) form an origin to a destination on an urban transportation network in which the arcs lay on irregular zones with different population densities. Hazmat are transported on a regular basis instead of a single shipment. In addition, different types of hazmat, posing different levels of risk, must be transported at the same time. We developed a methodology to incorporate the concept of equity in the spatial distribution of risk when multiple types of hazmat must be distributed along various simultaneous routes including not only the risk added by the transportation process but also other baseline risks from exogenous sources. The article describes the development of a multi-product multi-shipment hazmat routing model with equity constraints, departing from a theoretically rich single product single shipment hazmat routing model found in the literature, aimed to minimize the conditional expectation of the consequence of a catastrophic accident. The resultant modeling approach is a linear fractional programming model that incorporates a flexible set of linear constraints that allow a fair distribution of risk among populated zones, restricting the total level of risk below a socially acceptable threshold. We applied this modeling framework to two hypothetical examples and to an actual case in Santiago, Chile (a large capital city with over 6 million inhabitants) showing to be both mathematically tractable and useful for decision makers in practice.

1. Introduction

The transportation of potentially harmful products has attracted the attention of scientists, authorities and general public from a long time ago. However, recent events, such as the urban densification and homeland security threats have brought this topic to a new level of awareness imposing an urgent pressure over all the relevant actors to guarantee a safe and fair transportation of these products while at the same time keeping it cost at a minimum. The topic of hazardous materials (hazmat) routing has been extensively treated in the specialized literature; however, the main focus has been the transportation of one type of merchandise from an origin to a destination through an optimal route. The latter approach produces a socially beneficial solution only when a single shipment is to be sent. However, if the optimal route were used on a periodical basis, people living in the surrounding areas would become more exposed to the risks than the rest of the population, even though

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the total social risk may be at a minimum level. Then, the issue of social justice or equity on the risks bore by different segments of the population become an important part of the routing problem, as a new restriction: to guarantee that none of the population segments are exposed to a risk higher than a given threshold. The problem becomes more complex as more than one hazmat is being transported on a network because different products impose different risks on the population and the *total risk* will be a compounded effect. Thus, the problem to be solved in this article is that of finding a set of routes in a transportation network, that allow the movement of several types of hazmat on a regular periodic basis, without exposing any part of the population to a risk level higher than a predefined threshold.

This paper is organized as follows. In Section 2 various contemporary issues regarding hazmat transportation in the social context are presented. The corresponding literature is presented in Section 3. Section 4 defines some key concepts to be used in the modeling. Section 5 presents a Multi-Product Multi-Shipments Hazmat Routing Problem (along with a numerical example) which is improved in Section 6 by adding the equity dimension. Section 6 also incorporates a numerical example as well as the public policy aspects of the developed modeling framework. Section 7 presents a case study for a real life scenario. Finally, Section 8 presents the conclusions.

2. Key issues for routing hazmat under social constraints

The main safety concerns for hazmat transportation are accidents that cause multiple fatalities. That scenario typically occurs when a vehicle transporting hazmat, gets involved in an accident spilling out its material over densely populated areas. Accordingly, one of the main goals in the route choice process is to reduce the probability of an accident with fatalities. However, this is not the only objective to pursue, especially when multiple shipments of different hazmat take place over a highly populated area. In this context, parts of the population might be exposed to a variety of risks depending on the properties of the hazmat to be transported. Therefore, reducing the total risk as well as the consequence after an accident seems to be more appropriate.

Nowadays, society recognizes the fact that hazmat must be transported through populated areas when no other option is available. However, authorities are responsible not only for minimizing the population risk but also to guarantee that the risk be fairly distributed among the population. This aspect implies avoiding that any population group is subjected to a level of risk significantly higher than the rest, i.e., the risk imposed on the society should be distributed with equity. For example, if a single route has been identified as the one that optimizes a certain combination of the objectives mentioned in the previous section, using this route on a daily basis would result in an optimal allocation of risk for the whole population but at the same time it would unfairly increase the risk (by repeated exposure) to the population in the surrounding areas. The latter effect may take place regardless of the type of objective function or the inclusion of time-dependence or stochasticity in the optimized score. To reach an equitable risk distribution among the population and at the same time minimizing the total risk exposure, other routing options should be explored to avoid imposing inacceptable levels of risk (as an absolute value) as well as avoiding high differences in risk exposure to the population surrounding the chosen routes. Accordingly, in this paper the main goals are to develop a model to assist the choice of a set of routes that minimize the risk of catastrophic events (i.e. with low probability high consequence), incorporating equity concerns in such a way that the total exposure to risk (not only associated to hazmat transportation) on every populated zone is under acceptable levels. The fact that we deal with catastrophic events will define the type of objective function to be optimized. Considering equity in the risk distribution implies that instead of a single shipment, a rate of shipments per time unit must be analyzed as well as the diversity of substances being transported. These conditions impose additional demands on the modeling framework in order to make it a useful tool for public policy.

3. Literature review

During the last thirty years there has been a considerable amount of research on hazardous materials logistics. Indeed, since the early special issue on Risk Analysis published by the journal Management Science in 1984 (Vol. 30, No. 4) there has been an active research agenda in this field. Erkut et al. (2007) classify the articles in this area according to the following groups: risk assessment, routing, combined facility location and routing, and network design. Within the routing literature, most of the articles dealing with hazmat transportation focus on minimizing risk or cost, which are often the main objectives in modeling the routing problem (see for example Batta and Chiu, 1988; List and Mirchandani, 1991; Erkut and Verter, 1998; Glickman, 1991; Jin and Batta, 1997). The relevant literature presents also a myriad of objectives to be optimized; e.g. expected risk, exposed population, probability of an incident, conditional expectation of the consequence, etc. In many articles, the routing problem is viewed as that of optimizing some of these multiple objectives (Abkowitz and Cheng, 1988; Glickman, 1991; Jin et al., 1996 and Kara et al., 2003); in some cases the objectives include dynamic or stochastic properties. That is the case of Akgun et al. (2007), who defined time-dependent attributes as a function of weather conditions. Miller-Hooks and Mahmassani (1998) presented various procedures for determining optimal paths for hazmat routing in stochastic, time-varying networks. Chung et al. (2005) presented a method for finding non-dominated routes for multiple objectives in networks with stochastic attributes. Also Desai and Lim (2013) designed a stochastic dynamic programming approach to solve the problem of determining the optimal routing policies in a stochastic dynamic network. Research has evolved from a somewhat naïve approach (based on expected cost) to a more sophisticated compound score in the objective function. For

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