

A Path-Based Approach for Hazmat Transport Network Design

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The people living and working around the roads used for hazardous material (hazmat) shipments face the risk of suffering undesirable consequences of an accident. The main responsibility to mitigate the hazmat transport risk at a population zone belongs to the government agency with jurisdiction over that region. One of the common policy tools is to close certain road links to vehicles carrying hazmats. In effect, the road network available to dangerous goods carriers can be determined by the regulator. The transport risk in the region, however, is determined by the carriers' routing decisions over the available road network. Thus, the regulator needs to make the road closure decisions so that the total risk resulting from the carriers' route choices is minimized. We provide a path-based formulation for this network design problem. Alternative solutions can be generated by varying the routing options included in the model for each shipment. Each solution corresponds to a certain compromise between the two parties in terms of transport risk and economic viability. The proposed framework can be used for identifying mutually agreeable hazmat transport policies. We present two applications of the methodology to illustrate the insights that can be gained through its use: The first application focuses on hazmat shipments through the highway network of Western Ontario, Canada, whereas the second application studies the problem in a much larger geographical region that covers the provinces of Ontario and Quebec.

Key words: hazardous materials; transportation; network design; geographical information systems

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1. Introduction

The transportation industry has been mostly deregulated. A notable exception is transportation of hazardous materials (hazmats), mainly due to the associated public and environmental risks. Flammables, explosives, poisonous and infectious substances, radioactive materials, and hazardous wastes are common examples of materials in this category. Most hazmats, such as gasoline, fuel oil, and petroleum, are an integral part of our daily lives and industrial development. The overall safety record of dangerous goods carriers is good. The U.S. Department of Transportation (2005) reports 461 serious hazmat incidents in 2004, despite the fact that the number of daily hazmat shipments far exceeded one million. Nonetheless, these accidents caused a total of 13 fatalities, 44 major and 74 minor injuries, as well as about \$38 million in damages. Nonetheless, increasing shipment volumes raises the possibility of a catastrophic event such as the 1979 train derailment in Ontario, Canada, which resulted in a chlorine leak and consequently required the evacuation of 200,000 people. A more recent example is the November 2005 collision

in Sinaloa, Mexico that involved an ammonia truck and caused 39 fatalities. Thus, mitigation of hazmat transport risk is an increasingly significant challenge and concern for many governments.

The people living and working around the roads heavily used for dangerous goods shipments incur most of the transport risk. To reduce the risk in densely populated areas, the government can ban the use of certain road segments by hazmat carriers. In effect, the road network available for the carriers' operations is determined by the regulator. Most governments do not have the authority to impose routes on hazmat carriers. Thus, transport risk is an outcome of the carriers' route choices over the available network. In this paper, we analyze the regulator's problem of identifying the road segments in an existing network that should be closed to hazmat transportation. The objective of this network design problem is to minimize transport risk in the regulator's jurisdiction without threatening the economic viability of the transportation activity. Clearly, the problem involves multiple types of dangerous goods being shipped among multiple origin-destination pairs. Note that

the union of minimum risk routes for each shipment does not constitute a solution amenable to implementation. On such a network, it is likely that shorter routes than the minimum risk route would be available for some shipments. Because the carriers would naturally use the former, the regulator would be unable to reduce transport risk to the prescribed level in practice.

Mitigation of transport risk requires the implementation of a comprehensive approach by the regulator, which would involve the simultaneous use of a variety of policy tools. For example, emergency response teams specializing in hazmat incidents can be quite effective in reducing the undesirable consequences of such events. Inspection stations can be established to monitor carriers' compliance with regulations. The government can also set certain requirements with regards to driver training, container specifications, and accident insurance. Clearly, hazardous network design belongs to a large set of means for reducing transport risk and hence, the methodology presented in this paper is intended as a building block for an integrated policy design framework.

The hazmat transport network design problem was first posed and studied in the academic literature by Kara and Verter (2004), who presented a bi-level programming formulation that identifies the minimum risk design for the road network, i.e., the regulator's ideal solution. In the context of Western Ontario, Canada, they showed that it is indeed possible to achieve significant reductions in transport risk by optimizing the road links to be made available for hazmat shipments. However, this involves significant increases in transport costs, compared to the use of minimum cost routes (i.e., the carriers' preference), which constitutes a critical sticking point for the implementation of minimum risk designs in practice. This paper is motivated by the need to identify compromise solutions between the two parties. We present an analytical framework that can help engage hazmat carriers in the network design process by determining alternative forms of compromise in terms of cost and risk. This may ease the efforts to obtain the carriers' buy-in to the resulting hazmat transport regulations and consequently reduce the expenditures of the regulator for inspecting compliance.

We provide a path-based formulation for the hazmat transport network design problem. Our main modeling construct is a set of alternative paths for each shipment. This facilitates the incorporation of carriers' cost concerns in regulator's risk-reduction decisions. The paths that are not economically viable to the carriers can be left out of the model. Alternative solutions to the network design problem can be generated by varying the routing options included in the

model for each shipment. Each solution corresponds to a certain compromise between the regulator and the carriers in terms of the associated transport risk and cost. Information about the nature of the cost-risk trade-off would facilitate healthy negotiation between the two parties. Thus, the proposed framework can be used for identifying road-closure decisions that are mutually acceptable. Previous experiences with the macro-management of hazardous materials and wastes suggest that involvement of a stakeholder (i.e., carriers) early in the policy design process is crucial for successful implementation (Read 2006).

The remainder of this paper is organized as follows. Section 2 provides an overview of the literature on hazmat transportation and points out the lack of methodologies potentially helpful to a regulator. Our mathematical model is presented in §3, and its analytical properties are discussed in §4. We implemented the proposed method for solving the hazmat transport network design problem in Western Ontario, Canada. Section 5 describes the problem instance and reports on our analysis and insights. Section 6 outlines a much larger-scale application focusing on the neighbor provinces of Quebec and Ontario and depicts the means to tackle the challenges associated with problem size. Finally, §7 provides some concluding remarks.

2. Overview of Literature

The majority of prevailing studies on hazmat transportation focuses on two related problems: (i) assessment of the transport risk associated with a shipment, and (ii) identifying the route that minimizes transport risk. Erkut and Verter (1998) point out that various definitions of risk have been proposed in the literature, and the minimum-risk route varies with the way transport risk is represented. A popular measure is the number of people living within a threshold distance from the routes used by hazmat trucks. This model was originally suggested by Batta and Chiu (1988), and it emphasizes exposure to hazmats rather than the occurrence of an incident. Revelle et al. (1991) use a weighted combination of population exposure and transportation cost in finding routes for radioactively contaminated fuel rods. Alternatively, incident probability is suggested as a risk measure by Saccomono and Chan (1985) and Abkowitz et al. (1992). This model focuses on the likelihood of having a hazmat incident during transportation and ignores the possible undesirable consequences. Consequently, it is more suitable for the hazmats with relatively small danger zones. The expected risk model provides a means to incorporate both the probability and the consequence of a hazmat incident. For example, Erkut and Verter (1995) estimate the expected

number of people that would be evacuated due to an accident involving polychlorinated biphenyl (PCB) wastes. We refer the reader to List et al. (1991) and Erkut and Verter (1995) for reviews on the early literature on dangerous goods transportation. An overwhelming majority of the papers has focused on single commodity, single origin-destination hazmat routing problems. These problems, which typically belong to a carrier, can be reduced to a shortest-path model that uses the proposed risk measure as arc impedance.

Based on the recent comprehensive review of Erkut et al. (2007), we know of only five notable exceptions to the carrier-oriented perspective of the prevailing literature. List and Mirchandani (1991) present a multicommodity formulation for routing hazmats and locating hazardous waste-treatment facilities. Their model minimizes total cost, total societal risk, and maximum risk imposed on an individual. The application of the model in Albany, New York, however, is based on a number of simplifications including point representation of population centers and consideration of a single type of hazmat. Iakovou et al. (1999) provide a multicommodity network flow model for the problem of routing hazardous vessels. Their aim is to avoid overloading certain links of the transport network, which usually happens when the optimal route for each shipment is identified independent of the other shipments. The model is applied to the transportation of crude oil and refined petroleum products in the Gulf of Mexico. Note that the U.S. Coast Guard has the authority to designate the route to be followed by the vessels between an origin-destination pair.

As mentioned earlier, Kara and Verter (2004) proposed a bi-level programming model to the problem of designing a road network for hazmat transportation. Their model constitutes a link-based formulation, where the decision variables represent the status of each road link, i.e., open or closed by the regulator, and used or unused by the carriers. In the outer problem, the regulator determines the road links that would be closed to hazmat shipments so as to minimize the transport risk. Given the regulator's decisions, the inner problem represents the carriers' route choices on the available road network for each shipment. Kara and Verter (2004) represented the inner problem by the linearized Karush-Kuhn-Tucker conditions of its linear programming (LP) relaxation. As a result, the bi-level integer programming (IP) problem is transformed into a single-level mixed-integer programming problem. The authors analyzed the implications of alternative regulatory schemes on the structure of the hazmat transport network and showed that the carriers can actually benefit from increased involvement of the regulator in transport risk management. The economic viability of the regulator's policy decisions from the perspective of the carriers, however, are not incorporated in their model.

Erkut and Gzara (2008) considered a bi-objective (cost- and risk-minimization) version of the network design problem discussed by Kara and Verter (2004). They presented a heuristic algorithm that exploits the network flow structure at both levels, instead of transforming the bi-level IP problem to a single-level formulation. As a result, they achieved a noteworthy improvement in the computational performance. On the other hand, Erkut and Alp (2007) modeled the minimum-risk hazmat network design problem as a Steiner tree selection problem. This topology takes away the carriers' freedom in route selection and reduces the bi-level problem to a single level. However, it also results in circuitous (and expensive) routes. To avoid an economically infeasible solution, the authors considered adding edges to the Steiner tree. They proposed a greedy heuristic that adds shortest paths to the tree so as to keep the risk increase to a minimum.

3. A Path-Based Model

Let $G = (V, A)$ represent the existing road network, where V is the vertex set and A is the arc set. We use *population exposure* as a measure of transport risk. This amounts to assuming that the undesirable consequences of hazmat incidents occur within a threshold distance from the accident site.¹ Consequently, only the people within the threshold distance from a road link are "exposed" to a hazmat truck passing across the link. We use the following notation in developing the model:

- I : set of population centers, indexed by i ,
- M : set of hazmat types, indexed by m , and
- C : set of shipment categories, indexed by c .

The number of people in $i \in I$ exposed to a truck carrying hazmat $m \in M$ through link $a \in A$ is denoted by ρ_{ai}^m . Each shipment category $c \in C$ is characterized by its origin $o(c) \in G$, destination $d(c) \in G$, and the type of hazmat carried $m(c) \in M$. That is, all the shipments of hazmat type $m(c)$ from $o(c)$ to the consumers at $d(c)$ are consolidated in the same group for the purposes of our model. We use s^c to represent the number of trucks used for shipment category c . For brevity, we use the term shipment in the remainder of the paper to denote the movements of a single hazmat type between an origin-destination pair. The analytical framework proposed in this paper is based on a set of alternative paths for each shipment, which we denote by P^c (indexed by k). Each path included in P^c represents an option that is acceptable to the carrier for routing $m(c)$ between $o(c)$ and $d(c)$. The paths

¹The threshold distance depends on the hazmat type being shipped.

in P^c are listed in decreasing order with respect to the carrier's preferences.² For example, if the carrier's objective is to minimize the total distance traveled, then P_1^c is the shortest path and P_k^c is the k th shortest path between $o(c)$ and $d(c)$. Note that each path is, in fact, a set of road links connecting the origin to the destination. Let N_k^c denote the number of links in path P_k^c .

The open links in the existing road network determine the paths in P^c that are available for shipment c . Given the ordering of P^c , a carrier would normally use the path with the smallest index among the available paths for shipment c . Thus, there are three sets of decision variables in the path-based model:

$$\begin{aligned} X_k^c &= 1 && \text{if path } P_k^c \text{ is used for shipment } c, 0 \text{ otherwise,} \\ Y_k^c &= 1 && \text{if path } P_k^c \text{ is available for shipment } c, \\ &&& 0 \text{ otherwise,} \\ Z_a^m &= 1 && \text{if link } a \text{ is open for transport of hazmat } m, \\ &&& 0 \text{ otherwise.} \end{aligned}$$

The regulator's link-based decisions are represented by the Z_a^m variables. The consequences of these decisions in terms of path availability are captured by the Y_k^c variables, whereas the carriers' routing decisions are represented by the X_k^c variables. The hazardous network design problem can be formulated as follows:

$$\text{minimize } \sum_{i \in I} \sum_{c \in C} \sum_{k \in P^c} \sum_{a \in P_k^c} s^c \rho_{ai}^{m(c)} X_k^c$$

$$\text{subject to } \sum_{k \in P^c} X_k^c = 1 \quad c \in C \quad (1)$$

$$X_k^c \leq Y_k^c \quad c \in C, k \in P^c \quad (2)$$

$$Y_k^c \leq Z_a^{m(c)} \quad c \in C, k \in P^c, a \in P_k^c \quad (3)$$

$$Y_k^c \geq \sum_{a \in P_k^c} Z_a^{m(c)} - N_k^c + 1 \quad c \in C, k \in P^c \quad (4)$$

$$X_k^c \geq Y_k^c - \sum_{j=1}^{k-1} Y_j^c \quad c \in C, k \in P^c \quad (5)$$

$$X_k^c, Y_k^c \in \{0, 1\} \quad c \in C, k \in P^c \quad (6)$$

$$Z_a^m \in \{0, 1\} \quad a \in A, m \in M. \quad (7)$$

The above model approaches the hazardous network design problem from the regulator's perspective and aims at minimizing the total population exposure due to the carriers' routing decisions. Note that the total population exposure is a function of the number of shipments s^c as well as the number of people in the exposure zone for each shipment $\rho_{ai}^{m(c)}$. Although the risk-mitigation efforts in practice tend to

focus on high-volume shipments, the objective function accounts for the fact that low-volume shipments of certain hazmats, such as chlorine, can expose more people to transport risk. Constraints (1) guarantee that a single path is used for each shipment. Constraints (2) ensure that a path can be used only if it is available to hazmat shipments. Constraints (3) and (4) identify the available paths in terms of the regulator's link-based decisions. Constraints (3) state that a path cannot be used for hazmat shipments if any of its links are closed by the regulator. If all of the links in a path are open, then constraints (4) ascertain that the path is available for hazmat shipments. Constraints (5) ensure that the path with the smallest index among the available paths is used for each shipment.³ Note that the summation term in (5) drops when $k = 1$, and hence $X_1^c = Y_1^c$ is imposed by (2) and (5). Finally, constraints (6) and (7) specify the binary nature of the decisions variables.

There is always a feasible solution to the above problem as long as $|P^c| \geq 1$ for all the shipments. It is certainly possible to extend the model by adding constraints that limit the exposure at certain population centers. Such limits might be due to the presence of schools, hospitals, nursing homes, etc. In the event that these additional constraints cause infeasibility, however, artificial links can be added to the existing network G to enable the delivery of all shipments to their destination (i.e., the shipments can reach their destination via the resulting fictitious routes with high costs). The resulting shadow price information can be used in identifying where additional links need to be constructed so as to avoid exposing sensitive locations to hazmat transport risk. The addition of new links to the existing network, based on sensitivity information generated by the above model, can also be a means of identifying solutions that improve both population exposure and travel distance. The construction of new road links, however, often involves significant investments by the regulator as well as the involvement of decision/policy makers who are not primarily charged (or concerned) with hazmat transport risk-mitigation efforts. Therefore, we focus on reducing population exposure on the existing road network G in this paper.

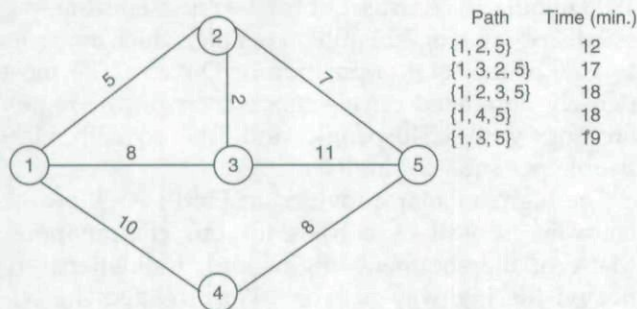
4. Analytical Properties of the Model

The path-based model assumes that carriers' preferences are accurately represented by the alternative path sets, P^c , $c \in C$. These sets need to be not only ordered appropriately, but also be comprehensive. If P^c does not include all the routes that constitute an

² In the event of a tie, the paths are listed in increasing order with respect to their transport risk.

³ These constraints are known as *closest assignment constraints* in the context of facility location models (see Gerrard and Church 1996).

Figure 1 An Illustrative Road Network



option for the carrier in shipping c , then the model would be unable to make a correct assessment of the resulting population exposure. To illustrate this, consider a hazmat shipment from node 1 to node 5 on the road network depicted in Figure 1. Assuming that travel time is the carrier's primary concern, the alternative path set for this shipment is also included in the figure. In the event that the regulator decides to ban the use of road link (1, 2) for hazmat shipments, paths {1, 2, 5} and {1, 2, 3, 5} would become unavailable. It is important that {1, 3, 2, 5} is included in the alternative path set because it would be the carrier's natural choice when link (1, 2) is closed. If {1, 3, 2, 5} is not represented as an alternative route, the model would identify {1, 4, 5} as the carrier's best option, whereas the carrier is more likely to use {1, 3, 2, 5} in reality.

A significant issue in developing the path-based model of a hazardous network design problem is the cardinality of alternative path sets. One extreme is when $|P^c| = 1$ for all shipments. This corresponds to the most desirable case for the carriers because only the shortest⁴ route for each shipment is deemed acceptable and the regulator is unable to intervene. The other extreme is the ideal scenario for the regulator, where *all* paths between the shipment origin-destination pairs are included in the model. In effect, the regulator's ability to mitigate population exposure by closing road segments is not constrained by economic viability. Note that this is the case recently analyzed in Kara and Verter (2004).

The explicit representation of alternative path sets in the path-based model makes it possible to determine compromise solutions between the two extremes. One way to reach a compromise between the regulator and the carriers is to include only the paths with lengths that are within a certain percentage of the length of the shortest path. For example, {1, 3, 5} would be excluded from the alternative path

set if the maximum acceptable travel time is 150% of that of the minimum time path in Figure 1. Alternatively, only the first K shortest paths for each shipment can be included in the alternative path sets. This would ensure that the carriers would not be forced by the regulator to use any route that is worse than their K th preference.

The problem of finding K shortest paths between an origin-destination pair have been well studied. It is desirable to focus on *loopless paths* in the context of dangerous goods shipments. This involves imposing the restriction that no vertex in V can be visited more than once along a path. In terms of worst-case performance, the prevailing algorithm for finding K shortest loopless paths is due to Katoh et al. (1982), and its complexity is $O(K|V|^2)$. Hadjiconstantinou and Christofides (1999) provide an efficient implementation of Katoh et al. (1982), as well as a comprehensive account of the literature on the K shortest-path problem. In an earlier paper, Miaou and Chin (1991) report on their computational experience with four K shortest-path algorithms in transporting nuclear spent fuel through the U.S. interstate highway network.

Highways are primarily built for connecting population centers to each other, and hence the shortest route between an origin-destination pair usually passes through heavily populated areas. This implies a trade-off between the regulator's objective of minimizing exposure to hazmat trucks and the carriers' objective of minimizing travel distance. Empirical studies of Erkut and Verter (1998) and Verter and Kara (2001) show the existence of such trade-offs in the United States and in Canada. Thus, one would expect that the path-based model would force *all* the shipments to increasingly inferior routes, from the carriers' perspective, as the cardinality of alternative path sets is increased. Although this intuition is certainly correct when there is a single shipment, it is incorrect for the general hazardous network design problem with multiple shipments. Note that a road link $a \in A$ that is closed to hazmat m when $|P^c| = \alpha$ can be open to shipments involving this hazmat when $|P^c| = \beta$, where $\beta > \alpha$.⁵ Clearly, the travel distance would be reduced for the shipments that are rerouted through link a in the latter solution. That is, increasing cardinality of the alternative path sets can reduce not only the overall population exposure but also the travel distance for some of the shipments.

The optimal solution of the path-based model determines not only the road links that should be closed to hazmat shipments by the regulator, but also the routes that would be used for each shipment on the resulting hazmat network. Because the alternative

⁴In the remainder of this paper, without loss of generality, we assume that the carriers' primary concern is travel distance. The proposed methodology is equally applicable when the carriers are aiming at minimizing travel cost or travel time.

⁵This can be observed in Table 4 by comparing the number of open links for $K = 40$ and $K = 50$.

path sets are indexed according to the carriers' preferences, the level of satisfaction of each carrier with the available road network is evident from the solution. For example, $X_k^c = 1$ indicates that the carrier's k th choice is used for shipment c . A carrier's preference index for each alternative path can be used to represent this information, i.e., $CP(P_k^c) = k$. We also define a regulator's preference index $RP(P_k^c)$, which indicates the ranking of P_k^c when all possible paths between $o(c)$ and $d(c)$ are listed in nondecreasing order with respect to population exposure. As we describe in the next section, the $CP(\cdot)$ and $RP(\cdot)$ values can be used for reaching an agreement between the regulator and the carriers concerning the cardinality of alternative path sets.

5. The Western Ontario Problem

In this section, we present the hazmat transport network design problem in Western Ontario, Canada, which was originally studied by Kara and Verter (2004). This enables us to compare our insights with those of the bi-level formulation of the problem. We first describe the problem data in detail and then discuss the analyses and our findings.

5.1. The Problem Data

The primary source of our data is Statistics Canada. Their records contain the necessary information on population centers and dangerous goods shipments. We used a geographical information system (GIS) to overlay the spatial distribution of population on the highway network of Western Ontario, as depicted in Figure 2. This GIS-based representation enabled us to generate the exposure zones around each road link and estimate our model parameters, i.e., ρ_{ai}^m .

There are a total of 543 census subdivisions in Ontario. To keep the problem tractable, we focus on the subdivisions with population density larger than 40 people per square kilometer. There are 66 such subdivisions in Western Ontario, and each is represented

as a population center in the model. According to the 1996 population census, our model represents the spatial distribution of 7.23 million people, which amounts to 95% of the total population of Ontario. The most densely populated census subdivisions in the region are York with 4,540 people, and Toronto with 4,099 people per square kilometer.

The highway map provided in ESRI's ArcView 3.1 software is used as a basis for our computations. Many of the shipment origins and destinations are not on the highway network. We projected the off-highway origin and destination points onto the closest highway segment. These projections represent the shipment origins and destinations on the Western Ontario highway system. Note that hazmat trucks are usually required to use the shortest routes in urban areas, between the highway and their actual origin/destination. The resulting network contains 48 nodes and 57 links.

We study the shipments of gasoline, fuel oil, petroleum and coal tar, and alcohol within Western Ontario. Shipments originating from and/or destined to locations outside the region are out of the scope of our analysis. Statistics Canada records suggest that these four materials account for 56% of all the hazmats transported through Canadian highways. The data set includes the origin and destination of each hazmat shipment, as well as the number of trucks used. However, the amount of hazmat carried and the route used by the carrier are not recorded. Thus, we assume that each truck is a full load and poses the same exposure risk. Again, to keep the model tractable, we focus on shipments with more than 500 trucks annually. As depicted in Table 1, the resulting model represents 78% of all the shipments in Western Ontario. A total of 53 shipments are modelled, i.e., 22 gasoline, 18 fuel oil, 12 petroleum and coal tar, and one alcohol shipment.

In assessing population exposure, we focus on the possible spill incidents. Gasoline, fuel oil, and alcohol pose similar risks in terms of the consequences of a spill. Transport Canada (1996) requires evacuation of the people within 800 meters of a spill site for these three materials, which we call H_{800} . In contrast, the evacuation distance is 1,600 meters for spills involving petroleum and coal tar, which we call $H_{1,600}$. Thus, $M = \{H_{800}, H_{1,600}\}$ in our model. When a hazmat

Figure 2 Population Centers and Highway System of Western Ontario

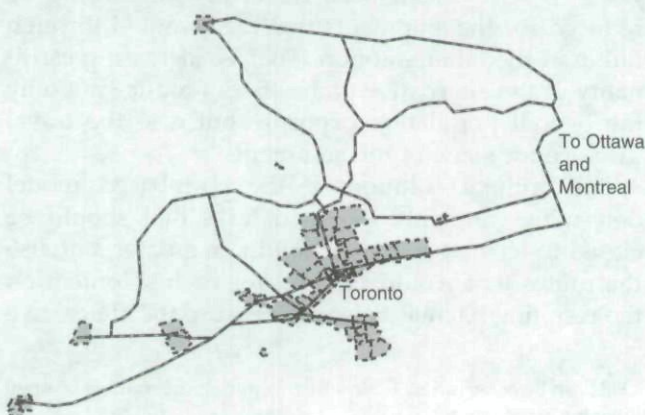


Table 1 Number of Hazmat Trucks in Western Ontario

Hazmat type	Number of trucks	Number of trucks
		in $s^c \geq 500$
Gasoline	45,106	37,221
Fuel oil	28,738	21,266
Petroleum and coal tar	25,920	20,566
Alcohol	2,129	519

truck uses a road link, all the people within the associated distance from that highway segment are exposed to the risk of being evacuated.

5.2. Analysis and Insights

The nature of the trade-off between the most preferable scenario to the regulator and that of the carriers constitutes the first step of our analysis. Recall that the regulator's ability to mitigate transport risk is maximized when *all* paths between the origin-destination pairs are included in P^c , $c \in C$. We used an enumerative procedure to generate a comprehensive list of alternative paths for each of the 53 shipments. There are a total of 14,504 alternative paths in the problem, and some shipments have more than 500 alternative routes. In constructing P^c , the alternative paths for the shipment are ranked in increasing order of their length, where the length of each road link is obtained through the GIS-based model. Only the shortest 100 paths for each shipment are included in the alternative path sets. We used CPLEX 6.0 for solving the resulting problem instance, which required 2.6 hours of CPU time. Table 2 presents the characteristics of the ideal solution for the regulator. The most preferable scenario for the carriers is when there is no government regulation, i.e., $P^c = P_1^c$ for each shipment. The optimal solution of this problem instance, which required merely a second, is also depicted in Table 2.

Population exposure is the transport risk measure that is minimized in our model. It is obtained by multiplying the number of people exposed to hazmat trucks with the number of trucks that they are exposed to. To express the level of exposure in more familiar terms, we use two average risk measures: individual risk and truck exposure. Individual risk is obtained by dividing population exposure by total population, which shows the average number of trucks an individual in Western Ontario is exposed to. Truck exposure is obtained by dividing population exposure by the total number of trucks, which shows the average number of people residing within the exposure zone of a truck along its path. Total travel distance is a proxy for the total transport cost to be incurred by the hazmat carriers, whereas path

length is the average distance to be travelled by a hazmat truck on the highway network prescribed by the model.

It is evident from Table 2 that there is a significant trade-off between the two extreme scenarios in terms of risk exposure and travel distance. Note that the exposure to hazmats is minimized under the regulator's solution, whereas travel distance is minimized under the "no regulation" scenario. Table 2 shows that the exposure to hazmat transportation can be significantly reduced by government regulation in Western Ontario. By closing certain road links to hazmat trucks, the individual risk can be reduced from 907 trucks to 67 trucks. On the average, however, this requires the carriers to incur a 120% increase in the distance they travel.

It is important to note that the figures depicted in Table 2 are the averages across 53 shipments. When the regulator does not incorporate economic viability in its decision-making process, some of the hazmat carriers may have to incur unbearable financial burdens for operating on the resulting transport network. Two such examples are provided in Table 3. In the ideal scenario for the regulator, the carrier transporting gasoline between Mississauga and Northumberland County will have to use a route that is indeed its 54th preference. The length of this path is about five times that of the shortest path for this shipment. The achievement of minimum population exposure would also require the petroleum carrier between Mississauga and Peterborough to use a route that is its 50th preference, which nearly triples the travel distance. Clearly, such policies would not be acceptable to the carriers and the regulator may have to compromise its risk-mitigation targets to ensure the carriers' participation in the implementation phase.

To generate a set of compromise solutions, we solved 10 instances of the Western Ontario problem, each with a different number of alternative paths included in P^c , $c \in C$. We started with $K = 10$ and

Table 2 The Two Extreme Scenarios

Criterion	Unit	Ideal scenario for the	
		Regulator	Carriers
Population exposure	truck-people	481.6 10^6	6,557.8 10^6
Individual risk	trucks/person	67	907
Truck exposure	people/truck	6,053	82,412
Total travel	km	27.9 10^6	12.7 10^6
Average path length	km/truck	351.5	159.9

Table 3 Solution Characteristics for Two Example Shipments

	Ideal scenario for the	
	Regulator	Carriers
571 gasoline trucks between Mississauga and Northumberland		
Truck exposure (people/truck)	10,477	871,001
Path length (km/truck)	1,005	217
RP(.)	1	51
CP(.)	54	1
548 petroleum trucks between Mississauga and Peterborough		
Truck exposure (people/truck)	10,477	421,717
Path length (km/truck)	965	325
RP(.)	1	41
CP(.)	50	1

Table 4 The Compromise Solutions

	Number of alternative paths included in P^c									
	10	20	30	40	50	60	70	80	90	100
Individual risk	629	120	77	77	75	67	67	67	67	67
Average length	249.3	317.6	329.7	329.7	332.5	351.5	351.5	351.5	351.5	351.5
Open H_{800} links	42	41	41	41	46	45	45	45	45	45
Open $H_{1,600}$ links	30	26	36	36	38	35	35	35	35	35
Worst $CP(\cdot)$	8	12	26	26	50	54	54	54	54	54
Worst $RP(\cdot)$	45	43	5	5	5	2	2	2	2	2
CPU time (min.)	42	44	1.5	4	54	6.4	11.5	44.2	20.8	42.3

appended 10 alternative routes to P^c in each instance.⁶ Table 4 depicts the optimal solutions to these problem instances. It is evident that individual risk decreases and average path length increases as K is increased.

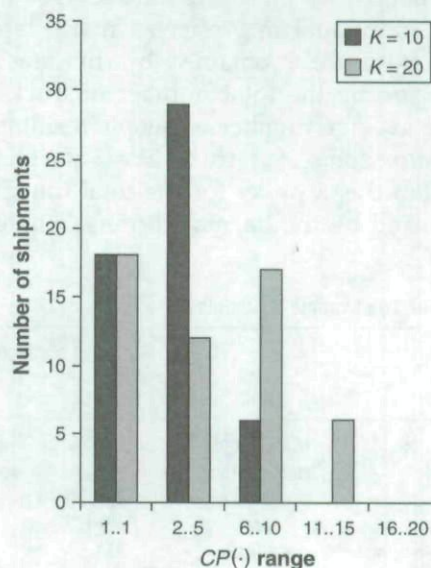
Each column in Table 4 corresponds to a hazmat network, which enables the carriers to use routes with $CP(\cdot) \leq K$. For $K = 10$, the regulator needs to close 15 road links to H_{800} shipments and 27 road links to $H_{1,600}$ shipments so as to minimize population exposure. This results in a 31% reduction in individual risk and a 56% increase in average travel distance over the “no regulation” scenario. When K is increased to 20, a further reduction of 81% can be achieved in individual risk by incurring an additional 27% increase in the average travel distance. The road links closed to hazmats for $K = 10$ are not a subset of the closed links for $K = 20$. The decisions pertaining to the availability of road links around Toronto constitute the main difference between the two policies. Figure 3 shows the distribution of carrier preference indexes over the 53 shipments for $K = 10$ and $K = 20$. Note that 18 shipments use their shortest path in both cases. For $K = 10$, the least preferable path used by a carrier has $CP(\cdot) = 8$, as depicted in Table 4. When K is increased to 20, the worst $CP(\cdot)$ increases only to 12. From the regulator’s perspective, the number of least exposure paths used in the $K = 10$ solution is 31, which increases to 43 when $K = 20$.

It is evident from Table 4 that the regulator’s ideal network constitutes the optimum solution for $K \geq 60$. In hindsight, the regulator’s most preferable scenario can be solved by including less than 3,180 paths (i.e., 53×60) in the model rather than 14,504. To guarantee a solution that gives the minimum attainable exposure, however, it is necessary to include all alternative paths in the model. Nevertheless, the regulator can use the $RP(\cdot)$ values in assessing the closeness of the solution to the ideal. For $K = 60$, for example, 51 shipments are sent through their least exposure routes, and only two shipments need to use a path with $RP(\cdot) = 2$. Based on such an observation, the regulator

can be convinced that $K = 60$ is indeed a very good solution. Note that the worst $RP(\cdot)$ does not converge to one in Table 4. This is because the ideal network of the regulator is not merely a union of the least exposure paths.

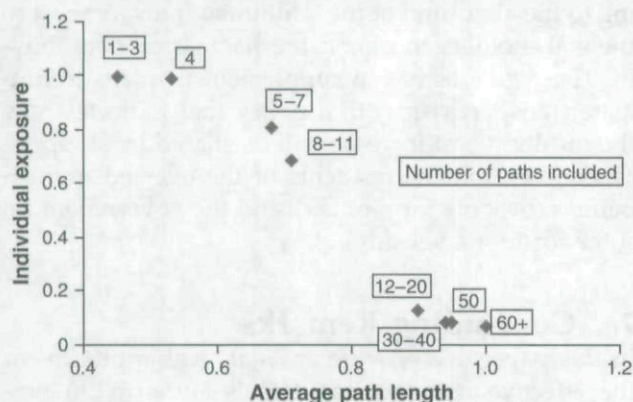
An interesting observation is that the number of open links and the CPU requirement do not have a monotone trend as K increases. For example, solving the model with $K = 20$ takes longer than the model with $K = 60$. This is because the optimality verification may require more time when a smaller number of paths are included in the model. During the branch and bound, 31 nodes were generated by CPLEX to solve the $K = 60$ case, whereas 9,281 nodes were required for solving the $K = 20$ case.

In closing this section, we display the trade-off between individual risk and average travel distance in Figure 4. The individual exposure and average path-length values corresponding to the problem instances in Figure 4 are normalized, i.e., the problem instance with the highest value is assigned a value of one. To develop the trade-off curve, we solved *all* instances of the Western Ontario problem where $K \leq 20$. We also

Figure 3 Distribution of Carrier Preferences for $K = 10$ and $K = 20$ 

⁶ If for any shipment the number of alternative paths is less than K , then P^c will contain all of the existing alternatives.

Figure 4 The Exposure-Distance Trade-Off in Western Ontario



used the eight additional instances from Table 4, i.e., $K = 30, 40, \dots, 100$. The K values associated with each point in Figure 4 are depicted in the rectangular boxes. Note that the 28 problem instances depicted in the figure result in only eight distinct solutions. For example, the left-most point in Figure 4 corresponds to the “no regulation” scenario, i.e., $K = 1$. The resulting individual exposure and average travel distance values remain the same when the second and third preferences of each shipper are included in the alternative path sets. Clearly, the right-most point represents the regulator’s ideal solution, which is reached when $K \geq 60$. Note that the network design with $K = 30$ (or $K = 40$) dominates the design with $K = 50$ because both impose the same transport risk while the latter involves higher transport cost. It is interesting that most of the possible exposure reduction is achieved when the routes with $CP(\cdot) \leq 12$ are included in the model for each shipment. This is because 43 of the 53 shipments use the minimum-exposure path when $K = 12$.

6. The Quebec-Ontario Problem

Having shown that the proposed framework can be useful for facilitating negotiation among hazmat carriers and the regulators, we move onto an illustration of its capability to tackle large-scale problem instances. To this end, we study the transportation of the same four hazmats through the highway networks of Ontario and Quebec. The network model used for representing these hazmat shipments has 205 links and 176 nodes. There are 181 census subdivisions in this region, each with population density larger than 40 people per square kilometer. The total number of shipments is 84, where each shipment involves the movement of more than 500 truckloads of hazardous cargo between its origin-destination pair. 69 of these shipments are H_{800} and the remaining 15 shipments are $H_{1,600}$, indicating their impact zone. There are 46 shipments within Ontario, 33 shipments

Table 5 Six Sample Shipments Across the Quebec-Ontario Network

Sample shipment	Number of trucks	Min. length (km)	Number of paths within % detour		
			50%	100%	150%
1	732	230	4	8	24
2	6,130	253	2	2	3
3	1,714	611	17	74	1,046
4	576	913	35	342	10,335
5	1,583	997	36	432	16,305
6	631	1,369	45	120	16,850

within Quebec, and five shipments between the two provinces. Verter and Kara (2001) reported on a GIS-based risk-assessment model for hazmat transportation across Quebec and Ontario highways, and hence the reader is referred to Verter and Kara (2001) for more details on this data set.

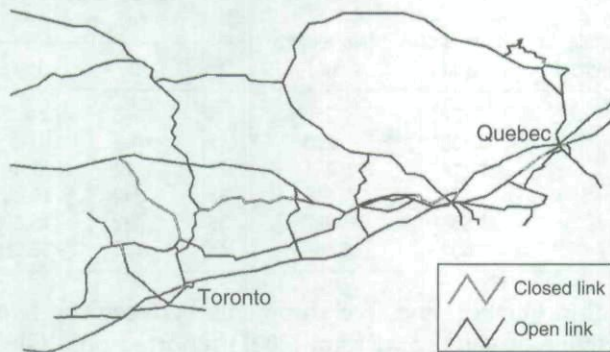
In the previous section, the alternative path sets were constructed by varying K , i.e., the upper bound on the value of $CP(\cdot)$. Some carriers, however, can emphasize the extent of additional driving (in comparison with the shortest path) that may be required, rather than the worst-case possibility of using the K th shortest path for a shipment. To incorporate such carriers, let D denote the maximum allowable percent detour from the shortest path. For example, the minimum-length route for shipment 1 in Table 5 is 230 kilometers, and the shipment involves 732 truckloads of cargo. For $D = 50$, only the routes with a length of 345 kilometers or less will be included in the set of alternative paths, and there are four such routes for this shipment.

To delineate the impact of allowed detours from the shortest path, we depict six of the 84 shipments in Table 5. These shipments are sorted according to the length of their shortest route. Table 5 also shows the number of alternative paths for each shipment for $D = 50, 100$, and 150. Clearly, for higher values of D , the number of alternative paths proliferate as the shortest-path length increases. Note that it is important to limit the cardinality of the alternative path sets to keep the problem tractable. Therefore, we use a pair of D and K values for tackling large-scale problems.

In Table 6, we summarize the characteristics of two network designs for $D = 100, K = 25$ and $D = 400$,

Table 6 Two Alternative Network Designs

	Allowed worst case		Average trade-off (%)
	$D = 100, K = 25$	$D = 400, K = 100$	
Individual risk	915 trucks	540 trucks	–41
Average length	232.3 km	343.3 km	48
Open H_{800} links	194 links	189 links	
Open $H_{1,600}$ links	196 links	193 links	
Worst $CP(\cdot)$	16th path	65th path	
CPU time	32 min.	5 hrs.	

Figure 5 The Gasoline, Fuel Oil, and Alcohol Network for $D = 100$ and $K = 25$ 

$K = 100$. The two highway networks available to hazmat shipments as a result of these policies are depicted in Figures 5 and 6, respectively. The most notable difference between these two designs pertains to the road links connecting Toronto to Montreal (leaving Toronto toward North-East). Note that the network with less population exposure (i.e., $D = 400$, $K = 100$) involves closing only five additional road links to H_{800} shipments and three additional road links to $H_{1,600}$ shipments. This instance of the problem with much larger path sets was solved within five hours, which we believe is a reasonable computational effort for a problem of strategic nature. Because the change from the road network preferable to carriers (i.e., $D = 100$, $K = 25$) to the regulator's preferable network involves closure decisions on a small number of road links (as in the Western Ontario problem—see the small changes in the number of open H_{800} and $H_{1,600}$ links with K in Table 4), the identification of such links by the proposed model can serve as a good starting point for the discussion between the two parties. Perhaps more importantly, we were able to identify an almost one-to-one trade-off between transport risk and cost, i.e., a 41% reduction in exposure can be achieved by a 48% increase in average travel distance.

Figure 6 The Gasoline, Fuel Oil, and Alcohol Network for $D = 400$ and $K = 100$ 

Of course, an agreement needs to be reached pertaining to the allocation of the additional transport cost to the stakeholders to obtain the hazmat carriers' buy-in. The regulator has to supplement its plans to mitigate transport risk with a policy that indicates how the resulting cost increase will be shared by shippers, carriers, customers, residents of the effected municipalities (in some form of tax), and the government (in some form of a subsidy).

7. Concluding Remarks

In this paper, we provide an analytical approach for the effective use of a regulator's authority to prohibit hazmat shipments across certain road links. The proposed model enables the regulator to limit the cost implications of risk-reduction policies. Note that the cost-risk trade-off depends on the topology of the existing road network, the spatial distribution of population centers, the location of the origin-destination pairs, and the type of hazmats being shipped. Thus, it is important to stress the case-based nature of the above observation, although the methodology is generic.

The main modeling construct in this paper is a set of alternative paths for each shipment that is mutually acceptable to the government and the hazmat carriers involved. We discussed the use of the maximum cardinality of alternative path sets K and the maximum allowable percent detour from the shortest path D as possible means of constructing the alternative path sets either individually (as in the Western Ontario problem) or jointly (as in the Quebec-Ontario problem). It is important that K and D constitute different ways of specifying the carriers' preferences, which would typically lead to different results. To illustrate this, we carried out two additional experiments with the Western Ontario problem. First, comparing Tables 2 and 4, we observed that the average travel distance increases 56% when K is raised from 1 to 10. We solved the Western Ontario problem with $D = 56$, which resulted in a solution that involves average travel distance of 166.7 kilometers and average individual risk of 906 trucks. A detailed analysis of this solution showed that 23 of the 53 shipments have only their shortest path in the alternative path sets because the other routing options are infeasible when $D = 56$. Consequently, this solution is very close to the carriers' ideal solution in Table 2. Second, we focused on the fact that the *worst* $CP(\cdot) = 8$ in the resulting Western Ontario hazmat network when $K = 10$ (see Table 4). From the carriers' perspective, the least-preferred path that will be used for hazmat shipments is 154% longer than the corresponding shortest path. Solving the problem with $D = 154$ yields the average travel distance of 267.9 kilometers and the

average individual risk of 267 trucks. Note that this solution is between the $K = 10$ and $K = 20$ solutions in Table 4. Because the different methods in constructing the alternative path sets identify different solutions, an agreement must be reached between the stakeholders in terms of this issue as well.

We remark here that the maximum cardinality of alternative path sets and the maximum allowable percent detour from the shortest path are equal for all shipments in our analysis. This is intended to establish a certain level of equity among the carriers. Clearly, the regulator can further reduce transport risk by devising hazmat-specific path set construction policies, i.e., by using K_m rather than K and D_m rather than D in the analysis. The use of different criteria (for constructing the alternative path set) for each hazmat type, however, involves additional challenges. Because the carriers often specialize in terms of the types of hazmats they transport, such a policy can induce inequality among the carriers with regards to the distribution of the economic burden of transport risk-reduction policies.

The methodology in this paper incorporates the regulator's risk concerns and the carriers' cost concerns. Another important issue pertinent to hazmat transportation is the equity in spatial distribution of risk. The perceived differences between the risk-exposure levels at different population zones can lead to public opposition to hazmat transportation. Also, heavy use of certain highway segments for hazmat shipments may increase the probability of incidents as well as the severity of consequences. Transport risk equity has attracted the attention of some researchers,⁷ although most regulators and carriers—particularly, the ones we collaborate with in Canada—do not seem to give this issue a high priority. The common way to include equity concerns of the public in a transport network design model is via a set of constraints limiting the level of risk imposed by the hazmat shipments on each arc. Note that to achieve a certain level of equity in the spatial distribution of risk, the trucks that carry portions of a large-volume shipment between an origin-destination pair may have to be distributed to multiple routes. Therefore, the incorporation of risk equity in our model requires relaxation of constraints (5), which stipulate that the carriers choose a single route among the available alternatives. Consideration of risk equity in the context of hazmat transport network design is a challenging and interesting OR problem, which is yet to be studied.

Integration of hazmat network design decisions with other means to reduce transport risk constitutes

a fruitful avenue for future research. For example, the optimal locations of emergency response stations (operated by the regulator) can be determined simultaneously with the road links that should be closed to hazmat shipments. The ability to promptly respond to a hazmat incident may enable the regulator to keep open some of the road links that are heavily preferred by the carriers. Through the use of an integrated model, it would also be possible to analyze the alternative ways of sharing the risk-mitigation costs between the regulator and the carriers. The development of such comprehensive frameworks is likely to improve the governments' performance in regulating the transportation of dangerous goods.

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⁷ Erkut et al. (2007) provides a review of the six papers on hazmat transport risk equity.

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