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Transportation Research Record 1193

Contents

Foreword

It is estimated that 1,000 new materials are added every year to the 19,000 separate hazardous materials in existence. Assessing the risk if such materials are released into the environment and writing rules and regulations to control their transportation is a daunting assignment. Consistent, reliable estimates of the location, quantities, and release accident rates for the material are needed by planners, yet accurate data are not easily found.

A risk assessment approach provides a logical structure for studying the possible routes where a hazard can occur or evaluating relative risks for transportation of hazardous materials by rail or truck. Unfortunately, a major drawback of risk assessment is the complexity of the method. There does not appear to be a general answer to the question of whether the truck or rail mode is safest, because it depends on the release accident rate (which varies with release severity, carrier type, vehicle type, and track or road type) and on other factors such as the size and design of containers.

That is not to say that nothing can be done or that no estimates can be made. One of the papers in this Record offers a model for locating emergency response capability on a road network. In general, this model can be used to evaluate the effectiveness of alternative emergency response systems on the basis of unique location criteria and a minimum coverage principle. The model is applied to a rural road network in southwest Ontario for a given distribution of risks associated with dangerous goods spills.

Hazardous materials regulatory controls for tunnels and bridges are extensive, detailed, and subject to constant changes. The objective of the regulations is to make shipping through the facilities safe by reducing, if not eliminating, the risk inherent in the transport of the hazardous products. The general lack of expertise among tunnel personnel and the lack of a scientific basis leading to the development of these regulations, however, have created problems for local authorities in updating the restrictions or in dealing with new materials.

Development of rules and regulations for shipment of hazardous materials through special facilities such as bridges and tunnels was the main objective of a study that was performed under a contract for the Virginia Department of Transportation. Two papers are based on that study. One provides a summary of the study and concentrates on the details of the analytical framework that was used to generate a set of criteria by which regulations for new and unlisted substances could be developed. A computer program using a knowledge-based expert system that identifies the appropriate regulations for an unlisted substance is being developed to help tunnel operators to respond to inquiries on hazardous materials.

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

F. F. SACCOMANNO AND B. ALLEN

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

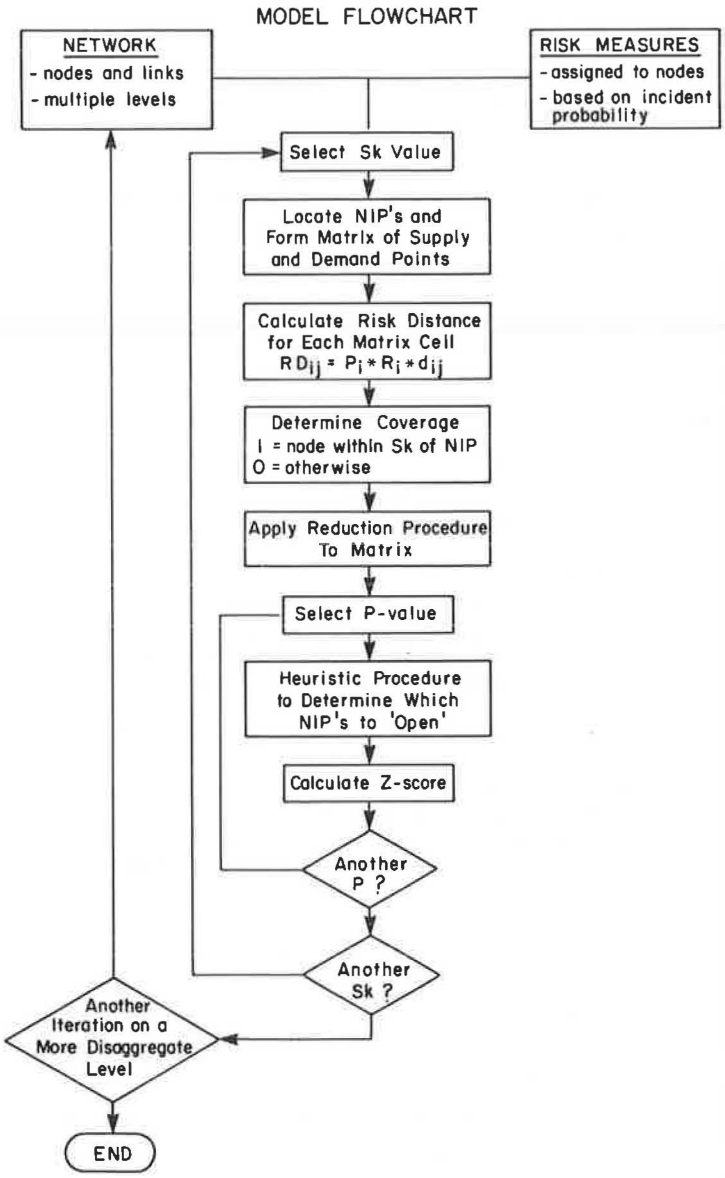

FIGURE 1 Model framework for locating emergency response capability.

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

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

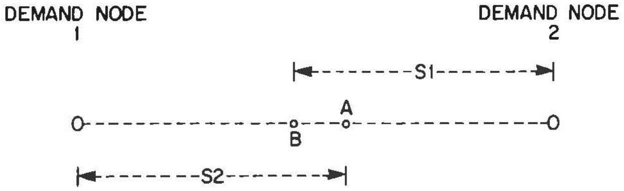

FIGURE 2 Location of NIPs for two nodes and a connecting link (*6*, p. 361).

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 = $(\text{j} \in N_j | d_{ij} \leq S_k)$, 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 ($\Sigma_i \Sigma_j \mathrm{RD}_{ij}$). *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*).

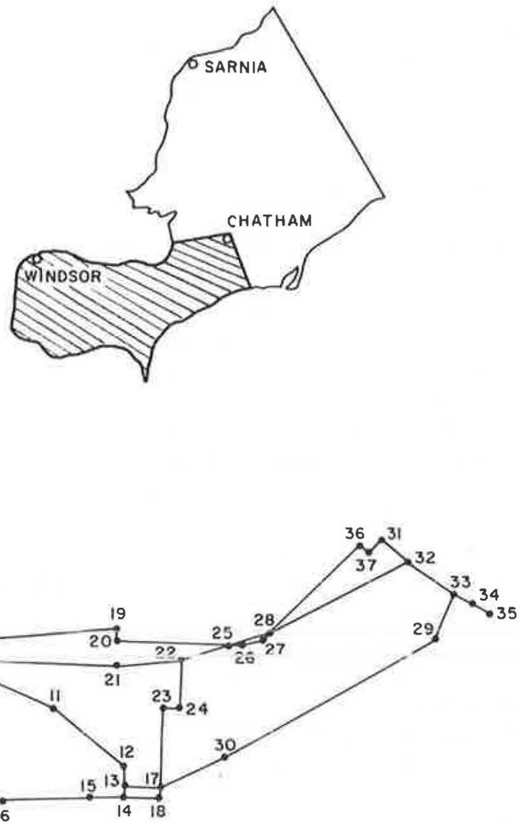

FIGURE 3 Southwest Ontario study area with associated network.

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 ($\Sigma_i \mathbf{R}_{ij}$) 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.

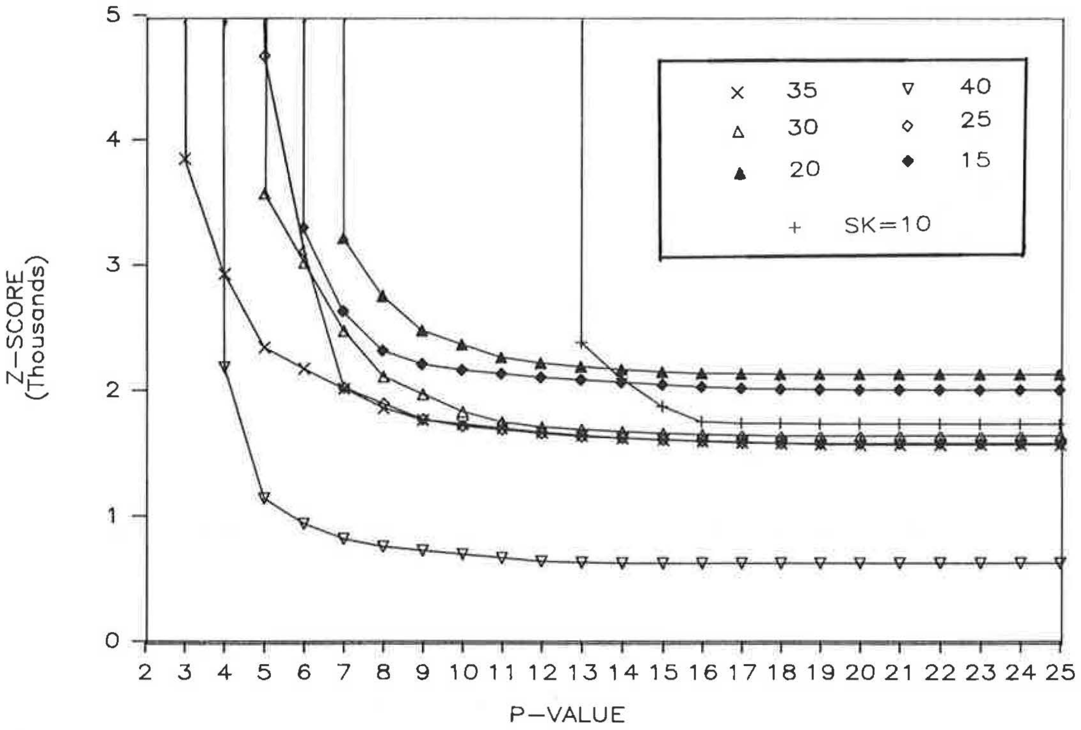

FIGURE 4 **Z-scores versus *P* values for different *Sks*.**

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

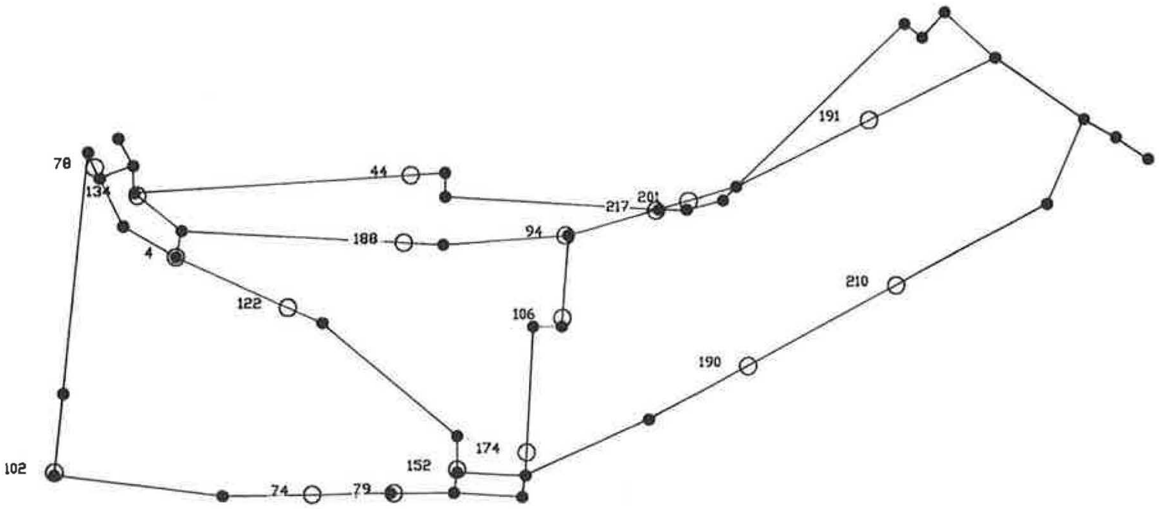

FIGURE 5 **Open centroids for $Sk = 30$ km at the minimum Z-score.**

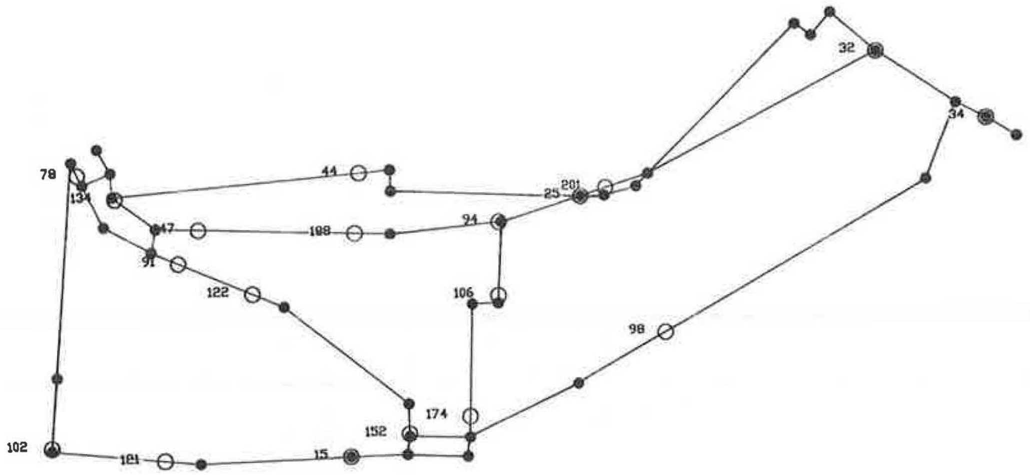

FIGURE 6 Open centroids for *Sk* = 30 km at the minimum *Z*-score with restricted secondary service.

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-

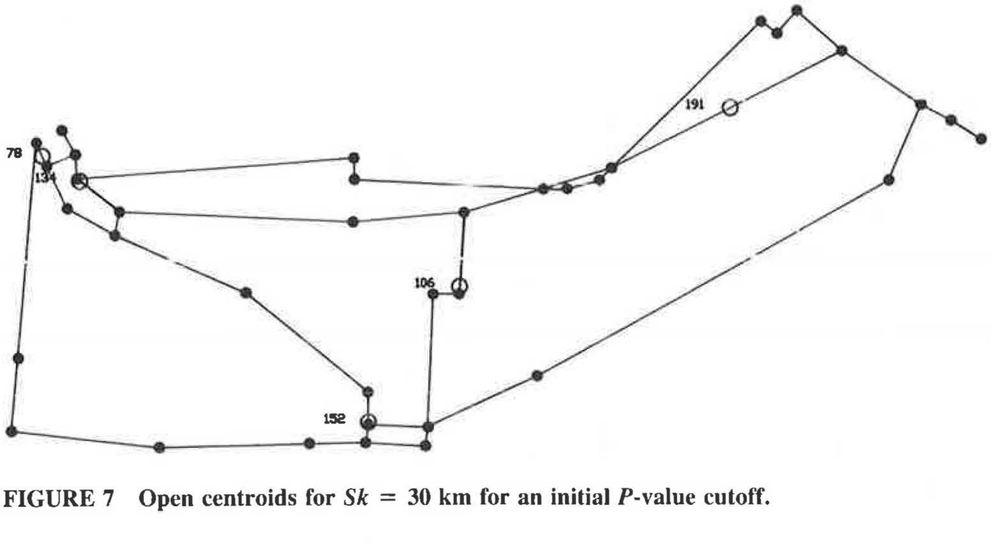

FIGURE 7 Open centroids for *Sk* = 30 km for an initial *P*-value cutoff.

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.

ACKNOWLEDGMENT

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Knowledge-Based Classification Scheme for Regulating the Flow of Hazardous Materials Through Tunnels and on Bridges

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Regulatory controls for handling hazardous material in tunnels and on bridges are extensive, detailed, and subject to constant changes. Local authorities responsible for tunnel and bridge facilities are concerned with developing facility restrictions for hazardous materials that will reduce the risk of death and injury without unnecessarily burdening commerce. The lack of expertise among tunnel personnel in general and the lack of a scientific basis on which to develop such regulations, however, have created problems for local tunnel authorities when they must update restrictions or create new ones for new materials introduced by industry. This paper describes the development of a prototype expert system to aid decision making about hazardous material safety in tunnel and bridge transportation. The regulatory process is modeled as a classification type of problem, which lends itself neatly to an expert system implementation. A heuristic problem solver, which is commonly used in solving classification problems, involves systematically matching the attributes of an unknown entity to a set of predefined solutions. For this study's application, the regulatory groupings inherent in existing tunnel regulations are the basis for the development of the solution space. The computer program developed uses knowledge that specifies the appropriate regulation applicable to a new commodity based on the material's physical and chemical properties.

Safety is a major concern for tunnel-bridge authorities. Local authorities are concerned with developing hazardous material restrictions to prevent such goods from causing injury, death, or property damages as they pass through the facilities. The objective of the regulations is to make shipping through the facilities safer by reducing, if not eliminating, the risk inherent in transporting hazardous products.

Hazardous material regulatory controls for tunnels and bridges are extensive, detailed, and subject to constant changes. Most existing tunnel-bridge rules and regulations have no provisions on how to deal with these changes; in some instances, they are entirely out of date. The lack of expertise among tunnel personnel in general and the lack of a scientific basis on which to develop such regulations, however, have created problems for local tunnel authorities when they must update restrictions or create new ones for materials being introduced by industry.

Local facility authorities often rely on the United States Department of Transportation (USDOT) Code of Federal Regulation Title 49 (49 CFR) when updating rules and regulations on the transportation of hazardous materials. Updating is done by adopting any changes made in 49 CFR. As of August 1985, all fifty states have adopted, completely or in part, the Federal Motor Carrier Safety (49 CFR Parts 390-399) and those portions about shipments on public highways (49 CFR Parts 171-178) for intrastate commerce (*1*). It is not surprising, however, for local authorities to feel uneasy about whether federal regulations provide for safety that is appropriate on a state level, since these federal regulations are made without consideration of special local circumstances. This is especially true for special facilities since hazardous materials present a greater risk when transported inside tunnels and on bridges than when they are shipped on the open road. This is reflected in existing tunnel-bridge safety regulations on transporting hazardous materials, which are generally more restrictive than those on open highways.

Risk assessment is one approach to aid decision making in regulatory control. Risk assessment provides a logical structure for studying possible hazard scenarios. This approach often reveals faults in current safety practice, the need to obtain more information about the problem, or the need for further study. Although risk assessment has effectively been used in several studies, regulatory procedures contain no specific legal mandate for its use. Currently, in evaluating inquiries, risk assessment can be used if desired (*2*). Most often, a regulatory decision, such as that for a permit or an exemption, is made without the benefit of risk assessment.

A major drawback of using risk assessment at the local level is the method's complexity. Few local jurisdictions have the expertise or the budget to use risk assessment's sophisticated mathematical techniques. Although computer packages and guidelines can provide a simple and rapid assessment of risk, many subjective evaluations and estimates must still be made in using them. Human expertise is still needed to run the program, interpret results, or estimate any gap in the database.

The complexity of risk assessment is compounded by the lack of high-quality data. Although hazardous materials agencies and organizations are aware of the importance of data collection and analysis, this area still needs improvement. The existence of gaps in the information database

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is one important reason for existing limits on the ability to predict risk in transportation safety.

The absence of data is more evident on the state and local levels. Although numerous hazardous materials databases exist at the federal level, the data they contain are too nonspecific to be useful for a particular state or locality. In its review of existing databases, the Office of Technology Assessment (OTA) reports that (*3*):

> Federal data collection activities are numerous and diverse, each providing modal transportation data of varying completeness . . . that no current federal resource could provide shipment information with the specificity desired by state and local jurisdiction.

Further, these databases are not easy to access. They do not use the same commodity identification codes and are not interactive. Although efforts for a coordinated spill reporting system are now being initiated at both the federal and local levels, their full implementation is at least a decade away (*4*).

Another problem facing the risk assessment practitioner is the evaluation of risk associated with toxic hazard. One part of an overall risk assessment where improvement is needed is in estimating the toxicity resulting from a toxic release. The main reason for the lack of precision here is the absence of any direct data for humans. For obvious reasons, direct tests on humans are not possible. Even in cases where deaths from toxic chemicals are known to have occurred, the lethal dosage is seldom known or available to estimate.

The prospect for modeling the hazardous materials regulatory problem is likely to be limited not only for the reasons cited but also because it is a new topic of research interest (*5*). Further, the number of materials involved is very great, making the approach difficult and time-consuming.

Subjective estimation is generally used to augment the limitations of risk assessment techniques. Subjective estimation is done by a panel of experts (*2*). These experts are assumed to be sufficiently familiar with the problems of concern and can meaningfully extrapolate their experience to the areas of interest.

Risk assessment techniques, such as statistical inference or fault tree modeling, provide the empirical information so that the subjective process of judging the relative safety of the various options can be performed on an informed basis. The major drawback of subjective estimation lies in forming the panel of experts. Experts are not readily available and are expensive to maintain. Maintaining a panel of experts at the local level would be too much of a drain on the budget of local jurisdictions.

Recent development in artificial intelligence (AI) opens new opportunities for addressing the problem. A study conducted by Virginia Polytechnic Institute and State University (VPI&SU), Department of Civil Engineering (*6*), to develop a single hazardous materials transportation safety regulations manual for Virginia's highway tunnels, bridges, and ferries, recognizes the dilemma of having the tunnel-bridge operators respond in a guessing manner to inquiries on hazardous material not listed in the manual. The study recommends an expert system implementation as the most appropriate way to resolve the issue. If expert knowledge is captured in a computer implementation form, expert advice is readily available and less expensive. This paper is a summary of the ongoing effort to build and develop an expert system application for tunnel and bridge operations.

Even though the prototype system does not incorporate all the situation-specific, problem-solving knowledge in tunnel-bridge regulatory control, the prototype developed provides a framework for further system evolution and development. Once fully developed, the system is expected to serve as a decision tool, not as a replacement for management decisions involved in the tunnel regulatory control of hazardous material.

BUILDING AN EXPERT SYSTEM

Building an expert system involves three basic tasks. These are discussed below.

1. Knowledge Acquisition: This aspect primarily deals with acquiring the necessary knowledge or "facts" about the domain or situation-specific problem-solving methods. The importance of knowledge acquisition cannot be overemphasized. The efficiency of the expert system depends on the acquired problem-solving knowledge.
2. Knowledge Representation: To be useful, the knowledge acquired (knowledge base) should be organized and structured in a computer-implementable form. Knowledge that is not adequately represented cannot be used (*7*).
3. Inference Mechanism: Inferencing is the process of generating alternate paths via a reasoning mechanism through the knowledge base to derive a conclusion (*8*). This involves selecting from the various pieces of knowledge in the system those few that, when combined, yield a conclusion or decision. To accomplish this task, the procedures or mechanism built into the system should search through the knowledge base in an efficient manner. If search is done at random, it will not be finished in a reasonable time.

The first two issues, task 1 and task 2, are pursued in this study. Task 3 is left for future work and is beyond the scope of the research objective. For this study's implementation, an expert system shell with a built-in inference engine is used.

System Goal

The objective of building the prototype expert system is to show that such a system provides a viable approach for real-time interactive regulatory control and to achieve a better understanding of what a tunnel-bridge consultative expert system should be capable of performing. Since the system developed is a research prototype to be used by the study group and not by tunnel-bridge personnel, the system developed allows some flexibility in such areas as degree of "user friendliness," extent of knowledge acquisition, and so forth. Nevertheless, features of the fully developed system, which are seen as essential for its eventual implementation, are defined to allow for a more realistic formation of the prototype system.

Developing a high-performance consultative system entails several demands. The foremost is to define the degree of abstraction of the fully developed system. The system must be useful to the personnel who will eventually use it. Usefulness implies competence, consistency, and ease of use.

The fully developed expert system is intended for use by technical staff or those responsible for regulation making to determine the specific quantity limitations of a substance. The system advises the user by suggesting regulatory actions appropriate for the hazardous cargo based on its characteristics. If advice is not reliable, the utility of the system is severely impaired.

The system's eventual implementation necessitates that the system be made familiar and friendly. The system must be easy to use and be understood by someone who is unfamiliar with computers. This is accomplished by:

- Designing the system around a simple rule syntax,
- Providing a "user friendly" support environment that simplifies the use of the system, and
- Making the system capable of explaining its action.

Another important consideration in building the system is the need to design the program to accommodate changes in the knowledge base. It is estimated that 1,000 new materials are added every year to the 19,000 separate hazardous materials in existence (*5*). An expert system designed in this area would require a continuous and systematic updating effort because it would have to contend with new substances each year. Furthermore, accumulation and codification of knowledge are important aspects in expert system development that make the program intelligent (*9*). Hence, knowledge should be structured to accept additional knowledge, as it becomes available, without existing knowledge having to be modified.

System Development Tool

The system developed is implemented using Insight 2+ (*10*). Insight 2+ is a system shell for developing expert systems. An expert system shell can be viewed as an expert system with all its basic components minus the knowledge base. An expert system shell provides the framework for building an expert system, in the same context as templates are built for accounting spreadsheet programs.

Use of an existing development tool or shell is based on the fact that there is no need to build from scratch at this point. The system developed in the study is a research prototype with two basic purposes: first, to show that artificial intelligence techniques can be effectively applied to the regulatory problem in question; and second, to develop an expert system framework for the problem that could eventually develop into a full system. Hence, an expert system shell is sufficient for the stated purpose of the study.

Insight 2+ has certain characteristics that are suitable for this study's implementation. It uses a simple yet versatile knowledge representation language called Production Rule Language (PRL). The basic construct of PRL is commonly known as the "IF-THEN" construct or, simply, production rule. The use of production rules results in a cause-and-effect structure for the knowledge base that is very similar to the way humans think. The domain knowledge expressed in a production rule format is easily accessible for evaluation and updating by human experts (*11*).

Another feature of Insight 2+ that serves the purpose of the system developed is its ease of use for unsophisticated users. Insight 2+ is totally menu-driven. All functions and fact acquisitions are accomplished through menu operations, with the selection made using function keys and keypad.

For a thorough discussion of the general structure and functions of Insight 2+, the reader can refer to INSIGHT 2+ reference manual (*10*).

Knowledge Source

Hayes-Roth et al. (*12*) classifies knowledge into two types: public and private. Public knowledge includes published literature that is available and accessible to anyone. Private knowledge refers to the expertise of individual experts in the specific field of the problem.

For this study, the major source of knowledge is public knowledge, such as chemical handbooks and current tunnel rules and regulations. Private knowledge is not considered, mainly because of the time and cost of acquiring it. Public knowledge is sufficient for the study's objective, which is to develop and evaluate an expert system for tunnel-bridge facilities that would be available to these facilities in the future. Public knowledge may have the disadvantage of being functional. It tells what, not why it was so. It is, nevertheless, a logical starting point for building the knowledge base.

PROBLEM-SOLVING KNOWLEDGE

The regulatory problem is characteristic of a class of well-structured problems commonly called classification. The solution or heuristic method (called knowledge in AI) used to solve a classification problem passes through easily identifiable phases of relating data from an unknown entity to a set of pre-enumerated solutions (*13*). Classification problems lend themselves neatly to expert system application. Many existing expert systems demonstrate successful applications of expert system techniques to these types of problems, among which are MYCIN (*14*), a diagnostic system, and EDAAS (*9*), an information analysis system.

In this section, the steps in developing the regulatory scheme for tunnel-bridge facilities are presented. The scheme is useful for finding an appropriate regulation for new commodities or for determining inconsistencies in the existing regulations when updated. It is the primary problem-solving component of the prototype knowledge-based system developed.

The overall scheme is based on a similar or close chemical relationship between hazardous materials. This approach, though heuristic in nature, circumvents the complexity and data constraints of a risk assessment methodology. The approach is rooted in using an existing system that assigns quantity limitations and packaging requirements to hazardous materials based on their harm potential. The following are the steps taken in developing the heuristic:

1. Selection of an existing system as point of reference.
2. Grouping the materials by their intrinsic properties and dispersive energy. Intrinsic properties (e.g., flammability, toxicity, reactivity) and dispersive energy (e.g., pressure, physical state, volatility) are dependent on the type of material shipped and reflect the relative harm potential of the substances.

Once the groupings (referred to here as "envelopes") are made, a comparative type of analysis is applied to determine the appropriate restriction. That is, properties of the unknown material are compared to the properties defining each of the envelopes.

Existing tunnel-bridge rules and regulations are logical starting points for the scheme illustrated. The restrictions imposed by these regulations reflect the degree of hazard or harm potential of the regulated material. They relate the acceptable quantity in tunnel facilities to the physical and chemical properties of the materials. As will become clear in the following example, tunnel-bridge rules and regulations have evolved through the years. The restrictions on hazardous materials currently regulated are not imposed in a random manner. Instead, certain criteria based on the materials' physical and chemical properties are followed.

Although it is debatable whether or not the restrictions reflect tolerable quantities in tunnel facilities, more than twenty years of implementation with good safety records attest to the reliability and effectiveness of these regulations (*6*). Because the restrictions have been enforced for so long, it is safe to assume that tunnel patrons have accepted or have learned to accept the restrictions.

Tunnel-bridge rules and regulations can be viewed as knowledge concerning the problem domain where experts are in agreement. A review of existing rules and regulations governing the transportation of hazardous materials through tunnels and bridges conducted in the VPI&SU study concludes that no major difference exists among them. The same restriction applies to a particular hazardous material, regardless of which one of the current regulations is referred.

Existing tunnel-bridge regulations are divided into the major hazard classes defined by the U.S. Department of Transportation (USDOT) (e.g., combustible liquids, compressed gases, etc. [*15*]). Each hazard class is further subdivided into the different notes that give the specific packaging and quantity restriction. These regulatory divisions form the basis for defining the individual envelopes.

The characteristics defining an envelope are determined by establishing commonality among the materials within the note and finding the difference with substances in other notes. These envelopes can be thought of as a set of baskets with unique characteristics defined by the physical and chemical properties of the materials inside it. If the properties of an unlisted material match the characteristics defining a particular basket, then the unlisted material belongs to that basket and should be subjected to the same restriction imposed on the basket. The assumption is that substances exhibiting similar characteristics will behave in the same manner, or will have the same severity of consequence when released under similar conditions.

It should be noted that the envelopes formed serve only as an aid to decision making. Other relevant characteristics that are unique to a particular hazardous material are considered in determining the final restrictions.

The flammable hazard class is used as an example to show the regulatory methodology. Figure 1 gives the packaging and total quantity limitations for the flammable liquids based on the existing rules and regulations. By converting this figure according to the dispersive energy (i.e., pressure, temperature, state of the matter, etc.) and intrinsic properties (i.e., toxicity, flammability, etc.) of the materials under each note, the resulting chart (Figure 2) defines the envelopes for each of the notes.

Having established the envelopes' chart for each hazard class, the problem becomes one of finding to which envelope a hazardous material, based on its properties, belongs. From this, the total quantity limitations for a particular substance are easily determined.

EXPERT SYSTEM IMPLEMENTATION

With the domain knowledge to work on already defined, it should be represented in a computer-implementable form. Representation of knowledge in an expert system requires efficient structuring of the goals of the system and the supporting facts (*7*). The effectiveness of the knowledge base depends on the way the knowledge contained is structured. Careful organization of the facts and the relationship constituting the domain knowledge of application is necessary. Structured knowledge is interpreted accurately and used efficiently by the system in pursuit of the stated objectives or goals (*10*).

How the knowledge is organized, represented, and accessed to solve this study's problem is the topic of this section.

System Architecture

The general structure of the regulatory system developed follows the "blackboard" concept popularized in Hearsay

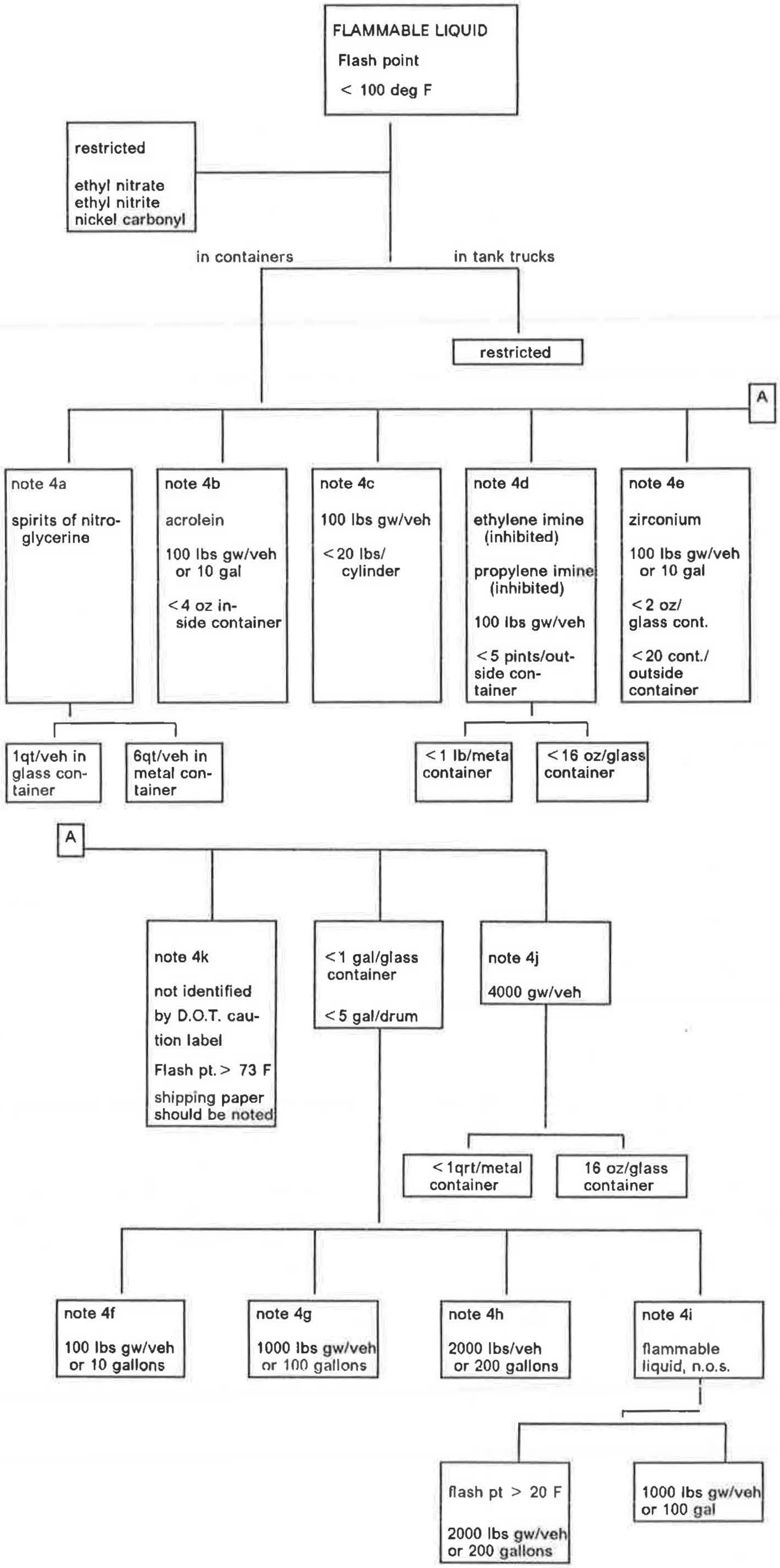


FIGURE 1 Rules and regulations chart for flammable liquids.

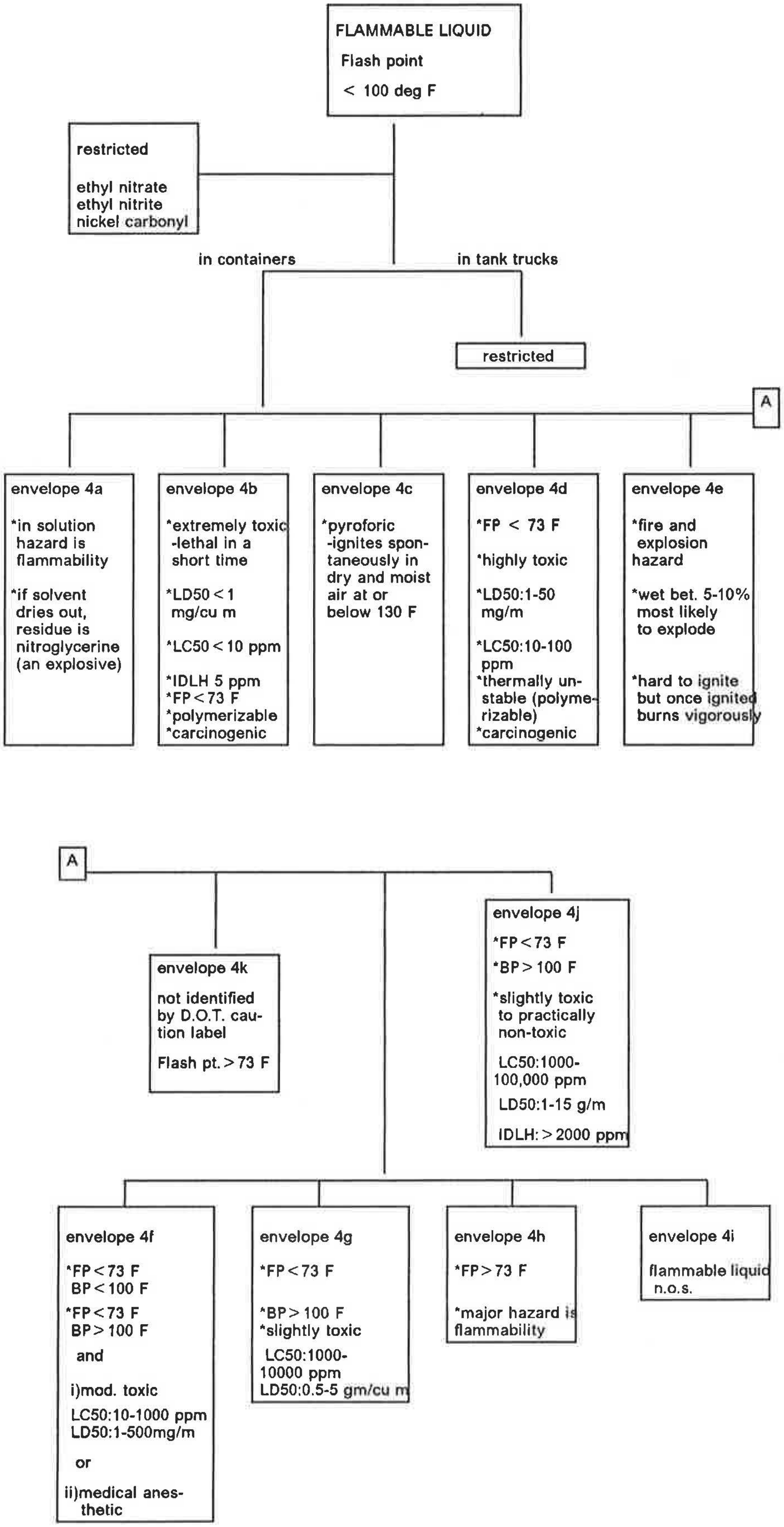


FIGURE 2 Characteristics defining the envelopes for flammable liquids.

II (*16*), a speech-understanding expert system. In blackboard architecture, the domain is partitioned into independent knowledge bases (KB), chained together via a control module. Each KB in a blackboard system structure has its own inference structure for solving a specific problem and communicates through a global database or working memory called blackboard. Inferences or conclusions from a KB are written on the blackboard. A control program analyzes the problem and transfers the control to the appropriate KB for execution.

The system architecture for this application is illustrated in Figure 3. The control module, the program controlling which KB is activated, is formulated as a rule-based program. Each KB is independent and represents a knowledge base for each of the hazard classes, into which the domain is partitioned.

One advantage of this type of architecture is the ease by which it can be modified to reflect the user's growing needs. Since the area of regulatory control for tunnel facilities is both large and constantly changing, it is necessary that the program be flexible and modifiable to accommodate new knowledge about the problem domain. Also, to justify the cost of developing the system, new KBs dealing with the other operations of the tunnel facility, such as management crisis, traffic control, monitoring, or scheduling, should be accommodated by the system.

Structuring the KBs in parallel allows flexibility and modifiability of the program. It enables KBs to be changed, added, or removed in an independent manner. Existing KBs can be enhanced as new knowledge is acquired without affecting the entire system. New KBs can easily be attached in parallel to the existing system, with minor changes in the control module. Next, the representation scheme used in organizing the knowledge within each KB is discussed.

Production Rules

The primary source of the domain of specific knowledge is a set of production rules, each with a condition-action type of relationship. The syntactic form of the production rule, as specified in Insight 2+ using PRL, must have a minimum of three components: the rule name, a supporting condition (premise), and a conclusion (action). An example of a PRL rule follows:

Rule criteria for flammable liquid
IF flash point is less than 100 degrees F
THEN evaluate as \ flammable liquid.

The rule name is "criteria for flammable liquid." The support condition of the rule is "Flash point is less than 100 degrees F." The conclusion of the rule is: "Evaluate as \ flammable liquid."

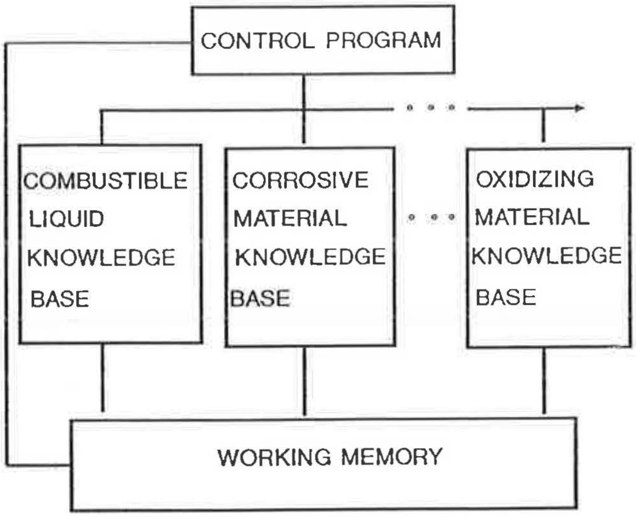


FIGURE 3 Expert system architecture for regulatory control.

Using an "IF-THEN" construct allows each rule to be programmed to represent a single, modular piece of the domain knowledge, and with all the necessary context written explicitly in the premise. This representation is useful when the system explains or gives reason for its action. Since the rules use a vocabulary of concepts common to the domain, they form, by themselves or in combination with other facts, a comprehensible statement of some knowledge about the domain.

The IF part of the rule may contain only facts. Hence, it is either true or false. The facts are usually expressed in the form "attribute = value" (i.e., flash point is less than 100 degrees F) or as a "property-present" condition that denotes the presence of a given property (i.e., material is explosive when dry).

The THEN either contains facts that are antecedents of other rules or an action. The actions are expressed through imperative verbs (i.e., regulation is note 4a) that are inferred if the supporting condition(s) is verified.

There are no limits to the number of antecedents that a rule can have. PRL allows as many supporting conditions as necessary to define a rule. Multiple antecedents are included, using the reserve words AND/OR. The same holds for the THEN part; rules can also have multiple conclusions.

The facts represented in the system can be partitioned into two types, namely:

- Hazard classes (flammable liquid, combustible liquid, poisons, etc.) and
- Physical and chemical properties (flash point, toxicity, volatility, etc.).

The partitioning can be expanded as the need arises or when new knowledge about the problem is acquired, including:

- Environmental factors (topography, weather);
- Population density in the vicinity and proximity of the facility;
- Facility preparedness (emergency response capability, sprinkler system, monitoring system); and
- Condition of transportation (quantity, packaging, etc.).

Similarly, actions can be of several sorts. The current implementation, however, is limited to the particular regulatory control. Other types of actions to extend the flexibility and usefulness of the system are:

- Traffic control and
- Management of critical events (fire, explosion, spill control, etc.).

The strategies built into the system for skillful inferencing of the knowledge contained in the rule base are described next. Such strategies are needed so that knowledge is used efficiently by the system during problem solving.

Control Structure

For the system developed, rules are invoked in a backward, unwinding scheme to produce a depth-first search of the goal tree. The choice of a backward chaining scheme is motivated by the type of application considered.

As seen in the discussion of the envelopes developed in the preceding section, it is clear that the process of identification is done by matching the characteristics of an unregulated hazardous material against the characteristics of the envelopes. As already mentioned, this type of heuristic search belongs to a class of well-structured problem solving called classification. The essential characteristic of the heuristic is that the problem solver selects from a set of preenumerated solutions. For this type of problem, a backward chaining is the most suitable inference mechanism to use.

A backward chain reasoning process starts with a goal to be established. In the pursuit of a goal, the system scans the knowledge base for all rules that can conclude that goal. These rules are invoked or retrieved for execution. The rule that does not have supporting condition(s) that are conclusions of other rules are verified first. The premise of each rule invoked is matched against the known facts or knowledge about the current session. The rules that have premises or IF portions verified, or matched the known facts, are executed or "fired." Its conclusion(s) becomes a known fact of the current session. This is illustrated in Figure 4.

The match-execute process continues until a goal is proven or disproved. If the goal is disproved, a new goal is pursued and the recursive pattern continues.

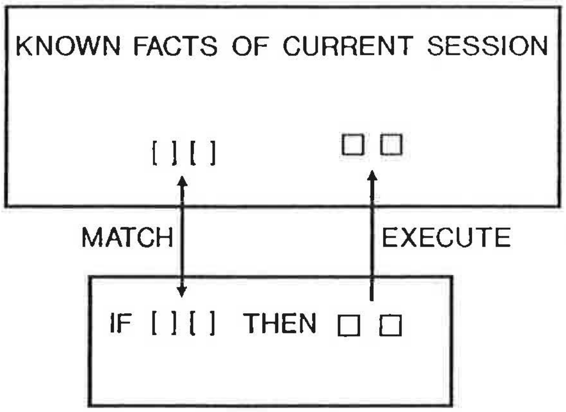


FIGURE 4 Match-execute process.

Sample System Session

To provide examples for the system's operation, an interactive session with the system is illustrated. The consultative system developed is fully menu-driven and uses the available support function in the expert shell for ease of use.

The program queries the user for facts to facilitate inferencing for the attainment of a particular goal. At any time within a knowledge-base session, the user can determine the current goal being pursued, find the reason why a particular query is posed, or ask for explanatory information to clarify a query. For this sample session, allylamine is taken as the unknown material with the following characteristics:

Hazard Class	:	Flammable Liquid
Flash Point	:	−4 deg F (−20 deg C)
Boiling Point	:	133.6 deg F (56.5 deg C)
Toxicity	:	LD50 = 106 mg/kg
		LC 50 = 286 ppm/4h
Others	:	Human irritant; no subsidiary hazard

The sample author-system interaction is shown in Figure 5. The bold text is the queries presented by the system, or the system's response to a user's query. The normal text and the underscored text are the user's responses, while the normal highlighted text is explanatory remarks from the author for a better insight of what is happening.

The session starts with a query from the control module. The goal of the control program is to determine the hazard class of the unknown material and activate the appropriate KB.

SUMMARY AND PLANS FOR FUTURE RESEARCH

This study shows that a consultative expert system to be accessed online is a viable approach to decision making in hazardous materials regulatory process for tunnel-bridge facilities. The study provides a useful framework for developing a rule-based system for representing the regulatory problem.

One limitation of the heuristic developed is that the criteria defining the envelopes are limited by the characteristics of the materials currently regulated. New commodities that are hazardous to society are constantly being developed and transported throughout the world. In this regard, the solution space can be expanded to accommodate these changes or new criteria may be added as they

---

```
              Regulatory Screening Assistant for Hazardous Materials
                                   What is :
     The material's name
     ALLYLAMINE

2 UNKN  3 STRT      6 WHY?     8 MENU     9 HELP    10 EXIT
```

The function keys highlighted at any screen session are the available functions that the user can use. Function key F6 is the user's link to Insight 2+ reporting system. It gives the line of reasoning, current rule being verified, current goal being pursued, and other miscellaneous reports related to the session.

```
              Regulatory Screening Assistant for Hazardous Materials
                        Can you identify the area of interest?
HAZARD CLASS is(are) RADIOACTIVE MATERIAL
HAZARD CLASS is(are) POISON
HAZARD CLASS is(are) COMPRESSED GAS
HAZARD CLASS is(are) FLAMMABLE LIQUID
HAZARD CLASS is(are) OTHER REGULATED MATERIAL
HAZARD CLASS is(are) FLAMMABLE SOLID
HAZARD CLASS is(are) CORROSIVE MATERIAL
HAZARD CLASS is(are) OXIDIZING MATERIAL
HAZARD CLASS is(are) COMBUSTIBLE LIQUID

2 UNKN   3 STRT    5 EXPL  6 WHY?  8 MENU   9 HELP    10 EXIT
```

The display now presented is a goal-selection menu. This is a list of possible conclusions that may be reached during the control module session. The system is asking if the user can narrow the list of possible conclusions. If the user is to select "UNKN" (function key 2), the system will proceed to evaluate the rules and continue to ask for information in an attempt to reach any of the above conclusions. At this point, HAZARD CLASS is(are) FLAMMABLE LIQUID *is selected since the hazard class of hazardous materials is generally known and written in the shipping paper.*

```
    ALLYLAMINE meets the definition of a flammable liquid
    Press function key F2 to access knowledge base.
```

Control will activate KB for flammable liquid when function key F2 is pressed.

FIGURE 5 Sample author-system interaction.

Regulatory Screening Assistant for Flammable Liquids

What is the flash point of ALLYLAMINE in degree F?

-4

2 UNKN 3 STRT 5 EXPL 6 WHY? 8 MENU 9 HELP 10 EXIT

The flammable liquid KB is now activated. The goal of this KB is to determine the applicable regulation for the unknown material.

Regulatory Screening Assistant for Flammable Liquids

What is the boiling point of ALLYLAMINE in degree F at 1 atmosphere?

133.6

Regulatory Screening Assistant for Flammable Liquids

Select what describes :

TOXICITY

EXTREMELY TOXIC
HIGHLY TOXIC
MODERATELY TOXIC
SLIGHTLY TOXIC
PRACTICALLY NONTOXIC
HARMLESS

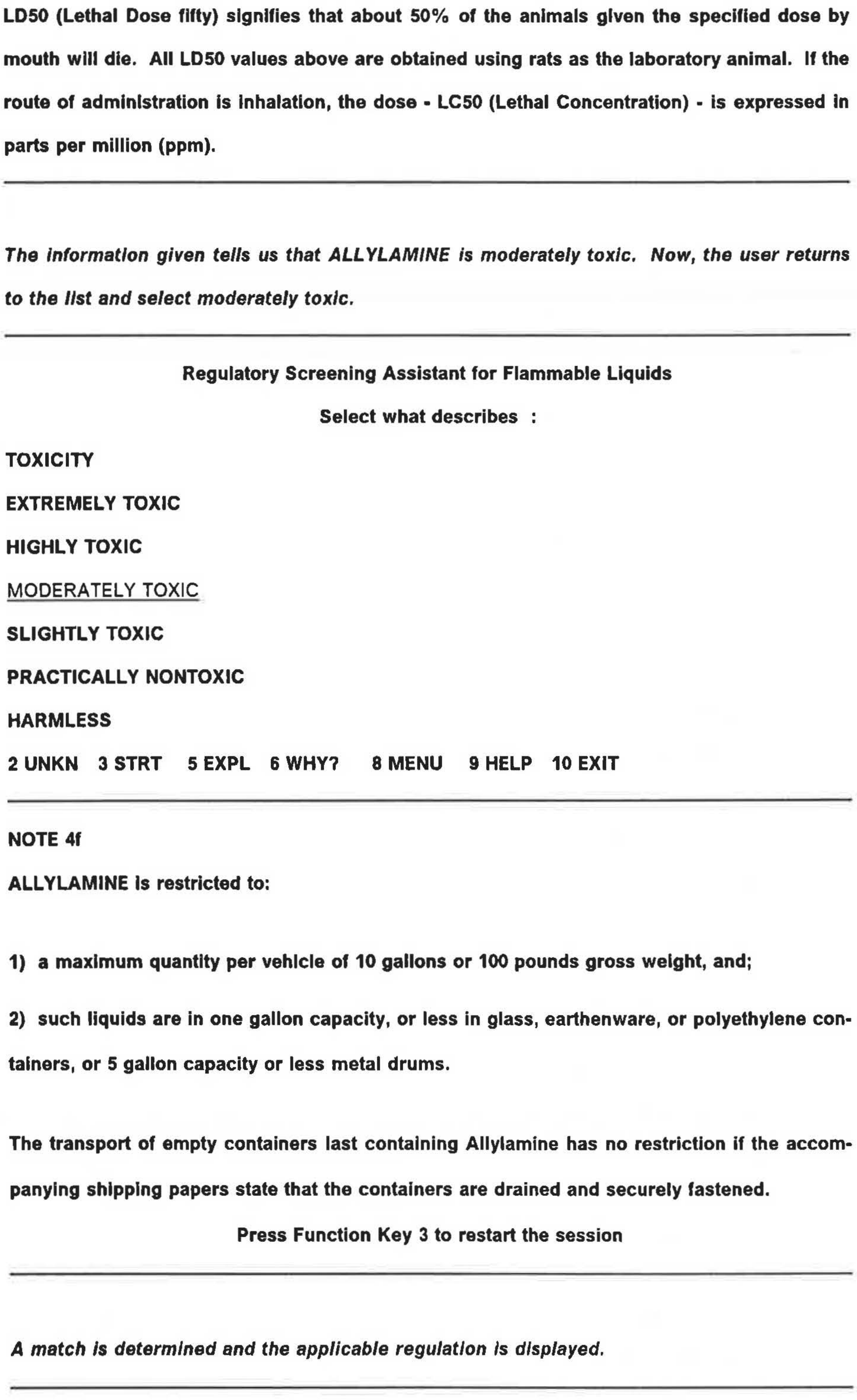
2 UNKN 3 STRT 5 EXPL 6 WHY? 8 MENU 9 HELP 10 EXIT

Again the user is presented with a list of choices to describe something which, in this case, is toxicity. Since the toxicity data given for ALLYLAMINE are numerical data, and not descriptive as presented by the system, there is a need for an explanatory information about the choices presented. To get explanatory information, Function key F5 is pressed.

Toxicity Classes

Descriptive Term	**LD50 (wt/kg)**	**LC50 (ppm)**
Extremely toxic	**≤ 1 mg**	**< 10**
Highly toxic	**1-50 mg**	**10-100**
Moderately toxic	**50-500 mg**	**100-1000**
Slightly toxic	**0.5-5 g**	**1000-10000**
Practically nontoxic	**5-15 g**	**10000-100000**
harmless	**≥ 15 g**	**> 100000**

FIGURE 5 *continued.*



LD50 (Lethal Dose fifty) signifies that about 50% of the animals given the specified dose by mouth will die. All LD50 values above are obtained using rats as the laboratory animal. If the route of administration is inhalation, the dose - LC50 (Lethal Concentration) - is expressed in parts per million (ppm).

The information given tells us that ALLYLAMINE is moderately toxic. Now, the user returns to the list and select moderately toxic.

Regulatory Screening Assistant for Flammable Liquids

Select what describes :

TOXICITY

EXTREMELY TOXIC

HIGHLY TOXIC

MODERATELY TOXIC

SLIGHTLY TOXIC

PRACTICALLY NONTOXIC

HARMLESS

2 UNKN 3 STRT 5 EXPL 6 WHY? 8 MENU 9 HELP 10 EXIT

NOTE 4f

ALLYLAMINE is restricted to:

1) a maximum quantity per vehicle of 10 gallons or 100 pounds gross weight, and;

2) such liquids are in one gallon capacity, or less in glass, earthenware, or polyethylene containers, or 5 gallon capacity or less metal drums.

The transport of empty containers last containing Allylamine has no restriction if the accompanying shipping papers state that the containers are drained and securely fastened.

Press Function Key 3 to restart the session

A match is determined and the applicable regulation is displayed.

FIGURE 5 *continued.*

are encountered. The heuristic developed in this study is useful enough to assist tunnel operators in decision making without the need for human experts. That is, only those materials that fail to find a match in the solution space require consultation with human experts. The recommendations given by the experts on these materials are then included in the database and, thus, improve the intelligence of the system.

The modularity of the system design provides ease for further development and enhancement of the expert system developed. This and other future research areas are discussed below.

1. One possible extension is to link the system to a hazardous material information system to further aid the decision process. One such information system is the Oil and Hazardous Material-Technical Data Systems.

2. Knowledge elicitation and codification is a continuing process. Hence, a subsystem should be developed so that knowledge is elicited from human experts through interaction with the system. Knowledge from human experts could greatly enhance the effectiveness of the envelopes.

3. The knowledge could be further enhanced by incorporating external programs such as simulation models, risk analysis, or fault tree modeling. Facts acquired from such models can be used by the system in its decision process.

4. As already mentioned, other KBs, such as management crisis and traffic control, can easily be attached to the system. Acquiring the knowledge on how tunnel-bridge operators and emergency response personnel react or respond to accidents, incidents, or traffic congestion inside tunnels and on bridges is the first step in developing the KBs for these domains.

5. The use of meta-level reasoning needs to be considered as rules accumulate. This is necessary to improve the efficiency of the search through the knowledge base. Metarules are strategic information imbedded in the rule base that suggests the best approach to attain the goal (7). They help or direct the inference engine search through the rule base efficiently.

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Benchmark Estimates of Release Accident Rates in Hazardous Materials Transportation by Rail and Truck

THEODORE S. GLICKMAN

Consistent, reliable estimates of release accident rates are essential when using risk assessment to compare the safety of rail and truck for a given shipment of hazardous materials. The estimates that appear in the literature have shortcomings or inconsistencies that make it difficult, if not impossible, to perform such a comparison. Yet claims are made that one transport mode is safer than the other, and risk assessors are using estimated accident rates that are out of date or inaccurate. This paper derives benchmark estimates of release accident rates for the two modes using Department of Transportation (DOT) incident reports to count the number of release accidents in 1982, and official statistics of the Interstate Commerce Commission (ICC) and the Census Bureau to evaluate the level of exposure to release accidents in that year. In addition to providing useful reference data for future risk assessments, the results show that there can be no general answer to the question of which mode is safer, since it depends on the release accident rate (which varies with release severity, carrier type, vehicle type, and track or road type) and such other factors as the size and design of the containers used.

One of the findings in the recent report of the congressional Office of Technology Assessment (OTA) on the transportation of hazardous materials (*1*) is that trucking is the least safe mode of transportation for hazardous materials. To be exact, the report says that "hazardous materials flow and accident data, poor as they are, show clearly that truck transport has the greatest risk of accidents." A recent advertisement placed by a railroad in a trade magazine (*2*, p. 9) echoed this conclusion in terms of hazardous waste, stating that "DOT statistics show that shipping hazardous waste by rail is actually safer than by over-the-road motor carriers." Neither the report's nor the advertisement's authors supported their statements with numerical accident rates for rail and truck transportation.

Risk assessment is the process of generating these frequencies and consequences, and it is essential to have consistent estimates of release accident rates for rail and truck when the purpose of the risk assessment is to compare the safety of these two modes of transportation. By "consistent," it is meant that in calculating the rates, the number of accidents is counted in the same way for both modes, the level of exposure to accidents is measured in the same way, and the same period of time is used to count accidents and measure exposure in each mode. The research in this paper was stimulated by the dearth of consistent, reliable estimates of rail and truck accident rates in the literature. As a result of this research, it was found that no simple answer exists to the question of which mode has a higher rate, since it depends (among other factors, such as the containers) on the size of the releases that are of concern, the carriers performing the transportation, the vehicles being used, and the types of track or roadway involved.

ACCIDENT RATES

Accident rates are estimated from historical data by calculating the ratio of the number of accidents that occurred during a given period to the level of exposure to accidents during the same period. Typically, accident rates are used to forecast the number of accidents in a given situation into the future, which is done by multiplying the accident rate by the anticipated level of exposure. Therefore, it is important that any such accident rate is deemed to be representative of the future situation. This usually means that the most recently available data were used to estimate the accident rate and that a sufficient amount of data was used. The choice of a time period may be limited by the fact that the accident data and the exposure data must both be available for the same period.

Exposure needs to be measured in terms that correspond to the kind of accidents in question, so that any increase in the level of exposure would result in a proportional increase in the number of accidents. For accidents arising from the mechanical failure of a vehicle or its fittings or appliances, exposure might be measured by the number of hours of operation. For accidents involving package or container failures, exposure might be measured by the number or volume of shipments. For accidents due to hazards encountered while in transit, exposure might be measured by the number of ton-miles or vehicle-miles.

RELEASE ACCIDENT DATA

The DOT's Office of Hazardous Materials Transportation maintains a database of all the reports it receives on trans-

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portation-related releases of hazardous materials. With the exception of battery spills and spills of paint and other consumer products in retail packages of five gallons or less, any unintentional release occurring during loading, unloading, transportation, or temporary storage associated with any mode of transportation (except pipelines) is supposed to be reported and reflected in this database. Concerns have been expressed in the literature about underreporting or misreporting of incidents (*1*, *3*), and one report performed for OTA attempted to estimate the magnitude of the shortfall (*4*), but there is no simple resolution to these problems.

The rail and truck incidents that were reported to DOT in 1982 are the ones used as the basis for the release accident rate calculations in this paper, because 1982 was the most recent year for which exposure data could be found for both of these modes. First the number of rail incidents was counted; then two separate counts were made of the number of truck incidents, depending on whether a for-hire truck or a private truck was involved.

Several different subsets of these incidents were also examined to see how accident rates vary as a function of these differences. In the rail mode the number of incidents in the subset involving tank cars only was counted separately, and in the truck mode the number of incidents in the subset involving only tank trucks was counted separately. Then for the entire set of incidents in each mode, and for both subsets, first the number of incidents in the subset referred to as "significant spills" (incidents in which the reported release quantities exceeded 5 gallons or 40 pounds) was counted separately; then the number of incidents in the subset referred to as "casualty related" (incidents in which the release resulted in a fatality or a reportable injury) was counted separately.

A summary of the release accident data extracted by counting the number of incidents in 1982 appears in Table 1.

EXPOSURE DATA

To obtain an estimate of the total number of car-miles of hazardous materials transported by rail in 1982, first for all types of cars and then for tank cars only, two data sources were used: (1) the ICC's File of Carload Waybill Statistics for 1982 and (2) output from the Princeton national rail network model. The Waybill File provides information about the locations of origination and termination of rail shipments, as well as the locations of the interlining junctions. By extracting the records for hazardous materials shipments from the file and then inspecting the car type field in each record to see whether or not the shipment was made in a tank car, a full description of the hazardous material carloads transported in all car types and in tank cars only in 1982 was obtained. Then the model's software was used to assign these carloads to routes through the network based on the origination/termination and junction information, and to compute the total number of car-miles in all car types and in tank cars only. The car-mile calculation is performed by multiplying the number of carloads on each link of the network by the respective length of the link in miles and summing the results of these multiplications to get the total number of car-miles transported by rail in all car types and in tank cars only.

TABLE 1 RELEASE ACCIDENT DATA SUMMARY

	Total	Significant Spills	Casualty-Related
All Types of Rail Cars and Trucks			
Rail	838	256	27
Truck (for-hire)	5314	1434	65
Truck (private)	357	233	11
Tank Cars and Tank Trucks Only			
Rail	736	197	25
Truck (for-hire)	936	692	31
Truck (private)	248	178	8

NOTE: Number of incidents reported to DOT in 1982.

TABLE 2 TRUCK-MILE STATISTICS FROM THE TRUCK INVENTORY AND USE SURVEY (*4*)

	Truck-Miles[a]
All types of trucks	
For-hire	9804
Private	6416
Tank trucks only	4428

[a] Millions of truck miles of hazardous materials in 1982.

The Census Bureau's most recent collection of truck transportation statistics in the United States is contained in the 1982 Truck Inventory and Use Survey (*4*). Table 2 shows the survey's statistics for the number of truck-miles of hazardous materials transported in for-hire and private trucks in 1982 (p. 78 of the summary volume) and for the number of truck-miles of hazardous materials in tank trucks in 1982 (p. 114), rounded to the nearest million.

To estimate the breakdown of the number of hazardous material truck-miles in tank trucks by for-hire trucks versus private trucks, the survey statistics relating to the truck-miles of all tank truck shipments of liquids and gases, whether hazardous or not (summary volume, p. 74) were used. These show that the fraction shipped in for-hire trucks was only 459.0 divided by 6609.5, or 6.94 percent. Applying this factor to the total of 4428 million truck-miles of hazardous materials in tank cars shown in Table 2 yields 307 million as the number of truck-miles transported in for-hire tank trucks and 4121 million as the number of truck-miles in private tank trucks.

The results of the exposure level calculations for both the rail mode and the truck mode are summarized in Table 3.

RELEASE ACCIDENT RATES

Dividing the accident data in Table 1 by the respective exposure data in Table 3 yielded the estimated release accident rates in Table 4. These estimates are shown to

TABLE 3 EXPOSURE DATA SUMMARY

	All Types of Rail Cars and Trucks	Tank Cars and Tank Trucks Only
Rail	549	402
Truck (for-hire)	9804	307
Truck (private)	6416	4121

NOTE: Millions of vehicle-miles of hazardous materials in 1982.

three or four significant digits and are expressed as the number of incidents per billion vehicle-miles (BVM), where the term *vehicles* is used to mean rail cars or trucks.

The upper half of Table 4 shows that, if all types of rail cars and trucks are taken into account, then the estimated release accident rate for rail is *higher* than the truck rate, for both for-hire and private trucking, regardless of whether all the incidents are considered or only a subset consisting of the more serious ones. If all incidents are considered, then the first column shows that the estimated railroad rate (1525 incidents per BVM) is almost three times as high as the estimated for-hire truck rate (542 incidents per BVM) and more than twenty-seven times as high as the estimated private truck rate (55.6 incidents per BVM).

If attention is limited instead to significant spill incidents only (i.e., those with reported release quantities above 5 gallons or 40 pounds), then the second column shows that the estimated railroad rate (466 incidents per BVM) is more than three times as high as the estimated for-hire truck rate (146 incidents per BVM) and almost thirteen times as high as the private truck rate (36.3 incidents per BVM).

Taking only casualty-related incidents into account (i.e., those in which a fatality or a reportable injury was attributed to the release), the third column shows that the estimated railroad rate (65.5 incidents per BVM) is almost ten times as high as the estimated for-hire truck rate (6.63 incidents per BVM), and more than thirty-eight times as high as the private truck rate (1.71 incidents per BVM).

Looking only at tank cars and tank trucks, the three columns in the lower half of the table show that the estimated railroad rate is *lower* than the respective, estimated for-hire truck rates for each of the three incident categories. The estimated for-hire tank truck rate exceeds the estimated rail tank car rate by a factor of 1.7 for all incidents, by a factor of 46 for significant spill incidents only, and by a factor of 1.6 for casualty-related incidents only.

TABLE 4 1982 RELEASE ACCIDENT RATES

	Total	Significant Spills	Casualty-Related
All Types of Rail Cars and Trucks			
Rail	1525	466	65.6
Truck (for-hire)	542	146	6.63
Truck (private)	55.6	36.3	1.71
Tank Cars and Tank Trucks Only			
Rail	1830	49.0	62.2
Truck (for-hire)	3049	2254	101
Truck (private)	60.2	43.2	1.94

NOTE: Incidents per billion vehicle-miles of hazardous materials.

It is evident throughout Table 4 that the estimated for-hire truck rate is much greater than the estimated private truck rate, for all types of trucks as well as for tank trucks only, regardless of whether all incidents are considered, or significant spill incidents only, or casualty-related incidents only.

Table 4 also reveals some interesting facts about tank-type vehicles in rail and for-hire truck transportation. In the rail mode, the rate for significant spills from tank cars is 49.0 incidents per BVM. This is much lower than the estimated rate for significant spills from *all* types of rail cars (466 incidents per BVM) and much lower than the estimated rate for spills from tank cars (1830 incidents per BVM). Therefore, rail tank cars appear to be designed well enough to avoid all but the smallest spills.

Compared to rail tank cars, the estimated rate for significant spills from for-hire tank trucks is much higher, with a value of 2,254 incidents per BVM. This is also much higher than the estimated rate for significant spills from *all* types of for-hire trucks (146 incidents per BVM), and somewhat lower than the rate for all spills from for-hire tank trucks (3,049 incidents per BVM). Thus, while tank trucks operated for-hire compare poorly to railroad tank cars and to all for-hire trucks in avoiding large spills, they are more successful in avoiding large spills than small spills.

A similar comparison in the case of private trucking of hazardous materials shows that tank trucks are less likely to be involved than all trucks in any accident involving a spill, and that the same is true when attention is limited to accidents with larger spills.

Note that the estimated release accident rates for the total incidents, involving all types of rail cars and trucks, do not agree well with the results of the incident rate analysis in (*4*), which are based on nine years of data (1976–1984) and which are expressed in ton-miles. (Conversion factors of 20,000 gal/carload and 8,000 gal/truckload may be assumed.) There are two principal reasons for the discrepancies: (1) the authors of (*4*) "compensated" for nonreporting by tripling the number of rail incidents and doubling the number of truck incidents, and (2) they used a slightly lower estimate of rail exposure based on the 1977 Waybill File and a substantially lower estimate of truck exposure based on the 1977 Commodity Transportation Survey.

QUALIFICATIONS ABOUT THE ESTIMATED RATES

Ideally, separate release accident rates should be estimated for each of the three major activities that are addressed by the hazardous material incident reports: (1) loading and unloading, (2) transportation, and (3) temporary storage. The reason is that the appropriate way to measure exposure level differs from one activity to the next. The number of tons or vehicles is an appropriate measure for loading and unloading, while the number of ton-miles or vehicle-miles is an appropriate measure for transportation, and the number of ton-hours or vehicle-hours is an appropriate measure for storage. The principal obstacle to producing separate rates is that DOT does not require the incident report to specify the activity being conducted when the release occurred, although in some cases this can be inferred from remarks written on the reports.

Because the total number of incidents was simply divided by the total number of vehicle-miles to obtain the estimated release accident rates in each category in Table 4, the following qualifications should be stated about the use of these estimates in risk assessment calculations. If the actual average length of haul for the situation in question is less than the average length of haul for the comparable shipments made in 1982, then there will be more loadings and unloadings per vehicle-mile; hence, the figure of interest in Table 4 will *under*estimate the actual release accident rate. Similarly, if the actual average length of haul is *greater* than the 1982 average, then the figure in Table 4 will *over*estimate the actual rate. Furthermore, if the situation in question involves temporary storage and the actual average storage time is *less* than the average storage time for comparable shipments made in 1982, then there will be less storage per vehicle-mile; hence, the figure of interest in Table 4 will *over*estimate the actual rate. Similarly, if the actual storage time is *greater* than the 1982 total, then the figure in Table 4 will *under*estimate the actual rate.

ADJUSTMENT OF THE ESTIMATED RATES BY TYPE OF TRACK AND ROADWAY

The estimation of release accident rates reflected in Table 4 was based on aggregate national statistics, with no distinction made about the type of track used in rail shipments and the type of roadway in truck shipments. In practice, however, most risk assessments deal with relatively localized situations, where the characteristics of the rail and truck routes involved can readily be identified and should be taken into account. The following approach provides a way to make adjustments in the estimates in Table 4 according to track type and roadway type.

A convenient way to distinguish among different types of railroad track is to use the six classes of track that are defined by the Federal Railroad Administration. The mandated speed limit is lowest on Class 1 track, which has the worst quality, and highest on Class 6 track, which has the best quality. In a report containing various kinds of hazardous material risk assessment statistics for rail transportation, Arthur D. Little, Inc., published estimates by track class of the accident rates for derailments on mainlines (*5*, Table 3-11). The results are shown in Table 5.

These rates can be used to develop factors for crudely adjusting the estimated rates in Table 4 in order to reflect differences in track type. (The adjustments are crude because the word *accident* is defined somewhat differently in Table 4 than in Table 5.) The factors shown in Table 5 are simply the ratios of the accident rate for each track class to the accident rate for all classes combined. Since the figures in Table 4 also relate to all classes combined, they can be adjusted for track class simply by multiplying them by the appropriate factor from Table 5.

TABLE 5 MAINLINE DERAILMENT ACCIDENT RATES (*5*)

Track Class	Accident Rate	Adjustment Factor
1	53.20	21.37
2	17.30	6.95
3	5.59	2.24
4	0.59	0.24
5/6	0.84	0.34
All	2.49	1.00

NOTE: Accidents per billion gross ton-miles.

For example, adjusted estimates by tracking class of the rate of release accidents for tank cars are shown in Table 6. A vast difference in the estimated rates from one track class to another is obvious.

As a basis for distinguishing among different types of roadways used by trucks, one can use the statistics published in the Federal Highway Administration's 1981 report on accident experience with large trucks (*6*). That report provides figures for the accident rates for all trucks by roadway type and for all roadway types combined, for California and Michigan, as well as for several other states (Table 33, p. 74). It also presents a figure for the accident rate for all trucks in California and Michigan combined (Table 6, p. 36). These figures are presented in Table 7 along with the results of calculations from these figures of the accident rate by roadway type for the two states combined. Adjustment factors calculated in the same way as the rail factors are also shown (with a similar caveat about their crudeness).

Using these factors, the adjusted estimates of for-hire tank truck release accident rates shown in Table 8 were obtained. Comparing Tables 6 and 8 to illustrate the effect that track type and roadway adjustments have on the relative safety of rail and for-hire truck transportation in tank-type vehicles, the following is evident. Although rail has a lower overall rate of release accidents for tank-type vehicles than for-hire trucking (1930 vs. 3049 incidents per BVM), if the rail transportation of hazardous materials in tank cars were confined to Class 3 track in some region,

TABLE 6 TANK CAR RELEASE ACCIDENT RATES BY TRACK CLASS

Track Class	Release Accident Rate
1	39,107
2	12,719
3	4,099
4	439
5/6	622
All	1,830

NOTE: Incidents per billion vehicle-miles of hazardous materials.

TABLE 7 TRUCK ACCIDENT RATES BY ROADWAY TYPE (*7*)

	Accident Rate			
Roadway Type	California	Michigan	Combined	Adjustment Factor
Rural freeway	169	81	141	0.60
Rural nonfreeway	289	146	244	1.04
Urban freeway	198	395	261	1.11
Urban nonfreeway	161	571	292	1.24
Overall	211	285	235	1.00

NOTE: Accidents per hundred million vehicle-miles.

while the distribution pattern of tank truck transportation among the different types of roadways in that region followed the national pattern, the railroad accident rate would be higher than the overall rate for the tank trucks that are operated for hire (4099 vs. 3049 incidents per BVM). By contrast, if the for-hire truck transportation of hazardous materials in tank trucks were confined to rural freeways in some region, then its accident rate would be higher than the overall rate for rail transportation in that region (3171 vs. 1830 incidents per BVM).

CONCLUSIONS

There is no shortage of estimates of release accident rates in the literature for both truck and rail transportation of hazardous materials. These estimates are measured in different ways, however, and they vary in terms of how accurate and current they are. In some cases it is hard to determine how good the estimates are because the references do not explain adequately how the numbers were obtained. These complications make it difficult, if not impossible, to compare the truck and rail rates that have been published in different sources.

In their study of the truck and rail transportation of propane (*8*), Battelle Pacific Northwest Laboratory (BPNL) estimated the release accident rates for the two modes in a consistent manner, and Table 9 shows a comparison of their results with those from this study. The comparison is a rough one, because their results are based on 1971–1976 data and are limited to propane shipments of hazardous materials. During that period, too, DOT was just beginning to collect reports, and the massive retrofitting of tank cars with protective features such as headshields and shelf couplers had not yet been done. The results in this paper, on the other hand, are for 1982 and are based on all shipments of hazardous materials. Both sets of results are for tank cars and tank trucks only. The authors' estimate for the truck mode is 2.4 times higher than theirs, while their rail estimate is 1.8 times higher than the authors.' Hence, in terms of release accident rates, the truck mode was found to be less safe than they found it and the rail mode, to be safer.

TABLE 8 FOR-HIRE TANK TRUCK RELEASE ACCIDENT RATES BY ROADWAY TYPE

Roadway Type	Release Accident Rate
Rural freeway	1829
Rural nonfreeway	3171
Urban freeway	3385
Urban nonfreeway	3781
Overall	3049

NOTE: Incidents per billion vehicle-miles of hazardous materials.

TABLE 9 COMPARISON OF RELEASE ACCIDENT RATES

	Ours	BPNL Propane
Tank trucks	685[a]	284[b]
Tank cars	1830	3258[b]

NOTE: Incidents per billion vehicle-miles of hazardous materials.
[a] Based on the rates in Table 4, weighted by the for-hire truck-miles and private truck-miles of petroleum products in the Census survey (*5*, pp. 76, 77).
[b] Obtained by dividing the release probabilities in Table 10.3 of (*8*) by the average shipment distances in Table 10.1.

Accident rates are fundamental to risk assessment, and the importance of having accurate estimates cannot be overstated. Along with data on the volumes of hazardous materials transportation on the routes of interest and information about the hazards of conducting transportation on those routes, accident rate estimates are one of the basic building blocks needed to calculate a risk profile. In a risk profile an evaluation is made of the frequency of hazardous materials transportation accidents as a function of the level of the consequence of the accidents for all routes collectively in the region of interest (or for any individual route segment of particular concern). Development of a risk profile requires that the release accident rates be combined with the flow data to calculate the release accident frequencies, and that the estimated spill quantities be combined with knowledge of the chemical, physical, or biological properties of the materials (depending on the impacts of interest) in order to calculate the accident consequences.

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DISCUSSION

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In the introduction to his work, the author is quite explicit about previous research efforts failing to develop consistent, reliable estimates of release accident rates due to methodological shortcomings, indicating that this paper represents a significant contribution by providing benchmark estimates in which we can have some statistical faith. On the contrary, it appears that the author has adopted a methodology that provides a classic illustration of many of the pitfalls identified by previous researchers and that, alas, we remain a long way from being able to develop the quality estimates that are so desperately needed. In fact, systemic problems in accident and exposure (volume) databases available for this type of application will deter development of reliable empirical estimates for years to come.

It is interesting to note the author's claim that by using only 1982 rail and truck accident and exposure data, some sort of consistency has been established. This is far from the case. First, as noted by the author, the accident/incident database used for truck and rail suffers from underreporting and misreporting. What the author does not state is that the underreporting may be as large as 30 to 50 percent, and it is not uniform across both modes, with truck underreporting being a more significant problem. The implications of this are twofold: (1) the reported accident/incident frequencies are biased toward making trucks look relatively safer, and (2) the accident rates reported in the paper should not be taken out of context by other analysts looking for accident rate estimates. In fact, given the known uncertainties in these numbers, carrying the rates out to two significant digits is clearly inappropriate.

The exposure (volume) data similarly suffer from consistency problems. The Waybill file (rail) and TIUS (truck) are collected using two completely different sampling designs with varying levels of precision. Whereas the Waybill file represents a sample of individual rail shipments, TIUS is based on a survey of truck owners who provide an annual estimate of their mileage and a percentage range of how often they are carrying hazardous materials. When aggregating from these data, one simply cannot claim that the "level of exposure to accidents is measured in the same way," as the author does.

There are also some troubling aspects to the accident rates reported in the paper. First, the author does not clarify what is meant by "vehicle-miles." In the case of rail, there would be major differences in the magnitude of the accident rates depending on whether this is defined as train-miles or car-miles. If it is train-miles, and the train is carrying ten cars loaded with hazardous materials, then the resulting accident rate would vary by an order of magnitude depending on the exposure definition. Second, knowing the methodological problems with the derived accident rates, it is inappropriate for the author to disaggregate by truck class and roadway type, particularly since (1) the reported classification data are for accident rates, and not release accident rates, and (2) the data come from 1981 and 1983 for truck and rail, respectively, and not from 1982, which is the author's prior analytic focus. While the latter point may seem trivial, it is important to recognize the downturn in the economy in 1982 that had a major impact on freight transport and safety statistics for that year alone.

In summary, it is apparent that some serious methodological flaws exist that render any widespread use of the reported rates dangerous to the extent that many people are looking for such numbers to plug into their risk assessments without knowledge of the derivation of these estimates. If it is any consolation, however, the author is not alone in his approach to this problem. He merely joins the rest of us who are struggling to perform risk estimation under conditions of limited data availability.

AUTHOR'S CLOSURE

The OTA report on hazardous materials transportation is a highly informative study, but some of the sweeping conclusions related to incident reporting and commodity flows were not justified by the analysis that was shown. One such conclusion, identified in the opening paragraph of my paper, is that "truck transport has the greatest risk of accidents." Another one, restated by the discussant in percentage terms in the second paragraph of his comments, is that "for rail and Interstate highway transport, the number of releases is underrepresented by factors of 3 and at least 2, respectively."

My objection to these conclusions, which I suppose are attributable to the discussant, is not that they are necessarily wrong but, rather, that they were not shown to be right. Given that the public deserves to have faith in congressional reports, it is unfortunate that the process by which these conclusions were reached was not subjected to an adequate peer review. It is unfortunate, too, that there are a number of mistakes in Abkowitz's comments on my paper, as the following point-by-point closure will demonstrate.

Note that in the cases where I have paraphrased the discussant's comment rather than quoted it verbatim, I have tried to preserve the essence of the actual statement.

1. "The underreporting [of incidents] may be as large as 30 to 50 percent and it is not uniform across both

modes, with truck underreporting being a more significant problem."

The credibility of these contentions is undermined by the careless use of apples and oranges in Chapter 2 of the OTA report, e.g., in the comparison of the HMIS and TAF databases on pp. 77 and 78. Moreover, if the EPA estimate cited on pp. 67 and 70 of the OTA report is true, that 90 percent of the releases over 100 gallons are reported, then underreporting does *not* appear to be a serious problem.

I suspect that a substantial number of smaller spills do go unreported, but I do not know how serious the problem is, nor do I know of any demonstrable reason why trucking companies would be worse at reporting than railroad companies. I also suspect that there was less underreporting in 1982, the year I used, than in the earlier years of OTA's 1976–1983 period, because of (a) the cumulative benefits of experience and (b) the 1981 reduction in reporting requirements.

2. Given the known uncertainties in the accident rate estimates, it is clearly inappropriate to carry them out to two significant digits.

The discussant is not using the term *significant digit* properly, as evidenced by the fact that the estimates in Table 4 were carried out not to two, but up to four, significant digits. This is a legitimate thing to do as long as the noninteger numbers that go into the calculation have at least four significant digits, which is true of the vehicle-mile numbers that I used.

3. One cannot claim that the level of exposure to accidents is measured in the same way when different sampling designs are used to collect the data.

This comment puzzles me for two reasons: (a) it has no basis in fact, and (b) Abkowitz himself did precisely the same thing when he compared ton-miles by truck, rail, and other modes in his paper in *Transportation Quarterly* (Vol. 40, No. 4, October 1986, pp. 483–502). An estimate is an estimate, regardless of how it is obtained. Some estimates may be more precise than others, but this does not preclude good estimates from being compared with not-so-good ones.

4. The author does not clarify what is meant by vehicle-miles. In the case of rail, it is not clear whether a vehicle is a train or a railcar.

The discussant's attention is drawn to the following statement in my first paragraph under the heading *Release Accident Rates*, which could not be clearer: "The term *vehicles* is used to mean rail cars or trucks." Even if Abkowitz had missed this statement, it strikes me as peculiar that anyone would think that the term *rail vehicle* means a train rather than a railcar.

5. "It is inappropriate for the author to disaggregate by track class and roadway type, particularly since (1) the reported classification data are for accident rates, and not release accident rates, and (2) the data come from 1981 and 1983 for truck and rail, respectively, and not from 1982."

With regard to the first part of this comment, I fully documented the method by which I obtained the estimates in Tables 6 and 8, with no attempt to pass them off as anything but "crude," stating that they were intended merely to illustrate "a way to make adjustments in the estimates in Table 4 according to track type or roadway type."

As for the second part, the discussant is wrong once again. The *1982 Truck Inventory and Use Survey* pertains to 1982 truck movements, not to 1981 (a fact that may be confirmed by calling Robert Crowther of the Bureau of the Census), and the 1982 File of Carload Waybill Statistics pertains to 1982 rail movements, not to 1983 (a fact that may be confirmed by calling Thomas Warfield of the Association of American Railroads).

6. "Some serious methodological flaws exist that render any widespread use of the reported rates dangerous to the extent that many people are looking for such numbers to plug into their risk assessments."

I encourage people to decide for themselves whether it would be "dangerous" to use the rates in my paper.

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Hazardous Materials Transportation Rules and Regulations at Bridge-Tunnel Facilities

BAHRAM JAMEI, ANTOINE G. HOBEIKA, AND DENNIS L. PRICE

Hazardous materials are transported every hour of every day through major and vital transportation facilities such as bridges and tunnels. The problem of identification, classification, regulation, and control of these toxic substances during transportation is one of tremendous magnitude and significance. Development of rules and regulations for shipment of hazardous materials through special facilities such as bridges and tunnels was the main objective of a study performed under contract for the Virginia Department of Transportation. During the conduct of this project many tasks were undertaken to produce a single manual of rules and regulations for bridge-tunnel facilities in the Commonwealth of Virginia. This paper is a summary of that study, and it concentrates on the details of the analytical framework that was used to generate a set of criteria by which regulations for new and unlisted substances could be developed in the existing manuals. For example, the methodology of developed rules and regulations for the flammable liquids hazard class is discussed to provide an overview of the entire analytical technique.

Hazardous materials are transported every hour of every day through vital transportation facilities such as bridges and tunnels. According to a recent report published by the Office of Technology Assessment (OTA), more than 60 percent of all hazardous materials shipments are made by trucks (containers, flat beds, and tanks) (*1*). A study by Price and Schmidt in 1978 at Virginia Tech disclosed that approximately 13 percent of all trucks in Virginia carried hazardous materials and 240 highway accidents involving hazardous materials could be expected in Virginia in a ten-year period (*2*).

The enormous damage to human health and the environment that can be caused by a single truck accident carrying hazardous materials is of great concern. Even though such incidents are relatively infrequent, shipment of such materials must be safely regulated in order to reduce harmful consequences.

A way to reduce the risks involved with the transportation of hazardous materials is to develop and deploy the proper regulations, information systems, container safety, enforcement, and training for emergency response personnel. This could be accomplished by providing more uniformity in federal, state, and local regulations and enforcement procedures and by encouraging coordination and cooperation among all levels of government agencies. Availability of more information about the transportation of hazardous materials would improve public knowledge in this matter. In addition, better government coordination in setting container regulations, including operational and procedural guidelines, is needed. Most important, a national strategy to provide training for emergency response and enforcement personnel is necessary at the state and local levels.

Lack of industries' familiarity and compliance with federal regulations of hazardous materials and inadequate government surveillance resulted in the passage of the Hazardous Materials Transportation Act (HMTA) of 1975. The basic intent of the law was to improve regulations and enforcement activities by allowing the Secretary of Transportation to set regulations applicable to all modes of transport. The most important existing federal regulations governing the transportation of hazardous materials are documented in Title 49 Code of Federal Regulations (49 CFR), parts 100 through 199.

The code consists of extensive specifications for containers, hazardous communication requirements such as vehicle placarding, and operating procedures for each mode of transport. Even though many states have adopted 49 CFR wholly or in part, in some cases states have developed their own regulations. This is true specifically for bridge and tunnel facilities throughout the United States, as documented in *A Summary of Highway Facilities Where Hazardous Materials Are Restricted* (*3*). Local jurisdictions and state governments controlling these facilities are concerned with developing regulations regarding the maximum quantity of hazardous materials per vehicle that they should allow to go through these vital bridges and tunnels without producing unreasonable risk to human health and the environment, as well as risk of damage to property in case of an incident involving such vehicles. State regulations concerning shipment of hazardous materials could be more restrictive than such federal regulations but not to the extent that they unreasonably burden interstate commerce.

RESEARCH OBJECTIVES

This paper contains a summary of the analytical framework that was developed as part of a study to produce a single hazardous materials regulation manual for bridge-tunnel facilities in the Commonwealth of Virginia. The emphasis was on a comprehensive assessment of existing regulations

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and on developing a set of criteria by which the shipment of new and unlisted hazardous materials through bridge-tunnel facilities could be regulated and controlled.

In the process of developing such a manual, the following tasks were performed:

- Task 1—review of literature related to existing hazardous materials' regulations and their development process;
- Task 2—review of hazardous materials' regulations on board ferry vessels;
- Task 3—inventory of tunnel facilities using a detailed questionnaire form and site visits by project team;
- Task 4—gathering of information about the hazardous materials flow through the facilities by conducting special surveys of carrier companies and industries, in addition to placarding trucks stopping at inspection stations;
- Task 5—development of a regulatory methodology based on the performance and safety records of existing regulations;
- Task 6—utilization of different hazardous materials rating schemes to disaggregate those substances that justify further regulatory investigations;
- Task 7—development of a technical regulatory process sensitive to the chemical properties of hazardous materials;
- Task 8—discussion of substances that needed regulatory modifications using expert systems;
- Task 9—evaluation of traffic conditions in and around the tunnels under emergencies; and
- Task 10—preparation and development of the manual.

This paper concentrates, however, on the results of tasks 5, 6, and 7 and briefly refers only when necessary to the findings of other tasks performed within this study.

DEVELOPMENT OF A REGULATORY FRAMEWORK

Findings of a literature review for the study revealed that all of the existing regulations for shipment of hazardous materials through bridge-tunnel facilities are similar. Furthermore, there is a lack of scientific methodologies leading to the development of such regulations. Weaknesses in these methodologies exist in determining the joint probabilities of an accident occurring in a tunnel or on a bridge that could lead to a chemical spill, and then evaluating the consequences and effects of such a spill in a specific environment to determine the tolerable risks and eventually using these findings to develop appropriate regulations.

The review concentrated basically on existing regulations on hazardous materials via five tunnel and bridge facilities in different states. These five facilities are (1) Big Walker and East River Mountain Tunnels (BW), (2) Chesapeake Bay Bridge and Tunnel (CB), (3) New York and New Jersey Port Authority tunnels and bridges (NY/NJ), (4) Maryland toll facilities tunnels and bridges (MD), and (5) Triborough Bridge and Tunnel Authority (TBTA) of New York.

In developing a basis for comparing existing regulations among the five different facilities, the regulations of TBTA were selected as the point of reference or framework for the analysis, as well as for development of the Hazardous Materials Tunnel and Bridge (HMTB) data file. There were several reasons for selecting TBTA regulations as the study base. First, the regulations were the most current of those of the five facilities analyzed. Second, the regulations of TBTA appeared to be more comprehensive than those of the other facilities (that is, they contained more material listings or descriptions), and they conformed most closely to the structure of the Hazardous Materials Table in 49 CFR, part 172.101. Third, the TBTA regulations contained the United Nations (UN) hazard identification (ID) number for each commodity, an added dimension in terms of commodity description.

Therefore, the current bridge-tunnel regulations were used as a starting point for developing such a regulatory framework. The basic reasons for utilizing existing regulations were:

1. The regulations were established and were widely accepted. The safety records of the bridge-tunnel facilities during the past twenty-five years indicated that the regulations have been performing reasonably well in preventing catastrophic disasters.
2. The transportation industries have been using these regulations for a long time, as the survey indicated. A substantial change in the regulations would have resulted in additional costs to shippers, a disturbance to their existing procedures, and the need to retrain their employees.
3. The weight limitations imposed on hazardous materials in the current regulations reflected the degree of hazard each substance holds.

Next, this study designed an approach to separate those hazardous materials that are subject to inconsistencies in the current regulations. That is, the effort was made to seek out those hazardous materials within a hazard class that have similar chemical properties and produce the same harm potentials, yet were given two different maximum allowable quantities per vehicle in the regulations. Those materials treated inconsistently were identified by the following procedure:

1. A list of highly dangerous substances was produced by utilizing the rating system of hazardous materials of major organizations and by consulting individual authorities on chemical substances.
2. Existing regulations for the preceding list of hazardous materials were studied closely to determine if any discrepancies exist. Such materials were then marked for further investigation regarding their unequal regulatory treatment.
3. Existing regulations for those substances in item 2 and certain other hazardous materials (whether new or

needing regulations) were analyzed to determine whether new regulations should be established or whether the current rules should be followed.

Basically there are two general approaches for selecting questionable substances discussed above: (1) a comparative approach and (2) a risk analysis system approach. The comparative approach relies on performance of existing regulations. It selects for further investigation only those substances that do not have the same regulations of allowable quantity per vehicle weight limitations, even though they do have chemical properties and characteristics similar to those of other substances in their class. This approach could also be used to determine the regulations for those substances that, for regulatory purposes, are either new or have been recommended by major organizations and experts as being highly dangerous and requiring further regulatory investigation.

The alternative strategy would have been to perform a risk analysis approach for every one of the substances and then produce a matrix of harm versus various scenarios and events that might occur in case of an incident involving release of the hazardous material. The outcome of this latter approach would then have been a risk analysis and cost-effectiveness measure for any specific rules and regulations concerning a substance. Unfortunately, because of time and money constraints, this approach is not feasible for this study. Besides, the data needed to implement such a study are not available, and the models necessary to conduct the analysis would have to be designed from scratch for tunnel operations. Therefore, it is not possible to conduct this approach in a year, as required by contract for this study.

Hazardous materials are classified in existing regulations according to their chemical properties and harm potentials. Even within a specific hazard class, such as flammable liquids or poisons, further divisions exist that carry their own specific characteristics by type of packaging, maximum allowable quantity per vehicle, and per package weights.

The effort was made in this study to characterize these regulatory divisions (here called "envelopes") within each hazard class by a set of chemical, physical, environmental, and other properties of the substances originally forming these divisions. The basic idea is that substances in each envelope within a general hazard class behave the same or have similar severity of harm when released and therefore should have a consistent and uniform set of regulations. The next step would be to extract substances that, based on their chemical properties and other characteristics, were placed in an inappropriate envelope. These substances and any other new or questionable hazardous materials could then be assigned to the appropriate envelopes by considering their chemical properties and matching them with the right envelope in the corresponding hazard class.

The flow chart in Figure 1 illustrates the entire process of selecting questionable substances and the steps involved in developing the regulatory methodology.

HAZARDOUS MATERIALS RATING SCHEMES

Hazardous materials ranking or classification systems are usually grouped into two major categories: classification systems established for regulatory purposes and classification systems used to facilitate emergency response in case of an incident.

Classification systems may categorize materials by specification of the hazard or degree of hazard associated with handling, transportation, disposal, or incident involving release of the substance. Currently, no single system incorporates the degree of hazard, corrective action, transportation limitation, storage, and handling of containers. One major reason for the lack of a unified system is that a single system may be impractical or too complicated from all the possible usage viewpoints.

For the purpose of the study and in order to address both regulatory and emergency response aspects of the existing schemes, six major classification systems were selected as described below:

1. International Maritime Organization Rating System (IMO). The system establishes criteria on harm mechanisms resulting from continuous discharges into the sea from stationary outfalls that could affect the marine environment (*4*).
2. National Fire Protection Association Rating System (NFPA). The system provides simple, readily recognizable, and easily understood markings that will give, at a glance, a general idea of the inherent hazards of any material and the order of severity of these hazards as they relate to fire prevention, exposure, and controls (*5*).
3. Glickman and Waddington Hazard Rating System. The system determines relative hazards based on the premise that if the contents of a hazardous material shipment are very dangerous and if the container is likely to release a large quantity of its contents in an accident, then the hazard rating for that shipment should be high (*6*).
4. N. Irving Sax's Toxicity Rating System (Sax's). The Sax's rating system basically addresses the issue of toxicity and its relative hazards (*7*).
5. National Academy of Sciences Rating System (NAS). The fire, health, water pollution, and reactivity hazards of bulk water transportation of industrial chemicals are evaluated (*8*).
6. United Nations Packaging System (UN). The system divides the hazardous materials of all classes other than class 1 (explosives), 2 (gases), 6.2 (infectious substances), and 7 (radioactive materials) into three main packaging groups according to the degree of danger they present.

These three packaging groups are as follows:

- Packaging group I—hazardous materials with great danger;
- Packaging group II—hazardous materials with medium danger; and
- Packaging group III—hazardous materials with minor danger (*9*).

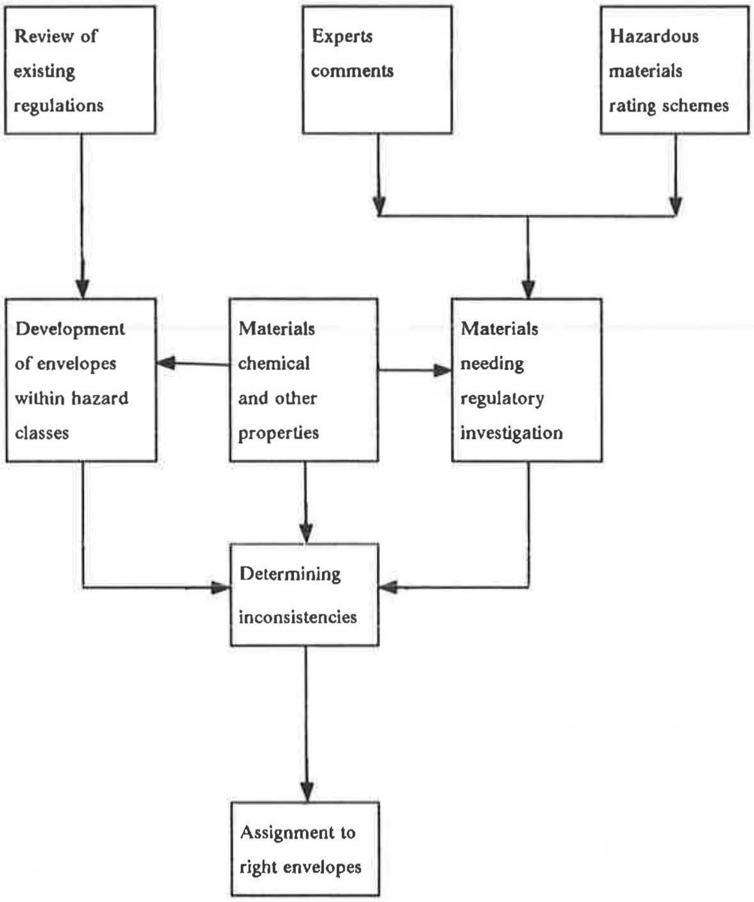

FIGURE 1 Framework of analysis.

Based on the preceding rating schemes and the expertise of many individuals, more than 700 substances were selected for investigation regarding their regulations for shipment via tunnels and bridges. In the next section of this paper, the analytical framework that was used to develop regulatory methodology is explained. Also, as an example, the methodology for flammable liquids hazard class is given in a more detailed format.

DEVELOPMENT OF TECHNICAL REGULATORY METHODOLOGY

In all of the reviewed regulatory sources, each hazardous material class, such as flammable liquids or poisons, had a different set of rules and regulations. Within a specific hazard class, further divisions defined the material's specific characteristics in terms of type of packaging, maximum allowable quantity per vehicle, and per package weights. The study characterized these regulatory divisions ("envelopes") within each hazard class by a set of chemical, physical, environmental, and other properties of the substances originally forming these divisions. Since substances in each envelope within a general hazard class behave the same or have similar severity of harm when released, the substances in each envelope should have a uniform set of regulations. The next step, as stated earlier, was to extract substances that, based on their chemical properties and other characteristics, were placed in an inappropriate envelope. These substances and any other new or questionable hazardous materials could then be assigned to the appropriate envelopes through a consideration of their chemical properties and by matching them with the right envelope in their corresponding hazard class.

It should be noted that the envelopes formed served only as an aid to arriving at a decision. Other relevant characteristics that are unique to a particular hazardous material were considered in determining the final restrictions.

V. C. Marshall (*10*) lists five principal factors that govern severity of consequence of spillage:

1. Intrinsic properties: flammability, toxicity, instability;
2. Dispersive energy: pressure, temperature, state of the matter, volatility;
3. Quantity present;
4. Environmental factors: topography and weather; and
5. Population density in the vicinity and proximity of property.

Factors 4 and 5 can be considered constant or unchanging. These factors are independent of the hazardous materials present. The other three factors are dependent on the type of material present and provide an indication of the harm potential of the material. Of these, the quantity present is one factor that can be controlled through regulation. The regulated amount will largely depend on the properties of the substance. The harm potential of a hazardous material can be effectively reduced to a tolerable magnitude by reducing the quantity present.

Harm potential is a function of the intrinsic property and dispersive energy of the material. By defining envelopes or grouping for each hazard class based on their harm potential, with environmental conditions and population density assumed constant, the severity of consequences becomes a function solely of quantity present. Analyzing these envelopes based on probable tunnel incident scenarios will give an estimate of the magnitude of harm for each envelope. From this, quantity limitation can be assigned for each envelope.

Analyzing tunnel incident scenarios and assigning the appropriate quantity limitation using risk analysis, simulation, or an impact matrix are too rigorous to be justified at the present time, even if the data necessary to do so existed. A rigorous approach would require a detailed study in the probability of release as a function of the transportation environment, traffic densities, container design, stowage, and the various factors that can influence the magnitude and occurrence of a breach in the containment system. A rigorous approach would be as prohibitively costly as it is difficult. Such an approach is too complex and highly theoretical; it would require, in most cases, data that simply do not exist.

To circumvent these methodological and data constraints, an alternative approach was devised. The approach is rooted in using an existing system that assigns quantities to hazardous materials that reflect their harm potential. The current tunnel-bridge regulations were a good starting point for such a scheme.

The flammable liquid hazard class is used here as an example to illustrate the regulatory methodology. Figure 2 gives the packaging and total quantity restrictions for the flammable liquids based on existing regulations. By converting this figure according to the dispersive energy and intrinsic properties of the materials under each note, the resulting chart (Figure 3) was developed. The chart defines the envelopes for each note with the corresponding packaging and quantity limitation. Having established these decision trees for each hazard class, the problem became one of finding to which envelope a hazardous material, based on its properties, would belong. From this, the packaging and total quantity limitations for a particular substance were easily determined.

In determining the envelopes for flammable liquids, susceptibility to burning was the basic criterion used. The range of the flammability limits and the amount of vapor produced by a flammable liquid at normal conditions give an indication of its susceptibility to burning or explosion. It is a well-known fact that gasoline, for example, does not burn; the vapors of gasoline burn. This was one of the major reasons for forming a common grouping for flammable liquids based on their characteristics, such as flash point, which is the temperature at which enough vapors are generated to momentarily support combustion and volatility. As shown in Figure 2, flammable liquids in tank vehicles are restricted. For those flammable liquids in containers, the weight limitations are either 100 pounds gross weight per vehicle (notes b through f) or greater (notes g through j). Three flammable liquids, namely, ethyl nitrate, ethyl nitrite, and nickel carbonyl, are totally restricted from passage.

The amount of vapor produced by a liquid at any temperature (volatility) is directly related to its vapor pressure and its boiling point. In general, the lower the boiling point and the higher the vapor pressure, the more hazardous the flammable liquid is. For flammable liquids with similar flash points, the one with the lower boiling point is considered the most hazardous. This is reflected in the National Fire Protection Association (NFPA) class rating given for flammable liquids; that rating is adopted here in forming the envelopes for this hazard class. Briefly, the NFPA system separates flammable liquids into three classes.

Class	*Flash Point*	*Boiling Point*
1A	Below 73 F (23 C)	Below 100 F (38 C)
1B	Below 73 F (23 C)	At or above 100 F (38 C)
1C	At or above 73 F (23 C) and below 100 F (38 C)	

Other factors that further separate the individual envelopes for this hazard class are toxicity, explosivity, ease of ignition, and burning rate.

The various combinations of the preceding characteristics defining each envelope are shown in Figure 3. As used here, explosivity refers to the immediate or instantaneous explosion hazard of materials that burn at an explosive rate. Explosion caused by the ignition of a flammable vapor cloud is not considered an immediate explosion hazard. Toxicity is defined in terms of lethal dose fifty (LD50) and lethal concentration fifty (LC50). To be consistent, only LD50 and LC50 values for rats as test animals were used.

One example of the changes made is the substance ethyl methyl ether, originally referred to in notes g, j, and k in Figure 3. After the chemical properties of the substance were reviewed, it was determined that the substance should belong to note f, with maximum gross weight per vehicle of 100 pounds.

The commodity table of the developed manual contains close to 2,700 substances, in comparison with 1,300 substances for the current Chesapeake Bay bridge-tunnel District manual and 650 substances for the Big Walker and East River mountain tunnels. There were also 56 new commodities in the table that had to be regulated. The hazardous material regulations for 69 substances had to be tightened based on new regulatory process. And finally, the regulations for 22 hazardous materials were relaxed. These numbers were obtained using the CFR 49, Table 172.101, as a reference base.

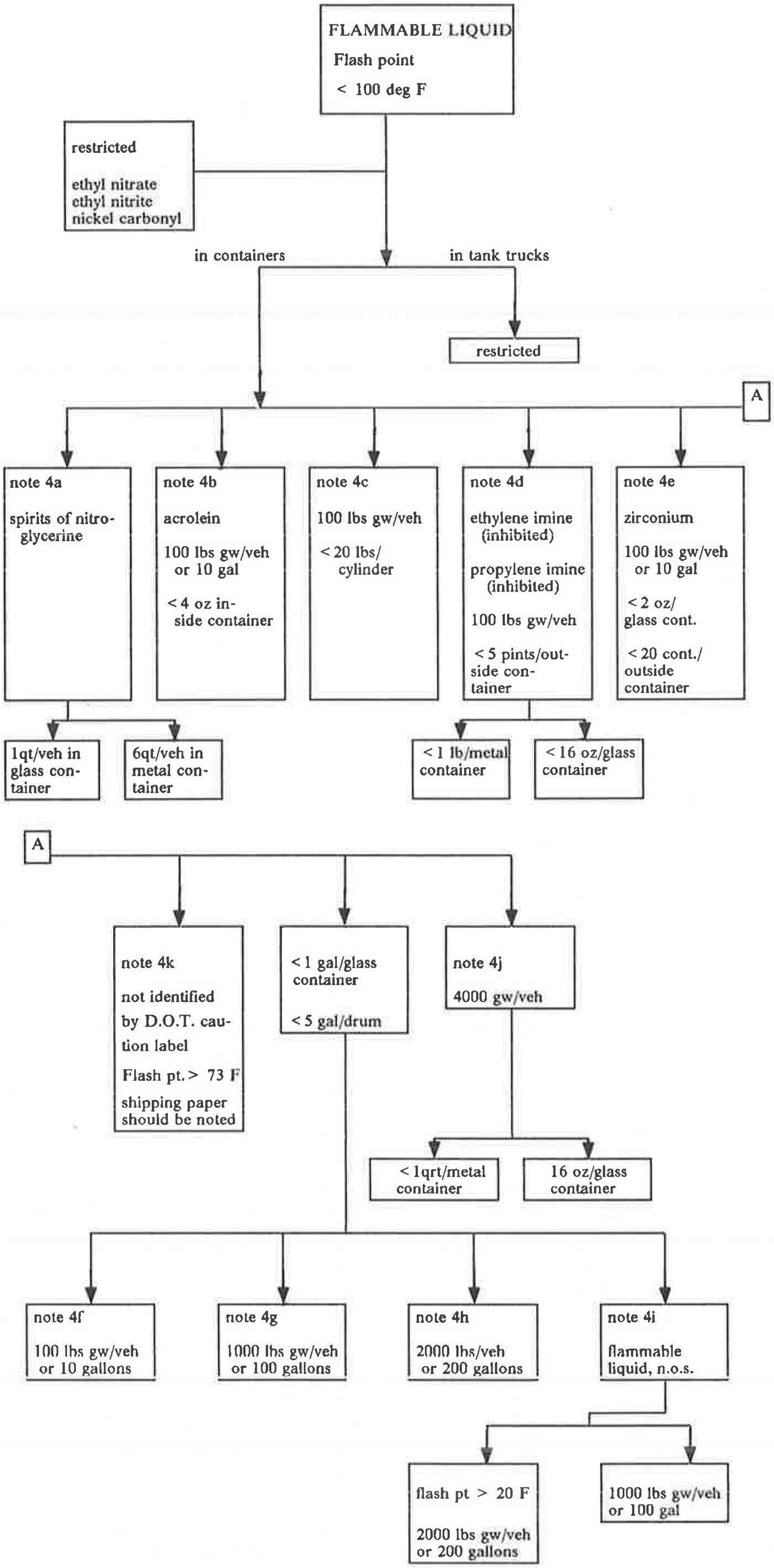

FIGURE 2 Rules and regulations chart for flammable liquids.

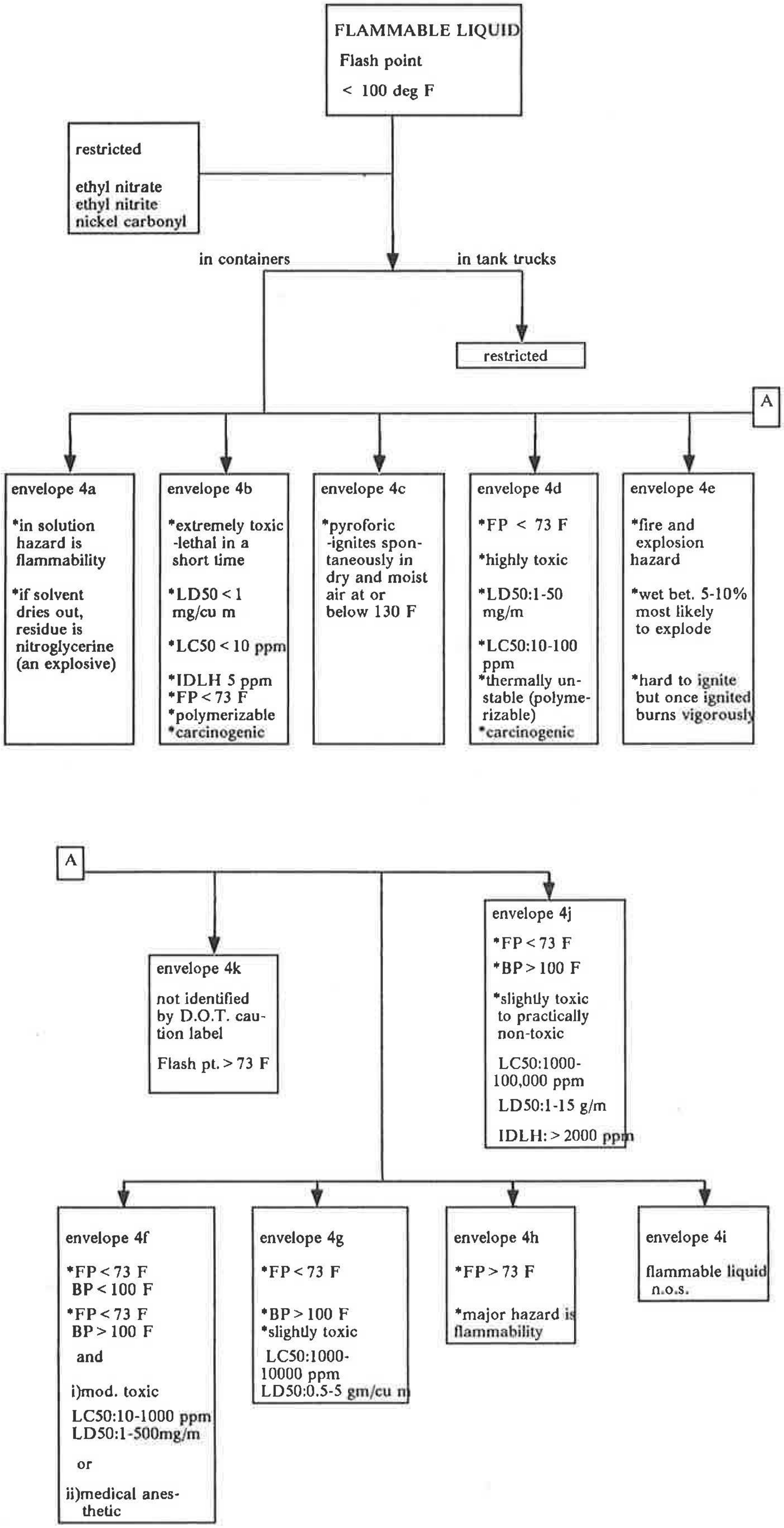

FIGURE 3 **Characteristics defining the envelope for flammable liquids.**

CONCLUSIONS AND RECOMMENDATIONS

The rules and regulations for transport of hazardous materials are presented in a manual that defines the weight limitations per vehicle and per package for a given material in each hazard class permitted to go through the bridge-tunnel facilities. The manual also contains the basis for regulations, general definitions, traffic rules and regulations, and toll schedules.

It is important to mention that the developed methodology should be updated regularly to respond to changes in federal and state regulations. Also, it is suggested that the state departments and the bridge-tunnel operators remain in continuing contact with the carriers and the industries involved in shipping hazardous materials to obtain necessary feedback about the workability of the rules and regulations adopted and to assist the operators in enforcing these rules.

The dilemma of having the tunnel operators respond in a guessing fashion to inquiries on hazardous materials not listed in the manual needs to be solved. A computer program using a knowledge-based expert system that identifies the appropriate regulations for an unlisted substance is being developed at Virginia Tech. The program, in a simplified manner, asks the user to identify some characteristics of the substance and then displays the regulatory notes that govern its passage through the bridge-tunnel facility. This artificial intelligence computer program will aid in updating and identifying the regulations for any new commodities that are introduced by industries. The program could be used by technical staff or those responsible for making regulations to determine the specific quantity limitations of a substance for shipment.

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