A Risk Averse Routing and Location Model for Hazardous Material Transportation

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Abstract–* *Risks associated with the transportation of hazardous materials (hazmats) and the location of hazmat facilities, are sometimes overlooked due in part to the small probability that an accident occurs during shipment. But when considering the catastrophic effects of an accidental release of a hazmat (nuclear fuel, radioactive materials, gasoline, toxic gases, medical waste, flammable materials, among others), appropriate locations and routing planning for reliable shipping are greatly desirable, instead of models that favor closeness or speed. This paper considers a single facility location and routing model for minimizing the expected number of hazardous material transport accidents. A risk adverse approach is used where users are concerned with the capability to establish safe routes to some service provider.

Keywords-- Hazmats Logistics, Network Reliability, Reliable 1-center, Location Theory

I. INTRODUCTION

This paper considers and integrated location and routing model for minimizing the expected number of hazmats shipping accidents. The problem of locating single hazmat storage/processing facility on a transportation network is solved by considering safest trucking routes, i.e., a pre-determined set of paths that minimize the expected number of accidents over a planning horizon. The problem finds application in hazardous materials logistics and provides with the most reliable location and route planning on a transportation network so that the effect of the worst case scenario is minimized. The objective function minimizes the maximum expected number of hazmat accidents with respect to all nodes over a planning horizon.

The problem presented in this paper is a modification of the *reliable* 1-*median* presented in [1], where the average performance is optimized by minimizing the total number of expected hazmats accidents. The model presented in this paper uses the same pre-designated route selection policy, but instead of optimizing the average performance, it minimizes the effect of the worst performance, i.e., center approach. This paper presents a model similar to the *reli-minmax* problem presented in [2], but uses the *k*-shortest path policy instead of the most reliable route policy. The model presented in this paper is considers node locations, which is a relaxation of the more general model presented in [3], where locations are not restricted to nodes.

II. GENERAL NOTATION AND ASSUMPTIONS

The transportation network is described by a connected, undirected graph $G(V,E)$, where $V = \{1, 2, \ldots, n\}$ is the node set and $E = \{e = (i,h): i,h \in V\}$ is the edge (link) set, with $|E| = m$. Hazmat transports are assumed to originate at the nodes. Associated with any node $j \in V$, there is a non-negative attribute w_j representing the frequency of hazmat shipments requested by node j. Associated with each edge $e \in E$ are two attributes. The first attribute is the edge length, $d_e > 0$. The edge length may also be viewed as the time it takes to traverse edge e or the cost per unit of demand traversing the edge. The second attribute, the accident rate λ_e, represents the average number of accidents per unit length. It is assumed that accidents occur at random and are unrecoverable. Let $0 \leq q_e \leq 1$ be the probability that an accident occurs on edge e during traversal. The probability that an accident does not occur during traversal, termed operational probability, is denoted by $p_e = 1 - q_e$, and is modeled following [1] and [4] as $p_e = e^{-\lambda_e d_e}$. The underlying assumption in these two papers is that accidents occur on the edges of the network according to the Poisson Process. The longer the edge length (or physical displacement from a node), the higher the probability that an accident occurs, i.e., the lower the operational probability is. The Poisson model also allows calculating the operational probabilities of the edges of the network based on their lengths and accident rates.

Let $\Phi_{jk} = \left\{P_{jk}^1, P_{jk}^2, P_{jk}^3, \ldots, P_{jk}^{r_{kj}}\right\}$ be the set of all r_{jk} feasible paths from node j to a facility located at $k \in G$. Let $P_{jk}^l \in \Phi_{jk}$, $l = 1, \ldots, r_{jk},$ be a subset of edges from E (including the newly created edges in case k is not a node) that represents a path from k to j in $G(V,E)$. For every path P_{jk}^l, let $A(P_{jk}^l)$ be the event that an accident occurs while traveling along the path, and $\bar{A}(P_{jk}^l)$, the event that an accident does not occur on that path. Assuming that accidents occur independently and are unrecoverable, the *Path Reliability* from j to k along path P_{jk}^l can be expressed as $R_{jk}^l = P\{\bar{A}(P_{jk}^l)\} = \prod_{e \in P_{jk}^l} p_e$. Reference [5] showed that the path reliability measure R_{jk}^l associated with path P_{jk}^l satisfies certain properties that are analogous but different to the properties of the traditional (distance) path. It follows that the probability that an accident occurs while traveling path P_{jk}^l is $(1 - R_{jk}^l)$.

III. SAFEST ROUTING AND RELIABLE LOCATION

A hazmat transport originating at node j requires that a truck travels from the service facility located at $k \in G$ to node j along some path in the network. Location of point k can be at any node of the network. The path selection policy is designed to find paths with shortest distances between the facility and the demand nodes. While moving along the network, we may need to know a small set of paths so that, in case a link is not operational, an alternative path may be used.

The *r* shortest paths policy finds a small set of shortest paths between any pair of points in the network, which defines a set of routes from each demand node $j \in V$ to facility $k \in G$. Polynomial time algorithms for finding the *r* shortest paths between two nodes of a network exist. See for example the algorithm developed by [6]. Let $\Phi_{jk}^r \subset \Phi_{jk}$ be the set of the *r* shortest paths joining *j* and *k*, where $|\Phi_{jk}^r| = r$. Let D_{jk}^l be the length of path $P_{jk}^l \in \Phi_{jk}^r$. Let's assume that the elements in set Φ_{jk}^r are ordered by path lengths in ascending order. Then it follows that $D_{jk}^1 \leq D_{jk}^2 \leq \cdots D_{jk}^r$. The probability associated with selecting a given path is a decreasing function of the path length. A realistic function for the path selection probability (Helander and Melachrinoudis, 1997), is defined as 1 if $r = 1$, and for $r \neq 1$:

$$P(S_{kj}^l) = \left(1 - \frac{D_{kj}^l}{\sum_{l=1}^r D_{kj}^l}\right)\frac{1}{r-1} \tag{1}$$

Let S_{jk}^l be the event that path $P_{jk}^l \in \Phi_{jk}^r$, $l = 1, \ldots r$, is selected for any trip $t = 1, \ldots, w_j$. The probability that an accident occurs when traveling from node *j* to facility *k* to on trip *t* given selection probabilities $P(S_{kj}^l)$, $l = 1, \ldots, r$ is

$$\sum_{l=1}^{r} P\{A(P_{jk}^l)\} P(S_{jk}^l) = \sum_{l=1}^{r} (1 - R_{jk}^l)\, P(S_{jk}^l) \tag{2}$$

III. Minimizing expected number of accidents: center approach

Let the Bernoulli random variable X_{jk}^t represent whether or not an accident occurs while traveling from node *j* to facility $k \in V$, where $X_{jk}^t = 1$ if an accident occurs on trip $t = 1, \ldots, w_j$ from *j* to *k*, $X_{jk}^t = 0$, otherwise. Under the *r*-shortest paths policy the parameter associated with the probability that an accident occurs when traveling from node *j* to facility *k* to on trip *t* is $P\{X_{jk}^t = 1\}$, depicted in (2). Let M_{jk} be the number of accidents when traversing from node *j* to facility *k*. The expected number of accidents when traversing from node *j* to facility *k* is:

$$E[M_{jk}] = \sum_{t=1}^{w_j}\sum_{l=1}^{r}(1 - R_{jk}^l)P(S_{jk}^l) = w_j\left(1 - \sum_{l=1}^{r} R_{jk}^l P(S_{jk}^l)\right) \tag{3}$$

Notice that $\sum_{l=1}^r P(S_{jk}^l) = 1$. A center approach for network performance and a Poisson process for disruption characterization, presented by [7], is used in this paper to find location $k \in V$ that maximizes the lowest performance of the network. A risk aversion approach is used where the maximum expected number of accidents, $E[M_{jk}]$, is minimized, or

$$min_{k \in V}\{max_{j \in V}\ E[M_{jk}]\} \tag{4}$$

IV. Solution Procedure

In this section a simple procedure is presented to find the location of node $k \in V$ that optimizes (4).

Procedure 1

Step 1: Use the algorithm proposed by [6] to find all reliabilities R_{ij}^r for all pairs $(i, j) \in V \times V$.

Step 2: For every node $k \in V$ find $F(k) = max_{j \in V} E[M_{jk}] = E[M_{ji}]$.

Step 3: Find $min_{k \in V} F(k) = F(k^*)$. The optimal location is node *k**.

V. Conclusions

Since due to incremental costs most practitioners hesitate to implement center approaches, a multi objective model can be easily implemented by adding an average performance model. The Pareto optimal solution could provide more cost efficient alternatives.

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