Finding Spatial Dissimilar Paths for HazMat Shipments*

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1 Introduction

The transportation of hazardous materials (hazmat shipment) covers a large part of the economic activities of the industrialized societies. In recent years, there has been increased public and governmental interest regarding hazmat management as the production of such materials is increased. Unfortunately, most hazardous materials are not used at their point of production, and they are transported over considerable distances. What differentiates hazmat shipments from the transportation of other materials is the risk associated with an accidental release of the hazardous materials during transportation. To such a respect, one of the main objective of the research is to provide appropriate answers to safety management associated to dangerous goods shipments, acting of concert with the principal actors of the goods movement and transport process.

The research in this area involves two main different issues. The former issue is related to risk assessment due to traversing the various segments of the routes, and a latter one concerns the selection of the safest and most economic routes to follow. A lot of work in the risk assessment has already been done, by modeling risk probability distribution over given areas, for example, taking the risk related to the carried substance and the transport modality (Abkovitz et al., 1984) and the environmental conditions (Patel et al., 1994) into account. There are several excellent review articles which address the literature related to modeling of risk for hazmat transportation; however, there is no universally definition of risk. In this work we refer to the

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traditional definition of risk over a link, that is the societal risk defined as the product of the population along the link within the neighborhood and the probability of an accident on that link (e.g., see Erkut et al., 1998).

The main problem related to the latter issue is that of finding optimal routes, while limiting and equitably spreading the risk in any zone. Optimal routes for hazardous material transportation should present a compromise between the (operational) transportation cost (for the company or the organization that wants to ship the hazardous material) and the societal cost (the potential risk cost to the society). As a matter of fact, these two factors usually conflict with each other. The goal of the analysis of hazmat routing is to find optimal routes that balances the two criteria. As a matter of fact, risk equity has to be taken into account whenever it is necessary to carry out several hazmat shipments from a given origin to a given destination. In this situation, the planning effort has to be devoted to distribute risk uniformly among all the zones of the geographical crossed region. This concept is well defined by Keeney in (Keeney, 1980), where a measure of the collective risk is determined with explicit reference to the equity.

The concept of dissimilar paths has also been considered in order to guarantee an equitable spread of risk (Akgün et al., 2000). To such a respect, different methods have been proposed in the literature, also in different contexts from the hazmat shipment, for generating a number of spatially dissimilar paths (e.g., see Akgün et al., 2000; Lombard et al., 1993; Kuby et al., 1997; Erkut, 1990; Carotenuto et al., 2003). Nevertheless, from the literature, it seems that the problem of spreading the risk equitably among the zones of the geographical region in which the transportation network is embedded currently needs further attention. This is originated, for example, by the case in which two selected paths with very few common links (and hence highly dissimilar) are geographically very close, such that the intersection of the two exposure zones around the paths is not negligible. This means that the population inside the intersection of the two exposure zones is influenced by the risk of both paths, implying a low degree of risk equity. To cope with this problem, Akgün, Erkut and Batta (2000) introduced a different definition of similarity based on the concept of buffer zone around a path, that allows to consider similar also paths that do not have common links but whose buffer zones are not disjoint.

In our approach, besides aiming to minimize both transportation cost and societal risk, we try to address risk equity, by taking into account the risk induced by a selected path also on populated links in the neighborhood of the path; that is, we take into account the risk coming from incident effect propagation. In particular, on the basis of a new definition of path similarity, we try to guarantee an equitable risk spreading by searching for paths fulfilling a certain threshold level of dissimilarity. We provide a mathematical formulation for the proposed model, and some heuristic algorithms, that are experimentally evaluated on an Italian geographical region.

2 Problem formulation and solution approach

The problem we consider is to find a set of routes for hazmat shipments from a given origin to a given destination over a road transportation network. In this context, the aim is to determine a set of routes that minimize the societal risk and transportation cost simultaneously, while spreading the risk equitably over the geographical region in which the transportation network is embedded.

The transportation network of the regional area under consideration is represented as a direct graph $G = (N, A)$, with N and A being the set of n nodes, and the set of m direct links of the network, respectively. Each link $h \in A$, according to a given level of data aggregation of the transportation network, corresponds to a road segment of the transportation network, and each node $i \in N$ corresponds to a road crossing.

In the following, w.l.o.g., we assume the population being located in the neighborhood of the links of the network, and, hence, we consider a (populated) zone for each link (i.e., populated links).

We consider the possible consequence of an incident happening on a link not only being restricted over the population living around that link, but also affecting population of a larger impacted zone that may include various other links. That is, an incident on a link may impact not only the population residing nearby that link, but also inhabitants living in the proximity of other links. In other words, the extension of the impacted zone may interest also populated links that are close to the link where the incident occurs. Clearly, the entity of the effect of the incident decreases with the distance from the point where the incident happens. As a consequence, the risk on the population living around another close link decreases with the distance between this link and the link that suffers the incident.

We consider that a hazmat vehicle traveling along a link $h \in A$ induces a certain (societal) risk $s_{h\ell} = prob_h^{inc} \times pop_\ell \times e^{-\alpha[d(h,\ell)]^2}$, where $prob_h^{inc}$ is the probability of an incident occurring to an hazmat vehicle on link h, pop_ℓ is the population living around (populated) link ℓ, and $d(h, \ell)$ is the (Euclidean) distance between the links. The last factor in the expression for $s_{h\ell}$ weights the consequence of the incident as a function of the distance, where α is the impact factor depending on the hazardous material under consideration. Accordingly, let $r_h = \sum_{\ell \in A} s_{h\ell}$ be the (total) risk induced over the population of the regional area where the transportation network is embedded.

In the following we consider only shipments between a given origin-destination pair. Therefore, on the given network G, let be given an origin $o \in N$ and a destination $d \in N$, and let P be the set of simple paths in G from origin o to destination d. For each path $j \in P$, let R_j be the risk incurred by the population due to a hazmat shipment on path j, and C_j be the (transportation) cost of path j. Denoting with $A_j \subseteq A$ the set of links of the path $j \in P$, let $R_j = \sum_{h \in A_j} r_h$, and $C_j = \sum_{h \in A_j} c_h$, where c_h is the (hazmat) transportation cost for traveling on link h.

To ensure the selection of a set of paths that also guarantee an equitable spread of the risk over the population, we introduce a new similarity index that generalizes the one given by Erkut et al., (1998), and require that the selected paths mutually satisfy a given dissimilarity threshold constraint. The spatial similarity index SI, we consider, is based on the following definition of similarity index between two paths p_q and p_r, allowing to consider in some sense similar also paths that are very close. The similarity index $S(p_q, p_r)$ of two paths p_q and p_r is defined as follows, and it depends on the (Euclidean) distance between the paths:

$$S(p_q, p_r) = \frac{1}{2}\left(\frac{\sum\limits_{h \in A_{p_q}} len_h \; e^{-\alpha\left(\min\limits_{\ell \in A_{p_r}} \{d(h,\ell)\}\right)^2}}{\sum\limits_{h \in A_{p_q}} len_h} + \frac{\sum\limits_{\ell \in A_{p_r}} len_\ell \; e^{-\alpha\left(\min\limits_{h \in A_{p_q}} \{d(\ell,h)\}\right)^2}}{\sum\limits_{\ell \in A_{p_r}} len_\ell} \right)$$

Hence, in our definition of $S(p_q, p_r)$, we do not consider the similarity of two paths only taking the length of common links into account, but we consider quasi-similar also paths that are not too far from each other, even if they have no link in common. The impact factor α allows to weight the similarity with respect to the distance between two links, according to the hazardous material under consideration. Note that for α that tends to infinity, in $S(p_q, p_r)$ only the lengths of the common links are considered, and, hence, we have the same definition given by Erkut et al., (1998).

The optimization problem we consider is therefore finding a set P^* of k distinct simple paths on the network $G = (N, A)$, from the origin $o \in N$ to the destination $d \in N$, so as to minimize the total risk and transportation cost of the paths, meanwhile satisfying the spatial dissimilarity threshold constraints. Let us introduce a binary variable x_j, such that x_j is equal to 1 if and only if path $j \in P^*$, and 0 otherwise. Then, the problem can be formulated as follows:

$$\begin{aligned} \min \quad z_1 &= \sum_{j \in P} R_j x_j \\ z_2 &= \sum_{j \in P} C_j x_j \end{aligned} \tag{1}$$

subject to

$$1 - S(p_q, p_r) \geq \rho \qquad \forall\, p_q, p_r \in P^* \tag{2}$$

$$\sum_{j \in P} x_j = k \tag{3}$$

$$x_j \in \{0, 1\} \qquad \forall\, j \in P \tag{4}$$

with $\rho \in [0, 1]$ being a given minimum allowed (threshold) level of the spatial dissimilarity. Constraints (2) impose that, for each pair of path $p_q, p_r \in P^*$, the spatial dissimilarity is not less than ρ. Constraint (3) imposes that the number of paths in the solution has to be equal to k.

The solution approach that has been used for the bi-objective problem is the weighting method. The weighting method specifies a set of non-dominated solutions by solving the integer-programming model which is defined by the constraint set of the original problem and an objective function defined by

$$\min \quad z = (w_1 \sum_{j \in P} R_j x_j + w_2 \sum_{j \in P} C_j x_j) \tag{5}$$

$$\sum_{i=1}^{2} w_i = 1 \quad \text{and} \quad w_i \in [0,1] \tag{6}$$

The transformation of the bi-objective problem into a set of single objective problem through the weighting method justifies the use of a fast and efficient heuristic algorithm for approximating the efficient frontier of the problem.

We propose some heuristic algorithms all based on the Yen's algorithm for the k-shortest path problem (Yen et al., 1971; Martins et al., 2001). They are, in practice, constrained k-shortest path algorithms, in order to take in due consideration risk propagation coming from nearby paths and to equitably spread the risk among zones of the geographical region in which the transportation network is embedded.

References

M. Abkovitz, M. Eiger and S. Srinivasan, "Estimating the release rates and costs of transporting hazardous waste", *Transp. Res. Record* 977, 22-30 (1984).

V. Akgün, E. Erkut and R. Batta, "On finding dissimilar paths", *Eur. J. of Oper. Res.* 121, 232-246 (2000).

P. Carotenuto, S. Giordani, and S. Ricciardelli, "Finding minimum and equitable risk routes for hazmat shipments", manuscript (2003).

E. Erkut, "The discrete p-dispersion problem", *Eur. J. of Oper. Res.* 46, 48-60 (1990).

E. Erkut and V. Verter, "Modeling of transport risk for hazardous materials", *Oper. Res.* 46, 625-642 (1998).

R.L. Keeney, "Equity and Public Risk", *Oper. Res.* 28, 527-534 (1980).

M. Kuby, X. Zhongyi and X. Xiaodong, "A minimax method for finding the k best differentiated paths", *Geogr. Analysis* 29, 315-329 (1997).

K. Lombard and R. L. Church, "The gateway shortest path problem: generating alternative routes for a corridor location problem", *Geogr. Sys.* 1, 25-45 (1993).

E. Martins and M. Pascoal, "A new implementation of Yen's ranking loopless paths algorithm", *Optimization 2001*, Aveiro, (2001).

M. H. Patel and A. J. Horowitz, "Optimal routing of hazardous materials considering risk of spill", *Transp. Res.* 28A, 119-132 (1994).

J.Y. Yen, "Finding the K Shortest Loopless Paths in a Network", *Manag. Sci.* 17, 712-716 (1971).

K. G. Zografos and K. N. Androutsopoulos, "A heuristic algorithm for solving hazardous material distribution problems", *Eur. J. of Oper. Res.* 152, 507-519 (2004).