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Hazmat facility location and routing analysis with explicit consideration of equity using the Gini coefficient

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ABSTRACT

This paper develops a model to analyze facility location and routing decisions in the context of hazardous materials transportation. A novel aspect of this model is the explicit consideration of equity using the Gini coefficient, an established computation to evaluate equity. To solve the model, we develop a method that combines Lagrangean relaxation with column generation and illustrate that method using a realistic case study. We present a case study of hazardous material railway transportation with consideration of social horizontal equity categorizing the population by household income.

1. Introduction

Hazardous materials (hazmat) are those materials that pose a substantial threat to the public and the environment. Hazmat handling and transport have historically resulted in small numbers of incidents and accidents. However, the hazmat transportation and facility location problems are important to consider because when accidents happen, the consequences can be significant. Furthermore, there is evidence that these accidents can affect populations that are not receiving a proportional share of the benefits from these activities or fair compensation for the risks, or that the risks falls disproportionately on marginalized groups in society.

Numerous studies have developed methodologies to assess the risk from hazmat transport by train and trucks. Verter and Kara (2001) presented a GIS-based methodology for assessing hazardous materials transport risk. This methodology considers the hazmat specific risk, population density distribution, and network topology. The study showed that it is not possible to make general conclusions of trade-offs between hazmat routing criteria. Therefore, the methodology presented a good framework to assess the risk of hazmat transport. Fabiano et al. (2002) developed a framework for risk assessment of highway hazmat transport. They considered network configuration, the distribution of population exposed, and traffic conditions including the presence of dangerous goods. The model includes the risk for regular traffic accidents and accidents from dangerous goods transport. Anderson and Barkan (2004) estimated railroad accident rates using train accident data from a ten year period. Gheorghe et al. (2005) developed a robust approach to estimate railway traffic risk that incorporates the frequency of release of hazardous substances from loss of containment accidents, consequences of accidents, and giving special attention to segments with higher risk, such as tunnels. Verma and Verter (2007) presented a risk assessment

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framework for railroad hazmat transport that focused on airborne risks. This model includes concentration level for hazmats and weather conditions, which can be integrated to better represent the variability of the risk from exposed population as a function of the distance to the rail line. It also considers the distribution of railcars, such as number of cars and their locations, to establish the accident risk. Verma (2011) presented a risk assessment methodology for hazmat derail risk when train length is considered. Verma et al. (2011) incorporated the risk assessment framework developed by Verma and Verter (2007) to railroad companies tactical planning. This model can incorporate the risk variability derived from the number of railcars in the same train.

There is extensive work on facility location and routing for hazmat. For a thorough review, see Das et al. (2012). ReVelle et al. (1991) formulated the facility location problem as a minimization of transportation burden (ton-miles) and perceived risk (tons-past people). They used a blend of shortest path methods and location methods to provide solutions to the multi-objective programing problem. Stowers and Palekar (1993) innovated by not restricting the potential facilities to previously identified locations. Jacobs and Warmerdam (1994) developed a linear flow model driven by cost and risk to analyze the facility siting problem, and studied the trade-off between hazardous-waste transport, storage, and disposal cost and risk. Nema and Gupta (1999) considered in their routing-facility model the type of waste and the technology for its treatment. Their model minimizes treatment, disposal, and transportation costs, and risk. They applied their model to a network with 16 nodes with 6 nodes being generators of waste, 2 nodes as potential disposal sites, and the remaining 6 nodes are intermediate nodes. Alumur and Kara (2005) addressed the facility location, treatment center technology selection, and routing selection of waste residues. Dadkar et al. (2008) developed a *K*-shortest path algorithm to identify a large set of routes to be used as potential hazmat transportation routes. This large set is used as input for a mixed-integer problem that identifies a subset of routes balancing the quality of the worst path and geographical diversity on the routes. Berglund and Kwon (2013) formulated the location-routing problem as a bi-level optimization in which the upper level is the minimization of facility construction cost, transportation cost, and component's risk. The lower level defines the uncertainty in the risk associated to the number of trucks required for a given shipment and the exposure risk of each arc. The problem is converted into a single level problem by replacing the inner maximization problem with its dual. For large-scale problems, the authors used a genetic algorithm. Boyer et al. (2013) built a more comprehensive multi-objective planning model including treatment and storage.

Some of this previous work also incorporates concepts of equity. For a review of equity measurements in site location analysis, see Marsh and Schilling (1994). Gopalan et al. (1990) developed a model for hazmat transport from a single origin to a single destination that minimizes total travel risk and spreads the risk equitably. Equitability is represented by guaranteeing that two geographical zones do not have a difference in risk greater than a defined threshold. Lindner-Dutton Lindner-Dutton et al. (1991) proposed an equitable solution to the sequencing problem of hazmat transportation between an origin and a destination. List and Mirchandani (1991) minimized risk and total costs to choose the best facility locations and associated routing. The authors incorporated equity by including the maximum level of risk impact per unit of population of all zones as a third objective of the minimization problem. They illustrated their method via a case study of the highway system around Albany, with 124 links and 86 nodes. Current and Ratick (1995) proposed a model to minimize transportation and storage risk considering them proportional to the exposed population. They also represented equity by minimizing the maximum total transportation exposure or exposure derived from stored material to all individuals. Giannikos (1998) proposed a multi-objective model to optimize: operating cost, perceived risk, maximum individually perceived risk, and the equitable distribution of the disutility caused by the operation of the treatment facilities. The authors used goal programing to solve the problem and tested their method with a hypothetical problem with 13 population centers, three of which generate hazardous waste, and five candidate locations. Carotenuto et al. (2007) focused on the problem of minimizing risk in hazmat transportation and spreading the risk equitably by constraining the maximum risk sustained by the population living near the network. They consider incident consequence by distance from the accident; hence accidents not only affect the population in the vicinity of the accident but in other links, with consequences decreasing with distance.

Conclusions of a number of studies as to whether hazmat facilities are equitably located among population groups are inconsistent. Davidson and Anderton (2000) analyzed population distribution in Resource Conservation and Recovery Act governed sites and their vicinities. They divided the population near these sites by ethnicity, and income among other attributes. Overall, their results do not suggest there are important environmental inequalities in this specific class of facilities. Atlas (2001) focused on evaluating the environmental equity of waste treatment, storage, and disposal facilities (TSDFs). He not only considered the nature of each hazardous risk but also the possible exposure paths to the TSDFs, the procedures designed to minimized that risk, and TSDFs safety records. Atlas (2001) found that "there was no pattern of the TSDFs or the risks that they posed being inequitably concentrated in disproportionately minority or low-income areas." Hamilton (2003) does an extensive review of the literature related to equity in hazmat facility locations. He lists the different definitions involved in describing hazmat risk, the material, facility type, and demographic group. For example with respect to the facility, researchers consider the plants that generate the material, or those that treat, store or dispose. The risks considered include dispersion of air emissions, the likelihood of water contamination and population ingestion. Hamilton (2003) provides references that have shown that minority groups are disproportionately exposed to Superfund sites, and that renters, individuals with fewer years of schooling, and people with income below the poverty line are more highly exposed to emissions from toxic facilities.

Origins and destinations of hazmats are surrounded by communities that receive some benefit or compensation for the hazmat but communities in the vicinity of hazmat routes do not necessarily share the same opportunity to receive benefits; therefore, considering community exposure equity in the transportation of hazmat may be even more important. Margai