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Bahar Y. Kara, Vedat Verter,

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Designing a Road Network for Hazardous Materials Transportation

Bahar Y. Kara

Department of Industrial Engineering, Bilkent University, 06533, Bilkent, Ankara, Turkey, bkara@bilkent.edu.tr

Vedat Verter

Faculty of Management, McGill University, 1001 Sherbrooke Street West, Montreal, Quebec, Canada H3A 1G5, verter@management.mcgill.ca

Dangerous-goods shipments remain regulated despite the widespread deregulation of the transportation industry. This is mainly due to the societal and environmental risks associated with these shipments. One of the common tools used by governments in mitigating transport risk is to close certain roads to vehicles carrying hazardous materials. In effect, the road network available to dangerous goods carriers can be determined by the government. The associated transport risk, however, is determined by the carriers' route choices. We provide a bilevel programming formulation for this network design problem. Our approach is unique in terms of its focus on the nature of the relationship between the regulator and carriers. We present an application of our methodology in Western Ontario, Canada.

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

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Many of the materials transported by trucks, trains, vessels, and planes are flammable, explosive, poisonous, corrosive, or radioactive. Despite being potentially harmful to the environment and to people, these materials are essential for industrial development. Hazardous materials (hazmats) are used extensively in fueling vehicles and heating homes/offices, as well as in manufacturing, mining, farming, and medicine. During the past decade, hazmat transportation reached unprecedented levels. In the United States, for example, there are at least 300 million hazardous shipments each year totaling approximately 3.2 billion tons.

The vast majority of dangerous-goods shipments arrive at their destination safely. In 1998, there were roughly 15,000 incidents related to hazmat transportation in the United States (U.S. Department of Transportation 1999). Only 429 of these were classified as "serious incidents," resulting in 13 deaths and 198 injuries. Given the large number of hazmat shipments, however, there remains the potential for catastrophic incidents with multiple fatalities, injuries, large-scale evacuations, and severe environmental damage. For example, 18 of the 20 deaths in a 1993 bus-truck collision in Quebec were attributed to the spill and explosion of gasoline from the truck (Transport Canada 1999). In 1996, over 16,250 gallons of chlorine were released from a derailed train in Montana, resulting in 1 fatality, 787 hospitalizations,

1,000 evacuations, and over \$4.5 million in cleanup costs. Due to the involuntary nature and potential magnitude of these undesirable consequences, special interest groups (for example, environmentalists, the media) and the public at large are very sensitive to the dangers of transporting hazmats. Thus, regulation of dangerous-goods shipments is usually within a government's mandate.

In this paper, we focus on a popular measure utilized by regulators in order to reduce the transport risk in their jurisdiction—that is, a government's authority to close certain road segments to hazmat transportation and, in effect, to decide the road network that can be used for hazmat shipments. There are a number of other policy tools available to a government agency for mitigating hazmat transport risk. These include requirements pertaining to driver training, driving hours, container specifications, and accident insurance. Establishment of inspection stations to monitor compliance with the regulations, and emergency response systems to minimize consequences of the incidents, are quite common. Although a comprehensive policy would typically involve the simultaneous use of these alternative means, this paper is confined to the selection of road segments (from an existing road network) that would be available to hazmat carriers.

Carrier companies and governments have quite different perspectives with regard to dangerous-goods

movements. Carriers are naturally in the pursuit of their bottom line, while satisfying the safety requirements stipulated by the regulator, whereas governments aim at reducing the public and environmental risk without threatening the economic viability of hazmat transportation. Another notable difference is the scope of the problem. A government has to consider all the shipments in its jurisdiction, which would typically involve a variety of hazmats and a large number of origin-destination pairs. A carrier, however, can plan each shipment separately. An overwhelming majority of the hazmat transportation literature adopts a carrier's viewpoint by focusing on problems with a single hazmat and a single origin-destination pair.

The main theme of the prevailing studies is assessment of the transport risk associated with a shipment and finding the route that minimizes this risk. The resulting minimum risk route is typically compared with the minimum cost route, assuming that a carrier would normally use the latter. Various definitions of risk have been proposed. Saccomono and Chan (1985) and Abkowitz et al. (1992) consider the likelihood of having a hazmat incident during transportation as their risk measure. This model does not incorporate the consequences of an incident and, hence, it is more suitable for the hazmats with relatively small danger zones. Batta and Chiu (1988) represent transport risk as the number of people living within a threshold distance from the route. This model 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. Alp (1995) and Erkut and Verter (1995a) focus on the expected number of people that would suffer the consequences of a possible hazmat incident. All of the above papers identify the minimum risk path for the shipment via a shortest path algorithm that uses the proposed risk measure as the arc impedance. The reader is referred to List et al. (1991) and Erkut and Verter (1995b) for comprehensive reviews on hazmat transportation.

We know of two notable exceptions to the carrier-oriented perspective of the literature. List and Mirchandani (1991) present a detailed model 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 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 U.S. Coast Guard has the authority to designate the route to be followed by the vessels between an origin-destination pair.

In this paper, we adopt the viewpoint of the regulator and analyze the problem of selecting a road network for dangerous-goods shipments from an existing transportation infrastructure. We provide a bilevel programming formulation that is unique in terms of its focus on the nature of the relationship between the government and the carriers. To the best of our knowledge, this problem has not been addressed before in the academic literature, and therefore we provide a detailed description and a formal definition in §1. Section 2 presents the mathematical formulation, whereas the development of a solution procedure based on the analytical properties of the model is outlined in §3. An application of our methodology in Western Ontario is summarized in §4. Finally, some concluding remarks are provided in §5.

1. The Hazardous-Network Design Problem

In regulating dangerous-goods shipments, a government agency would typically be concerned with the transport risk imposed on the population centers due to heavy hazmat traffic. Ideally, the total risk can be minimized if the minimum risk route were to be used for each shipment. In most jurisdictions, however, the agency in charge of hazmat transport is not equipped with the legal power to designate the route to be used between an origin-destination pair. Typically, the policy tool available to the agency is the authority to prohibit the use of certain road segments by trucks carrying (certain types of) dangerous goods. The remaining roads constitute the "hazardous network" on which hazmat carriers would be allowed to operate. Note that it is the routing decisions of the carriers on the available network that determine not only their own operational costs, but also the total transport risk imposed on the public. In this context, the problem on which we focus in this paper is defined as follows: Given an existing road network, the *hazardous-network design problem* involves selecting the road segments that should be closed to hazmat transport so as to minimize the total risk. A schematic representation of the problem is depicted in Figure 1. Clearly, we approach the hazardous-network design problem from a strategic perspective in this paper. In the last section, however, we will comment on the use of tactical decisions (such as time-based curfews on some road links) in reducing the transport risk.

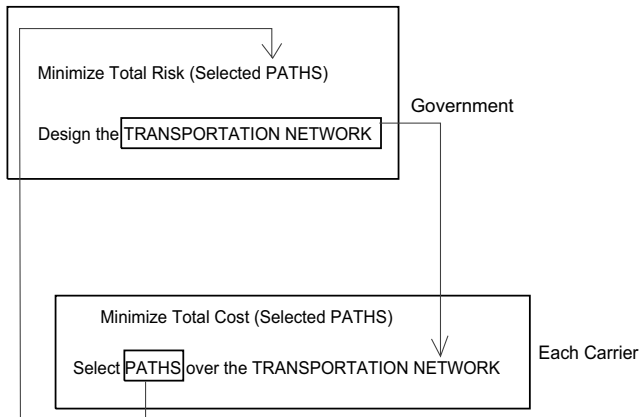


Figure 1 Hazardous-Network Design Problem

It is important that the solution to the hazardous-network design problem is determined by the choices of two *distinct* (groups of) decision makers, i.e., the government and the carriers. Although their decisions collectively influence the outcome, each stakeholder has a different set of objectives. In modeling the problem, for example, we analyze the case where *population exposure* is the risk measure used by the government and the distance traveled is the basis for the carriers' route choices. Naturally, there are other possible objectives for each party. For example, the government might prioritize reduction of the total incident probability, whereas the carriers might put more emphasis on the total operational costs and/or insurance costs. Note that the government agency is in a leader position here due to its legal authority, whereas the carriers have to follow the regulations in order to be able to continue their operations. Hence, we propose a bilevel framework to represent the problem as depicted in Figure 1.

Our approach is different from the prevailing methodology in the following two ways. First, we make an explicit attempt to capture the leader-follower relationship between the government and the carriers by the use of a bilevel framework. This is because the effect of each stakeholder's decision on the other party is only indirect. That is, the government can only influence the carriers' decisions through designing the hazardous network, whereas the carriers can influence the governments' decisions via the risk implications of their route choices. Therefore, in this problem, there is not a single body who can make the trade-off between these two typically conflicting objectives. Since the determination of a realistic set of weights would be problematic, aggregation of the two objectives in a single additive objective function may not produce a solution that is mutually acceptable.

Second, we recognize that identifying the minimum risk route for each shipment and simply defining the

hazardous network as the union of these routes may not produce the best result for the regulator. Although this has become a common practice in the risk-assessment literature, the regulator's ability to implement the prescribed solution is questionable. Note that the inclusion of all the minimum risk routes in the network does not guarantee their use by the carriers. Each road link included in the network would be open to all shipments (of certain hazmat types). Thus, the network may contain alternatives for routing some of the shipments, in which case the carriers would use the routes with minimum cost. Unless the routes are actually designated by the regulator, the traditional approach to hazardous-network design would always underestimate the resulting transport risk.

Now we turn to the mathematical formulation of the bilevel structure we propose for the hazardous-network design problem. Although the mathematical model is developed for population exposure and travel distance as the relevant objectives, our methodology can easily be used for other risk and cost measures.

2. A Bilevel Model

Evidently, the hazardous-network design problem lends itself to a bilevel programming formulation. The *outer problem* belongs to the regulator and involves decisions to determine the road links that should be included in the network, whereas the *inner problem* belongs to the carriers and entails the routing decisions on the available network. As depicted in Figure 1, the regulator needs to make the network design decisions so that the total risk resulting from the carriers' route choices is minimized.

We represent the existing road system by network $G = (N, A)$, where N denotes the set of nodes and A denotes the set of road links (indexed by $(i, j): i, j \in N$) that connect the nodes. Typically, a variety of dangerous goods are transported across G from their origin ($o \in N$) to their destination ($d \in N$). The set of hazmat types is represented by M (indexed by m). Let C (indexed by c) denote the set of all shipments across G . Each shipment $c \in C$ is characterized by its origin $o(c)$, destination $d(c)$, and the type of hazmat carried $m(c)$.

Let P denote the set of population centers (indexed by p) affected by the hazmat transportation activity. We assume that the undesirable consequences of a hazmat incident occur within a threshold distance from the accident site, which depends on the hazmat type. That is, when a hazmat truck travels across a road link, only the people within the threshold distance from the link are exposed to the truck. Thus, the

following notation is used in the model:

Parameters

- $\rho_{ij}^{p,m}$ the number of people in p exposed to a truck carrying hazmat m through link (i, j) ,
- l_{ij} length of link (i, j) ,
- n^c number of trucks used for shipment c .

Decision Variables

- Y_{ij}^m 1 if link (i, j) is available for transportation of hazmat type m , 0 otherwise,
- X_{ij}^c 1 if link (i, j) is used for shipment c , 0 otherwise.

The hazardous-network design problem can be formulated as follows:

$$(HND) \quad \min \sum_{Y_{ij}^m \in \{0,1\}} \sum_{p \in P(i,j) \in A} \sum_{c \in C} n^c \rho_{ij}^{p,m(c)} X_{ij}^c$$

where X_{ij}^c solves:

$$\min \sum_{c \in C} \sum_{(i,j) \in A} n^c l_{ij} X_{ij}^c \quad (1)$$

s.t.

$$\sum_{(i,k) \in A} X_{ik}^c - \sum_{(k,i) \in A} X_{ki}^c = \begin{cases} +1 & i = o(c) \\ -1 & i = d(c) \\ 0 & \text{o.w} \end{cases} \quad \forall i \in N, c \in C \quad (2)$$

$$X_{ij}^c \leq Y_{ij}^{m(c)} \quad \forall (i, j) \in A, c \in C \quad (3)$$

$$X_{ij}^c \in \{0, 1\} \quad \forall (i, j) \in A, c \in C. \quad (4)$$

The inner problem is represented by (1)–(4). Note that the binary decision variables of the outer problem, i.e., Y_{ij}^m , constitute parameters for the inner problem. Given the values of Y_{ij}^m , the inner problem boils down to a minimum cost network flow model. Constraints (2) are the flow balance requirements, whereas (3) ensure that only the links made available by the government can be used by the carriers. In fact, the inner problem decomposes into $|C|$ constrained shortest path problems and the route choices made for these $|C|$ shipments, i.e., X_{ij}^c , determine the objective function value of the outer problem. As evident from *HND*, we simply add the risks imposed by the transport activity on different links, which results in the linearity of the objective function. The additivity of impacts from two or more links around a population center is, in fact, an assumption we made. One can easily think of instances where there exist nonlinearities associated with the superposition of multiple risk impacts.

If the existing road network is connected, there is always a feasible solution to *HND*. Thus, the model accurately represents real life, where the hazmat shipment between an o-d pair needs to be carried out despite the undesirability of the associated risk. It is possible, however, to extend *HND* so as

to limit the exposure at any population center by adding the following constraint to the outer problem: $\sum_{(i,j) \in A} \sum_{c \in C} n^c \rho_{ij}^{p,m(c)} X_{ij}^c \leq \beta_p$, where β_p is the maximum allowable exposure at population center p . A possible motivation for posing such limits might be the presence of schools, hospitals, nursing homes, etc. at a population center. The X_{ij}^c values determine whether this constraint is satisfied. However, the resulting level of exposure at each population center is a concern primarily for the regulator, and hence this constraint belongs to the outer problem. We suggest caution in using constraints of the above form because they can impose infeasibility. Similarly, the number of trucks traversing any link can be constrained, i.e., $\sum_{c \in C} n^c X_{ij}^c \leq \gamma_{ij}$, where γ_{ij} is the maximum number of trucks allowed on link (i, j) . Since the level of hazmat traffic on a link is among the regulators' concerns, this constraint would be appended to the outer problem as well.

3. Solution Methodology

In this section, we present a solution methodology for *HND* that takes advantage of its analytical properties. For ease of exposition, we will focus on the basic model formulation. We start with a brief overview of the relevant literature.

Bard (1998) provides a comprehensive overview of the state of the art in bilevel optimization algorithms. The most common solution strategy for linear bilevel problems is based on representation of the inner problem by the use of its Karush-Kuhn-Tucker (KKT) conditions. For bilevel problems with integer or binary variables, however, branch and bound has been the prevailing solution scheme. In this section, we present a solution algorithm for *HND* that takes advantage of its structural properties.

As noted in the previous section, the inner problem (1)–(4) has to be solved on the basis of a set of available links determined by the outer problem. Once the Y_{ij}^m values are given, however, the inner problem is unimodular (Wolsey 1998). Hence, the integrality requirements (4) in the inner problem can be replaced by $X_{ij}^c \geq 0$ without loss of optimality. This enables us to represent the inner problem via the KKT conditions of its LP relaxation. The optimum solution to the inner problem can be obtained by solving the feasibility problem defined by (2), (3), and the following set of constraints:

$$X_{ij}^c \geq 0 \quad \forall c \in C, (i, j) \in A \quad (4')$$

$$n^c l_{ij} - w_i^c + w_j^c - v_{ij}^c + \lambda_{ij}^c = 0 \quad \forall c \in C, (i, j) \in A \quad (5)$$

$$v_{ij}^c X_{ij}^c = 0 \quad \forall c \in C, (i, j) \in A \quad (6)$$

$$\lambda_{ij}^c (X_{ij}^c - Y_{ij}^{m(c)}) = 0 \quad \forall c \in C, (i, j) \in A \quad (7)$$

$$v_{ij}^c \geq 0, \lambda_{ij}^c \geq 0, w_i^c \text{ free} \quad \forall c \in C, (i, j) \in A. \quad (8)$$

Thus, *HND* can be reformulated as a single-level model by representing the inner problem with the equivalent feasibility problem. The objective functions of the single-level model and the outer problem are the same. Note that unimodularity of the inner problem is based on Y_{ij}^m being a set of parameters at this level. In the single-level representation of the hazardous-network design problem, however, optimal values of Y_{ij}^m and X_{ij}^c are determined simultaneously. This structural change in the coefficient matrix causes the loss of unimodularity. Therefore, it is necessary to reimpose integrality on the X_{ij}^c variables by replacing (4') with (4) in the single-level model.

Although the inner problem in *HND* can be eliminated as described above, the resulting mixed integer program contains nonlinear Constraints (6) and (7). These constraints can be linearized by taking advantage of the binary nature of X_{ij}^c and Y_{ij}^m variables. When R is a large number, the following constitutes the linearization:

$$v_{ij}^c \leq R(1 - X_{ij}^c) \quad \forall c \in C, (i, j) \in A \quad (6')$$

$$\lambda_{ij}^c \leq R[1 - (Y_{ij}^{m(c)} - X_{ij}^c)] \quad \forall c \in C, (i, j) \in A. \quad (7')$$

Thus, the following model is equivalent to (*HND*):

$$\begin{aligned} (HND') \quad & \min \sum_{p \in P} \sum_{(i, j) \in A} \sum_{c \in C} n^c \rho_{ij}^{p, m(c)} X_{ij}^c \\ & \text{s.t. } (2), (3), (4), (5), (6'), (7'), (8) \\ & Y_{ij}^m \in \{0, 1\} \quad \forall m \in M, (i, j) \in A. \end{aligned}$$

(*HND'*) is a linear model with binary variables, which is amenable to solution via the commercial

solvers available in the market. The solution of the model prescribes the road network that should be available to hazmat carriers, as well as the carriers' route choices on this network. The corresponding objective function value determines the minimum population exposure attainable by banning certain road segments to hazmat trucks.

Although the discussion in the section is confined to the basic model, *HND*, the solution methodology is equally valid for its extensions, outlined in the previous section. This is because the unimodularity of the inner problem is not affected by the constraints added to the outer problem.

4. Application in Western Ontario

In this section, we present an application of the proposed methodology to determine the highway segments in Western Ontario that should be closed to trucks carrying dangerous goods. Our study is focused on shipments of gasoline, fuel oil, petroleum and coal tar, and alcohol. According to Statistics Canada, which constitutes our primary source of data, these four materials account for 56% of all the hazmats transported through Canadian highways. Note that the model requires detailed information on population exposure across the region of interest, i.e., $\rho_{ij}^{p, m}$. Geographical information systems (GIS) provide an effective framework for estimating these risk parameters. We used ESRI's ArcView 3.1 software in developing a GIS-based representation of the population centers, highway system, and hazmat shipments in Western Ontario. Figure 2 depicts the population centers and the highway system, which constitute

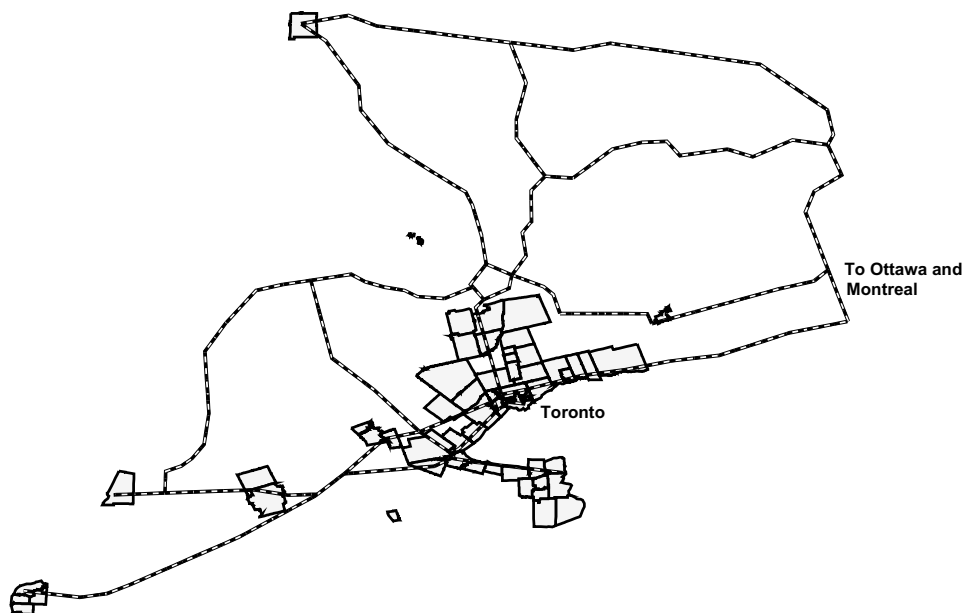


Figure 2 Population Centers and Highway System of Western Ontario

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the first two layers of information in our GIS-based model.

The records of Statistics Canada indicate the origin, destination, and hazmat type of each shipment, as well as the number of trucks used. We assume that each truck containing the same hazmat poses the same risk, because reliable information on the actual amounts carried is unavailable. More importantly, there is no record of the actual routes used by the carriers. In 1998, there were over 100,000 shipments within Western Ontario involving gasoline, fuel oil, petroleum and coal tar, or alcohol. Shipments originating from and/or destined to locations outside the region are not included in this statistic. We focus on the o-d pairs with an annual shipment volume of more than 500 trucks. The transportation between these o-d pairs amounts to 78% of all the shipments within Western Ontario. Table 1 presents a summary of the shipment data used in our analysis.

According to the 1996 population census, there are 66 census subdivisions in this region with a population density larger than 40 people per square kilometer. Each such subdivision constitutes a population center in our model. Consequently, we represent 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 and Toronto, with 4,540 and 4,099 people per square kilometer, respectively.

We use the highway map provided in ArcView 3.1 as a basis. In its original form, this highway network is not suitable for representing hazmat transportation. Note that only a few of the shipment origin and destination points are actually on a highway. Nevertheless, trucks are usually required to use shortest routes in urban areas, when they are off the highway system. Thus, we represent the origin and destination points in our model by projecting their original location onto the closest highway segment. Consequently, the nodes of our model include the origin and destination points as well as the highway intersections and highway endpoints. Each existing highway segment between a node pair is represented as a link. The resulting network model of Western Ontario has 48 nodes and 57 links.

Transport Canada (Transport Canada 1996) requires evacuation of the people within 800 meters of a spill

site if the incident involves a gasoline, fuel oil, or alcohol truck. Since these three materials pose the same exposure, we refer to them as the H_{800} group. The evacuation distance is 1,600 meters for spills involving petroleum and coal tar, which we call H_{1600} . Thus, $M = \{H_{800}, H_{1600}\}$ in our model. When a hazmat truck uses a road link, all the people within the associated distance from that highway segment are exposed to the risk of being evacuated.

Using the GIS-based model, we determined the exposure zones around each link for evacuation distances of 800 meters and 1,600 meters. We estimated the $\rho_{ij}^{p,m}$ values by overlaying the population zones on these exposure zones. The GIS-based model also enabled us to estimate the length of each road link, i.e., l_{ij} . The hazardous-network design model for Western Ontario is based on these values, and it is solved using CPLEX 6.0.

The optimal solution indicates the 45 links that should be open to the trucks carrying gasoline, fuel oil, or alcohol. The optimal road network for the petroleum and coal tar trucks, however, contains only 32 links. The resulting total population exposure in Western Ontario is 481.6 million truck-persons. In simpler terms, the provincial government can reduce the average exposure of an individual to 66.6 trucks per year by regulating hazmat shipments. This corresponds to an average travel distance of 351.5 kilometers and an average exposure of 6,053 people per truck.

For ease of exposition, we present a part of the optimal solution in Figure 3. The decision associated with Link 30 provides a good example of the complexities in regulating hazmat shipments. This is the segment of Ontario Highway 6 between Ontario Highways 401 and 403. Link 30 is on the minimum population exposure route for the 528 fuel oil trucks travelling between Halton Hills and Ancaster. When this link is open to H_{800} shipments, however, it would also be used by the 1,434 gasoline trucks between Mississauga and Brant County, since it is on their shortest route. The net impact of opening Link 30 to H_{800} shipments is an increase in total population exposure. Consequently, the fuel oil trucks are forced to follow a different path than the minimum exposure route between Halton Hills and Ancaster. It is interesting that Link 30 remains open to H_{1600} shipments at the optimal solution.

In the process of developing the model, we had a number of meetings with the government agencies responsible for dangerous-goods shipments in Ontario and Quebec. Given the variety of hazmats transported, it is quite clear that these agencies do not have the resources to implement an intricate set of regulations that vary with each material. Therefore, the number of hazmats represented in the model is

Table 1 Hazmat Shipments in Western Ontario

Hazmat Type	Number of o-d Pairs	Trucks
Gasoline	22	37,221
Fuel Oil	18	21,266
Petroleum & coal tar	12	20,566
Alcohol	1	519

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Figure 3 Roads Available for Trucks Carrying Gasoline, Fuel Oils or Alcohol

important in terms of applicability of the proposed solution. This is the underlying reason for us to categorize the four materials into two groups. A related question is “What is the implication of designing a *single network* common to all hazmat types?” It is possible to answer this question by solving a variant of *HND*, where Y_{ij}^m are replaced by Y_{ij} . Under this policy, Link 30 would be closed to H_{1600} shipments as well. This implies that 2,565 petroleum and coal tar trucks will have to take routes different than their minimum exposure path. Taking the argument to the other extreme, the question would be “What is the implication of providing the government agency with the authority and resources to designate *shipment-specific* routes?” In answering this question, one needs to minimize objective function of the outer problem subject to Constraints (2) and (4). The resulting model decomposes into a set of shortest path problems (one for each shipment), where population exposure parameters constitute the arc impedances. The impact of having *no regulation*, on the other hand, can be estimated by minimizing objective function of the inner problem subject to Constraints (2) and (4). The task, again, boils down to solving a set of shortest path problems. Table 2 summarizes the implications of these alternative regulatory schemes.

The level of government intervention increases as one gradually moves from “no regulation” to “shipment-specific” regulations. In Western Ontario,

the implementation of a “single network” policy that does not differentiate among hazmats would result in an average truck travel distance of 354.6 kilometers, which exposes each individual to an average of 68 trucks. If the regulator were to obtain the legislative power and the resources required for a “shipment-specific” regulatory scheme, then the individual exposure would reduce 2.4%. This regulatory change would also lead to a 1.4% reduction in the average travel distance. It is important to note that regulation of hazmat transportation, in any one of the three forms presented in Table 2, does make a significant difference in terms of population exposure.

The extent of government regulation is an issue on which the stakeholders are likely to disagree. Currently, many governments have the authority to close certain road segments to hazmat shipments in their jurisdiction. It is possible that the trucking industry would object to any extension of government

Table 2 Implications of Alternative Regulatory Schemes

	No Regulation	Single Network	Hazmat-Specific	Shipment-Specific
Population Expo. (10^6)	6,557.8	491.7	481.6	481.2
Individual Expo. (trucks)	906.8	68	66.6	66.4
Truck Expo. (people)	82,412	6,179	6,053	6,048
Total Travel (10^6 km)	12.7	28.2	27.9	27.8
Truck Travel (km)	160	354.6	351.5	349.6

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authority to further interfere with their operations. One of the interesting findings of our study is that both parties are better off when minimum exposure routes are used for all shipments. It is quite intuitive that the total population exposure can be reduced by increasing government intervention. Table 2 shows, however, that the total travel distance also decreases as a result of increased level of detail in government regulation. Although this win-win situation seems counterintuitive, it can be explained by the coupling effect of link-based regulation on hazmat shipments.

5. Concluding Remarks

In this paper, we present an analytical approach for the problem of designing a road network for hazmat shipments. Our model represents the distinct decisions made by the regulator and the carriers, as well as their interaction in determining the total cost of transportation and the total transport risk. As we demonstrate in the context of Western Ontario, the proposed framework can be useful not only for identifying the road segments that should be closed to hazmat shipments, but also for evaluating alternative regulatory schemes. The model can also be used for identifying the risk and cost impact of adding new links to an existing road network (e.g., the Quebec government is considering the completion of Highway 30, which will allow trucks to avoid passing through the heavily populated island of Montreal).

We approached the problem from a long-term perspective in developing the proposed hazardous-network design model. Note that our problem parameters include the annual number of trucks between each origin-destination pair and the population census data. From an operational viewpoint, it is highly probable that the shipments are not uniformly distributed throughout the year. Moreover, there can be significant differences in the population of each census subdivision between the daytime and the nighttime. Based on the nature of these variations, a regulator may find it sufficient to impose time-based curfews on some road links, rather than completely banning their use by the hazmat carriers (i.e., a 24-hour curfew). It is conceivable that a judicious choice of time-based curfews will lead to significant reductions in transport risk. There are two major challenges in implementing this approach. First, there is a methodological challenge. Cox and Turnquist (1986) developed a basic model to find the truck departure time for a given route that minimizes the delay due to curfews. Nozick et al. (1997) extended the basic model to also incorporate time-varying arc impedances. Optimization of time-based curfews in a regulator's jurisdiction, however, requires further extension of these models to a multiple shipment setting, which is nontrivial. Second, and perhaps more

important, the time-based variations in the problem parameters are not usually included in the readily available data sets, which would require massive data collection efforts in a real-life application.

Assessment of the minimum possible transport risk in a region is traditionally based on the assumption that the minimum risk route would be used for each shipment. Carriers, however, would normally use the shortest paths on the road network available to them. Thus, our framework also constitutes a means for estimating the margin of error in the traditional risk-assessment methods. When the minimum exposure routes are used for all shipments in Western Ontario, the average travel distance for a hazmat truck is 349.6 kilometers (Table 2). On a road network that is defined as the union of these minimum exposure routes, however, the carriers would be able to reduce this average to 348 kilometers by using shorter routes. As a result, the actual population exposure would be 5% higher than the level of exposure estimated by the traditional minimum exposure model.

Our results indicate that significant reductions in exposure risk can be achieved in Western Ontario through government intervention in the route choices of carriers. Note that the price tag of these risk reduction measures would be at least a 100% increase in the total cost of transportation. Clearly, it is unrealistic to expect the trucking companies to bear this additional cost in full. It is equally unacceptable, however, to have the carriers reflect all of the cost increase onto their customers, i.e., the shippers of hazmats and hazardous wastes. Therefore, it is crucial that government's risk reduction efforts include the development of a mutually acceptable mechanism for allocation of the associated costs among the trucking companies, government, and shippers. The structure of such a cost-sharing framework is out of the scope of this paper.

One of the challenges in designing a hazardous network is the use of common road links for different shipments. Clearly, the number of links used for multiple shipments will have to increase as the number of shipments increases. However, location of the origin and destination points and topology of the existing road network are also key factors that reduce the possibility of using an exclusive path for each shipment. In this paper, we present a *link-based* formulation to assist the regulator in identifying the best way to limit the carriers' routing choices. That is, our decision variables represent the status of each road link (i.e., open/closed and used/unused for each shipment). An alternative model for the hazardous-network design problem would be a *path-based* formulation. In such a model, the decisions would be the paths that are open to hazmat shipments and the best path for each shipment. Note that the set of

alternative paths between each origin-destination pair is, in fact, determined by the regulator's link-based decisions. Therefore, the path-based model needs to include a third set of decision variables that represents the availability of each link for hazmat shipments. Naturally, a path would constitute an alternative route for hazmat carriers only if none of its links are closed by the regulator. Although the link-based model proposed in this paper constitutes a more compact formulation, the path-based model would have the additional capability of characterizing the routing alternatives offered to the carriers by the regulator. We believe that such a characterization might prove useful during the negotiations between the two parties. Thus, our immediate research agenda is to implement a path-based formulation in tackling the hazardous-network design problem in Western Ontario.

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