Locating Emergency Response Capability for Dangerous Goods Incidents on a Road Network

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A model is presented for locating emergency response capability on a road network. The process is treated as a minimum set covering problem, in which a minimum acceptable level of response is assigned to all nodes on the network. The demand for response capability at these nodes is a function of the potential for dangerous goods spills and the associated risks to nearby population and property. Response capability represents a general measure of the ability of the emergency response system to serve the needs of a specific location, and could reflect any number of actual response facilities, such as fire stations. The model is applied to a rural road network in southwestern Ontario for a given distribution of risks associated with dangerous goods spills. Each assignment of emergency response capability on the road network is assessed in terms of changes in external service standards and location policies. The model can be applied iteratively to increasingly more detailed representations of the same network.

A critical factor in the seriousness of a spill involving dangerous goods is the time interval between the initial release and the start of containment procedures (*1, 2*). This factor is greatly affected by the allocation of emergency response units in relation to potential spill sites on a transportation network. The problem is especially significant for the transport of dangerous goods, where spills may take place at considerable distances from the nearest emergency response unit.

In general, emergency response units tend to be located near population concentrations. In Ontario, Canada, more than 20 percent of all fire stations are situated in larger municipalities with more than 50,000 inhabitants (*3*). Police and ambulance services are characterized by similar concentrations in larger municipalities. Dangerous goods spills do not always take place within the boundaries of larger municipalities, however, but may occur at any point in the transportation network where these types of commodities are shipped. In Canada, as in many other countries, much of the road and rail network is situated in sparsely populated rural areas at great distances from the nearest responder. Spills that take place in these areas are subject to unacceptable response delays and greater damages.

Emergency response systems tend to be multipurpose in nature, such that the containment of dangerous goods spills is only one of many tasks requiring emergency response. The location of emergency response units based solely on proximity to potential spill sites is impractical, since it could result in very high service and infrastructure costs for other service aspects of the response system—for example, fire protection. The essential consideration in locating emergency response on the basis of spill potential should be the provision of a minimal level of response capability, in case a spill takes place.

The primary objective of the model discussed in this paper is to establish a minimum coverage framework for locating emergency response capability on a rural road network. Within the context of this study, the term "response capability" refers to any number of actual response facilities, such as fire or police stations, at specific points on the network. Points on the road network where response capability is assigned are referred to as "response capability centroids." The minimum coverage algorithm for establishing response capability centroids can be applied iteratively on increasingly detailed representations of the network. The sensitivity of the location pattern to changes in external location criteria and service standards can be assessed. An application of the model to a rural section of the highway network in Ontario, Canada, illustrates the process.

METHODOLOGY

Conceptual Basis of the Network Location Covering Problem

An approach suggested by Toregas et al. (*4*) and Church and Meadows (*5, 6*) provides a solution for the network location covering problem by placing facilities on a network in terms of a preselected service constraint. This constraint is usually based on the maximum distance that a respondent would have to travel to the most distant user within the respondent's range of jurisdiction; it represents the lowest acceptable performance of the system as applied to each potential user on the network. The network location algorithm, based on a minimum coverage criterion, permits a decision maker to establish a minimum level of service for unique and infrequent events, such as a dangerous goods spill. It also ensures that no potential spill

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site on the network is situated farther away than a critical time interval from initial response.

Three basic assumptions are required for this algorithm (*4*):

1. Potential spill sites must be represented as a finite set of points on the network (*Ni*), usually corresponding to network intersections but in some cases also corresponding to the location of major population concentrations in the region. Candidate locations for emergency response capability must also be a finite set of points (*Nj*). The set of spill sites is a subset of candidate locations for response capability assignment, such that $Ni < Nj$. In this study, candidate locations for emergency response capability are not limited to network nodes but may also include any number of points on the network links.
2. Maximum acceptable response time or distance is selected exogenously for all potential spill sites on the network (*Sk*). To satisfy the coverage constraint, at least one candidate site for response capability must be located within *Sk* units of all spill sites *Ni*. The term *Sk* is viewed as a minimum performance criterion, which can be evaluated in a trade-off function that includes monetary as well as other risk considerations.
3. As each point in the candidate location set *Nj*, response capability is perceived in a binary fashion; that is, this capability is either present (assigned 1) or absent (assigned 0).

Based on these assumptions, the allocation of response capability can be reduced to a problem of covering each potential spill site from at least one point on the network within a maximum acceptable response distance of *Sk* units. The service area associated with each response centroid consists of any number of population centers, or network nodes, that are situated within *Sk* units.

Basic Model Components

An outline of the model for locating emergency response capability on a network is illustrated in Figure 1. The framework consists of three basic components: network specification, network location, and evaluation and sensitivity analysis.

Network Specification

Initially, a road network is defined as a series of links and nodes situated at various distances from one another. For the purpose of this model, potential network spills of dangerous goods are confined to nodal locations. Accordingly, all incidents taking place on each link are assigned to the nearest node.

Criteria that reflect the nature and intensity of calls for service at each node of the network must be established. These criteria represent the levels of potential demand placed on the response system for all types of emergencies.

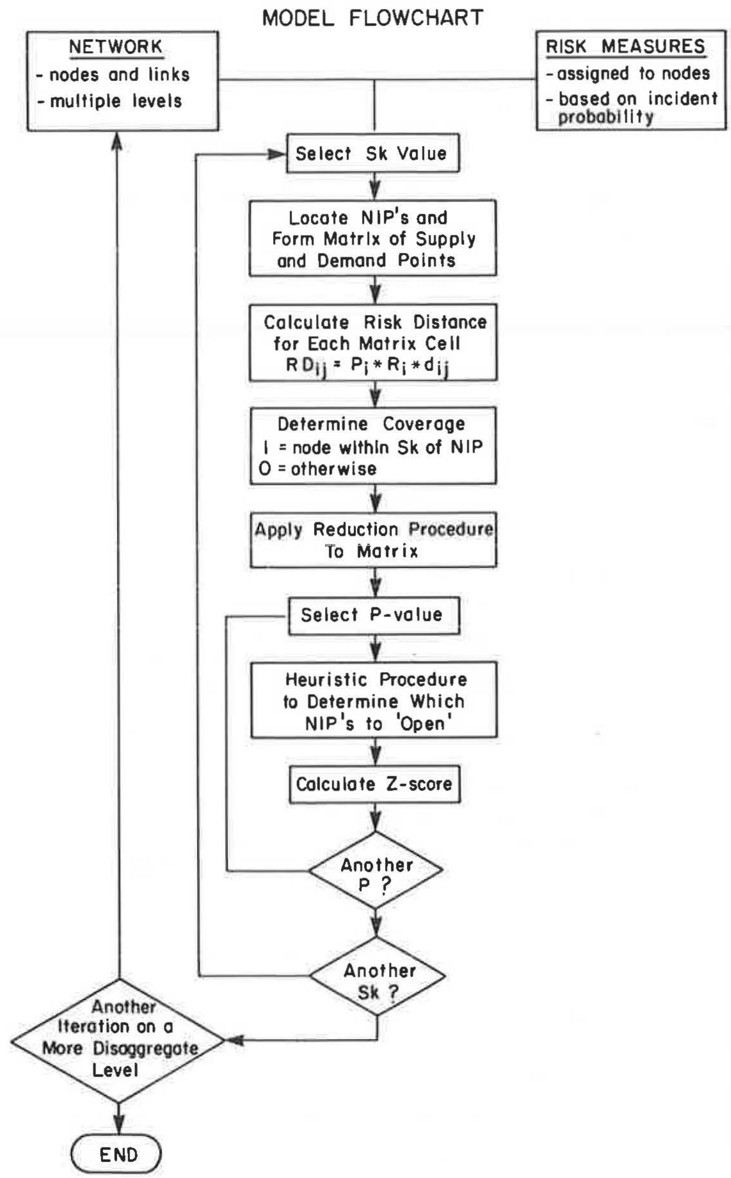

FIGURE 1 Model framework for locating emergency response capability.

For the potential spill of dangerous goods, this criterion has been defined as a simple risk expression of the form:

$$R_i = I_i^k \alpha_k P_i^k \tag{1}$$

where

I_i^k = probability of an incident at node i involving dangerous good k;
α_k = probability of a release of dangerous good k, given a prior incident; and
P_i^k = population "at risk" at node i from the release of dangerous goods k.

Simple risk expressions such as Equation 1 can be modified to reflect a range of risk mitigating factors (*7*). Equation 1 provides an indication of the level of response capability required by node *Ni*, measured in terms of the expected

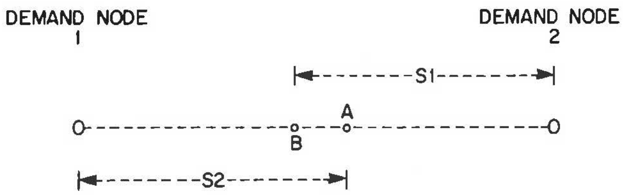

FIGURE 2 Location of NIPs for two nodes and a connecting link (*6*, p. 361).

number of people affected by a potential spill of dangerous goods.

For a given maximum response time or distance (*Sk*), it is possible to establish a finite set of candidate points (*Nj*) for locating response capability. The finite set of candidate points for locating response capability are referred to as network intersect points, or NIPs. Figure 2 illustrates the location of NIPs for two nodes and an interconnecting link. The two points A and B are network intersect points, since A is a point on the link that is *S*2 units from node 1 and B is *S*1 units from node 2. In this figure, the set of NIPs comprise the original nodes (1 and 2) and the intermediate points, A and B. As noted by Church and Meadows (*6*), if node 2 reflects a higher level of risk than node 1, then point A would be an optimal placement for emergency response, satisfying the maximum distance constraint *Sk* for both nodes.

The set of NIPs for a more extensive network is obtained through the application of standard tree building techniques. These NIPs form a choice set of candidate locations for response capability from which a limited number are selected for actual assignment. An integral part of this process is the network location covering problem.

Network Location Covering Problem

A number of techniques are available for solving the network location covering problem. Hakim (*8*) developed the classical *p*-median approach, through which facilities are placed on a network so that the average distance or travel time on the network is minimized. This approach was applied by Daskin (*9*) in a study of response to medical emergencies. The *p*-median approach is best suited for problems where a single dominant criterion is considered in the location decision. Locating response capability on the basis of minimum average time to potential spill sites is inappropriate, since this approach ignores other and, in some cases, more important considerations in the overall response program.

Toregas et al. (*4*) modified Hakim's *p*-median approach by including a maximal distance constraint, so that decision makers can select a minimum level of facility utilization for a specific type of call. In the modified *p*-median approach, response distance or time on the network is not minimized; thus the resultant pattern of response capability is not optimal with respect to spill sites. The primary consideration here is that a critical level of response is present for all potential spill sites in case an incident takes place. This critical level of response is expressed as the maximum acceptable distance (or time) to each potential spill site.

The inclusion of a maximum distance constraint results in a mixed integer programming problem. Toregas et al. (*4*) suggest using linear programming techniques to solve this problem. Church and Meadows (*6*) modified the Toregas procedure for the situation, where the set of NIPs is not coincident with the set of demand nodes on the network. This results in a 0-1 programming algorithm of the form:

$$\text{Min } Z = \sum_{i=1}^{Ni} \left[\sum_{j} R_i d_{ij} \right] \bar{y}_i \tag{2}$$

subject to

$$\sum_{j \in N_i} x_j + y_i \geq 1 \qquad \text{for all } i \in N_i \tag{3}$$

$$\sum_{j \in N_j} x_j = p \tag{4}$$

$$x_j = (0,1) \qquad \text{for all } j \in N_j \tag{5}$$

$$y_i = (0,1) \qquad \text{for all } i \in N_i \tag{6}$$

where

x_j = 1 if a response unit is located at NIP *j*,
x_j = 0 otherwise;
N_i = $(j \in N_j | d_{ij} \leq S_k)$, the set of response unit sites eligible to provide coverage to demand node *i*;
y_i = 1 if demand node *i* is not covered by a response unit within *Sk* distance,
y_i = 0 otherwise;
p = the number of response capability units assigned networkwide; and
RD_{ij} = $R_i d_{ij}$ (risk-distance for node pair *ij*).

Equation 2 suggests a minimization of the total weighted risk-distance (RD_{ij}) for each demand node *i* to the nearest open capability point *j*. Risk-distance is defined as the product of the distance from potential spill site *i* to response capability point *j*, and the risk associated with dangerous goods spills at node *i* (as in Equation 1). Constraint Equation 3 ensures that all demand nodes are fully assigned. Constraint Equation 4 ensures that only *p* capability units are assigned regionwide. Constraint Equation 5 reflects the binary nature of the response capability assignment to the set of NIPs *j*. Constraint Equations 3 and 6 restrict the response area for each NIP *j* to a distance of *Sk* units for all associated demand nodes.

Toregas and Revelle (*10*) suggest using a location set covering (LSCP) approach for solving this type of algorithm. In the LSCP approach the minimum number of response capability units to be located are determined so that no demand node is situated farther away than a specified maximum distance from any respondent. Alternatively, Church and Revelle (*11*) suggest a maximal covering location (MCLP) approach. In the MCLP approach, the number of response capability units to be located on the network are specified exogenously to the algorithm. Recent applications of the MCLP approach are documented by Chung (*12*) and Eaton et al. (*13*). In the MCLP approach the location of response units on the road network is established so that all demand nodes are served within a maximum response distance of the nearest respondent. In this study, a modified version of the MCLP approach has been selected.

Khumawala (*14*) has noted that in most cases, LP techniques for solving the network location covering problem developed by Toregas and Revelle (*10*) will yield noninteger solutions. A number of techniques have been suggested for dealing with this computationally difficult problem. Two of these techniques are (a) the addition of a cut constraint on the objective function (Equation 2) and (b) the use of branch and bound procedures that are sensitive to various maximum distance parameters. The basic problem with the use of the LP approach, however, remains computational inefficiency, particularly for a large number of candidate points on the network.

A computationally efficient approach for solving the preceding problem is presented later in this paper. This approach, developed by Khumawala (*14*), makes use of heuristic techniques in optimizing a weighted risk-distance objective function. The product of this analysis is a set of centroids on the network to which response capability is assigned.

Evaluation and Sensitivity Analysis

The primary consideration of the preceding algorithm is to assign a level of response capability to a response centroid at the regional scale without considering explicitly either the nature of the response or the level of response capability at each point on the network. For example, the number of fire or police stations that are required to contain a spill of a given magnitude on the network (i.e., communities and intersections) is not at issue in this model, and remains unknown. The term "response capability" can represent any number of fire or police stations and serves only to identify the need for some level of response allocation based on a selected criterion, such as risk distance to potential spill sites. The assignment may become more specific through iterative applications of the model to increasingly more detailed representations of the network. Although in this study the model addresses response solely in terms of containing dangerous goods spills, other concerns can be considered individually through iterative applications of the algorithm to a range of service criteria.

The level of service associated with alternative response assignments is expressed in terms of networkwide "*Z*-scores" or total risk-distance ($\Sigma_i \Sigma_j$ RD$_{ij}$). *Z*-scores are estimated for different service standards and location criteria—for example, maximum allowable response time (*Sk*), number of networkwide centroids to be assigned (*P*), and distribution of potential spill risks for all nodes on the network. The model also permits an evaluation of response system location objectives through changes in service standards—for example, comparing location decisions based on potential spill sites with decisions based on fire protection for small communities in the rural region.

COMPUTATIONAL FEATURES OF THE NETWORK LOCATION MODEL: APPLICATION TO SOUTHWESTERN ONTARIO

NIPs Reduction Procedure

An aggregate road network serving a rural area of southwestern Ontario, Canada, was selected for model application in this study (Figure 3). The SW Ontario network consists of 37 nodes and 44 links. Approximately three quarters of the nodes in the network correspond to locations of communities in the region. A summary of data related to each node is provided in Table 1.

For a maximum service distance of Sk = 30 km, the network in Figure 3 gives rise to a large set of 219 NIPs. Depending on the nature of the network, this set may include any number of redundant candidate points. To enhance the efficiency of the search algorithm, matrix reduction procedures have been applied to obtain a choice set of NIPs for which column and row dominance are eliminated. A detailed treatment of matrix reduction procedures for this type of problem is found in Roth (*15*).

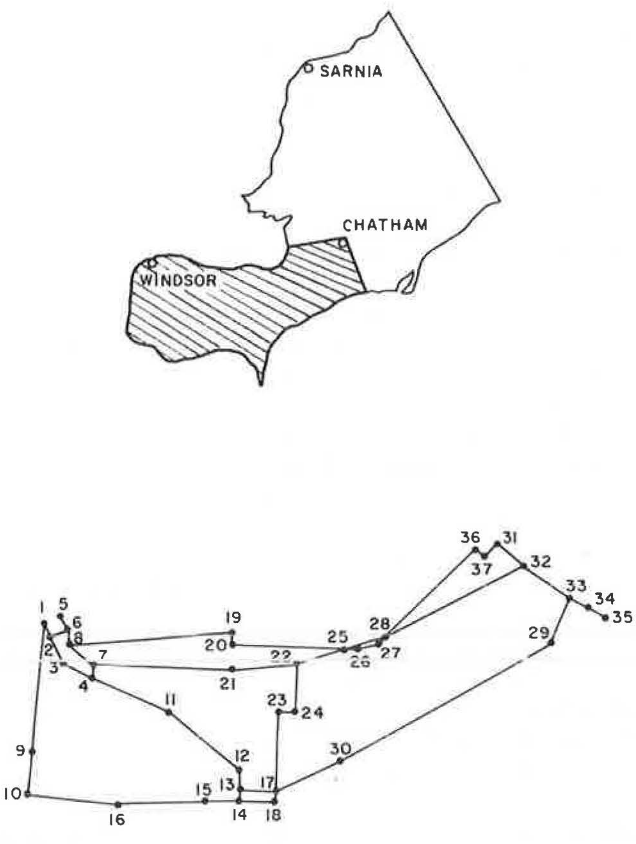

FIGURE 3 Southwest Ontario study area with associated network.

TABLE 1 SUMMARY OF NODE STATISTICS

No.	Origin	Destination Node	*X*-Coordinate	*Y*-Coordinate	Population	Area	Density	Risk
1	1	1	986.0	34.2	26,344	37.04	711.23	0.06
2	1	2	987.0	31.9	26,344	37.04	711.23	0.05
3	1	3	989.0	27.7	36,344	37.04	711.23	0.06
4	1	4	993.7	25.0	26,344	37.04	711.23	0.07
5	1	5	988.6	35.4	26,344	37.04	711.23	0.06
6	1	6	989.9	33.0	26,344	37.04	711.23	0.04
7	1	7	994.2	27.3	26,344	37.04	711.23	0.09
8	1	8	990.0	30.6	32,708	43.23	756.60	0.09
9	2	1	983.8	13.0	10,941	100.08	109.32	0.04
10	2	2	983.0	5.8	5,308	87.88	60.40	0.04
11	3	1	1006.6	19.2	17,648	348.84	50.59	0.04
12	4	1	1018.5	9.2	2,474	41.09	60.21	0.04
13	4	2	1018.5	6.0	2,474	41.09	60.21	0.03
14	4	3	1018.2	4.2	2,474	41.09	60.21	0.04
15	4	4	1012.6	4.2	5,134	4.33	1185.68	0.04
16	4	5	997.8	4.0	7,292	146.52	49.77	0.04
17	5	1	1024.5	5.7	6,264	4.38	1430.14	0.04
18	5	2	1024.2	3.8	6,264	4.38	1430.14	0.05
19	6	1	1017.5	32.3	10,594	97.46	108.70	0.04
20	6	2	1017.5	30.2	2,202	68.60	32.10	0.04
21	6	3	1017.3	26.0	2,202	68.60	32.10	0.08
22	6	4	1028.4	26.8	816	47.83	17.06	0.08
23	6	5	1025.2	18.8	4,829	151.79	31.81	0.04
24	6	6	1027.8	18.8	4,829	151.79	31.81	0.04
25	7	1	1036.4	29.0	4,325	112.02	38.61	0.07
26	7	2	1038.8	29.0	1,941	78.03	24.88	0.05
27	7	3	1042.0	29.8	1,941	78.03	24.88	0.05
28	7	4	1043.2	31.0	1,941	78.03	24.88	0.07
29	7	5	1070.7	29.4	3,789	147.90	25.62	0.04
30	7	6	1035.5	10.6	3,507	112.56	31.16	0.04
31	8	1	1061.8	46.2	1,600	100.92	15.85	0.04
32	8	2	1066.2	42.2	1,600	100.92	15.85	0.08
33	8	3	1074.0	36.8	4,044	3.43	1179.01	0.05
34	8	4	1076.9	35.2	1,600	100.50	15.92	0.03
35	8	5	1079.8	33.3	1,600	100.50	15.92	0.03
36	9	1	1058.2	45.2	24,826	244.79	101.42	0.06
37	9	2	1059.8	44.0	23,591	158.23	149.09	0.06

In this model, the Roth procedure has been modified for the situation where two or more NIPs serve the same set of nodes. In this case, the NIP *j* with the lowest overall risk-distance ($\Sigma_i R_{ij}$) is selected for inclusion in the reduced set of candidate sites. When further reduction procedures cannot be applied, the resultant matrix of NIPs is termed cyclic and the reduction process is stopped.

For Sk = 30 km, an application of matrix reduction techniques to the original set of 219 NIPs yields a reduced set of 48 possible candidate locations for response capability. The discussion now focuses on determining the optimal assignment of response capability for this reduced choice set of NIPs.

Heuristic Solution to Network Location Covering Problem

Khumawala (*14*) presents two heuristic methods for assigning *p* centroids to a network—the delta and omega methods. The delta method consists of computing minimum savings (in terms of a risk-distance measure) attained through an assignment of response capability to each candidate site—that is, establishing a response centroid at each site. The omega method, on the other hand, consists of computing the total savings for an assignment relative to centroids that have already received response units in previous iteratives. Centroids on the network where response capability has been assigned in the foregoing algorithm are referred to as "open." In the absence of a prior location of response capability, these sites are referred to as "closed."

The preferred heuristic for this model is the omega method. The delta method has problems once NIPs have been added to the network since it relies on the unit being open to serve each node. This is problematic, since the heuristic starts with only a portion of the NIPs being open, and some of them are superior to the closed NIPs. Once NIPs start closing, however, they are replaced by other NIPs that may be inferior. Thus, it may be necessary to reopen NIPs (or at least consider them in further steps). Since the omega method starts with no facilities open, it is better to open the best NIPs progressively.

The omega method is concerned with estimating the total risk-distance savings from opening each NIP relative to savings associated with other NIPs previously opened. The procedure begins with all candidate NIPs closed. Omega is the symbol used to denote these savings in risk-distance associated with each site opening. The procedure begins with a nonempty set of open NIPs (theta). The initial element in the set can be either a NIP that must be open since it is the only one that can serve a node or an artificially started NIP (typically, a point that serves some node with the greatest degree of savings relative to any other NIP). Once a NIP has been opened, the *Z*-score or total risk-distance for each of the other closed NIPs is calculated relative to the open NIP. Thus if the open NIP will serve a node with a risk-distance value of 165 and another NIP can serve the same node with a value of 139, then the savings associated with closing the former in favor of the latter is 26. If a node is not served better by any presently closed NIP, then it is considered to be best served by the open NIP. In the next iteration, the closed NIP with the largest omega value (total savings in risk-distance) is opened and serves as a new basis for comparison with other closed NIPs. The process continues iteratively unit the desired level of p (the number of response capability centroids assigned to the entire network) is attained or until no further NIP may be opened that can better serve the set of nodes. *Z*-scores reflecting the total risk-distance associated with each assignment are then computed for each value of p.

Khumawala's approach has been modified in this study by allowing candidate NIPs to be closed even after they have been considered open in a previous step. Since these NIPs may not be best serving for any nodes, they become redundant.

Results of Sensitivity Analysis

A FORTRAN program was written to establish emergency response centroids on the SW Ontario road network for different values of p (the networkwide total centroids) and *Sk* (the maximum allowable response distance).

The results of an application of the model for a selection of *Sk* values is summarized in Table 2. For *Sk* = 30 km, feasible solutions are possible at values of p greater than 4. For $p \leq 4$, at least one node is not covered by a response centroid within the maximum allowable service distance *Sk*. The term m in the *Z*-score represents an infinite risk-distance. For values of $p \geq 18$, the *Z*-score remains unaffected since additional NIPs associated with this range of p become redundant. As illustrated in Figure 4, the improvement associated with each additional value of p steadily decreases for all values of *Sk*. The reduced incremental benefits in coverage for higher values of p must be considered in terms of overall system costs in determining the "optimal" cutoff point for the networkwide number of response centroids.

As expected, the minimum number of centroids required to cover all nodes in the SW Ontario network generally decreases for higher values of *Sk*. This reduction, however, is not always accompanied by a corresponding reduction in the minimum *Z*-score. This may be due to the reduction heuristic that, in the interest of overall efficiency, eliminates some candidate sites that are best serving for specific nodes.

With the exception of *Sk* = 40 km, the number of open

TABLE 2 SUMMARY OF ANALYSIS

	Sk 10		*Sk* 20		*Sk* 30		*Sk* 40	
P-Value	Open NIPs	*Z*-Score	Open NIPs	*Z*-Score	Open NIPs	*Z*-Score	Open NIPs	*Z*-Score
2	—	—	—	—	—	—	2	2M + 5027.60
3	—	—	—	—	3	3M + 6604.80	3	1M + 2186.80
4	—	—	—	—	4	1M + 6066.39	4	2186.20
5	5	11M + 2677.20	5	4M + 3203.70	5	3571.10	5	1139.10
6	6	9M + 2688.50	6	2M + 3207.10	6	3019.50	6	937.80
7	7	7M + 2720.20	7	3212.80	7	2475.10	7	817.80
8	8	5M + 2767.30	8	2750.70	8	2109.40	8	755.30
9	9	4M + 2310.60	9	2478.60	9	1968.50	9	723.60
10	10	3M + 2313.40	10	2364.30	10	1828.90	10	694.60
11	11	2M + 2324.50	10	2265.00	11	1747.20	11	666.10
12	12	1M + 2336.70	11	2219.20	12	1708.90	12	637.60
13	13	2385.80	12	2191.90	13	1687.10	13	629.90
14	14	2096.30	13	2167.90	14	1671.90	13	624.00
15	15	1873.40	14	2149.30	15	1657.50	14	623.80
16	16	1751.80	15	2138.80	16	1647.90	14	623.80
17	17	1741.90	16	2134.00	17	1642.60	14	623.80
18	18	1737.50	17	2132.20	18	1637.60	14	623.80
19	19	1736.10	17	2132.20	18	1637.60	14	623.80
20	20	1734.90	17	2132.20	18	1637.60	14	623.80
21	20	1734.90	17	2132.20	18	1637.60	14	623.80
22	20	1734.90	17	2132.20	18	1637.60	14	623.80
23	20	1734.90	17	2132.20	18	1637.60	14	623.80
24	20	1734.90	17	2132.20	18	1637.60	14	623.80
25	20	1734.90	17	2132.20	18	1637.60	14	623.80

NOTE: Dashes indicate that computations were not carried out at this value of p.

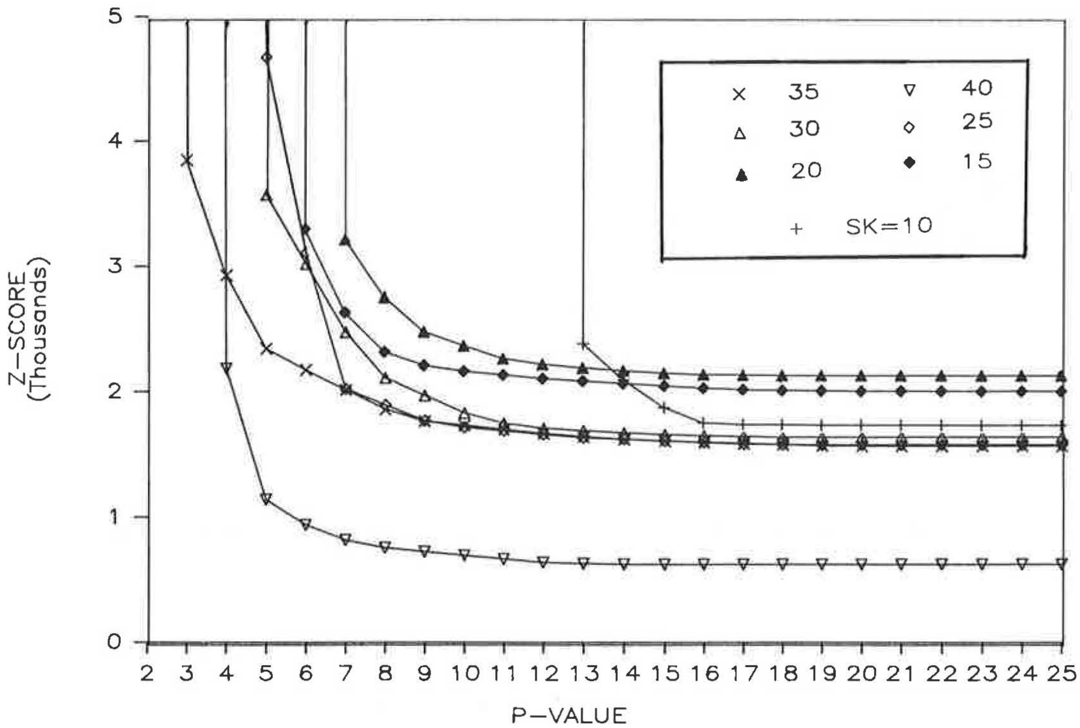

FIGURE 4 Z-scores versus *P* values for different *Sks*.

centroids associated with each minimum Z-score varies slightly between 18 and 21 units for all values of *Sk*. The minimum Z-score appears to act in a similar manner with no clear trend among *Sk* values.

A major aspect of this sensitivity analysis becomes the acceptable value for the maximum allowable service distance, *Sk*. One of the objectives of this process is to assign response centroids to the network so as to minimize total Z-scores (networkwide risk-distance). In the absence of a strong relationship between Z-score and *p* value for a given value *Sk*, the individual distance from each node to the nearest response centroid becomes important. As *Sk* increases, the maximum response times naturally increase. If the response time is too long, then the effectiveness of the overall response system to contain spills is reduced to an unacceptable level.

In the absence of information on facility infrastructure and operating costs, it is difficult to suggest an "optimal" allocation of response capability for the SW Ontario road network. In this assignment the lowest Z-score is obtained for a value of $Sk = 40$ km, and $p = 14$ open centroids. At $Sk = 35$ km, only three response centroids are required to serve the entire network for the first feasible solution. However, the minimum Z-score at $Sk = 35$ km is higher

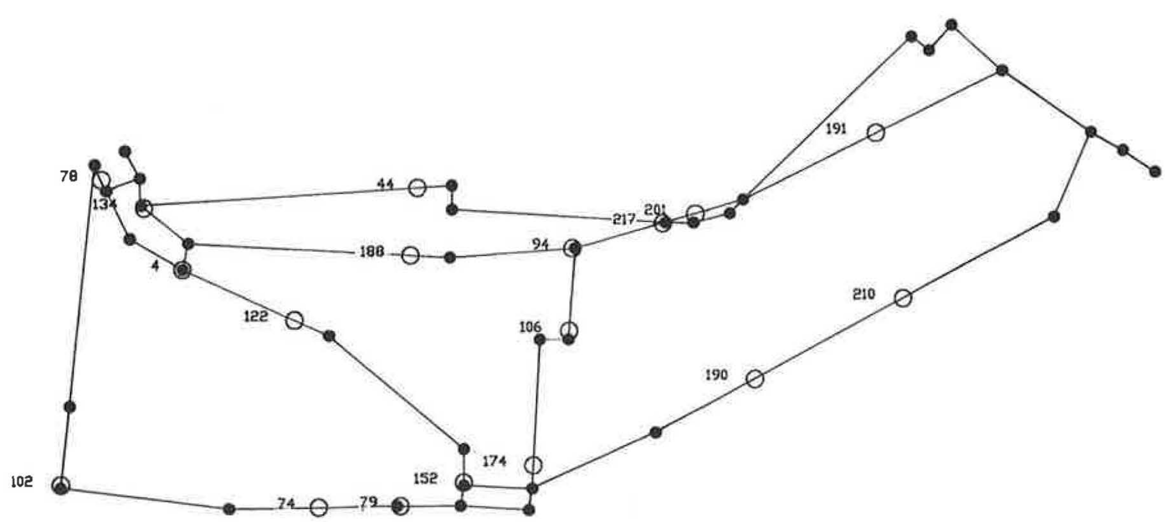

FIGURE 5 Open centroids for $Sk = 30$ km at the minimum Z-score.

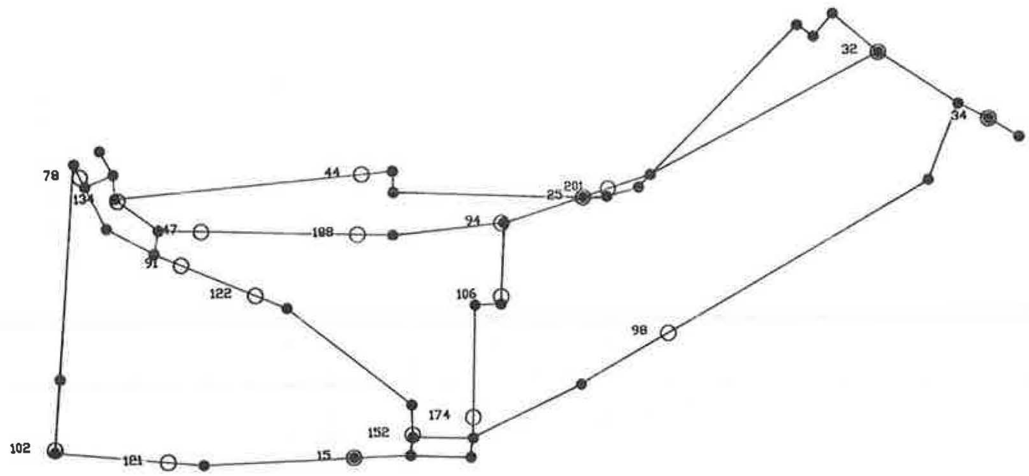

FIGURE 6 Open centroids for *Sk* = 30 km at the minimum *Z*-score with restricted secondary service.

than at *Sk* = 40 km. Figure 5 illustrates the location of open centroids on the SW Ontario road network for an *Sk* value of 30 km. For this assignment *p* = 18 open centroids is required to minimize the *Z*-score. An important consideration in the assignment algorithm is the impact of providing service to nodes outside the immediate area of jurisdiction, with a distance exceeding *Sk*. The assignment in Figure 5 is based on the assumption that all nodes in the network have to be considered within the range of secondary coverage from any given centroid regardless of distance. As the size of the network increases, it becomes infeasible to provide secondary coverage to nodes at great distances from a given centroid. It is thus reasonable to consider the situation where the range for secondary service is restricted.

Figure 6 represents the allocation of centroids for an *Sk* value of 30 km, assuming that secondary coverage is restricted to nodes with a distance not greater than 2.5 times *Sk* from each centroid. The major impact of this adjustment has been to increase the number of open centroids to *p* = 19 at the minimum *Z*-score, and to shift the location of these open centroids closer to their associated service nodes. The minimum *Z*-score associated with the restricted secondary coverages is higher than the value obtained when all nodes are considered in the secondary coverage rule.

From Figure 4 the highest improvements in system performance, as expressed by changes in the *Z*-score, are associated with the initial values of *p*, the total number of centroids to be assigned. If the value of *p* for assignment is taken where the relationship tapers off rather than at the minimum *Z*-score, the number of response centroids assigned to the network is reduced appreciably. Figure 7 illustrates the location of response centroids for *Sk* = 30 km given the selection of an earlier cutoff point. Obviously, networkwide service costs can be reduced considerably for this assignment, since the entire network is served from only five open centroids.

In this comparison of the *p*-value at the minimum *Z*-score and at the point of first total coverage, the ini-

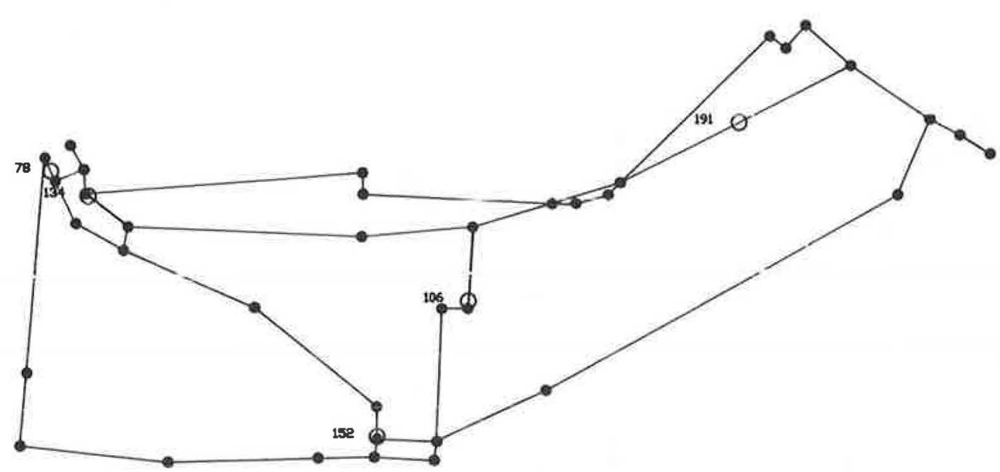

FIGURE 7 Open centroids for *Sk* = 30 km for an initial *P*-value cutoff.

tial p-value is preferred. The minimum Z results in redundancy of coverage and increased costs in excess of the benefits derived. The initial p is more rational and efficient.

CONCLUSIONS

Financial constraints reduce the likelihood of locating emergency response facilities on a road network solely on the basis of proximity to sites where spills of dangerous goods are likely. An alternative criterion, which is more cost-effective, is to locate response capability on the network so as to provide a minimum level of "acceptable" service to potential spill sites.

The network location covering problem, adopted in this study, locates elements on a network in terms of a preselected maximum distance constraint. This constraint represents the lowest acceptable performance of the emergency response system. Matrix reduction techniques are used to obtain a nonredundant set of candidate sites for assigning response capability. A heuristic approach is incorporated into the location model to ensure that the choice set of response sites on the network is an integer solution.

An application of the model to a rural road network in SW Ontario has indicated that the spatial distribution of response capability centroids on the network is sensitive to the choice of (1) the maximum acceptable response distance and (2) the total number of response capability centroids assigned to the entire network. Both of these factors are policy inputs that are exogenous to the location algorithm.

In general, this model can be used to evaluate the effectiveness of alternative emergency response systems, based on unique location criterion and a minimum coverage principle.

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