Quantitative Risk Assessment Decision-Support Model for Locating Hazardous Materials Teams

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A risk-based decision-support model is presented for locating hazardous materials (hazmat) teams on a regional road network. The model attempts to minimize the total networkwide risk, while ensuring that the response times to all demand nodes are within an acceptable limit. The relevance of the model as a decision-support tool is demonstrated through a case application to a regional road network in southwestern Ontario. The case study has demonstrated some useful decision-support features of the proposed model concerning issues such as how many hazmat teams should be allocated in a region and where they should be located.

The transportation of hazardous materials (hazmat) poses special risks for population and the environment. Effective planning and location of emergency response can play an important role in reducing these risks.

Emergency response can involve a number of tasks, such as fire fighting, ambulance and police services, and hazmat containment and cleanup. In this paper, the response to accidents involving hazmat is assumed to be delegated exclusively to specially trained and equipped hazmat teams. The U.S. Department of Labor's Occupational Safety and Health Administration defines hazmat teams as specially trained and equipped individuals who manage and control incidents involving a wide range of hazardous materials (*1*).

In many jurisdictions, decisions concerning the establishment and management of hazmat teams are undertaken at the local level (*2*). It is common practice to host such teams within existing fire stations so as to keep initial costs to practical limits.

There is no guarantee that such an approach will lead to the most efficient allocation of resources vis-à-vis minimizing the risk within a region and ensuring that all communities in the region are served to some minimum acceptable standard. Smeby (*3*) indicated that since the 1980s there has been a significant increase in the number of hazmat teams in the United States, with many of these teams being called on to respond only on rare occasions involving hazmat incidents—usually not more than once a year. A number of jurisdictions have begun to question the need for separate hazmat teams at specific locations, suggesting a consolidation of emergency response capability in larger communities.

But many communities have neither the population nor industrial activity needed to justify the placement of a hazmat team. These communities, however, may be situated in proximity to routes where large amounts of hazmat are transported. Populations residing in these communities would be exposed to risk, and this risk would need to be considered in the location of hazmat teams. A comprehensive hazmat response plan is required to ensure that risk to the entire region—all communities—is taken into account in the location of hazmat teams (*4*).

This research has two primary objectives: (*a*) to develop a risk-based decision-support model for locating hazmat teams on a regional road network and (*b*) to illustrate the practical features of the decision-support model through a case study application. A case study involving the location of hazmat teams on a regional road network in southwestern Ontario is presented. The goal is to illustrate how the proposed model can help address various practical questions that planners and decision makers face: How many hazmat teams should be located regionwide? Where should they be located? What are the risks for the region as a whole and at individual locations? What are the implications of closing certain teams or moving them from one location to another?

CURRENT PRACTICE IN HAZMAT TEAM LOCATION

The process of locating hazmat teams is rather subjective and may lead to inappropriate allocation of resources. Frequently, hazmat teams are located in areas of high population concentration (larger communities in the region), at the expense of underservice to marginal locations that are also exposed to hazmat risks.

Much of the academic research in the area of transportation of hazmat has focused on the problem of hazmat routing and post-accident management (*5, 6*). In many cases, research in the area of hazmat teams' location has pertained to specific types of hazmat with unique characteristics. For example, List (*7*) and List and Turnquist (*8*) proposed a model for locating emergency response teams based on the risks posed by radioactive waste.

While actual practice in locating hazmat teams favors a location at population concentration, many researchers have used either minimum distance or minimum response time as location criteria (*9–11*).

Both current practice and past academic research consider only some factors and ignore other important ones that affect hazmat accidents risks. It is clear that there is a lack of systematic risk-based approach for locating hazmat teams on regional bases. Yet such an approach is needed to ensure that hazmat teams are located in a cost-effective and practicable manner.

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HAZMAT LOCATION DECISION-SUPPORT MODEL

This section presents a risk-based decision-support model that can be used to locate hazmat teams on a regional road network. The developed model consists mainly of two components: (*a*) a time-dependent quantitative risk assessment (QRA) model that estimates the risk for the entire network and at its specific nodes and (*b*) a location optimization model for locating hazmat teams on the network based on the risk involved.

"Risk" is defined as the expectation of fatalities that result from the transportation of a certain volume of different types of hazmat on different links of the network. This current research uses the number of fatalities as a risk measure. Other consequence measures such as evacuation area, cleanup costs, and environmental impacts can be equally used in the proposed modeling framework.

Risk consists of two fundamental components: (*a*) the frequency of accidents involving hazmat and (*b*) their consequent damages (number of fatalities). Within the scope of this research, the interest is only in accident-induced risk. The frequency of hazmat accidents is a function of vehicular accident rates, breach of containment, and release rates and volumes. Consequence damage, on the other hand, is a function of type of hazmat, amount and rate of release, hazard area, exposure or response time, population distribution, and other factors (*12*).

The location model introduced in this paper minimizes network-wide risk within a region while ensuring that the maximum response time at more remote locations does not exceed some preset thresholds.

Time-Dependent Quantitative Risk Assessment Model

In the time-dependent QRA, response times from hazmat teams are a direct input to the process of estimating consequences caused by each hazmat accident. In general, the longer a hazmat team takes to reach an accident location, the more severe the consequences, because a longer response time usually means larger quantities released. In addition, a longer response time would result in higher ignition probability for flammable substances and longer exposure time for toxic materials.

Because the QRA model is time dependent, risk estimates will differ for different locations of hazmat teams. Time-dependent QRA is used to estimate the risks resulting from different hazmat teams' location strategies, which are then used as an input to the location optimization model, to determine the optimal locations for the hazmat teams. Figure 1 illustrates the model framework for locating hazmat teams in a region.

For practicality, the time-dependent QRA model is assumed to be discrete, that is, demand for service occurs only at nodes and accidents occurring on links are aggregated to the nearest nodes. The hazmat teams can be assigned only to a predefined set of nodes, and no locations are permitted on links. Network links serve only as connections between nodes with estimated travel times.

One might consider a regional highway network as shown in Figure 2. The network is represented by a number of directed links and nodes G (N, A), where N is a set of network nodes, $N = \{j, j = 1, 2, 3, \ldots, nd\}$ and A is a set of network links, $A = \{l, l = 1, 2, 3, \ldots, nm\}$. The nodes represent population centers as well as highway intersections and intermediate point on long links.

A potential demand node j represents a node that may experience a hazmat accident-induced release. The released material escapes to the surrounding environment, forming a hazard area. Within the hazard area, there are different levels of hazmat concentrations starting with the highest concentration near the release node and decreasing outward. Population within this hazard area will suffer certain health-related consequences.

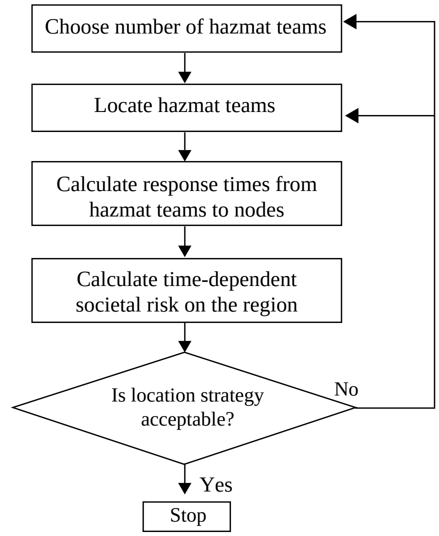

FIGURE 1 Model framework for locating hazmat teams.

It is assumed that the nearest hazmat team located at node i will respond to the release at node j within a response time T_{ij}.

Over the network, there exists a set of nf fire stations, denoted by F, where $F = \{i, i = 1, 2, 3, \ldots, nf\}$. The fire stations are assumed to exist only on a subset of network nodes (i.e., $F \subset N$), and these fire station nodes are the only sites that can host a hazmat team. The number of hazmat teams to be allocated on the network is denoted as np, where $np \le nf \le nd$.

Consider k different types of hazmat and r different types of releases, and then each (k, r) pair represents a different release scenario.

For a given hazmat type, k, the frequency of release of type r at node j is given by Frq_j^{kr}. Csq_{ij}^{kr} denotes number of fatalities at node j that would result from release scenario (k, r) when the nearest hazmat team located at node i responds to the release.

The two risk components are combined to calculate R_{ij}^{kr}, the expectation of fatalities at node j when response is provided by a hazmat team at node i for hazmat type k and release type r, such that

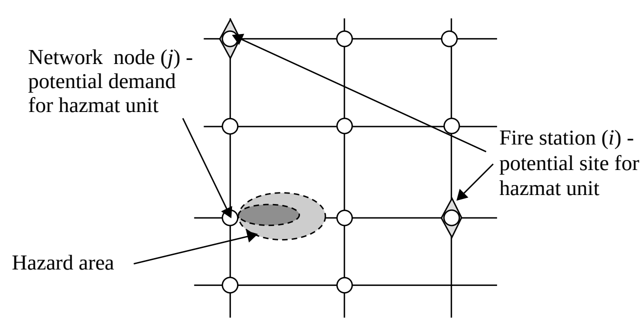

FIGURE 2 Schematic of highway network and hazmat team locations.

$$R_{ij}^{kr} = Frq_j^{kr} * Csq_{ij}^{kr} \tag{1}$$

Frq_j^{kr} can be estimated either from statistical prediction models or from analysis of historical hazmat accidents and releases. Consequence analysis usually involves a number of consequence models for different hazmat types and release scenarios.

For all types of hazmat and release scenarios (k, r), the risk estimate from Equation 1 can be combined to yield the total expected number of fatalities at location j, where the nearest hazmat team is located at i, such that

$$R_{ij} = \sum_k \sum_r R_{ij}^{kr} \tag{2}$$

Location Optimization Model

In the proposed location model, the objective is to find the optimal location of the *np* hazmat teams among the *nf* possible candidate nodes, to minimize the total network risk. At the same time, one ensures that response times at any marginal nodes do not exceed some preset threshold ($T_{\max}$). It is assumed that the nearest hazmat team located at node i will respond to the release at node j in a time equal to response time T_{ij}.

For a given location strategy, there is a unique measure of total network risk over all nodes, such that

$$R = \sum_j \sum_i R_{ij} * z_{ij} \tag{3}$$

where z_{ij} is a decision variable that equals 1 if node j is covered by a hazmat at node i and zero otherwise.

The location problem of our interest can now be formally stated as the following:

$$\min R = \sum_j \sum_i R_{ij} * z_{ij} \tag{4}$$

subject to

$$z_{ij} = \begin{cases} 1 & \text{if node } j \text{ is covered by a team at node } i \\ 0 & \text{otherwise} \end{cases} \tag{5}$$

$$N_j = \{i; R_{ij} \le R_{\max}, \text{and } T_{ij} \le T_{\max}\} \tag{6}$$

$$\sum_{i \in N_j} z_{ij} = 1 \qquad \text{node } j \text{ must be covered by one location within } N_j \text{ set} \tag{7}$$

$$y_i = \begin{cases} 1 & \text{if a hazmat team located at } i \\ 0 & \text{otherwise} \end{cases} \tag{8}$$

$$0 \le z_{ij} \le y_i \qquad \text{no coverage from } i \text{ to } j \text{ unless a facility exists at } i \tag{9}$$

$$\sum_i y_i = np \qquad \text{total number of hazmat teams to be located} \tag{10}$$

The foregoing problem is generally known in the literature as the *P*-median problem with maximum cost constraint (*13*). The problem has been proved to be in the nondeterministic polynomial time class (NP hard), which means that no exact polynomial algorithm is known yet to solve this type of problems. Heuristic algorithms, including genetic algorithms, are usually used to reach a reasonable near optimal solution.

The foregoing model has been implemented with Visual Basic as a Windows application program. The following is a list of steps that the user can take to address various decision-support problems:

1. Import road network data including nodes and links.
2. Specify the available data and information. Accordingly, the program will direct the user to different calculation routes as follows:
   a. For network link travel times, the user has two options: use direct travel times on different links or let the program calculate travel time based on link length and posted speed;
   b. For hazmat traffic volumes, the user has the following four options: (1) specify hazmat volumes in the annual average daily traffic (AADT) field of link record for each hazmat type, (2) provide hazmat traffic volumes as a total AADT for all types of hazmats on each link, (3) use total truck volumes on each link, and (4) use total vehicles AADT on each link. With these options, the user has the freedom to study only the effects of different types of hazmats, specify certain routes for certain hazmat types, or examine the movement of all hazmats on the network.
3. Calculate the shortest path using available information. With this function, the user has the option of using his or her own estimates of dispatch and mitigation time.
4. Calculate the potential risk at different network nodes. The user has the option of either providing accident and release rates or using default values.
5. Have the ability to allocate a given number of hazmat teams to the network nodes and examine the resulting risk
6. For small networks, have the ability to determine all possible locations for a certain number of hazmat teams using enumeration, and hence determine the optimal location solution.
7. For large networks, have the ability to determine a set of good solutions to choose from, using genetic algorithms.
8. Have the ability to increase or decrease the number of hazmat teams to be located and examine the resultant risk and optimal location.

CASE STUDY

This section uses a simple network problem to illustrate the application of the developed model and associated solution. The objective of the case study is to investigate several issues concerning the locations of hazmat teams on a network, including the following:

1. Risk implications of the current location of the hazmat teams in the southwest Ontario region,
2. Effectiveness of the current strategy as compared with an optimum location over the network for the same number of teams,
3. Effectiveness of both current and optimal location strategies when fewer hazmat teams are located, and
4. Sensitivity of risk to various hazmat team closure and relocation options.

Data Inputs

Transport Canada defines more than 3,000 regulated types of hazardous materials (dangerous goods). For purpose of demonstration, three representative types of hazmat were selected: (*a*) ammonia to represent pressured liquefied toxic gases, (*b*) propane to represent pressure liquefied flammable gases, and (*c*) gasoline to represent flammable liquids. As a group, these classes of hazmat represent over 70% of all types of hazmat transported in Canada.

At atmospheric pressure and temperature, ammonia, propane, and other liquefied petroleum gas exist in a gas state. They are usually pressure liquefied and vaporize under atmospheric pressure.

Gasoline and other liquids are usually transported at atmospheric temperature and pressure. When gasoline is spilled, a portion of it will evaporate and form a flammable vapor cloud above the liquid pool.

Four release scenarios are investigated in this case study: large spill, small spill, large leak, and small leak. A spill is equivalent to an instantaneous release usually associated with a catastrophic failure of the containment system. The duration of a spill could be brief, lasting up to 30 min. A leak, on the other hand, involves a continuous release usually caused by a minor failure of the containment system. Leaks can take up to several hours.

In Figure 3 is a geographic information system representation of the selected case study area with the different node numbers. The road network is represented as a directed graph with 32 nodes and 92 links. Currently, the area is served by 12 fire departments located at Paris, Brantford, Oakville, Burlington, Milton, Hamilton, Drumbo, Cambridge, Kitchener, Guelph, Mississauga, and Woodstock. Of these 12 departments, 4 have hazmat teams, namely, Mississauga, Hamilton, Burlington, and Cambridge.

It was assumed that emergency vehicles would suffer a 20% delay from free-flow travel time. Dispatch and mitigation times were set to 3 and 5 min, respectively. Wind speed of 17.5 km/h blowing from the west was assumed with D stability class and a temperature of 21°C.

Population distributions for the region were obtained from 2001 Canada census data. Estimates of percentages of different hazmat types transported in Canada were as follows: 64.61% for flammable liquids, 3.58% for flammable liquefied gases, and 0.98% for toxic liquefied gases (*14*).

Annual average daily truck traffic (AADTT) for links was obtained from Transport Canada, Ontario Region (*15*), with a total freight movement of 2,147,274 truck km per year.

The 1999 National Roadside Study (*16*) suggested that hazardous materials accounted for 9.85% of all truck traffic (by ton). The volumes of hazmat materials transported on different links of the case study network were estimated on the basis of a fixed percentage of the total truck volumes. AADTT was used to estimate the expected number of hazmat accidents on each link of the network.

Estimates of Release Frequencies

Table 1 shows average release amounts and release probabilities for different release scenarios. Average release amounts for different release scenarios were obtained from Transport Canada [Dangerous Goods Accident Information System (DGAIS)] for 1988 to 2000.

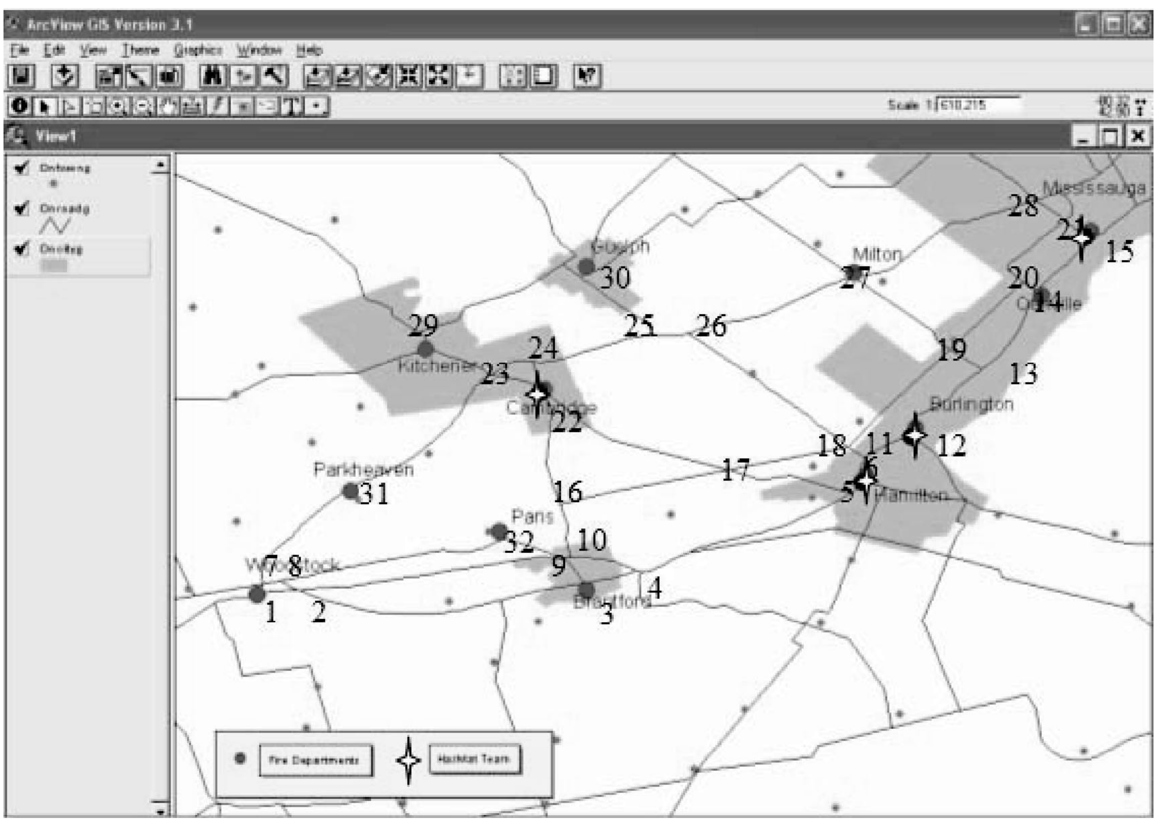

FIGURE 3 Geographic information system representation of southwestern Ontario case study area.

TABLE 1 DGAIS Average Release Rates (kg/min) and Probabilities Given an Accident (%) for Different Release Scenarios

Scenario	Rate and Probability	Propane	Ammonia	Gasoline
Small spill	Release rate (for up to 30 min)	4.7	9.0	12.8
	Release probability (%)	0.55	0.44	0.73
Large spill	Release rate (for up to 30 min)	645	336	626
	Release probability (%)	1.09	0.87	1.34
Small leak	Release rate (for up to 120 min)	0.6	0.06	1.9
	Release probability (%)	0.24	0.08	0.12
Large leak	Release rate (for up to 120 min)	121	35	92
	Release probability (%)	0.10	0.19	0.30

An overall large tanker truck accident rate of 0.924 accident per million vehicle kilometer (mvkm) was assumed, based on the Ontario Accident Data system for 1997 to 1999 (*Reference Manual of the Transport of Dangerous Goods Through Road Tunnels, Quantitative Risk Model,* version 002; unpublished intermediate report from the Organisation for Economic Co-operation and Development, 1999).

Release probabilities were obtained by estimating the conditional probability of release given an accident using DGAIS data as given in the aforementioned reference manual. These estimates represent the weighted average of a number of accident scenarios for Ontario, such as collisions, overturns, and others.

Combining release probabilities from Table 1 with the accident rate yields the frequency of release on a per mvkm basis.

Analysis of Location Strategies

In this section, five location strategies are considered: (*a*) relocating existing hazmat teams, (*b*) reducing the number of hazmat teams, (*c*) maintaining the level of network risk subject to the closure of one team and reallocation of another, (*d*) increasing the number of hazmat teams, and (*e*) exploring nonfire stations as candidate locations.

Strategy 1. Relocating Existing Hazmat Teams

Currently, there are four hazmat teams located at Nodes 6, 12, 15, and 22. If the same four teams are located according to the total network risk minimization criterion, the optimal location will be at Nodes 6, 14, 22, and 27. Table 2 summarizes the total network risk, maximum node risk, and maximum node response time estimates for the current and optimal allocations of four hazmat teams.

The authors noted that total network risk has been reduced by 6% for the optimal location. This 6% corresponds to a reduction of 0.44 fatality every 100 years for the same volume of hazmat movements. The four nodes suggested by the optimal solution differ significantly from the current location (one node in common). Both location strategies have a maximum response time of 58 min.

Figure 4 illustrates the relationship between total network risk and all possible location solutions, in increasing order. The current solution (Nodes 6, 12, 15, 22) yields a total network risk within the best 6% of all solutions. The optimum solution, by definition, gives rise to the lowest network risk.

For this case study, results fall within a fairly narrow band. Although the best location is about 40% better than the worst one, the difference is less than 5 fatalities per 100 years. On the basis of only the number of fatalities, and given the uncertainty in estimating different risk input parameters, decision makers might want to make their decisions on factors other than the estimated hazmat transportation risk, for example, economical or managerial factors.

Strategy 2. Closing One of the Existing Hazmat Teams

This section investigates the possibility of closing one of the hazmat teams and how such a decision will affect total risk estimate. Table 3 shows a comparison between the location of the current four teams and the proposed three hazmat teams.

The best location to close is at Node 6, which will result in the lowest increase in total risk of 2.9%. However, Node 6 represents the city of Hamilton. Yet the hazmat team at Hamilton is responsible for responding to other non-transport-related hazmat incidents within the city, and it is therefore impractical to close. The next

TABLE 2 Risk and Maximum Response Time for Current and Optimal Locations of Four Hazmat Teams

	1st	2nd	3rd	4th	Total Risk (fatalities/year)	Max Risk (fatalities/year)	Max Response Time (min)
Current locations	6	12	15	22	0.0710	0.0105	58.8
Optimal locations	6	14	22	27	0.0666	0.0107	58.8

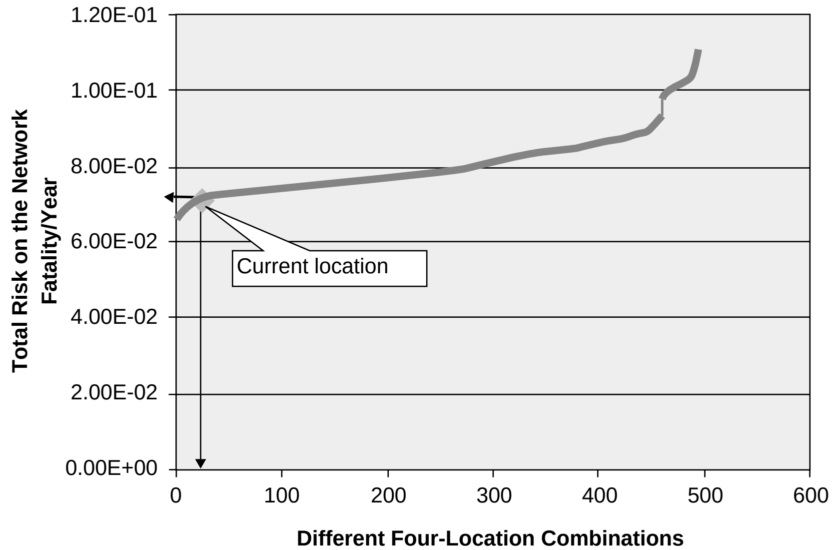

FIGURE 4 Relationship between all possible location solutions and total risk in region.

choice is to close the team at Node 12, Burlington, with an increase in total risk of 3.9% from current value. In this case, given the population involved, the closure of Burlington instead of Hamilton would probably be recommended.

Strategy 3. Maintaining Network Risk While Closing One Team and Reallocating Another

Keeping the teams at Nodes 6 and 22, closing the team at Node 12, and relocating Node 15 to Node 14 will result in a maximum risk of 0.07279 fatalities a year and a maximum response time of 59 min. The new locations are at Nodes 6, 14, and 22, corresponding to cities of Hamilton, Oakville, and Cambridge. This change will result in a slight increase in maximum network risk, with the same maximum response time.

Strategy 4. Increasing the Number of Hazmat Teams

Figure 5 shows the relationship between optimal minimum total risk and number of hazmat teams on the network. Increasing the numbers of hazmat teams as expected results in a decrease in total network risk. The rate of reduction in network risk is greatest up to five hazmat teams, after which the relationship flattens out. If the number of hazmat teams is a reflection of cost, it is suggested that there be four to five teams for this case study region.

Strategy 5. Exploring Nonfire Stations as Candidate Locations

Previously, the authors restricted the location of hazmat teams to those nodes that currently housed fire stations. This restriction limits the ability to obtain solutions that may further minimize risk. Table 4 summarizes model results for locating hazmat teams with no limitation on a host node, with or without a fire station. For comparative purposes, Table 4 also includes the current four-team strategy. These solutions are obtained by considering all possible combinations of locations using the model.

Adopting either the restricted or unrestricted location strategy yields a reduction in total network risk. As expected, the lowest risk is associated with the unrestricted allocation of four hazmat teams (over 5% reduction). The unrestricted strategy appears to be espe-

TABLE 3 Results from Proposed Loss of One Existing Hazmat Team

	1st	2nd	3rd	4th	Total Risk (fatalities/ year)	Max Risk (fatalities/ year)	Max Response Time (min)	Change in Total Risk (%)
Current	6	12	15	22	0.0710	0.0105	59	
1st alternative	6	12	15		0.0771	0.0105	76	8.6
2nd alternative	6	12		22	0.0830	0.0133	59	16.9
3rd alternative	6		15	22	0.0738	0.0105	59	3.9
4th alternative		12	15	22	0.0730	0.0105	59	2.9

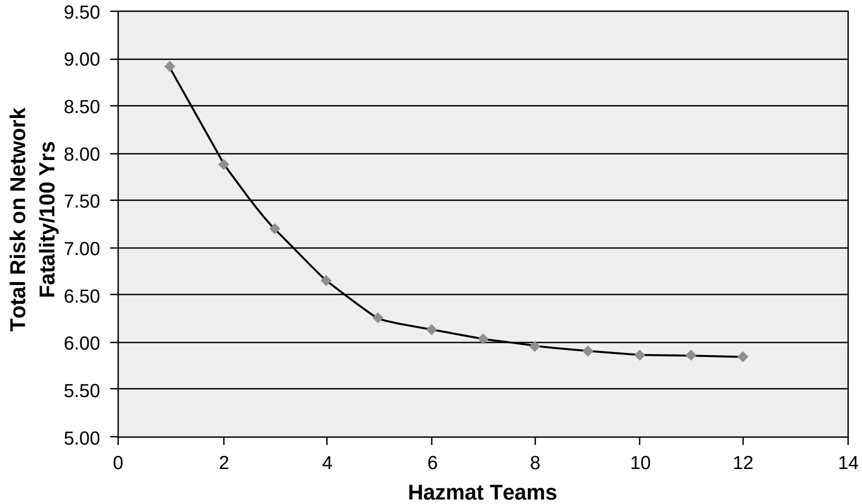

FIGURE 5 Relationship between total risk and number of hazmat teams on road network.

cially desirable, based on a much lower maximum risk at the marginal node. All strategies satisfy the maximum 60-min response time and hence are feasible.

Notwithstanding the fact that the unrestricted strategy yields the lowest risk, there is a practical issue as to whether it would be possible to locate hazmat teams at locations that are not currently served by fire stations. On the basis of this practical consideration, adapting a restricted four-hazmat-team location strategy for this region would be recommended.

Investigating Location of Teams on Network

This section uses the same case to investigate the effects of the number of hazmat teams on the resulting networkwide risk and maximum response time. The investigation considers four scenarios by varying the total number of hazmat teams from one to four.

One Hazmat Team

If one hazmat team is used, the best risk-minimization option is to allocate the team to Oakville (Node 14) with a total risk of 8.9 fatalities per 100 years. This location solution does not satisfy the maximum response time restriction of 60 min at some remote locations (nodes). For example, with this solution, the response time to Woodstock (Node 7) is 109 min, which is almost double the maximum acceptable response time.

When the main concern is the maximum response time on the region, the best location is Cambridge (Node 22, near the geometric center of the network). This solution results in a total risk of 10.5 fatalities per 100 years. The corresponding maximum response time is 85 min (Node 20, near Oakville), which is still not acceptable. The authors note that for a one-team scenario no solution yields a maximum response time less than 60 min.

Two Hazmat Teams

For a two-team scenario, the best solution is to locate one team at Hamilton (Node 6) and the other at Oakville (Node 14), which yields a total network risk of 7.89 fatalities per 100 years and a max response time of 76 min (Woodstock, Node 7). Given the maximum response time standard of 60 min, this solution is still not acceptable.

However, moving these two hazmat teams to other nodes can result in an acceptable solution. For example, moving the hazmat team from Hamilton (Node 6) to Cambridge (Node 22) results in total risk of 7.94 fatalities per 100 years and a maximum response time of 59 min. After all possible solutions for the two-hazmat-team scenario were considered, this solution yielded the lowest network risk subject to an acceptable maximum response time.

Three Hazmat Teams

The optimal location solution for three hazmat teams consists of Oakville (Node 14), Hamilton (Node 6), and Milton (Node 27). This

TABLE 4 Comparison of Location Strategies for Four Hazmat Teams

Strategy	Location (nodes)				Total Risk (fatalities/year)	Max Risk (fatalities/year)	Max Response Time (min)
Current	6	12	15	22	0.0710	0.0105	59
Restricted to fire stations	6	14	22	27	0.0666	0.0107	59
No restriction	11	21	23	27	0.0629	0.0074	59

solution yields the lowest network risk of 7.19 fatalities per 100 years. The max response time for this solution is still not acceptable, valued at 76 min (Woodstock, Node 7). However, moving the hazmat team from Milton (Node 27) to Cambridge (Node 22) would result in an acceptable maximum response time of 59 min. This is achieved, however, at a higher network risk of 7.28 fatalities per 100 years.

Four Hazmat Teams

If four hazmat teams are available, they should be located at Oakville, Hamilton, Milton, and Cambridge to minimize the total networkwide risk. Different from the previous scenarios, this solution is also feasible, for the resulting maximum response time is 59 min. Total network risk for this solution is 6.66 fatalities per 100 years. Compared with the current four-team solution, the model suggested a different solution with a 6% reduction in total risk and a same maximum response time of 59 min.

CONCLUSIONS

In this paper, a risk-based decision-support model was presented for locating hazmat teams in a region. The model was intended to provide a practical platform for evaluating the trade-offs between system costs (number of facilities allocated), total network risk and individual node risk, and response time thresholds. The case study has demonstrated some useful features in resolving questions, such as how many hazmat teams should be allocated in a region and where they should be located. It also provided insights into issues related to team closure and relocation. The work represents the initial effort toward the development of a full-fledged risk-based decision-support tool. Future work will focus on refining and extending the proposed model in the following directions:

- The proposed model could be extended to explicitly consider the costs of installing new hazmat teams or relocating existing hazmat teams. As a result, the location optimization model can be modified to consider the number of hazmat teams to be allocated as a decision variable.
- The proposed model assumes that hazmat teams are set up only for dealing with hazmat accidents on highways. In reality, hazmat teams are planned to undertake multiple tasks, including hazmat incidents both on highways and at fixed facilities such as manufacturing plants and school labs. As a result, a comprehensive hazmat resource allocation system must take into account the benefits of responding to hazmat incidents other than those occurring on highways. Future research needs to address development of models for estimating risks associated with non-transportation-related hazmat incidents.
- The hazmat resource allocation problem was cast to a discrete network model in which incidents were assumed to occur at nodes only, and incidents on a link were aggregated to the ending nodes of the link. The implications of the aggregation process need to be further investigated.
- The proposed model follows the framework of QRA in which benefits are measured according to risk. Risk in this context was defined as the expected fatalities that could be caused by hazmat incidents. Two issues need to be investigated further. First, other risk measures such as environmental damage may also be important and need to be considered in locating hazmat teams. Second, uncertainty in incident frequency and consequence should be estimated, and those effects on location solution be evaluated.

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