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Contents

Foreword

Safe and efficient movement of hazardous materials is essential for public and transporter safety and for continued growth of the national economy. The papers in this Record will assist public and private professionals involved with transport of hazardous materials in making knowledgeable decisions in this critical area.

Rhyne compares use of simplified risk indicators with detailed probabilistic risk analyses in evaluating alternative routes for transport of hazardous materials. He finds that similar results can be obtained from both approaches, but validity of the simplified approach heavily depends on understanding assumptions made in formulating the risk indicators.

Risk assessments for transport of hazardous materials are contingent on estimates of accidents and release rates. Harwood et al. report a new truck accident rate model for estimating accidents and hazardous materials release rates. Statistical tests are described that determine whether accident rates based on site-specific data or system-wide values are appropriate for particular route segments.

Zografos and Warkov discuss the effects of nontechnical factors on hazardous materials routing and siting decisions. They surveyed Connecticut fire chiefs regarding tradeoffs between cost and safety of hazardous materials truck transport and locations of hazardous materials storage facilities in rural areas. They found that the respondents were strongly influenced by their own expertise and other nontechnical factors.

Statistical fatalities from risk model estimates and actual fatalities resulting from transport of chlorine and liquefied petroleum gas by truck and rail are compared by Saccomanno et al., who find differences that are explained in terms of expected interval times between designated events for each mode and type of material. A discussion by Purdy and a closure by the authors are included in the paper.

Abkowitz et al. discuss issues involved in design and development of a system for assessing the impacts associated with transport of nuclear waste from its generation sites to a repository. They focus on the Time Management Information and Analysis System (TMIAS) being developed for Nevada.

Use of geographic colocation techniques for integrating transportation and nontransportation models is described by Katz-Rhoads and Yearwood. The techniques used simultaneously maximize mobility and payload and minimize response time, in accordance with the computerized system called "Improve Delivery of Emergency Airport Services" (IDEAS).

Gorys addresses issues involved with transport of dangerous goods in the province of Ontario. He focuses on the quantity of dangerous goods produced, their movement, and degree of risk to transporters and the general public.

Considerations associated with regulating the routing of trains carrying hazardous materials are discussed by Glickman. He describes regulatory approaches, insights from accident experience, related research, and problems in estimating population exposure and determining preferred routes.

Radwan et al. forecast quantities and shipment routes for hazardous materials within Arizona in the year 2000. Effects of new regulations and waste minimization activities were incorporated into the projections. The results can be used as input into risk analyses.

Evaluating Routing Alternatives for Transporting Hazardous Materials Using Simplified Risk Indicators and Complete Probabilistic Risk Analyses

William R. Rhyne

One of the more frequent uses of risk analysis in hazardous materials transportation is in the analysis of alternative routes. The analysis techniques can usually be characterized either as a simplified risk indicator or as a complete probabilistic risk analysis. In the simplified risk indicator approach, factors that are constant (or nearly constant) for all alternatives are neglected to make computations easier. Complete probabilistic risk analysis provides quantitative evaluations of consequences such as fatalities or injuries, as well as the associated frequencies. Gaining the increased level of information provided by complete probabilistic risk analysis requires more effort at greater cost than does a simplified risk indicator analysis. Both analysis techniques were used to study one railroad and two highway routes for transporting chlorine. None of the simplified risk indicators used produced a ranking of alternatives consistent with the ranking of the complete probabilistic risk analysis for both transport modes. For the truck transport mode, one risk indicator produced results consistent with the complete probabilistic risk analysis results. The validity of the simplified risk indicator approach depends on understanding the assumptions associated with the indicator selected.

Hazardous materials are transported safely every day. Spectacular accidents, although relatively infrequent, are reminders of the harm that can be done and underscore the need to become more aware of these risks and attempt to reduce them. Routing of hazardous material shipments to avoid high-density population areas and highways with high accident rates is one way to reduce risks. One of the more frequent uses of risk analysis in hazardous materials transportation is to assess alternative routes.

Complete probabilistic risk analyses determine how frequently specified consequences such as fatalities, injuries, and property damage occur. Simplified risk indicator analysis, on the other hand, measures parameters proportional to the frequency or consequence, or both, usually for two or more different risk situations. Complete probabilistic risk results provide much more information, but the analysis requires proportionally more effort and input data than simplified risk indicator analysis.

The complete probabilistic risk analysis technique is applied to a relatively simple hazardous material transportation example, and the results are compared with those of several simplified risk indicator analyses. The sample problem is defined, and results are presented for several simple risk indicators. A complete probabilistic risk analysis of the example problem is summarized. The conclusion that simple risk indicators are potentially unreliable is valid for more realistic, more complex situations. The simplified risk indicator approach is depicted as a reduced form of the complete probabilistic risk analysis. Various risk indicators are obtained by neglecting several terms of the complete risk formulation that are nearly equal for all alternatives being evaluated. Some of the implicit assumptions associated with each term of the complete risk formulation are presented. The validity of the simple risk indicator approach depends on the assumptions associated with neglected terms of the complete probabilistic risk formulation.

Only accident consequences resulting from the hazardous cargo are considered; fatalities and injuries from an accident that are not related to the cargo are not addressed.

ROUTING EVALUATION USING SIMPLE RISK INDICATOR ANALYSIS

Suppose that a company that produces chlorine has an opportunity to obtain a new customer, the ACME Processing Company. ACME has built a new plant near the town of Green Valley, and, as part of its commitment to the town council of Green Valley, ACME has promised to perform a risk analysis of hazardous materials entering and leaving the facility. All parties have agreed to let the results of the risk analysis determine which transportation mode is to be used, because the net effect of all other factors influencing the choice result in no strong recommendation for either mode.

Three combinations of route and mode choices appear feasible, as shown in Figure 1:

1. A relatively short highway route (on US-40) through the center of Green Valley;
2. A longer highway route [on State Route (SR) 230] through a low-population suburban area, bypassing the town entirely; and
3. A direct-rail route through a residential area and an industrial park within the town limits of Green Valley.

After investigating each of these three options, the data presented in Table 1 were obtained. (This part of the example problem has been made simple enough that complex

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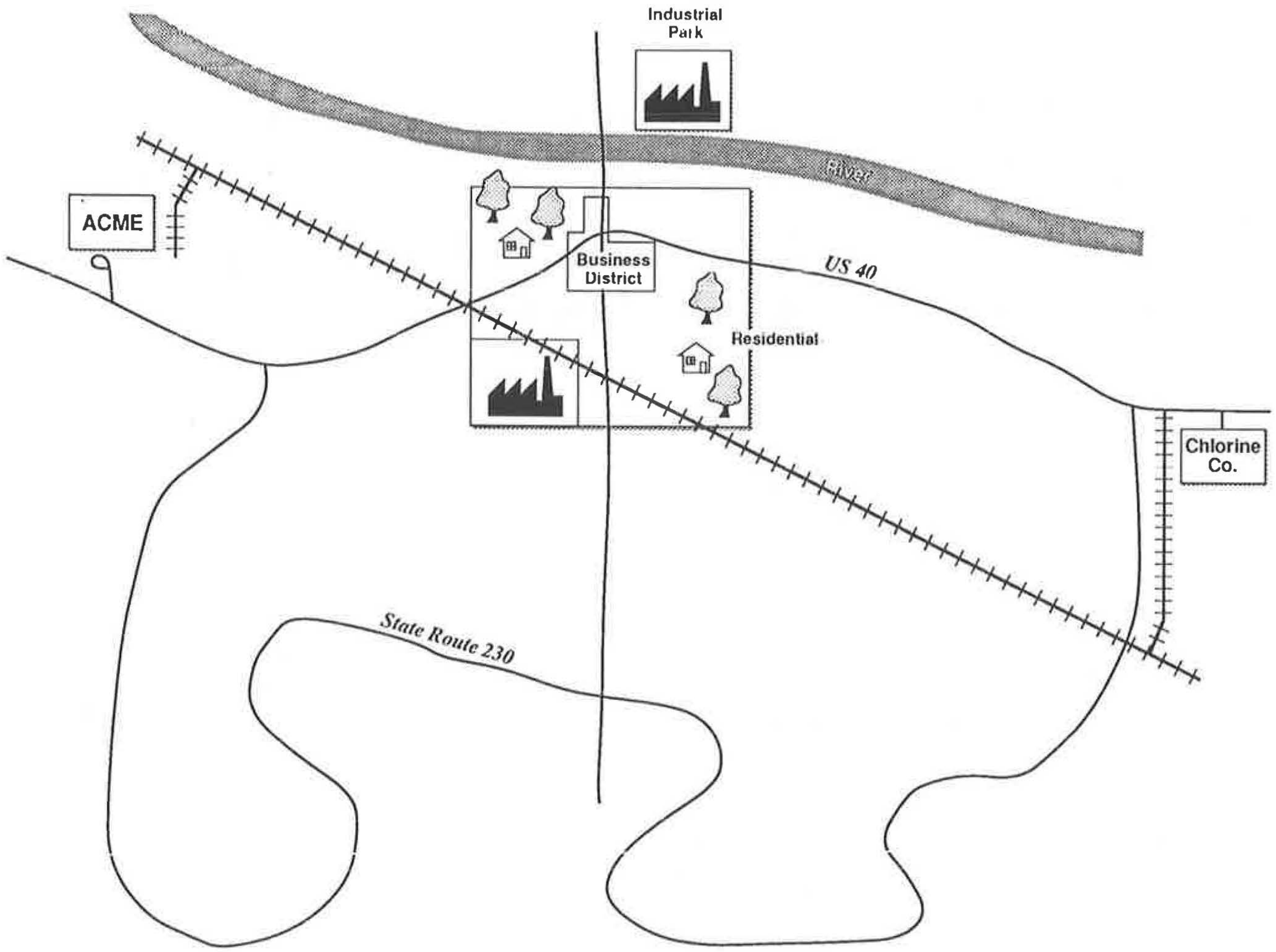

FIGURE 1 Route and mode alternatives.

calculations are not required. The general applicability of the conclusions developed from this simplified example is demonstrated in a later section.)

The data in Table 1 are sufficient to perform the risk evaluation with frequently used risk indicators. The results of these evaluations are presented in Table 2 for two situations: (a) the three rail and highway route alternatives, and (b) the two highway route alternatives alone, for comparison purposes. The first indicator, total distance in miles traveled, is generally recognized as a poor risk indicator when used alone; it is included here primarily for completeness. Using this risk indicator for the two truck alternatives, the shorter highway route, on US-40, is ranked as best and the longer highway route, on SR-230, is ranked as worst. Because the postulated rail shipment transports 4.5 times as much chlorine as the postulated highway shipment, the highway results have been multiplied by 4.5 to allow comparison of the three alternatives on the basis of equal tonnage. Thus, the rail route becomes the shortest effective route and is ranked as best.

The second and third risk indicators considered are miles times accident rate and miles times population density. No variation in the rankings occurs for these first three indicators. A potential problem exists: the route through the low-density population zone, that is expected to be the best option (especially between the two highway alternatives), is ranked worst.

The next indicator of risk, miles times accident rate times population density, produces a reversal of the rankings of the two truck alternatives. Although this risk indicator provided reasonable ordering of the two truck alternatives, it will be shown in the next section that the rail route through the high-density population zone is not the best.

ROUTING EVALUATION USING COMPLETE PROBABILISTIC RISK ANALYSES

One good way to proceed into more detailed risk analyses is to use fault tree methodology. Figures 2–4 show portions of the complete fault tree for a chlorine transport release. Accidental releases are emphasized, although spurious opening of a relief valve during normal operation is also considered. The transport accident tree is based on the tree developed by Andrews et al. (*1*). Quantification of the frequency component is begun by inserting data from the Sandia National Laboratory (SNL) data base [Dennis et al. (*2*)] on the basis of failure thresholds for the railcar and tank truck. Failure

TABLE 1 DATA FOR ALTERNATIVE ROUTE ANALYSIS

Parameter	Rail Route	Highway US 40	Highway SR 230
Route Length (Miles)			
Suburban	100	75	200
Residential	20	20	--
Industrial/Business	5	5	--
Total	125	100	200
Amount of Chlorine per Shipment (Tons)	90	20	20
Truck Accident Rate(a) (Accidents/Truck Mile)			
Suburban	--	5×10^{-6}	5×10^{-6}
Residential	--	15×10^{-6}	--
Business	--	10×10^{-6}	--
Train Accident Rate(a) (Accidents/Train Mile)	1.1×10^{-5}	--	--
Population Density(a) (Persons/Km^2)			
Suburban	400	400	400
Residential	1300	1300	1300
Business/Industrial	4000	4000	4000

(a) Sources for these values given in text (*5–7*)

TABLE 2 QUALITATIVE SUMMARY OF SIMPLE RISK INDICATOR ANALYSES

Transport Option	Miles	Miles X Accident Rate	Miles X Population	Miles X Accident Rate X Population
<u>Highway Mode Only</u>				
Truck-Suburban	Worst	Worst	Worst	Best
Truck-Urban	Best	Best	Best	Worst
<u>Rail and Hwy Modes</u>				
Truck-Suburban (a)	Worst	Worst	Worst	Medium
Truck-Urban (a)	Medium	Medium	Medium	Worst
Train (a)	Best	Best	Best	Best

(a) Normalized for Payload Difference.

thresholds for the railcar (*1*) are presented in Table 3; those for the tank truck were developed from the railcar values using similitude principles. The frequency values given by Andrews et al. (*1*) were modified (a) by the train accident rate given in Table 1, (b) by using less conservative values for selected failure thresholds such as the magnitude of the mechanical force required to weaken walls or to remove insulation, and (c) by selected changes in the application of the SNL fire data. The final frequency results are presented in Tables 4 and 5. These results are based on the assumption that failures in the tank body result in large releases and failures in relief valves result in small releases. Because multiple truck accident rates are used, the parameter *R* is used in Table 4 for accident rate.

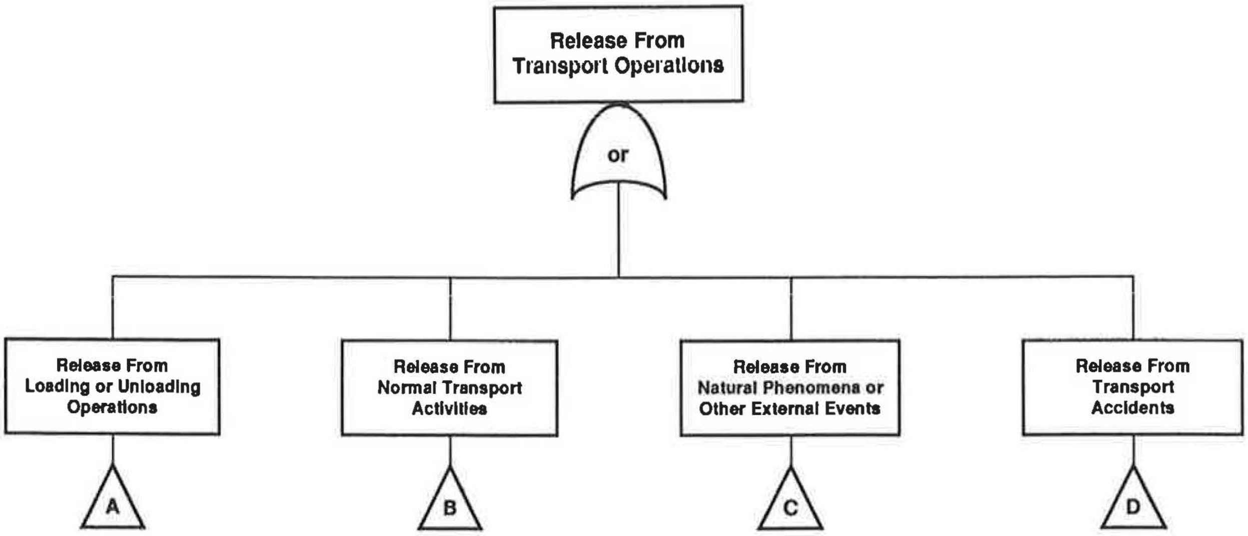

FIGURE 2 Fault tree for releases from transport operations.

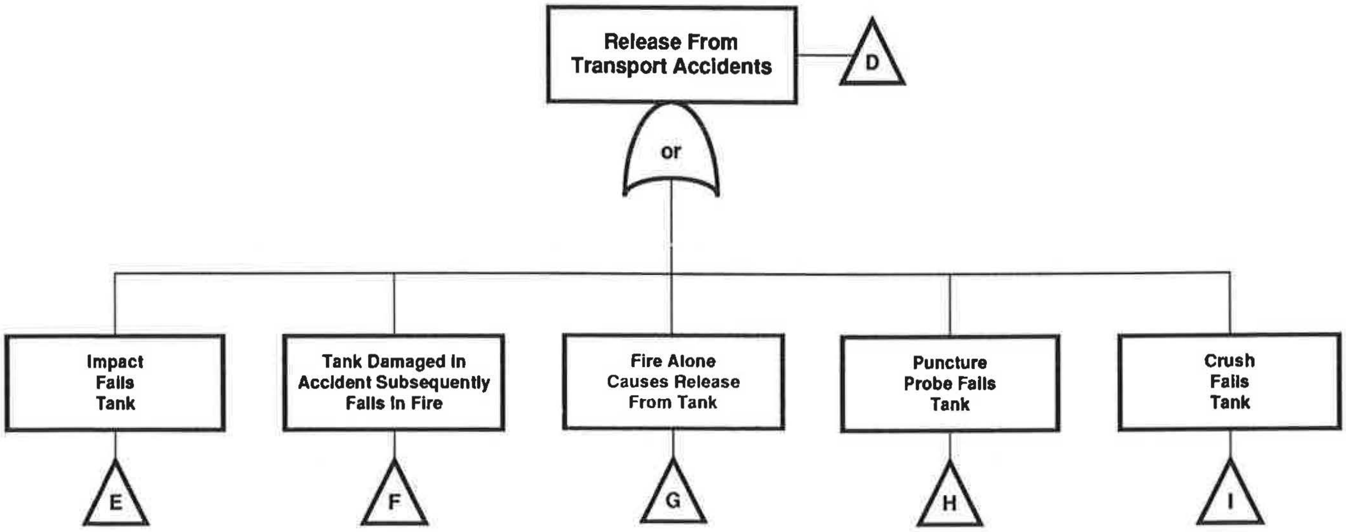

FIGURE 3 Fault tree for releases from transport accidents.

The normal approach for consequence analysis is to subdivide each route into segments with a constant accident rate and population density; for this example, seven such segments are defined. Each release type (four in this example) is analyzed by projecting the area of the downwind plume that would produce various health effects (for example, fatalities in a small area and injuries in a larger area). The area affected depends on meteorological parameters; one or more sets of meteorological parameters can be considered at each geographical location. Variations in the wind direction can be important for situations in which the population density varies significantly in different directions. Clearly, the number of cases that must be calculated can rapidly increase to unwieldy numbers.

A relatively simple consequence analysis was developed to reduce the number of cases that need to be evaluated. (The general applicability of the conclusions developed from this simplified example is presented in the next section.) The following assumptions are made in order to limit the example to a few transparent calculations.

- A single meteorological condition (Pasquill neutral) exists at all geographical locations.
- To preclude unrealistically large calculated consequences for large downwind plume areas, the population density in the downwind direction for the business and industrial zones is 4,000 persons/km^2 for the first 4 km^2 affected, 1,300 persons/km^2 for the next 14 km^2, and 400 persons/km^2 thereafter. For the residential zone, the population density is 1,300 persons/km^2 for the first 20 km^2 and 400 persons/km^2 thereafter.
- A single health effect is considered, that all persons within an area receiving an exposure of at least 1,000 ppm–min have the potential to become fatalities (*3*).
- The considerable potential for mitigation by evacuation, sheltering, or simply walking away from the chlorine plume (which is visible and produces irritating effects at

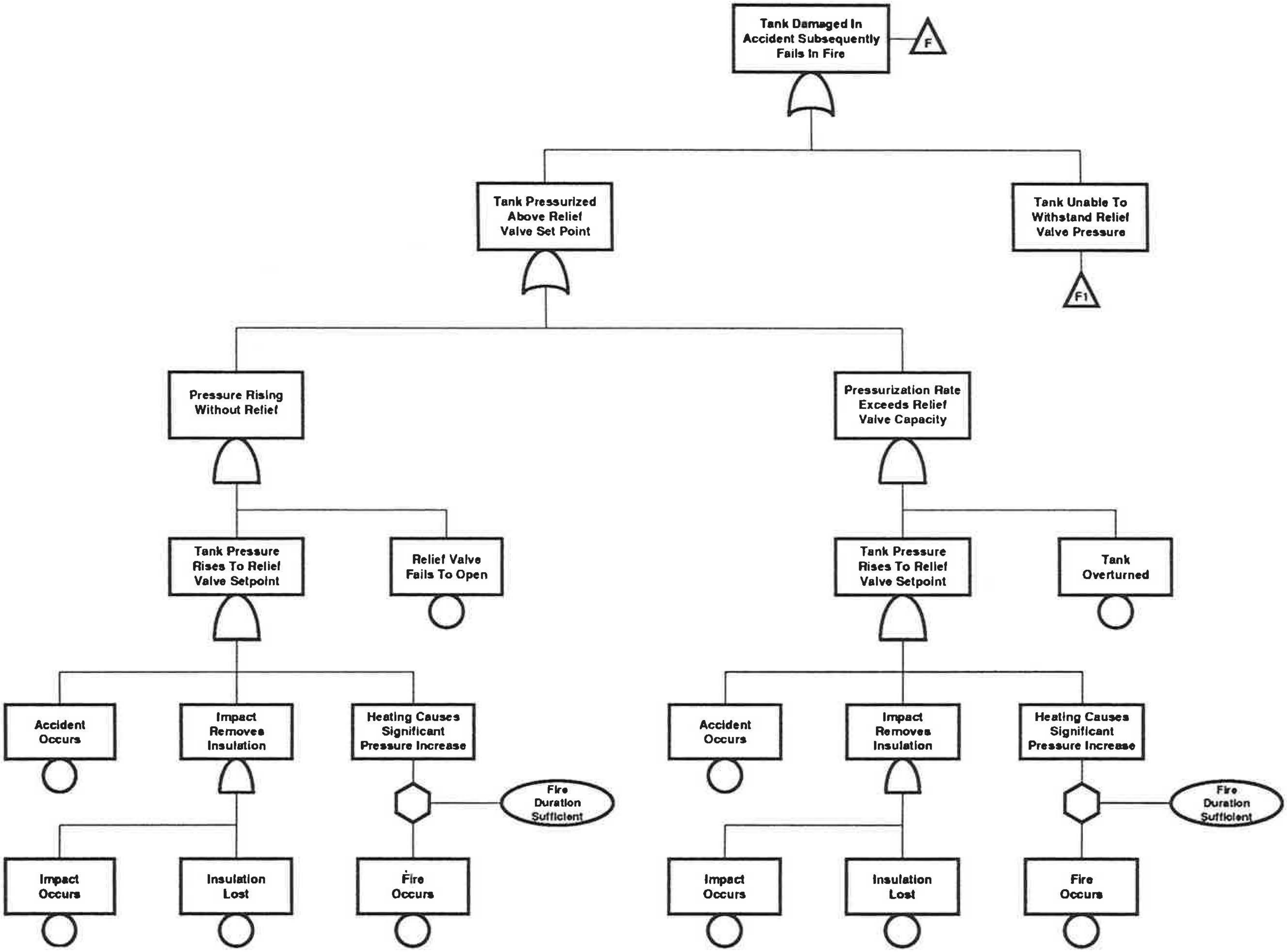

FIGURE 4 Fault tree for failure of tank by mechanical and thermal forces.

TABLE 3 90-TON 105A500 RAILCAR FAILURE THRESHOLDS (*1*)

	Side	End
IMPACT	**18 mph**	**23 mph**
PUNCTURE	**1.16 in. steel equivalent thickness**	
CRUSH	**134,000 lb distributed along length**	
FIRE	**Insulated**	**10% Insulation Loss**
Internal Pressure Is 375 psig	100 min	35 min
Upright Tank Fails As Level Falls	290 min	100 min
Overturned Car Fails Due To Insufficient Relief Rate Of Liquid	164 min	55 min

TABLE 4 MAJOR CONTRIBUTIONS FOR TRUCK TRANSPORT ACCIDENTS

LARGE RELEASE (a)			
(b) R X 1.1 X 10^{-2}	87%		Impact fails tank
R X 1.7 X 10^{-3}	13%		Puncture fails tank
R X 1.3 X 10^{-2}	100%		
LARGE RELEASE WITH FIRE (a)			
R X 8.6 X 10^{-5}	78%		Fire fails tank walls weakened in accident (insulation damage implicit)
R X 9.2 X 10^{-6}	8%		Fire drives off tank contents, hot walls collapse when liquid level drops to 50%
R X 7.3 X 10^{-6}	7%		Overturned tank in fire, liquid relief valve flow insufficient
R X 3.6 X 10^{-6}	3%		Overturned tank in fire, insulation damage aggravates liquid relief flow inadequacy
R X 3.1 X 10^{-6}	3%		Fire drives off tank contents faster due to insulation damage, walls collapse @ 50% full
R X 1.1 X 10^{-4}	99%		
GAS RELEASE (a)			
R X 1.3 X 10^{-3}	68%	(c)	Impact on valves causes failure
3.0 X 10^{-9}	32%	(c)	Spurious opening of relief valve during normal transport (Value is frequency per trip)
R X 1.9 X 10^{-3}	100%		
LIQUID RELEASE (a)			
R X 9.6 X 10^{-6}	96%		Fire actuates relief valve failure, tank overturns, fire too short to cause wall failure
R X 3.9 X 10^{-7}	4%		Impact on valves, excess flow valve defective
R X 1.0 X 10^{-5}	100%		

(a) Per truck mile.

(b) R is the truck accident rate.

(c) Based on R = 5 X 10^{-6}/mile.

TABLE 5 MAJOR CONTRIBUTIONS FOR TRAIN TRANSPORT ACCIDENTS

LARGE RELEASE [(a)]		
8.4×10^{-8}	90%	Impact fails side or end
5.0×10^{-9}	6%	Puncture fails tank car
3.5×10^{-9}	4%	Crush fails tank car
9.2×10^{-8}	100%	
LARGE RELEASE WITH FIRE [(a)]		
1.6×10^{-9}	38%	Fire drives off tank car contents, hot walls collapse when liquid level falls to ~50%
1.5×10^{-9}	36%	Impact weakens wall so that fire causes failure at the relief valve pressure (insulation damage implicit)
5.4×10^{-10}	13%	Overturned tank car in fire, liquid flow through relief valve insufficient energy release
3.6×10^{-10}	8%	Fire drives off contents faster because insulation damaged in accident, walls collapse @ 50% full
1.9×10^{-10}	5%	Overturned tank car in fire, liquid flow through relief valve less effective due to insulation damage in accident
4.2×10^{-9}	100%	
GAS RELEASE [(a)]		
3.0×10^{-9}	64%	Spurious opening of relief valve during normal transport
1.4×10^{-9}	30%	Fire activates relief valve failure, car upright, fire too short to fail walls (60 - 120 min)
3.1×10^{-10}	6%	Impact fails valves
4.7×10^{-9}	100%	
LIQUID RELEASE [(a)]		
4.6×10^{-10}	100%	Fire activated relief valve failure, car overturned, fire too short to fail walls (~60 min)

[(a)] Per train mile.

concentrations much less than those producing fatalities) is assumed to reduce fatalities to 1 percent of the persons originally in the exposed area (*4*).

- A gravity dispersion model followed by a Gaussian dispersion model for neutral meteorological conditions can be approximated by a simple expression (*3*):

Area (in m^2) affected by an instantaneous release =
$273 \cdot (\text{weight of release, in kg})^{1.13}$, and

Area (in m^2) affected by a continuous release =
$6.1 \times 10^4 \cdot (\text{rate of release, in kg/sec})^{1.13}$.

- For puncture, impact, and crush failures, 50 percent of the tank content is released instantaneously. For tank failures caused or followed by fire, 100 percent of the tank content is released instantaneously. The relief valve flow rate is 3.9 kg/sec of vapor or 9.8 kg/sec of liquid (*1*).

With these simplifications, only 28 different consequences need to be evaluated for the three route alternatives. Each of the 28 has an associated frequency from Tables 4 and 5.

At this point, considerable information has been developed that can be used in a variety of ways. From Tables 4 and 5, the three alternatives can be ranked on the basis of the frequency of occurrence of a large release; Table 6 presents the ranking of the alternatives using frequency of a large release (with and without fire) as a risk indicator. This risk indicator does not meet the definition of a complete probabilistic risk result, because the consequence is described only qualitatively as a large or small release.

If risk is defined as the product of frequency and consequence, then the expected number of fatalities for each alternative can be computed by summing the products for each accident scenario. Table 6 indicates that the use of the "mean value of risk" measure reverses the "frequency of large release" rankings. Because the release amount and the area affected are calculated explicitly for the mean value of risk, these rankings are much more reliable than the others.

The frequency and consequence information can also be displayed by plotting cumulative frequency *F* as a function of consequence *N*, as shown in Figure 5. Two general conclusions can be drawn from the figure. On the left side of the figure (the low-consequence, high-frequency portion), one ranking of alternatives results (train is best, and truck through the suburban zone is worst). In contrast, the high-consequence, low-frequency results produce the opposite ranking. The crossing of truck and train *F–N* curves is characteristic of truck and train routing comparisons. Both sets of results are summarized in Table 6.

TABLE 6 QUALITATIVE SUMMARY OF RISK ANALYSIS RESULTS

Transport Option	Frequency of Large Release [b]	Mean Value of Risk	Low Consequence, High Frequency	High Consequence, Low Frequency
Highway Mode Only				
Truck-Suburban	Worst	Best	Worst	Best
Truck-Urban	Best	Worst	Best	Worst
Rail and Hwy Modes				
Truck-Suburban [a]	Worst	Best	Worst	Best
Truck-Urban [a]	Medium	Medium	Medium	Medium
Train [a]	Best	Worst	Best	Worst

[a] Normalized for Payload Difference.

[b] Since the consequences are only categorized as "large" or "small" release, this risk indicator does not meet the definition of a complete probabilistic risk result.

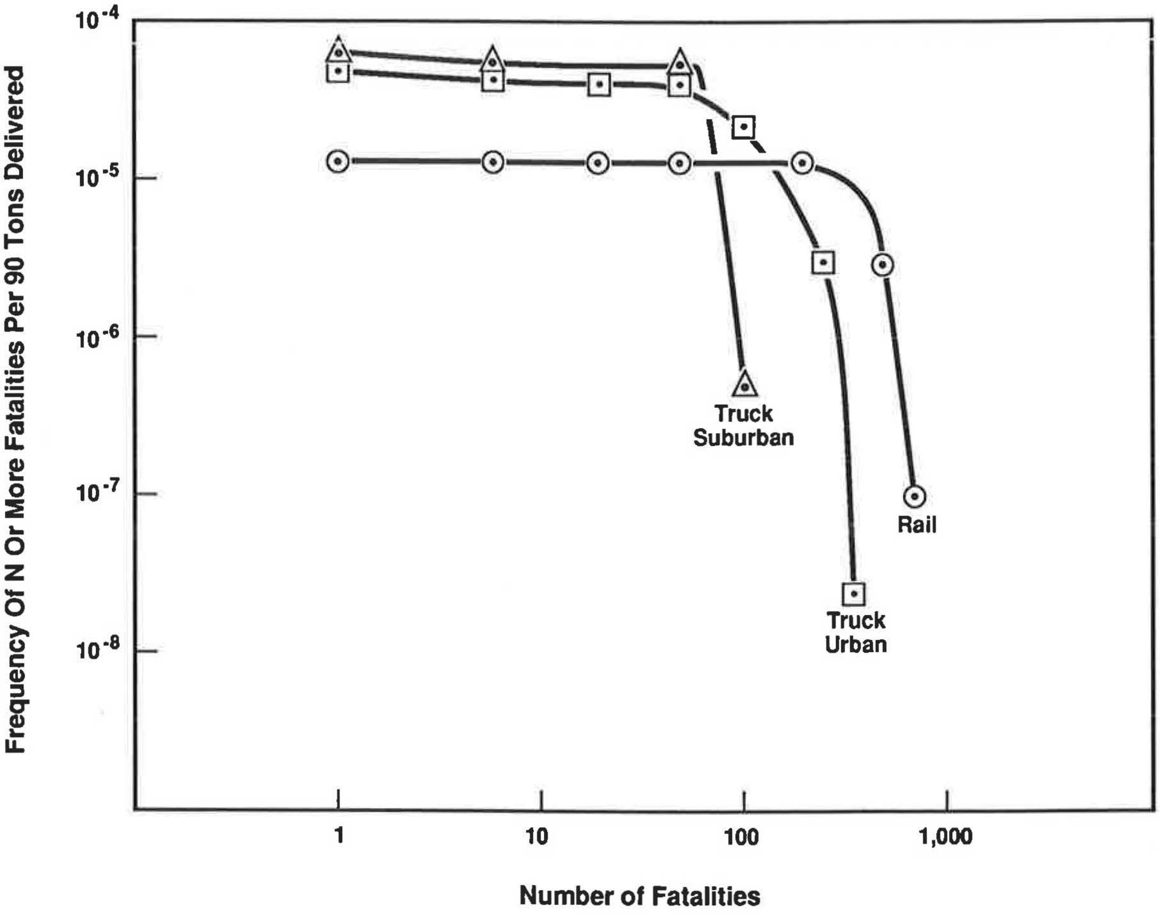

FIGURE 5 *F–N* curves for different transportation options.

Tables 2 and 6 indicate that considerable variation in the ranking of the three alternatives results from using the different types of risk analyses. Most decision makers are more concerned about the potential for large, catastrophic events; therefore, the ranking of truck suburban over truck urban or rail would probably be the choice made. The ranking of the highway mode over the rail mode is appropriate only for this example and is not a general conclusion for hazardous material transportation.

VALIDITY OF RESULTS FOR COMPLEX SETS OF INPUT PARAMETERS

The conclusion that simple risk indicators are potentially unreliable is valid both for complex and simple problems, because complex problems can be viewed as multiple sets of simple problems. The detailed results both of the simplified risk indicator and the complete probabilistic risk analyses are highly dependent on the values used for input parameters. Therefore, the parameters used in this simple problem should be demonstrated as reasonable to ensure the validity of the results.

State Routes 58 and 95 in the vicinity of Oak Ridge, Tennessee, were used to characterize the highway routes. In the business district, the highway is four undivided lanes with traffic signals and left turn lanes at all intersections. In the residential area, the highway is also four undivided lanes but has few traffic signals; access from local businesses and recreational facilities is unlimited. In the suburban area, the highway varies from two to four undivided lanes, but shoulders are wide and paved. The speed limit is posted as 45 mph in the residential area and 55 mph in the suburban area, but, at least in part because of the good geometric condition, actual speeds are frequently higher. Jovanis et al. (*5*) reported Interstate accident rates (3.8 accidents per million mi) that are consistent with many other reported values. Jovanis also reported values for state highways (28 accidents per million mi) and local streets (16 accidents per million mi) that are consistent with data from the American Trucking Associations (*6*,*7*). On the basis of these data and the earlier highway characterizations, accident rates for the illustrative example were chosen to be 5 accidents per million mi in the suburban area, 15 accidents per million mi in the residential area, and 10 accidents per million mi in the business district.

The rail accident rate was chosen as 5 accidents per million mi (*8*) times 2.2 to convert the average rate to a Class 3 track rate. The 2.2 value was derived by Nayak et al. (*9*).

The population densities were chosen to be consistent with a transportation study performed by Finley (*10*) for the Nuclear Regulatory Commission.

Fault trees developed by Pacific Northwest Laboratories (PNL) and reported by Andrews et al. (*1*) can be quantified using models developed by SNL (*2*) and continue to be used for transportation risk analyses when modified by more recent data (*11*). The results of similar PNL and SNL analyses for other hazardous materials are still useful in practical applications (*12*). In fact, more recent data and a more elaborate evaluation procedure (*13*) confirm the SNL methodology and results.

The use of fatalities as a single measure of hazard for simplification is not generally recommended for a realistic study, because the extent of injuries should not be ignored in most alternative route analyses. An analysis with multiple hazard measures is essentially several analyses, each with a single, different hazard measure. The meteorological parameters used can have a substantial effect on the area calculated to experience the selected hazard measure. Ideally, several sets of meteorological parameters, each with an associated conditional probability, would be used in a detailed probabilistic application. For this example, one set of parameters is sufficient to illustrate that the simple risk indicator approach is potentially unreliable. The usual simple risk indicator approaches do not take meteorological conditions into consideration.

For many analyses, simple or complex, the rankings provided by the risk indicators would agree with each other and with rankings generated from complete probabilistic analyses. To demonstrate that the simple risk indicator approach is potentially unreliable, it is only necessary to show that one analysis produces inconsistent results. The parameters describing the analysis need to be reasonable, as are the ones used in the example presented.

SIMPLIFIED RISK INDICATOR ANALYSIS AS A REDUCED FORM OF COMPLETE PROBABILISTIC RISK ANALYSIS

Complete probabilistic risk analyses consider both the frequency of an accident and the magnitude of its consequences. The risk R_i for an accident scenario is a function of the scenario frequency (F_i) and the scenario consequences (C_i), according to Kaplan and Garrick (*14*):

$$R_i = f(F_i, C_i) \tag{1}$$

For transportation risk, this expression can be further detailed:

$$\begin{aligned} R_i = f(&F_{1a} \times M_a \times P_{2ab} \times P_{3abc} \times P_{4ad} \\ &\times P_{5ae}, A_{abc} \times X_{ace} \times N_{ad}) \end{aligned} \tag{2}$$

where

F_{1a} = frequency of an accident per mile in transport link a primarily for highway (or rail track) type and conditions, vehicle type, and traffic conditions;
M_a = number of miles in link a;
P_{2ab} = probability that the accident in link a results in accident forces of type b (e.g., mechanical or thermal forces);
P_{3abc} = probability that release class c occurs, given that the accident force type b occurs in link a and depending on the force magnitude and the container capability to resist the force;
P_{4ad} = probability that population distribution class d occurs in link a;
P_{5ae} = probability that meteorological condition e occurs in link a;
A_{abc} = release amount for release class c, given force type b occurs in link a;
X_{ace} = area impacted and health effect of the hazardous material for meteorological condition e for release class c; and

N_{ad} = number of persons in population class d in link a.

The overall risk is obtained by summing all scenarios:

$$R = \Sigma R_i \tag{3}$$

Complete probabilistic risk analyses usually differ in (a) the level of detail (i.e., the extent that risk components are aggregated before numerical values are assigned) and (b) the methodology used to assign numerical values (e.g., fault trees versus regression analyses of historic data to determine release probability).

This section will address the use of reduced forms of Equation 2 and some of the associated implicit assumptions. The first assumption is that risk is the product of frequency and consequence; thus, the lowest product of the terms of Equation 2 defines the option with the lowest risk. For simplicity of presentation, the following additional assumptions will be based on only one release class ($c = 1$), one population distribution along each link type ($d = 1$), and one meteorological condition ($e = 1$). Thus, $P_4 = P_5 = 1$. If it is desired to compare options x and y, then the question is whether R^x is less than, greater than, or equal to R^y. Using Equation 2, the question can be reformulated as follows:

$$\text{Compare } F_1^x M^x P_2^x P_3^x A^x X^x N^x \text{ and } F_1^y M^y P_2^y P_3^y A^y X^y N^y \tag{4}$$

If some terms are the same for both options (e.g., if $P_2^x = P_2^y$, $P_3^x = P_3^y$, $A^x = A^y$, and $X^x = X^y$), then Equation 4 is simplified to the following expression:

$$\text{Compare } F_1^x\, M^x\, N^x \text{ and } F_1^y\, M^y\, N^y \tag{5}$$

The remainder of this section will address the explicit and implicit assumptions involved in simplified forms such as Equation 5.

A routing study for a single transport mode could be based on minimizing the product F_1MN (of accident rate, number of miles, and exposed population). Use of this simple risk indicator for risk minimization includes some important assumptions. Clearly, the approach would be valid only if the same container is to be used on all potential routes; thus, the container failure thresholds and the container response to the accident force types would be the same. On this basis, the P_3 parameter (the probability that the container will fail from the accident force) is neglected; however, this omission also implies that the force magnitude is the same for all potential routes. For most routing decisions, it is probably not practical to try to include route-dependent variations in the frequency and magnitude of mechanical threats (e.g., bridge abutments or rock outcrops). On the other hand, the model usually used for estimating the magnitude of the threat from fires (*2*) explicitly includes a factor for the effectiveness of the response of a local fire department. The omission of the P_3 factor, therefore, invokes the assumption that all routes have equal fire-fighting response capability.

The P_2 parameter represents the distribution between the various accident threat types (e.g., impact, puncture, crush, fire, and immersion). Data are not generally available to make a distinction between the relative distribution of accident force types as a function of road type or track class; therefore, omission of the P_2 term may be a practical necessity. The P_2 and P_3 terms together represent the probability of container failure, given an accident. Some data have been presented on the probability of a hazardous material release, given an accident, as a function of highway class and as a function of urban or rural demography (*15*). Presumably, such data account for more than fire-fighting response variation; therefore, the use of F_1MN as a risk measure ignores any potential variation in release probability, given an accident, as a function of road class, population density, or both.

The computed release amount, given a release, is a strong function of the level of detail in the engineering analysis of the response of the container to the accident forces and a weak function (if any) of the transport link type. Thus, the omission of the A parameter for routing analyses involving only one transport mode is a practical approach.

The X parameter represents the effect of the released material on the population in the vicinity of the accident. For hazardous materials whose release affects the surrounding area by a downwind plume, omission of this term implies that meteorological parameters are the same for all routes being considered.

CONCLUSION

Several simple risk indicators used for routing analyses can be considered as reduced forms of the complete probabilistic risk equation; however, conflicting results can be obtained when they are used. For route selection involving a single transport mode, only the miles times accident rate times population exposed (*MARP*) risk indicator produces results consistent with the complete probabilistic risk analysis. For two transport mode comparisons, none of the results from the simple risk indicators examined are consistent with the complete probabilistic risk analysis results. The semicomplete indicator, frequency of a large release, is also unreliable for either one or two transport modes. The use of simple risk indicators involves certain assumptions, and it is important that the analyst be aware of any implicit assumptions when using them.

Use of the *MARP* risk indicator for routing choices involving one transport mode includes the potentially important assumptions, that both the emergency response capability for reducing fire threats and the meteorological effects on dispersion of toxic materials do not vary for the alternatives. The *MARP* risk indicator was successful for comparing the truck alternatives for the example at least in part because these two factors were held constant for all routes in all levels of analysis. For many decisions, the *MARP* risk indicator will be a practical one for single-mode routing analyses.

Simple risk indicators do not provide as much information regarding the safety of hazardous material transport as do complete probabilistic risk analyses. However, simple risk indicators can be useful in some decisions involving two or more alternatives. The appropriate calculational approach is a function of the decision to be made, practical constraints such as data availability, and budgetary resources available. Before deciding to use a simple risk indicator, the complete probabilistic risk formulation should be the starting point, and terms should be eliminated only after careful consideration of the assumptions involved in their omission.

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Truck Accident Rate Model for Hazardous Materials Routing

DOUGLAS W. HARWOOD, JOHN G. VINER, AND EUGENE R. RUSSELL

Estimates of accident and release rates are essential for conducting risk assessments in routing studies for highway transportation of hazardous materials. Recently published literature has emphasized both the importance of these rates in risk assessment and the significant shortcomings of the available data. New truck accident rates are developed as a function of roadway type and area type (urban or rural) from state data on highway geometrics, traffic volume, and accidents. Release probabilities in accidents have been derived from a combination of federal and state truck accident data bases. A revised model for the accident probability portion of the U.S. Department of Transportation hazardous materials routing guidelines is recommended, and its application is illustrated using accident and release rates derived to substitute for existing default values. Statistical tests based on the chi-squared and Poisson distributions are provided to determine whether accident rates based on site-specific data or system-wide values, such as those derived here, should be used for any particular route segment.

The most widely accepted risk assessment model for identifying preferred routes for hazardous materials transportation is that presented in the U.S. Department of Transportation (DOT) guidelines. This model was first presented in the 1980 FHWA publication *Guidelines for Applying Criteria to Designate Routes for Transporting Hazardous Materials* (*1*). This document was recently updated and republished by the DOT Research and Special Programs Administration (*2*).

The DOT guidelines are based on the selection of minimum-risk routes, on which risk is determined for individual route segments by the equation

$$\text{Risk} = (\text{Accident Probability}) \times (\text{Accident Consequences}) \qquad (1)$$

The DOT guidelines contain procedures for determining (a) accident risk on the basis of accident rate and route segment length, and (b) accident consequences on the basis of either the number of persons potentially exposed or the value of property potentially exposed to hazardous materials releases. Updated procedures and improved data have been developed for assessing the accident probability term in Equation 1.

A recent critique (*3*) has identified several potential approaches to strengthening the accident probability portion of the DOT guidelines. These recommendations are based on several perceived weaknesses in the current guidelines, including the following:

- Default values of accident rates in the DOT guidelines are based on accident predictive models that are 15 to 20 years old and that may be out of date (*4–6*).
- The models apply to accident rates for all vehicle types rather than to truck accident rates. All-vehicle accident rates are based primarily on passenger car accidents, whereas highway transportation of hazardous materials is conducted by truck.
- The DOT guidelines implicitly assume that all accidents are equally likely to result in a hazardous materials release. In fact, recent research (*3,7*) has established that some types of accidents are much more likely than others to result in a release.
- The DOT guidelines recommend that observed accident rates for the specific route segments under analysis, rather than the default values, be used whenever possible. However, no statistical guidance is given on whether the observed accident rate is based on a sufficiently large sample of accidents to be statistically reliable or whether the differences between the observed accident rates and the default values are statistically significant.

Recently, Glickman (*8*) has clearly illustrated the significant quality shortcomings in much of the accident rate data currently available for hazardous materials transportation risk assessments. Better data are needed to substitute for the default values presented in the DOT guidelines. These data can be developed from existing federal and state data bases of truck accident rates and hazardous materials release probabilities. Procedures for applying statistical tests are also needed, in order to determine whether it is better to use observed accident rates from a given highway segment or the truck accident rates derived here.

The truck accident rates presented in following sections are weighted averages of system-wide data for the state highway systems of three states. The selected states have mergeable computer files of accident, roadway, and traffic volume data that were required for this analysis. The quality of data from these three states, which include data on the percentage of trucks in the traffic stream, is among the best in the nation. Accident rates for specific roadway types are known to vary from state to state, so highway agencies that have adequate data are encouraged to develop their own default values of truck accident rates using the procedures outlined. At present, about 15 states are known to have the file-merging capability

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required to develop system-wide truck accident rates for specific roadway types.

DETERMINATION OF TRUCK ACCIDENT RATES

A key element in comparing the risks of alternative routes for hazardous materials transportation is having reliable data on truck accident rates for use in determining the relative probabilities of hazardous materials releases. The effect of roadway and area type on truck accident rates must be accounted for in routing studies. For example, freeways generally have lower accident rates than other types of highways, and urban highways (especially nonfreeways) generally have higher accident rates than rural highways. These differences between highway and area types are well known for all-vehicle accident rates, but they have only been demonstrated for trucks in studies based on a limited number of highway sections (*3*,*9*,*10*). Therefore, in developing improved truck accident rates for use as default values in hazardous materials routing studies, emphasis is placed on accounting for the effects of roadway and area type.

The analysis of truck accident rates required three types of data: highway geometrics, traffic volumes, and accident records. In order for the analysis to be accomplished efficiently, these data had to be available in computerized form using common location identifiers (e.g., mileposts) so that the three types of data could be linked together. Many state highway agencies have been computerizing and linking their data files and have, or soon will have, the capability to perform this type of analysis.

No state currently has the necessary data and linking capability to analyze all public highways in the state. The best systems available include only highways under the jurisdiction of the state highway agency. Preliminary discussions were conducted with several agencies whose mergeable records cover the entire state highway systems, and three state agencies with the most complete, mergeable, and easy-to-use computer files were selected for participation in the study. These states were California, Illinois, and Michigan.

Highway geometric files were needed to define the characteristics of highway segments to which truck volume and accident data could then be added. Highway geometric files typically consist of relatively short route segments (0.35 mi or less in length) for which data on the geometric features of the segment are included. The data extracted from geometric files for each segment were

- Number of lanes,
- Lane structure (divided or undivided),
- Access control (freeway or nonfreeway),
- Direction (one-way or two-way), and
- Area type (urban or rural).

Traffic volume files were used in the analysis to obtain the annual average daily traffic (AADT) and either the average daily truck volume or the percentage of trucks in the traffic stream. In all three states, these truck volume data were given in the same location reference system as the highway geometric and accident data. Because nearly 89 percent of accidents in which hazardous materials are released involve combination trucks (tractor-trailers), it would be desirable to limit the accident analysis to combination trucks only (*3*). Unfortunately, truck volume data for combination trucks are seldom available on a system-wide basis. Therefore, it was necessary to use truck volume data and accident data for all commercial vehicles. Because traffic counts of all commercial vehicles typically include both trucks and buses, it was necessary to include bus accidents in the analysis as well. Although undesirable, the inclusion of data for buses should not have a major effect on the accident rates, because the proportion of bus accidents and bus exposure is usually small (typically less than 5 percent).

The truck accident data used for the analysis were a subset of the accident files for all vehicle types maintained by all state highway agencies. The following accident characteristics were used: the numbers and types of vehicles involved, the type of collision (if any), and the accident severity (most were severe injury). The roadway and traffic characteristics associated with these accidents were obtained from the geometric and traffic volume files. Each accident-involved vehicle was treated as a separate observation (i.e., an accident involving two trucks was counted as two accident involvements).

Data Processing

The processing of these data was conducted in a series of five steps shown in Figure 1, using the Statistical Analysis System.

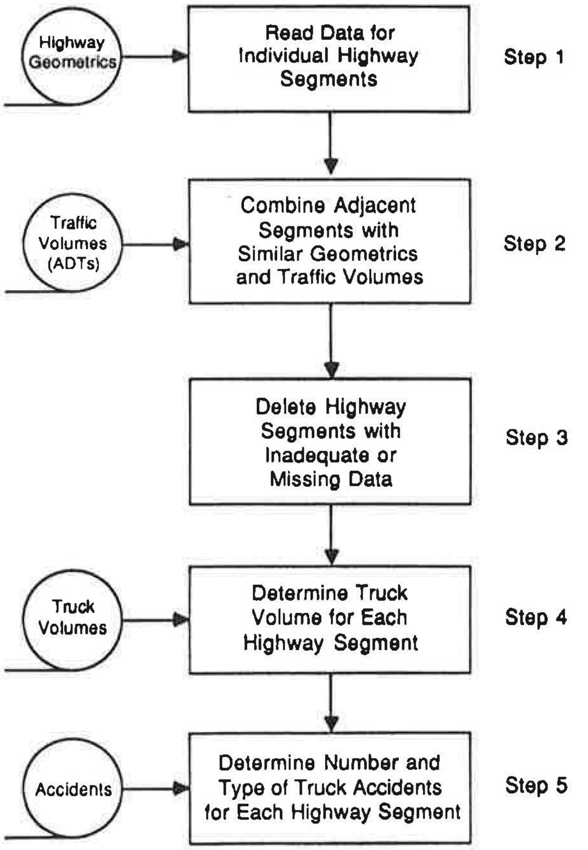

FIGURE 1 Step-by-step process for merging data from highway geometrics, truck volumes, and accident data files.

The key element in the processing was linking the appropriate truck volume and accident data to individual roadway segments from the highway geometric file using common location reference systems (e.g., mileposts). Each step in the linking of the data from these files is described in the following paragraphs.

Step 1

Geometric data needed for the individual roadway segments were read from the highway geometric file. The highway class (roadway type and area type) of each roadway segment was determined from the available data. The highway classes were

- Rural two-lane highways,
- Rural multilane undivided highways,
- Rural multilane divided highways,
- Rural freeways,
- Urban two-lane streets,
- Urban multilane undivided streets,
- Urban multilane divided streets,
- Urban one-way streets, and
- Urban freeways.

Step 2

Individual roadway segments, which have relatively short average lengths, were merged into longer segments whenever adjacent segments matched in highway class and other selected variables and had average daily traffic (ADT) volumes within 20 percent of one another. When adjacent highway segments were merged, their ADT volumes were combined using a weighted average by length, as follows:

$$\mathrm{ADT}_C = \frac{\mathrm{ADT}_1 L_1 + \mathrm{ADT}_2 L_2}{L_1 + L_2} \tag{2}$$

where

ADT_C = average daily traffic volume on combined segments,
ADT_i = average daily traffic on Route Segment i (i = 1, 2), and
L_i = length (mi) of Route Segment i (i = 1, 2).

Step 3

Any roadway segments for which accident or truck volume data were not available or which did not fit within one of the highway classes selected were eliminated from the analysis. The data bases used for this analysis were complete, and only about 0.2 percent of the roadway segments had to be eliminated because of missing data.

Step 4

Truck volumes for the merged sections were obtained from the volume file. The truck volume data were used with the length of the segment to compute the annual vehicle-miles (veh-mi) of truck travel on each segment:

$$\mathrm{TVMT}_i = \mathrm{TADT}_i \times L_i \times 365 \qquad i = 1, 2 \tag{3}$$

where

TVMT_i = annual truck travel (veh-mi) on Route Segment i, and
TADT_i = average daily truck volume in vehicles per day on Route Segment i.

Step 5

Data on truck accidents were obtained from the accident files. Each truck accident involvement was classified by year, accident severity, and accident type. The common location reference system that links the accident and geometric files was used to determine which segment the reported location of each accident fell within and to total the number of accident involvements within each segment by year, severity level, and accident type. The result of Step 5 was a file containing the truck volumes and truck accident histories for individual highway segments that can be used to compute truck accident rates and release probabilities.

Data Analysis

The average truck accident rate for each highway class was computed as the ratio of total truck accidents to total vehicle-miles of truck travel for that highway class. The following equation was used:

$$\mathrm{TAR}_j = \sum_i \frac{A_{ij}}{\mathrm{VMT}_{ij}} \tag{4}$$

where

TAR_j = average truck accident rate for Highway Class j,
A_{ij} = number of accidents in one year on Route Segment i in Highway Class j, and
VMT_{ij} = annual vehicle-miles of travel on Route Segment i in Highway Class j.

This procedure was applied to all existing geometric, traffic volume, and accident files for the state highway systems of California, Illinois, and Michigan that could be linked by mileposts. Tables 1 and 2 present the truck accident rates and truck accident type distributions, respectively, for California. Similar tables were also prepared for Illinois and Michigan state highways. Table 3 presents the average truck accident rates for each highway class in each state and the weighted three-state average.

The truck accident rates in Table 3 are appropriate for use as default values for hazardous materials routing studies in which data more suited to local conditions are not available. Highway agencies are encouraged to develop comparable default values for their own data, whenever possible.

The data in Table 3 clearly indicate the effect of two key variables related to hazardous materials routing—roadway

TABLE 1 TRUCK ACCIDENT RATES ON CALIFORNIA STATE HIGHWAYS, 1985–1987 (*3*)

Highway class		Total length (mi)	No. of sections	Average truck ADT (veh/day)	No. of truck accident involvements[a]	Truck travel (MVM)	Truck[b] accident rate (per MVM)
Area type	Roadway type						
Rural	Two-lane	8,808.96	2,607	392	6,577	3,784.97	1.73
Rural	Multilane undivided	209.13	334	858	1,070	196.58	5.44
Rural	Multilane divided	726.85	450	1,839	1,801	1,463.45	1.23
Rural	Freeway	2,068.20	405	4,791	5,759	10,850.90	0.53
Rural	TOTAL	11,813.14	3,796	1,260	15,207	16,295.90	0.93
Urban	Two-lane	513.49	648	748	1,778	420.69	4.23
Urban	Multilane undivided	141.50	341	1,116	2,251	172.84	13.02
Urban	Multilane divided	754.18	793	1,644	4,996	1,427.47	3.50
Urban	One-way street	22.26	47	1,387	223	33.81	6.60
Urban	Freeway	1,969.65	817	8,395	28,860	18,107.00	1.59
Urban	TOTAL	3,401.07	2,646	5,414	38,108	20,161.81	1.89
TOTAL		15,214.21	6,442	2,388	53,315	39,781.10	1.34

[a] Accidents involving two or more trucks are counted as two or more involvements.

[b] Computed from Equation (4).

type and area type—on truck accident rate. An attempt was made to determine the relationship between two traffic volume factors (AADT and percentage of trucks) and truck accident rate, but no consistent results were obtained. Consideration of the effects of additional geometric variables (including lane widths, shoulder widths, ramps, intersections, and driveways) on truck accident rates was beyond the scope of the study, but to determine these effects and incorporate them in hazardous materials routing studies as well would be desirable. However, that the development of reliable relationships between geometric features and accidents is a difficult statistical task should be recognized. Previously reported attempts to determine incremental effects of individual geometric features on accident rates have had mixed results, and no set of geometric-accident relationships is widely accepted.

DETERMINATION OF HAZARDOUS MATERIALS RELEASE PROBABILITIES

The probability portion of the DOT routing guidelines is based entirely on accident probabilities. Of course, an accident involving a hazardous materials-carrying truck cannot lead to potentially catastrophic consequences unless the hazardous materials being transported are released. Thus, the current risk assessment methodology implicitly assumes that hazardous materials releases are equally likely in all accidents.

A recent FHWA study (*3,7*) has indicated that the probability of a hazardous materials release given an accident involving a hazardous materials-carrying truck varies markedly with the type of accident. Table 4, created from data from the FHWA motor carrier accident reports, indicates that release probabilities are highest in single-vehicle noncollision accidents and truck-train collisions and lowest in multiple vehicle collisions. Furthermore, the various highway classes have distinctly different patterns of accident types. For example, the percentage of single-vehicle noncollision accidents (which have the highest probability of producing a hazardous materials release if an accident occurs) is about twice as high on rural highways as on urban highways (*3*). Therefore, the probability portion of the DOT guidelines should include a term representing the probability of release given an accident. Default values for this term are developed in Equation 5.

Table 4 was developed from the FHWA motor carrier accident reports because, for each accident-involved truck, this data base documents both whether the truck was carrying hazardous materials and whether the hazardous materials were released. For users to derive values comparable to those in Table 4 for their own state would be desirable, but only three states (Louisiana, Missouri, and Wyoming) currently have both data items needed to make this determination in their accident records systems (*3,7*).

The probability of a hazardous materials release given an accident varies between highway classes because it varies with accident type and because the distribution of accident types varies markedly between highway classes. For example, Table 2 indicates that the proportion of single-vehicle noncollision accidents (which are likely to result in a hazardous materials release) is nearly 50 percent higher on rural two-lane highways than on rural freeways. The probability of a release given an accident involving a hazardous materials-carrying vehicle for a particular highway class can be computed as

$$P(R|A)_j = \sum_k P(R|A)_k \times P(k)_j \tag{5}$$

where

$P(R|A)_j$ = probability of a hazardous materials release given an accident involving a hazardous materials-carrying vehicle for Highway Class j,

$P(R|A)_k$ = probability of a hazardous materials release given an accident involving a hazardous materials-carrying vehicle for Accident Type k (from Table 4 or equivalent state data), and

TABLE 2 TRUCK ACCIDENT TYPE DISTRIBUTION ON CALIFORNIA STATE HIGHWAYS, 1985–1987 (*3*)

		Percent of accident involvements										
Highway class		Single-vehicle noncollision accidents			Single-vehicle collision accidents					Multiple-vehicle collision accidents		
Area type	Roadway type	Run-off road	Overturned	Other	Coll. w/ parked vehicle	Coll. w/ train	Coll. w/ nonmotorist[a]	Coll. w/ fixed object	Other collision	Collision w/passenger car	Coll. w/truck	Coll. w/other vehicle
Rural	Two-lane	4.5	6.6	4.4	2.4	0.0	0.6	7.0	5.7	29.8	26.6	12.4
Rural	Multilane undivided	3.6	7.5	3.9	4.3	0.0	0.4	7.5	5.7	27.4	26.1	13.7
Rural	Multilane divided	3.6	4.0	3.8	3.9	0.0	0.2	6.1	4.7	33.4	26.4	13.8
Rural	Freeway	3.5	3.3	3.8	3.8	0.0	0.4	7.4	5.0	31.3	22.3	19.4
Rural	TOTAL	3.9	5.1	4.1	3.2	0.0	0.5	7.1	5.3	30.6	24.9	15.3
Urban	Two-lane	1.5	2.6	3.4	3.6	0.0	0.3	5.1	3.9	39.6	30.7	9.3
Urban	Multilane undivided	0.2	0.6	2.6	8.5	0.0	0.8	5.1	4.0	41.3	30.1	6.9
Urban	Multilane divided	0.8	1.3	2.4	7.0	0.0	0.6	5.7	3.8	43.7	28.1	6.6
Urban	One-way street	0.0	2.2	0.9	9.4	0.0	1.3	6.3	2.2	45.7	27.4	4.5
Urban	Freeway	0.6	1.0	1.3	1.9	0.0	0.2	3.2	1.7	50.6	25.6	13.9
Urban	TOTAL	0.6	1.1	1.6	3.1	0.0	0.3	3.8	2.2	48.6	26.4	12.3
TOTAL		1.6	2.3	2.3	3.1	0.0	0.4	4.7	3.1	43.4	26.0	13.1

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[a] Nonmotorists include animals, pedestrians, and bicycles.

TABLE 3 TRUCK ACCIDENT RATES BY STATE AND COMBINED (*3*)

Highway class		Truck accident rate (accidents per million veh-mi)			
Area type	Roadway type	California	Illinois	Michigan	Weighted average[a]
Rural	Two-lane	1.73	3.13	2.22	2.19
Rural	Multilane undivided	5.44	2.13	9.50	4.49
Rural	Multilane divided	1.23	4.80	5.66	2.15
Rural	Freeway	0.53	0.46	1.18	0.64
Urban	Two-lane	4.23	11.10	10.93	8.66
Urban	Multilane undivided	13.02	17.05	10.37	13.92
Urban	Multilane divided	3.50	14.80	10.60	12.47
Urban	One-way street	6.60	26.36	8.08	9.70
Urban	Freeway	1.59	5.82	2.80	2.18

[a] Weighted by veh-mi of truck travel.

TABLE 4 PROBABILITY OF RELEASE GIVEN THAT AN ACCIDENT HAS OCCURRED, AS A FUNCTION OF ACCIDENT TYPE (*3,7*)

Accident type	Probability of release
SINGLE-VEHICLE NONCOLLISION ACCIDENTS	
Run-off-road	0.331
Overturned (in road)	0.375
Other noncollision	0.169
SINGLE-VEHICLE COLLISION ACCIDENTS	
Collision with parked vehicle	0.031
Collision with train	0.455
Collision with nonmotorist	0.015
Collision with fixed object	0.012
Other collision	0.059
MULTIPLE-VEHICLE COLLISION ACCIDENTS	
Collision with passenger car	0.035
Collision with truck	0.094
Collision with other vehicle	0.037

$P(k)_j$ = probability that an accident on Highway Class j will be of Accident Type k (i.e., proportion of truck accidents for each accident type presented in Table 2 on Highway Class j from state accident data).

The probabilities in Table 5 are appropriate for use as default values in hazardous materials routing studies if data more suited to local conditions are not available.

REVISED PROCEDURES FOR DETERMINING ACCIDENT PROBABILITIES

In the current DOT guidelines, the probability of a hazardous materials accident is computed in the risk assessment model from the following equation:

$$P(A)_i = \mathrm{AR}_i \times L_i \qquad (6)$$

where

$P(A)_i$ = probability of a hazardous materials accident for Route Segment i,
AR_i = accident rate per vehicle-mile for all vehicle types on Route Segment i, and
L_i = length (in miles) for Route Segment i.

The availability of these truck accident rate and release probabilities permits estimation of the probability of a hazardous materials accident in which a release occurs. The probability of a releasing accident should be computed with the following equation (which replaces Equation 6 in the DOT guidelines):

$$P(R)_i = \mathrm{TAR}_i \times P(R|A)_i \times L_i \qquad (7)$$

where

$P(R)_i$ = probability of an accident involving a hazardous materials release for Route Segment i,

TABLE 5 PROBABILITY OF HAZARDOUS MATERIALS RELEASE GIVEN THAT AN ACCIDENT HAS OCCURRED, AS A FUNCTION OF HIGHWAY CLASS (3)

Highway class		Probability of hazmat release given an accident			
Area type	Roadway type	California	Illinois	Michigan	Weighted average[a]
Rural	Two-lane	0.100	0.074	0.073	0.086
Rural	Multilane undivided	0.100	0.071	0.064	0.081
Rural	Multilane divided	0.087	0.064	0.062	0.082
Rural	Freeway	0.083	0.111	0.095	0.090
Urban	Two-lane	0.077	0.059	0.069	0.069
Urban	Multilane undivided	0.064	0.052	0.055	0.055
Urban	Multilane divided	0.068	0.048	0.058	0.062
Urban	One-way street	0.066	0.050	0.056	0.056
Urban	Freeway	0.062	0.055	0.067	0.062

[a] Weighted by veh-mi of truck travel.

TAR_i = truck accident rate (accidents per vehicle-mile for Route Segment i,
$P(R|A)_i$ = probability of a hazardous materials release given an accident involving a hazardous materials-carrying truck for Route Segment i, and
L_i = length (mi) of Route Segment i.

Equation 7 is more appropriate for hazardous materials routing analyses than Equation 6 because (a) risk is based on the probability of a hazardous materials release rather than just the probability of an accident, and (b) risk is based on truck accident rates rather than all-vehicle accident rates. Equation 7 retains the proportionality of risk to route segment length, which is central to all routing analyses.

Table 6 presents typical values of truck accident rates and release probabilities taken from Tables 3 and 5 that can be used as default values in Equation 7. However, users are encouraged to develop default values from average data for their own jurisdiction. A key aspect of Table 6 is that both truck accident rates and release probabilities vary with area type (urban or rural) and roadway type.

The DOT guidelines encourage users to base accident rates on site-specific accident histories, whenever possible. The guidelines do not appear to recognize the need for caution in using accident rates based on small sample sizes of accidents, which are typical of the relatively short route segments often used in risk assessments. For example, consider three 0.5-mi route segments on alternative routes. Suppose that, in a 3-year period, one of these segments experiences no truck accidents, another experiences one truck accident, and the third experiences two truck accidents. To treat the first segment as having no risk of a hazardous materials release would certainly be incorrect, but this is the conclusion one would reach using the site-specific accident rate in Equation 6. To presume that, because the third segment has twice as many accidents as the second segment, it also has twice the risk would also be incorrect. The guidelines could be revised to incorporate a minimum time period or a minimum number of accidents needed to establish reliable accident rates. However, because default values of accident rates are available, to rely on default values of accident rates for specific highway classes (e.g., rural two-lane highways or urban freeways) developed on a statewide or system-wide basis is usually more appropriate. An exception to this general rule occurs when the accident frequency for a specific route segment is either substantially higher or lower than the system-wide accident rate for its highway class. Because accident occurrence is a random variable, site-specific accident data cannot be presumed to indicate true

TABLE 6 DEFAULT TRUCK ACCIDENT RATES AND RELEASE PROBABILITY FOR USE IN HAZARDOUS MATERIALS ROUTING AND ANALYSES (3)

Area type	Roadway type	Truck accident rate (accidents per million veh-mi)	Probability of release given an accident	Releasing accident rate (releases per million veh-mi)
Rural	Two-lane	2.19	0.086	0.19
Rural	Multilane undivided	4.49	0.081	0.36
Rural	Multilane divided	2.15	0.082	0.18
Rural	Freeway	0.64	0.090	0.06
Urban	Two-lane	8.66	0.069	0.60
Urban	Multilane undivided	13.92	0.055	0.77
Urban	Multilane divided	12.47	0.062	0.77
Urban	One-way street	9.70	0.056	0.54
Urban	Freeway	2.18	0.062	0.14

differences in risk between segments unless a statistical test indicates that these differences are statistically significant.

In most cases, the truck accident rates shown in Table 6 or, preferably, the average values for the user's own jurisdiction should be used as the value of TAR_i in Equation 7. However, a simple statistical procedure based on the chi-squared test can be used to determine whether the actual accident frequency for a particular route segment is enough larger or smaller than the expected accident frequency to warrant replacement of the default truck accident rates by site-specific rates based on accident histories. This procedure is used as follows.

Step 1

Obtain truck accident data for a particular highway segment. The truck accident data should cover as long a time period as possible without introducing extraneous effects caused by traffic, geometric, or operational changes. This observed accident frequency is referred to as A_o.

Step 2

Compute the expected number of truck accidents for that same time period using system-wide default accident rates such as those presented in Table 6. The expected truck accident frequency can be computed as

$$A_e = \text{TAR} \times \text{TADT} \times L \times 365 \times N \times 10^{-6} \qquad (8)$$

where

A_e = expected number of truck accidents,
TAR = expected truck accident rate (accidents per vehicle-mile) on the basis of Table 6 or state data,
TADT = average daily truck traffic (vehicles per day),
L = length of highway segment (miles), and
N = duration of study period (years).

If $A_e \geq 5$, the chi-squared procedure given in Step 3A should be used. If $A_e < 5$, the accident sample size is too small to use the chi-squared procedure, and an alternative procedure (presented in Step 3B) based on the Poisson distribution should be used.

Step 3A

If $A_e \geq 5$, compare the expected and observed number of accidents by computing the chi-squared statistic as follows:

$$\chi^2 = \frac{(A_e - A_o)^2}{A_e} \qquad (9)$$

where

χ^2 = chi-squared statistic,
A_e = expected number of truck accidents, and
A_o = observed number of truck accidents.

If $\chi^2 \leq 4$, then the expected and observed number of accidents do not differ significantly at the 5 percent significance level. Therefore, the system-wide default accident rate should be used instead of site-specific accident data.

If $\chi^2 > 4$, then the expected and observed number of accidents differ significantly. This result indicates that the observed accident rate is lower or higher at the 5 percent significance level than the system-wide default value. In this case, the system-wide default accident rate should be replaced by a value based on the site-specific data. If the site-specific accident rate is greater than the default accident rate, the site-specific rate should be used. If the site-specific accident rate is less than 50 percent of the default accident rate, 50 percent of the default accident rate should be used. The latter restriction is based on judgment and is included to keep very low short-term accident experience or poor accident reporting levels in a particular jurisdiction from causing misleading results. Even if the roadway segment has experienced no accidents during the study period, there is still risk involved in transporting hazardous materials over the segment, and use of 50 percent of the default accident rate is recommended.

Step 3B

An alternative procedure based on the Poisson distribution is used whenever $A_e < 5$, because the chi-squared test is not applicable to this small accident sample size. Table 7 presents critical values from the Poisson distribution for testing the significance of differences from the expected number of accidents.

If A_o exceeds the critical value given in Table 7 for the known value of A_e, then the expected and observed accident frequencies differ significantly. In this case, the system-wide default accident rate should be replaced by the site-specific accident rate, calculated as

$$\text{TAR} = \frac{A_o \times 10^6}{\text{TADT} \times L \times 365 \times N} \qquad (10)$$

If $A_e < 5$, it is recommended that the default accident rate should never be decreased, because the available sample size is rarely adequate to indicate a true accident rate lower than the expected value.

NUMERICAL EXAMPLES

Two simple numerical examples can illustrate the recommended risk assessment procedures, with emphasis on the revised procedures for determining accident probabilities.

TABLE 7 CRITICAL VALUES OF THE POISSON DISTRIBUTION

Expected accident frequency (A_e)	Critical value of A_o at the 5% significance level
1.0	4
1.5	5
2.0	6
2.5	6
3.0	7
3.5	8
4.0	9
4.5	9

The first example indicates the way a state would use truck accident rates and release probabilities on the basis of its own data. The second example demonstrates use of the default values of truck accident rates and release probabilities in Table 6.

Both examples address the relative risks of hazardous shipments on the simple highway network shown in Figure 2. Hazardous materials shipments must move from Point 1 to Point 5 by either Route A or Route B, which are 16.5 and 11 mi long, respectively. Route A is composed of three segments designated 1–2, 2–3, and 3–5, and Route B is composed of two segments designated 1–4 and 4–5. Route A has a substantial proportion of its length on nonaccess-controlled facilities (two-lane and multilane divided highways), whereas Route B is entirely on freeways. Route B is shorter than Route A, but nearly half of its length is in an urban area with a high population density. Route A is longer but predominantly rural. The numerical examples address the relative risks of hazardous materials transportation on the basis of differing assumptions concerning the truck accident rates and volumes on the alternative routes.

Example 1—Use of an Agency's Own Data

Example 1 involves a state highway agency that has used its own truck accident, truck volume, and geometric data to develop locally applicable values for truck accident rates and release probabilities using the procedure presented in the previous section. For illustrative purposes, the California truck accident rates presented in Table 3 and the California release probabilities presented in Table 5 will be used in this example.

Table 8 presents the basic state truck accident data for each route segment and the application of the chi-squared test to determine whether the expected truck accident rate or the site-specific accident rate should be used. For each route segment, the expected number of truck accidents in 3 years is compared with the actual number of truck accidents observed during that length of time. For route segments 1–2, 2–3, 3–5, and 1–4, the calculated value of χ^2 is less than 4.0, indicating that the state's estimate of the expected truck accident rate should be used in preference to the site-specific accident data. The use of the site-specific accident data would be misleading in these cases, because there is no evidence that their deviations from the expected values are not just random. Route Segment 4–5 was expected to experience 43.5 accidents in 3 years, but 65 accidents actually occurred. In this case, the computed value of χ^2 is 10.62, which is substantially greater than 4.0 and which is highly statistically significant. For this segment, the state should use the site-specific accident rate of 2.37 accidents/million veh-mi computed from Equation 10, rather than the expected value of 1.59 accidents/million veh-mi.

Table 9 presents the application of the recommended revisions to the DOT risk assessment method. Accident probabilities for each route segment in the revised method are determined as the product of the expected state truck accident rates developed in Table 8, the release probabilities from Table 5, and the route segment lengths. The accident consequences are represented by the number of persons potentially exposed to hazardous materials releases per unit length, calculated from the population density along the route segment and the impact zone width. In this case, an impact zone width of 0.5 mi on either side of the roadway was selected.

The population risk for each route segment in Table 9 is computed as the product of the accident probability and the number of persons exposed per unit length. The total population risk for each route is the summation of the risks for each of the individual segments that make up the route. The results (in Table 9) indicate that Route A involves slightly less risk than Route B. Route A would be the preferred route for hazardous materials shipments unless there are qualitative or subjective factors present that favor Route B. Qualitative and subjective factors that may influence the choice between alternative routes for hazardous materials transportation are identified in the DOT guidelines (*1*,*2*) and include special populations, special property, and emergency response capabilities.

Example 2—Use of Default Accident Rates

Example 2 addresses the same highway network used in the first example, with slight changes to the truck volumes and

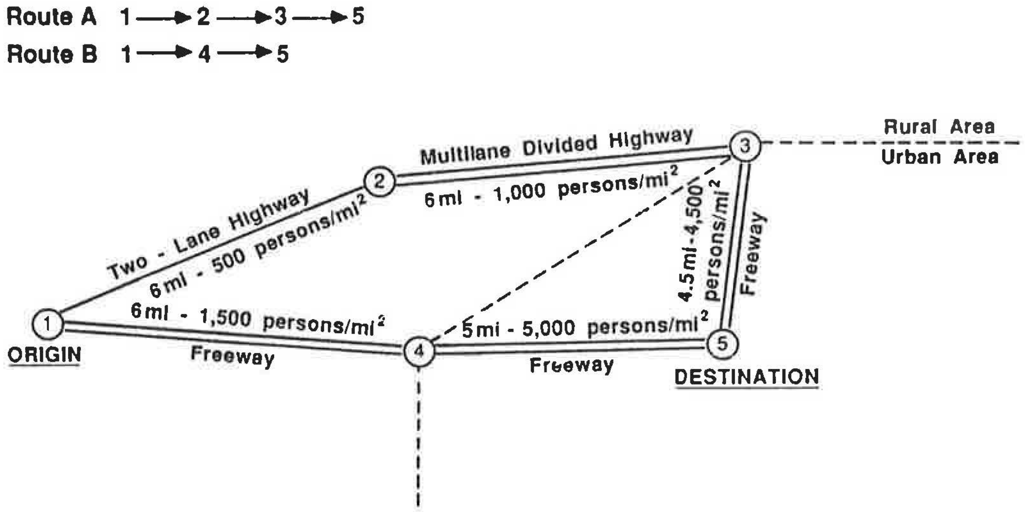

FIGURE 2 Highway network considered in numerical examples.

TABLE 8 COMPARISON OF TRUCK ACCIDENT RATES USING CHI-SQUARED TEST—EXAMPLE 1

(1) Route	(2) Route segment	(3) Area type	(4) Roadway type	(5) Expected truck accident rate (accidents per million veh-mi)[a]	(6) Truck ADT (veh/day)	(7) Length (mi)	(8) Expected number of truck accidents in 3 years[b] (A_e)	(9) Observed number of truck accidents in 3 years (A_o)	(10) Chi-squared statistic[c] (X^2)	(11) $X^2 > 4$?	(12) Truck accident rate for use in risk assessment (accidents per million veh-mi)
A	1-2	Rural	Two-lane	1.73	500	6.0	5.7	7	0.30	No	1.73
	2-3	Rural	Multilane divided	1.23	1,000	6.0	8.1	5	1.19	No	1.23
	3-5	Urban	Freeway	1.59	4,500	4.5	35.3	44	2.14	No	1.59
B	1-4	Rural	Freeway	0.53	1,500	6.0	5.2	9	2.77	No	0.53
	4-5	Urban	Freeway	1.59	5,000	5.0	43.5	65	10.62	Yes	2.37[d]

[a] From Table 1.
[b] From Equation (4).
[c] From Equation (5).
[d] From Equation (10).

TABLE 9 RISK ASSESSMENT FOR HAZARDOUS MATERIALS ROUTING USING REVISED FHWA METHOD—EXAMPLE 1

(1) Route	(2) Route segment	(3) Truck accident rate (accidents per million veh-mi)[a]	(4) Probability of release given an accident[b]	(5) Length (mi)	(6) Release probability[c]	(7) Population density (persons/mi²)	(8) Impact zone width (mi)	(9) Total persons exposed[d]	(10) Persons exposed per mi[e]	(11) Population risk[f]
A	1-2	1.73	0.100	6.0	1.038	800	0.5	4,800	800	830
	2-3	1.23	0.100	6.0	0.738	1,000	0.5	6,000	1,000	738
	3-5	1.59	0.062	4.5	0.444	5,000	0.5	20,000	5,000	2,218
										3,786
B	1-4	0.53	0.083	6.0	0.264	1,000	0.5	7,000	1,000	264
	4-5	2.37	0.062	5.0	0.735	5,000	0.5	20,000	5,000	3,674
										3,938

ROUTE A INVOLVES LESS RISK THAN ROUTE B

[a] From Table 8.
[b] From Table 5.
[c] Calculated as (3) x (4) x (5) from Equation (7).
[d] Calculated as (7) x (5) x (8) x 2.
[e] Calculated as (9)/(5).
[f] Calculated as (6) x (10).

accident experience on some of the route segments. This example illustrates the use of the default truck accident rates and release probabilities in Table 6.

Table 10 presents the basic accident data for each route segment and application of the chi-squared test. The calculated values of χ^2 for route segments 2–3, 3–5, and 1–4 are less than 4.0, as in the first example, indicating that the default truck accident rate should be used rather than the site-specific accident rate. As in the first example, the calculated value of χ^2 for route segment 4–5 is greater than 4.0, indicating that the site-specific accident rate should be used rather than the default value.

Route Segment 1–2 in Table 10 represents an important exception to the chi-squared test. This route segment is expected to experience only 2.9 truck accidents in a 3-year period. The chi-squared test is not applicable when the expected number of truck accidents (A_e) is less than 5, so the alternative test based on the Poisson distribution should be used. Interpo-

TABLE 10 COMPARISON OF TRUCK ACCIDENT RATES USING CHI-SQUARED TEST—EXAMPLE 2

(1) Route	(2) Route segment	(3) Area type	(4) Roadway type	(5) Expected truck accident rate (accidents per million veh-mi)[a]	(6) Truck ADT (veh/day)	(7) Length (mi)	(8) Expected number of truck accidents in 3 years[b] (A_e)	(9) Observed number of truck accidents in 3 years (A_o)	(10) Chi-squared statistic[c] (X^2)	(11) $X^2 > 4$?	(12) Truck accident rate for use in risk assessment (accidents per million veh-mi)
A	1-2	Rural	Two-lane	2.19	200	6.0	2.9	8	d	Yes[d]	6.09[e]
	2-3	Rural	Multilane divided	2.15	1,000	6.0	14.1	9	1.84	No	2.15
	3-5	Urban	Freeway	2.18	4,500	4.5	48.3	55	0.93	No	2.18
B	1-4	Rural	Freeway	0.64	1,500	6.0	6.3	9	1.16	No	0.64
	4-5	Urban	Freeway	2.18	5,000	5.0	59.7	76	4.45	Yes	2.77[e]

[a] From Table 6.
[b] From Equation (8).
[c] From Equation (9).
[d] Chi-squared test is not applicable because $A_e < 5$. Therefore, A_o is compared to a critical value of the Poisson distribution (6.8), as interpolated from Table 7.
[e] From Equation (10).

lation in Table 3 indicates that the critical value of the Poisson distribution is 6.8 accidents when $A_e = 2.9$. Because this route segment experienced more than this critical number of accidents in 3 years, the site-specific accident rate, computed in accordance with Equation 10, has been used rather than the default value.

Table 11 presents the application of the revised FHWA risk assessment procedure to the data for the second example. These calculations are entirely analogous to those for the first example in Table 9. The results indicate that, for the conditions in the second example, Route B involves slightly less risk than Route A. Route B would be the preferred route for hazardous materials shipments unless there are qualitative or subjective factors that favor Route A.

CONCLUSION

The accident probability portion of the DOT hazardous materials routing guidelines can be realigned to more realistically address the likelihood of accidents involving hazardous materials releases. Equation 7 provides the recommended method for determining the relative probability of a hazardous materials release for shipments on a particular route segment. The key elements in the revised guidelines are explicit consideration of (a) the truck accident rates and (b) the probability of a release given an accident. Truck accident rates are more directly applicable to the risk of accidents involving hazardous materials-carrying vehicles than the all-vehicle accident rates used in the current FHWA guidelines. Furthermore, the inclu-

TABLE 11 RISK ASSESSMENT FOR HAZARDOUS MATERIALS ROUTING USING REVISED FHWA METHOD—EXAMPLE 2

(1) Route	(2) Route segment	(3) Truck accident rate (accidents per million veh-mi)[a]	(4) Probability of release given an accident[b]	(5) Length (mi)	(6) Release probability[c]	(7) Population density (persons/mi²)	(8) Impact zone width (mi)	(9) Total persons exposed[d]	(10) Persons exposed per mi[e]	(11) Population risk[f]
A	1-2	2.19	0.086	6.0	1.130	800	0.5	4,800	800	904
	2-3	2.15	0.082	6.0	1.058	1,000	0.5	6,000	1,000	1,058
	3-5	2.18	0.062	4.0	0.608	5,000	0.5	20,000	5,000	3,041
										5,003
B	1-4	0.64	0.090	6.0	0.346	1,000	0.5	7,000	1,000	346
	4-5	2.77	0.062	5.0	0.858	5,000	0.5	20,000	5,000	4,290
										4,636

ROUTE B INVOLVES LESS RISK THAN ROUTE A

[a] From Table 10.
[b] From Table 6.
[c] Calculated as (3) x (4) x (5) from Equation (7).
[d] Calculated as (7) x (5) x (8) x 2.
[e] Calculated as (9)/(5).
[f] Calculated as (6) x (10).

sion of hazardous materials release probabilities, which vary markedly between accident types, makes the revised procedures more sensitive to differences in accident patterns between highway types (e.g., freeway versus nonfreeway).

The revised procedures are equally applicable to routing decisions based on a highway agency's own truck accident data and decisions based on the default values of truck accident rate and release probability presented here. The use of truck accident rates based on an agency's own data is generally preferable, because these values will be most suited to local conditions.

Default values of truck accident rate and hazardous materials release probability can be developed from existing state data bases of truck accident and exposure data. Data bases containing traffic accident records, ADT volumes, and the percentage of trucks for individual highway segments that can be linked together by a common location identifier (e.g., a milepost system) have been developed by a number of state highway agencies. Default estimates of truck accident rate and hazardous materials release probability have been developed from data for the entire state highway systems of three states.

Site-specific accident data must be used cautiously when the available accident sample sizes for a particular route segment are small, as they often are. The chi-squared test has a key role in the decision to use either the default value of truck accident rates or the truck accident rates based on site-specific data for any given route segment. In the special case where the expected number of truck accidents is less than 5, a test based on the Poisson distribution should be used in place of the chi-squared test.

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Hazardous Materials Siting and Routing Decisions: Factors Affecting Preferences of Fire Chiefs

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Hazardous materials routing and siting decisions are based on multiple objectives, which often conflict. These objectives usually express risk, cost, and equity criteria. Multicriteria decision-making models for hazardous materials routing and siting are available. A common characteristic of these models is the generation of noninferior solutions. A solution is noninferior if no other solution can improve one of the objectives without degrading at least one other objective. Given the fact that only one of the noninferior solutions can be selected, it is necessary at a certain point of the decision-making process to consider the preferences of the decision makers. The preferences of decision makers are affected by their expertise and other nontechnical factors. A telephone interview survey of fire department chiefs in 95 Connecticut cities and towns concerned tradeoffs between cost and safety of hazardous materials transportation and their preferences for hazardous materials storage facilities in rural areas. The survey identified factors affecting these preferences and indicated that community self-interest is one determinant of fire chiefs' preferences.

The production and transportation of hazardous materials is an unavoidable process in any industrial society. A number of industrial activities of vital economic importance are dependent on the uninterrupted flow of hazardous materials shipments. Data from the Chemical Manufacturers Association, the Fertilizer Institute, and the Department of Energy indicate that a substantial hazardous materials volume is produced and transported every year in the United States (*1*). Surveys of hazardous materials movements indicate that approximately 1.5 billion tons were transported within the United States during 1982 (*2*).

Although hazardous materials production is associated with technological growth and economic development, the danger associated with its accidental release is substantial and sometimes catastrophic for humans and the environment. The high risk associated with hazardous materials transportation has drawn considerable attention at local, national, and international levels (*3–5*), resulting in a regulatory framework to enhance the safety of hazardous materials movements. Most of the existing regulations impose spatial or temporal restrictions, or both, on hazardous materials movement. The idea behind restricting the routing is to enhance the safety by (a) minimizing the accident probability, and (b) minimizing the consequences of accidents.

Route selection for hazardous materials shipments depends on the location of the origin and destination of these materials. Obviously, there is an interaction between decisions related to the location of hazardous materials production and storage facilities and decisions about hazardous materials routing to and from the facilities (*6,7*).

Besides risk, transportation cost is a major consideration in hazardous materials routing decisions. However, routes that may minimize the transportation risk may not minimize the transportation cost (*8*). In fact, there is a tradeoff between cost and safety. Finally, the distribution of risk is an important criterion that should be taken into account in selecting routes for hazardous materials shipments. Selection of routes on the basis of risk minimization may result in inequalities in risk distribution (*8*).

Hazardous materials transportation decisions involve a number of decision makers and require the consideration of multiple and sometimes conflicting objectives. The intervention of decision makers is required to resolve the conflict between the different objectives of groups involved in and affected by transportation of hazardous materials.

Multicriteria decision-making models for location and routing that incorporate the preferences of decision makers are important when dealing with hazardous materials transportation decisions. The orientations of the actors involved in this process are affected by a number of factors. Some of the factors influencing the preferences of a particular group of actors, namely fire chiefs, will be studied.

First, existing hazardous materials routing and siting models will be described. Next, the necessity of incorporating the preferences of decision makers in hazardous materials routing and siting decisions is explained. An empirical model is presented for the identification of some factors influencing the preferences of decision makers when they are examining tradeoffs between conflicting objectives. Finally, the findings and conclusions of this study are presented.

EXISTING MODELS FOR HAZARDOUS MATERIALS ROUTING AND SITING DECISIONS

In its general form, the hazardous materials routing problem can be expressed as follows: given a graph $G = (V, L)$, with a node set V, $|V| = v$, a link set L, a set of nodes O representing the origins of hazardous materials shipments (i.e., production facilities), and a set representing the destinations D of the hazardous materials shipments (i.e., storage or transshipment facilities), find the path or paths connecting the origin-destination pairs in such a way as to minimize a set of

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criteria *M* associated with the links of the transportation network. The following categories of criteria are usually used in hazardous materials routing models: (a) criteria expressing cost, (b) criteria expressing risk, and (c) criteria expressing equitable distribution of risk. When the origin or destination of the hazardous materials shipments, or both, is not predetermined, then the routing problem becomes more complicated, and the location decision for the production and storage facilities should be made at the same time as the routing decision. Combined location-routing models have been proposed (*9,10*) for the simultaneous location of hazardous materials production and storage facilities and the routing of hazardous materials between them. A common characteristic of the existing combined location-routing models is the consideration of multiple criteria. Mirchandani and List (*10*) presented a model that considers the following criteria: (a) total risk, (b) maximum risk per person, (c) transportation cost, and (d) cost of the treatment facilities. Zografos and Samara (*9*) presented combined location-routing models that consider the following criteria: (a) risk caused by the location of treatment and storage facilities, (b) transportation risk, (c) transportation cost, and (d) equitable distribution of risk.

Models found in the hazardous materials routing literature can be classified according to the number of criteria used to determine the best paths between origins and destinations. If only one criterion is used, the models are characterized as single-objective optimization problems, and the well-known shortest-path problem is used to find the best path connecting the origin-destination pair. Single-objective hazardous materials models have been proposed by Robbins (*11*), Brogan and Cashwell (*12*), and Batta and Chiu (*13*).

When more than one criterion are used for routing of hazardous materials, the models are characterized as multicriteria decision-making problems. Multicriteria routing models can be used to study tradeoffs between conflicting routing objectives (e.g., risk versus cost or total risk versus equitable distribution of risk). Multicriteria formulations of the hazardous materials routing problem have been proposed by Zografos and Davis (*8*), Abkowitz and Cheng (*14*), Robbins (*11*), and Turnquist (*15*).

INCORPORATING DECISION MAKERS' PREFERENCES IN HAZARDOUS MATERIALS ROUTING AND SITING DECISIONS

Multicriteria hazardous materials routing and siting models usually consider combinations of the following objectives: (a) minimization of risk, (b) minimization of cost, and (c) equitable distribution of risk. A common characteristic of these existing models is the generation of efficient (or noninferior) solutions. A solution of a multicriteria decision-making model is efficient if no other solution can improve one of the objectives under consideration without causing a degradation in at least one other objective (*16*).

As an example of the concept of efficiency in the hazardous materials routing environment, the two following objectives are assumed to be of interest in a routing problem: (a) minimization of risk and (b) minimization of cost. The set of efficient solutions for this example will contain routes that outperform each other in terms of risk or in terms of cost, but not both.

By this definition of efficiency, the set of efficient solutions contains a number of alternative solutions, only one of which can be implemented. Therefore, the selection of the implemented alternative requires the intervention of the decision maker. This requirement means that at a certain stage of the solution process the decision maker has to express preferences with respect to the conflicting objectives, implicitly or explicitly. The noninferior solution selected after the intervention of the decision maker is called the best compromise solution. Therefore, the best compromise solution is the solution that maximizes the utility of the specific decision maker.

The intervention of the decision maker in the solution process implies that the best compromise solution depends on the values, perception, and attitude of the decision maker or group of decision makers. Therefore, it is important to identify the factors affecting the judgment of decision makers involved in hazardous materials transportation decisions before trying to formulate their utility functions, which are required for the identification of the best compromise solution.

FACTORS AFFECTING PREFERENCES OF DECISION MAKERS

A comprehensive survey of fire chiefs was undertaken to (a) examine perceptions and attitudes of fire chiefs related to hazardous materials siting and routing decisions and (b) identify some factors affecting their attitudes and preferences. Fire chiefs represent only one of the groups of decision makers involved in hazardous materials management actions. However, they were selected as the survey population because of their high degree of involvement and responsibility in hazardous materials emergencies and because of their recognition as one of the major actors in the hazardous materials management process.

Data Collection and the Survey Population

During spring 1989, 95 randomly selected fire chiefs from throughout the state of Connecticut were interviewed by telephone (*17*). The data drawn examined the fire chiefs' preferences regarding tradeoffs between transportation risk and transportation cost, as well as the location of hazardous materials storage facilities in low-density areas. The design used fire chiefs to provide information concerning their fire departments and the status of programs serving Connecticut's 169 towns. The telephone interview data were used to measure fire chiefs' awareness, perception, attitudes, and experience with various aspects of hazardous materials transport in the state, including routing and siting issues.

Drawing on a list provided by the state fire administrator, interviews were conducted with chiefs of fire departments serving the state's 21 largest cities and towns. Another 74 interviews were completed with fire chiefs selected from half of the remaining 148 towns. This stratified random sample can be weighted to represent all 169 towns in the state (*17*).

Data Analysis

The collected data were analyzed in two stages. In the first stage, some descriptive statistics were derived to determine whether there was a universal consensus among the decision makers regarding the tradeoff questions. In the second stage, the data were cross classified according to a set of variables that described personal, demographic, and locational characteristics of these decision makers. This type of cross classification was deemed necessary to examine the effect of the classification variables on the preferences.

Descriptive Findings

The study population of fire chiefs had a median age of 45 years and served 60 small towns (1980 population up to 7,500), 89 midsized towns (7,500 to 39,999), and 20 big cities (40,000 and over). According to the State of Connecticut Functional Classification System, 65 percent of the sampled towns are in the path of an expressway, and another 67 percent have at least one principal arterial highway. In combination, 46 percent of the towns have both an expressway and a principal arterial highway, while another 40 percent have one or the other. Approximately 40 percent of the fire chiefs said they were well informed in dealing with hazardous materials transport problems, but the majority described themselves as only partially informed. They divided equally (49 percent well informed) in selecting these terms to describe how much they know about the hazards of specific materials such as gasoline, propane, sulfuric acid, and incinerator ash. About 43 percent had received over 40 hr of hazardous materials transport training during the past 3 years; they also reported an average (median) of 7 years of work experience related to hazardous materials transport.

Other survey questions measured the inevitable tradeoffs that affect public policy development (e.g., economics versus safety, risk distribution and safety, and risk-related siting decisions). The following question illustrates one of these tradeoffs:

> To maximize the safety of hazardous materials transported to manufacturing facilities, it may be necessary to raise the price consumers pay for certain products. All things considered, do you prefer increasing safety in hazardous materials transport even if that means increased prices, or do you want to keep consumer prices down even if that means there is no increase in hazardous materials transport safety?

Nine of 10 (93 percent) fire chiefs opted for increased safety and higher prices, and 5 percent endorsed no increase in safety or prices. The fire chiefs were clearly safety minded. At the same time, they were reluctant to support restricted routing regulations that would entail an economic cost to the town they serve (e.g., providing escorts for hazardous materials shipments on town routes). A meaningful comparison on safety versus price, of course, would involve a study population of shippers and carriers, manufacturers, and legislators.

Another tradeoff was described in the following question: "How often do you think putting a hazardous materials facility in a low-risk location means increasing the risk to people along the route leading to that facility?" Three out of 10 fire chiefs answered "all the time" to this tradeoff; the remainder (69 percent) responded "sometimes." The issues here are far more complex than those of the price versus safety question.

The final tradeoff question read as follows: "It's a good idea to store hazardous materials in rural areas, because most people live in cities and suburbs." In this instance, the sample was equally divided: 53 percent agreed, 45 percent disagreed, and 2 percent couldn't offer a response.

There are some factors that contribute to the cleavage among fire chiefs in their assessment of these different questions. The population size of the towns and cities fire chiefs serve is likely to offer insight into their approval of (or opposition to) rural hazardous materials storage facilities, as would self-described expertise and reported experience with hazardous materials transportation.

Bivariate and Multivariate Analysis

A set of classification variables describing (a) expertise of the fire chiefs in hazardous materials management, (b) experience of the fire chiefs, (c) location of the town in relation to the major transportation corridors, and (d) town population was used to account for the preferences of the fire chiefs. These variables were derived from the questionnaire survey as follows:

1. Index of expertise (EXPERT): This index was derived from two survey items. The first question was, "In dealing with hazardous materials transport problems, would you say you are well informed, only partially informed, or not informed at all?" (Well informed = 1, all others = 0). The second item read, "How well informed would you say you are on the hazards of specific materials such as gasoline, propane, sulfuric acid, and incinerator ash? Would you say you are well informed, only partially informed, or not informed at all?" (Well informed = 1, all others = 0).
2. Index of experience with hazardous materials (ZEXPER): This index measured experience with hazardous materials transportation from the following items: "How many hours of hazardous materials training have you had in the last three years . . .?" (41 hr or more = 1, 40 hr or less = 0); and "How many years of work experience have you had related to hazardous materials transport?" (8 years or more = 1, less than 8 years = 0).
3. Index of highway systems (HIGHWAY): This index measured experience with hazardous materials transport from the following items: "Expressway intersects town?" (Yes = 1, no = 0) and "Other principal arterial?" (Yes = 1, no = 0).
4. Town population, 1980 (POP3): (40,000 and over = 3, 7,500–39,999 = 2, under 7,500 = 1).
5. Store in rural areas (RURAL): (Agree = 1, disagree = 0).
6. Hazardous materials facility in low-risk area (RISKLOC): (All the time = 1; sometimes, etc. = 0).

Results

A series of two-way tables predicting RURAL and RISKLOC on the basis of the four independent variables produced the following results. Fire chiefs in the large and midsized cities and those scoring high on self-attributed expertise on hazardous materials matters were more likely than their counterparts to agree that it is a good idea to store hazardous materials in a rural area, away from population centers. The index of expertise used here is based on self-attribution and would be improved if information were available concerning certification of hazardous materials training. However, support for this policy position is not directly related to hazardous materials work experience or to a town's score on the highway system index. (Table 1 presents a summary of results.) At the same time, none of these predictor variables significantly predicted responses to the item concerning risk to nearby residents along routes leading to a low-risk location.

Risk estimation studies have indicated that the public-at-large and technical experts employed by large organizations differ substantially in their appraisals of risk. For example, state and local government agencies frequently make judgments about risk in conjunction with the development of policies concerning the siting of facilities considered obnoxious by the public-at-large. The hazardous materials transport system addresses these issues as well. For this reason, self-designated expertise is a significant factor in the support of rural hazardous materials storage facilities. That fire chiefs serving big and midsized communities would be twice as likely as their counterparts in small communities to opt for rural storage facilities is not surprising.

However, the larger the community the greater the likelihood of having self-contained breathing apparatus, encapsulating suits, and detection equipment to deal with hazardous materials. In addition, the larger cities probably maintain an array of fire suppressant equipment, trained emergency responders, and emergency room mitigation teams. In brief, notwithstanding their greater capacity for effective community response, metropolitan area fire chiefs favor exporting this form of risk to less populated areas.

The critical question concerning expertise is the following: Is judgment on the siting of storage facilities anchored exclusively in the self-interest of communities served by fire chiefs, or does expertise operate across the board, in towns of every size, on behalf of this policy? The data were disaggregated by city size to answer this question. The results are presented in Table 2. On a general linear model (*18*), the results clearly indicate that structural factors influence risk estimation. Expertise (self-defined) predicted support for rural hazardous materials storage locations among fire chiefs in the big and midsized cities, but not in the small towns. Table 2 also indicates the effect of expertise on support for this policy within the three categories of city size when each of the remaining variables is statistically taken into account.

In the small towns, none of the predictor variables (self-defined expertise, type of highway system, and work-related hazardous materials experience) accounted for the position taken by fire chiefs on this matter. In midsized and large cities, the results were noteworthy; only expertise explained the difference, and expertise predicted a preference for rural sitings among those fire chiefs serving large and midsized cities even when type of highway system and experience were taken into account.

CONCLUSIONS

Hazardous materials routing and siting decisions involve multiple and conflicting objectives. These objectives represent the interests of the various groups affected by the decisions.

Multiple-objective programming formulations, which have been proposed to solve the hazardous materials routing and siting problem, require the intervention of the decision makers to identify the best compromise solution. However, the determination of the best compromise solution is affected by the background of the decision maker and the size of the community served. One of the findings of this study was that fire chiefs assigned a higher priority to the safe transport of hazardous materials than to transport costs. There was general concern on this issue. When it came to the question of financial commitments necessary to achieve higher safety levels,

TABLE 1 CORRELATES OF SUPPORT FOR SITING AND ROUTING POLICIES

CORRELATE	RURAL (% AGREE)	RISKLOC (% "ALWAYS")
POP3		
"Big" City	60%*	35%
"Mid-sized"	62	27
"Small"	37	30
EXPERT		
"High" (2)	78%*	24%
"Middle" (1)	39	33
"Low" (0)	43	31
EXPERIENCE		
"High" (2)	58%	28%
"Middle" (1)	55	26
"Low" (0)	46	35
HIGHWAY INDEX		
"High" (2)	59%	31%
"Middle" (1)	47	29
"Low" (0)	50	25

Note: Chi square not significant at .05 level if asterisk is missing.

TABLE 2 REGRESSION ESTIMATES FOR RURAL VARIABLE BY TOWN SIZE WITH SELECTED CONTROLS

Dependent Variable	Independent Variables		
	EXPERT	HIGHWAY	ZEXPER
RURAL	POP3 = 1 (Small)		
b Value	-.020	-.073	.170
p	.923	.725	.407
RURAL	POP3 = 2 (Mid-Sized Towns)		
b Value	.375	-.039	-.105
p	.025	.733	.520
RURAL	POP3 = 3 (Large Towns)		
b Value	.456	-.039	-.076
p	.065	.869	.750

however, the fire chiefs also indicated that they were not ready to use strategies that would require municipal financial expenditures (e.g., escorts) to achieve this goal.

Another finding related to the siting of hazardous materials storage facilities. The survey question asked whether hazardous materials should be stored in low-density (rural) areas. The analysis of the survey data indicated that the fire chiefs were biased in siting decisions by the self-interest of the community they served. This conclusion stemmed from the finding that self-defined expertise predicted support for a rural location of hazardous materials storage facilities among fire chiefs in the big and midsized cities but not in the small, rural towns. Overall, these findings offered additional evidence that social and other structural criteria (*19*), as well as objective technical features of decision making, affect risk assessment in this policy arena.

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Fatality Risk Curves for Transporting Chlorine and Liquefied Petroleum Gas by Truck and Rail

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When compared to observations from historical data, statistical risks often reflect significant discrepancies. The basic problem concerns the way objective statistical risks are represented. Risk is defined as the product of the probability of an incident and its consequent damages, averaged over all possible outcomes. Statistical risk can be expressed more completely as a relationship between the frequency of occurrence of an event (*F*) and the number of people affected (*N*). Because *F–N* curves represent the entire risk spectrum associated with each incident, they can also be used to estimate anticipated interval times between consequent events for the transport of a given class of dangerous commodity. A number of *F–N* curves for the road and rail transport of chlorine and liquefied petroleum gas were established. These results were compared with *F–N* curves reported elsewhere in the literature. Discrepancies between statistical fatalities from the risk model estimates and observed fatalities from the data are explained in terms of the expected interval times between designated events for each mode and type of material.

In its final report, the Toronto Area Rail Transportation of Dangerous Goods Task Force (*1*) suggested that 4.1 fatalities per year could be expected to take place in the Greater Toronto area as a result of all rail shipments of dangerous commodities. Recognizing that this estimate may have been conservative, the Task Force revised their estimates downward and suggested a rate of 1.4 fatalities per year, a value considered to be more reflective of actual risks in the Toronto region. A report (*2*) prepared by the Institute for Risk Research (IRR) suggested that average Canada-wide fatality rates were 0.0108/million tonne-km and 0.0035/million tonne-km for chlorine shipments by road and rail, respectively, on the basis of an average population density of 600 persons/km^2.

When compared with historical data, most statistical estimates tend to overpredict the hazards associated with the shipment of dangerous commodities by road and rail. In Canada, there has never been a death attributed directly to the transport of chlorine, or indeed any dangerous good, for all the years that data have been collected. The Railway Progress Institute in the United States maintains annual records of loss of lading incidents for various dangerous goods. In the 16-year period from 1965 to 1980, there were only 16 such incidents involving rail chlorine shipments for all of North America, accounting for a total of 8 fatalities and 169 personal injuries. All 8 fatalities were reported in a single chlorine accident. The Health and Safety Executive has reported that in more than 60 years of road operations in the United Kingdom only three cases of major releases were reported. The safety record on rail was equally impressive. Although a number of minor leakages were observed, none of these incidents actually resulted in personal injuries or fatalities (*3*).

Wide discrepancies between statistical and observed risks have created problems of credibility for risk analysis models. Shippers have been complaining that they are being forced to implement costly safety measures on the strength of unsubstantiated statistical risk estimates. In the interest of credibility, any such discrepancy between statistical and observed risks must be resolved.

Risk is generally defined as the product between the probability of an incident and its consequent damage, and is frequently expressed as an expectation of damage, taking into account all damage classes and their associated probabilities. The basic problem with this approach is that the expected value of damage reflects only one point on the entire risk spectrum, that is, the mean. The expectation of damage is a poor indicator of those extreme events along the risk spectrum that reflect low-frequency but high-damage potential. Measuring risk through expectation gives rise to a situation whereby an incident that causes 1,000 deaths once every 100 years has the same expected fatality rate as an incident that causes 10 deaths every year for a 100-year period. The ramifications for verifying these risks in the data are important. That the former incident is reflected in a data base spanning a period less than 25 years is unlikely, whereas the latter incident, because it is expected to occur at least once each year, can be easily verified by experience. Unfortunately, incidents involving the transportation of dangerous commodities such as chlorine are essentially representative of very low-frequency and high-consequence events and are difficult to verify in data assembled over a limited number of years.

The following two objectives were accomplished:

1. Establishing fatality-frequency (*F–N*) curves for incidents involving the transport of chlorine and liquefied petroleum gas (LPG) by road and rail and comparing these results with *F–N* curves reported elsewhere in the literature and with observed fatalities from the historical data base.
2. Applying simulation techniques to *F–N* curves for specific dangerous commodities, obtaining time intervals between designated incidents on road and rail for chlorine and LPG, and comparing these intervals with time frames reflected in the available data bases.

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ESTIMATING OBJECTIVES RISKS FOR CHLORINE AND LPG

Risk is generally defined as the potential realization of undesirable hazards, in this case the transport of certain dangerous commodities by road and rail. In estimating risk, two constituent components need to be obtained—the probability of occurrence of a given incident and the magnitude of the undesirable hazard (e.g., fatalities, personal injuries, and properties damaged). The probability of a dangerous good incident on road and rail will be expressed in terms of occurrences of accidental release per carload of chlorine and LPG transported over a given distance. Factors that affect the probability of release for different tanker components include tanker design features, speed of operation, and nature of the release mode (the type of containment system fault). The release mode affects both the rate and volume of material released in each incident. Control factors for the consequent damages (in this case the number of fatalities) include the spill environment and the distribution of population in the vicinity of each incident. Because in this analysis the basic concern is with verifying statistical risk in the accident data base, risk is defined assuming the prior occurrence of an accident on a given mode for each shipment of chlorine and LPG. The risk measures discussed have been estimated by applying a comprehensive risk model to road and rail shipments of chlorine and LPG in Canada. A detailed description of this approach is provided by IRR (*2*) and Saccomanno et al. (*4*).

Release Profiles for Dangerous Goods in an Accident Situation

Aggregate release probabilities were estimated for each road and rail incident using a fault tree analysis of the tanker containment system (*5*). Fault trees are based on a mechanistic analysis of containment system faults in an accident situation. For both chlorine and LPG bulk tankers, two containment system faults were considered—releases from tank shells (including tank wall, tank head, and manway cover failures) and releases from valves (including pressure relief valves, liquid valves, outlet valves, etc.). Table 1 presents release probabilities estimated from fault trees as applied to road and rail shipments of chlorine and LPG, respectively.

The release probabilities in Table 1 suggest that for chlorine rail shipments approximately 11.8 percent of all railcar accidents, most of which occur through minor venting of the pressure relief valve in an accident situation, result in loss of lading. This can be compared to a release occurrence of 1.6 percent for similar shipments of chlorine by road. For LPG shipments, the aggregate release probabilities in an accident situation were estimated as 3.2 percent for rail and 3.7 percent for road.

Among other factors, the hazard area associated with each incident involving road and rail shipments of chlorine and LPG is affected by the type and volume of material released in each incident. In this study, two types of release have been considered for both materials—instantaneous and continuous releases. Instantaneous releases refer to a situation where the bulk of material is released immediately following an accident. Continuous releases, on the other hand, take place over an extended period of time, in some cases up to several hours. Under certain conditions, some releases can be both instantaneous and continuous. For LPG, only instantaneous releases have been considered, as the hazard area associated with continuous releases was found to have a negligible effect on total risks. For each type of release and material, three volume-rate classes are considered:

Instantaneous Releases		*Continuous Releases*	
Class	*Tanker Volume (%)*	*Class*	*Rate (kg/sec)*
Chlorine			
High	100	High	14.5
Medium	69	Medium	3.9
Low	39	Low	0.1
LPG			
High	100	Not modeled	–
Medium	90	Not modeled	–
Low	69	Not modeled	–

Before obtaining estimates of release frequencies for different volumes and rates of material involved, to establish a relationship between the containment system failure mode (from the fault tree analysis) and the volume and rate of material released was necessary.

In order to determine the conditional probabilities of release for different failure modes, all incidents involving compressed gases (Class 2 incidents) as reported in the CANUTEC data file were analyzed for the 1986–1987 period (*2*). A total of 38 releases were observed in the data base, of which 6 took place on rail and 32 on road. These releases were grouped according to the type and size of release and by the primary containment system failure mode (i.e., shell or valve). All major spills were assumed to be instantaneous in nature, whereas minor leaks were assumed to be continuous. In addition, all valve releases were assumed to be continuous. Some releases reported in the CANUTEC data base could not be used in this analysis, because they were not identified as being either shell or valve initiated.

Given the lack of observations in the CANUTEC data base, a significant degree of intuitive adjustment and smoothing was applied to the resultant contingency table of releases to reduce the number of empty cells. Table 2 presents the proportion of releases associated with different failure modes (shell and valves) for different release profiles (instantaneous and continuous). These proportionalities were estimated for road and rail shipments of all dangerous commodities, and are applied here both to chlorine and LPG shipments.

Combining the release probabilities from Table 1 with the proportionate values from Table 2 yields the release probabilities for different types of release and release rates both for chlorine and LPG shipments. These values are presented in Table 3 for road and rail.

Estimation of Hazard Areas and Lethality

For different types of dangerous commodities, the corresponding hazard area is affected by four factors—release rates and volumes, material properties, extent of damage being considered, and environment. Given the spill size, various damage propagation models were used to establish the cor-

TABLE 1 ACCIDENT-INDUCED RELEASE PROBABILITIES FOR DIFFERENT TANKER FAULTS (PER 100 TANKCAR ACCIDENTS)—OUTPUT FROM FAULT TREE ANALYSIS

	Rail	
	Chlorine	LPG
Tank Shell	1.097	2.900
Tank Head	0.067	.....
Tank Wall	0.995	.....
Manway Cover	0.035	.....
Tank Valves	0.906#	0.290
Gas Valve	0.165	.....
Relief Valve	0.453#	.....
Liquid Valve	0.165	.....
Outlet Valve	0.123	.....
	Road	
Tank Shell	1.460	2.300
Tank Valves	0.165	1.400

\# excludes "normal" releases which are estimated as 9.747

TABLE 2 MATERIAL RELEASED BY TYPE AND CONTAINMENT FAULT [BASED ON CANUTEC DATA (*1*)]

	Release Proportionalities (%)					
	Instantaneous			Continuous		
	High	Medium	Low	High	Medium	Low
Fault Type						
Rail						
Tank Shell	20.0	40.0	35.0	5.0	----	----
Valves	----	----	----	25.0	35.0	40.0
Road						
Tank Shell	20.0	25.0	35.0	10.0	5.0	5.0
Valves	----	----	----	30.0	30.0	40.0

TABLE 3 TANKER RELEASE PROBABILITIES ($\times 10^{-3}$) IN AN ACCIDENT SITUATION

	High	Medium	Low
Rail			
Chlorine			
Instantaneous	2.19	4.39	3.84
Continuous	27.18*	37.29*	42.61*
	(1.68)	(1.59)	(1.81)
LPG			
Instantaneous	5.80	11.60	10.15
Continuous	2.18	1.20	1.16
Road			
Chlorine			
Instantaneous	2.92	3.65	5.11
Continuous	1.96	1.23	1.39
LPG			
Instantaneous	4.60	5.75	8.05
Continuous	6.50	5.35	6.75

* Includes normal pressure valve venting
() Excludes pressure valve venting

responding hazard area for different classes of damage. The damage propagation relationships used in this analysis are discussed in-depth in IRR (*2*). The IRR model uses a Gaussian expression to estimate the area affected by the dispersal of a heavier-than-air toxic plume for materials such as chlorine. Critical concentration isolines for chlorine were established for different classes of damage and varying environmental conditions. Hazard areas for flammable and explosive substances, such as LPG, were determined on the basis of empirical relationships reported in the literature. Critical damage isolines were established as a function of the proportion of hydrocarbons and TNT equivalents in the material involved. Critical distances from each incident depend on the assumed level of damage associated with each release. In this analysis, two classes of fatality impact have been considered: 50 and 1 percent fatalities. The percentages in these criteria refer to the proportion of people killed within a given critical distance of each incident.

The payload capacity of rail bulk tankers carrying chlorine and LPG was assumed to be 90 and 63.5 tonnes, respectively. Truck tankers are smaller than rail, and were assumed to have a payload capacity of 27 tonnes for chlorine and 18 tonnes for LPG. The actual damages associated with in-transit incidents involving chlorine and LPG depend on the distribution of people and properties in proximity to each incident. To standardize the derivation of *F–N* curves, the population density for the Toronto-Sarnia road and rail corridors in southern Ontario was selected as being representative of general Canadian conditions. Both these corridors were assumed to have a weighted average population density of 600 persons/km^2.

The hazard areas associated with the 50 and 1 percent fatality damage isolines are presented in Tables 4 and 5 for road and rail shipments, respectively. These hazard areas have been estimated both for chlorine and LPG releases. A weighted average fatality rate (deaths per capita of exposed population in the hazard area) was estimated for each hazard area using the following expression:

$$FR = (HA_{1\%} - HA_{50\%}) * KR_{30\%} * SF + HA_{50\%} * KR_{80\%} * SF \qquad (1)$$

where

$HA_{1\%}$, $HA_{50\%}$ = hazard areas for 1 and 50 percent lethality, respectively;

$KR_{30\%}$, $KR_{80\%}$ = average 30 and 80 percent kill rates, respectively;

SF = shield factor for people who are indoors at the time of the incident.

The shield factor in Equation 1 is based on air infiltration rates for typical Canadian houses assuming that 90 percent of the population are indoors at the time of the incident. An in-depth discussion of shielding factor adjustments for dangerous goods incidents is available in Wilson (*6*) for Canadian conditions and in Purdy (*7*) for the United Kingdom. In this analysis, an *SF* value of 0.10 was applied both to road and rail incidents involving chlorine and LPG. This factor assumes that only 10 percent of expected fatalities from the damage propagation models would actually occur, because most people would be indoors during the incident, and hence be shielded from the full impact of the hazard.

The actual numbers of people killed given an incident involving chlorine and LPG can be obtained directly by multiplying each of the fatality rates in Tables 4 and 5 by the corresponding population densities in the vicinity of each spill. Assuming a population density of unity (1 person/km²), the total number of fatalities were estimated for each release type and rate. These values are presented in Tables 4 and 5 on the basis of population density exposed. To obtain the

TABLE 4 HAZARD AREAS AND FATALITIES FOR DIFFERENT RELEASE PROFILES ON ROAD

Material	Type of Release	Hazard Area (Km²) 50% Fatality (800 PPM)	Hazard Area (Km²) 1% Fatality (300 PPM)	Fatalities ** per density exposed
Chlorine	Instantaneous			
	High	1.072	1.112	0.0870
	Medium	0.855	1.059	0.0745
	Low	0.804	0.832	0.0652
	Continuous			
	High	0.650	1.160	0.0673
	Medium	0.043	0.078	0.0045
	Low	0.001	0.002	0.0001
LPG	Instantaneous			
	High	0.07	0.13	0.0021
	Medium	0.07	0.12	0.0021
	Low	0.05	0.09	0.0015

** Population density of 1 pers. per sq. km.

Assumed wind speed 5 KM/H.

Atmospheric stability condition D.

TABLE 5 HAZARD AREAS AND FATALITIES FOR DIFFERENT RELEASE PROFILES ON RAIL

Material	Type of Release	Hazard Area (Km^2) 50% Fatality (800 PPM)	Hazard Area (Km^2) 1% Fatality (300 PPM)	Fatalities ** per density exposed
Chlorine	Instantaneous			
	High	1.282	1.360	0.1049
	Medium	1.202	1.264	0.0980
	Low	1.107	1.158	0.0901
	Continuous			
	High	0.650	1.160	0.0673
	Medium	0.043	0.078	0.0045
	Low	0.001	0.0017	0.0001
LPG	Instantaneous			
	High	0.23	0.41	0.0070
	Medium	0.21	0.37	0.0063
	Low	0.16	0.29	0.0049

** Fatality rates based on a 1 person per sq. km. density within the hazard area.

Assumed wind speed 5Km/H.

Atmospheric stability condition D.

total number of fatalities, these rates are multiplied by the corresponding population density along a given corridor.

F–N CURVES FOR ROAD AND RAIL TRANSPORT OF CHLORINE AND LPG

Release probabilities for different release rates given in Table 3 can be compared with the corresponding fatality rates in Tables 4 and 5 with an assumed population density of 600 persons/km² to yield cumulative *F–N* plots for each mode and type of material. For this analysis, average accident rates were estimated for typical road and rail corridors in Southern Ontario (*2*). These rates are 0.036 accidents per million tonne-km for trucks and 0.0052 accidents per million tonne-km for rail, on the basis of assumed car payloads of 27 tonnes for trucks and 90 tonnes for railcars.

F–N curves can be shifted vertically to reflect changes in the volume of material being shipped and distance covered, or scaled horizontally to reflect changes in population densities and classes of damage. In this analysis, the frequency values on the *F–N* curves have been adjusted to reflect 10,000 rail carloads of chlorine and LPG shipments over a distance of approximately 250 km, or 180 million tonne-km both for rail and road transport.

Discussion of Results

The resultant *F–N* curves for chlorine and LPG (Figures 1 and 2, respectively) are downward sloping. As the number of fatalities (*N*) increases, the cumulative frequency of release

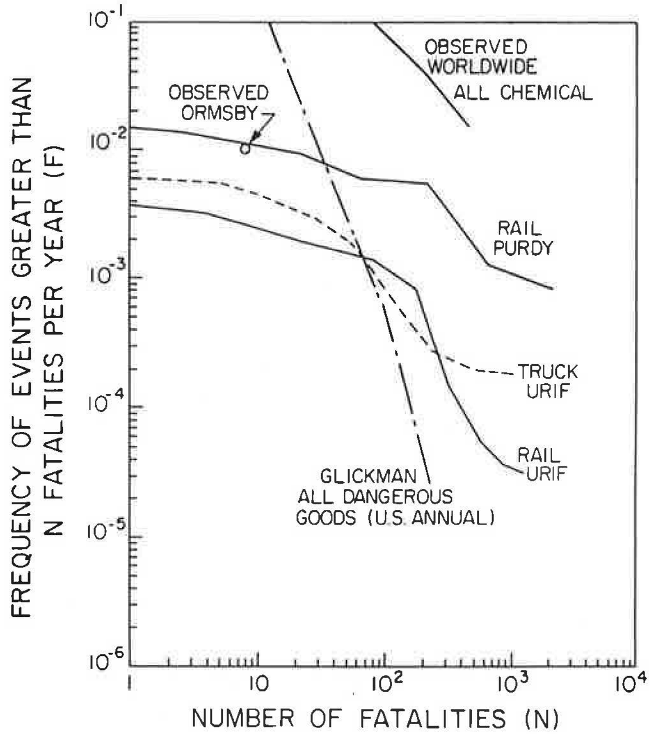

FIGURE 1 **Predicted and observed risks of transporting 180 million tonne-km of chlorine on a typical corridor.**

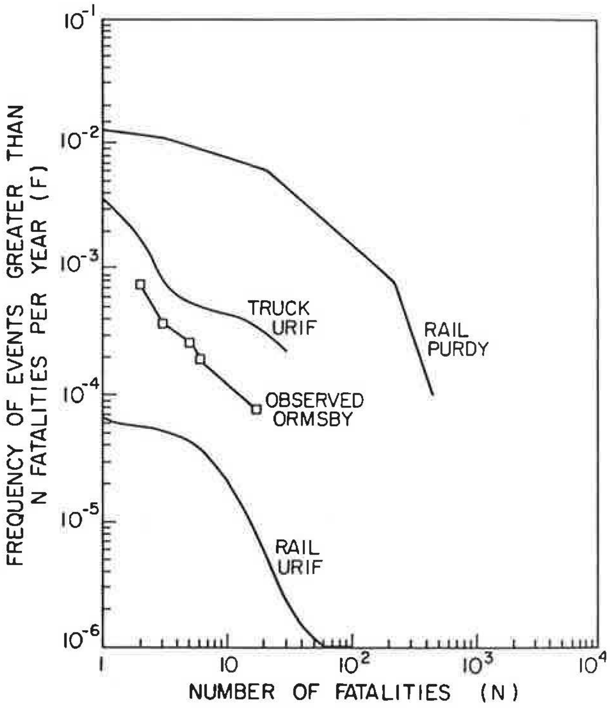

FIGURE 2 **Predicted and observed risks of transporting 180 million tonne-km of LPG on a typical corridor.**

(*F*) required to sustain this damage decreases correspondingly. As expected, given its more confined hazard area for fatalities, the reduction in cumulative frequencies is specially pronounced for LPG both for road and rail transport options. LPG incidents reflect much lower maximum consequence events for the same volume of 180 million tonne-km shipped. LPG incidents reflect a maximum fatality rate of 95 fatalities per incident compared to 3,500 fatalities per incident for chlorine. At the lower range of damages (fewer than 10 fatalities per incident), the frequencies of LPG fatalities are lower than for chlorine incidents, although the difference in these frequencies between the two materials is not as pronounced as at the higher level of damage. This shift in the *F–N* curve to lower levels is specially significant for the rail mode, for which LPG incidents reflect fatality levels that are on average 2.5 orders of magnitude lower than for chlorine.

A comparison of *F–N* curves between road and rail yields some interesting results. Incidents involving chlorine reflect lower frequencies than LPG incidents at the lower fatality range of damage, that is, fewer than 10 fatalities per incident. For higher levels of fatalities, chlorine frequencies are significantly higher than LPG frequencies. This relationship holds true for both modes, but is specially significant for rail given the higher volume shipped on a carload basis.

For chlorine, differences in the *F–N* curves for road and rail transport are not pronounced. Rail transport generally reflects lower levels of risk than road for the *F–N* curves, but the differences are not significant. For LPG shipments, the rail option reflects significantly lower risk levels than road for all levels of fatality damage. As discussed, this comparative analysis of fatality risks between road and rail has been adjusted by the volume-distance of shipment and the density of exposed population to provide for a fair comparison between the two modes. Actual field conditions would reflect significant differences in population densities between typical road and rail corridors, e.g., the Sarnia-Toronto road has a large population density.

Literature Comparisons of *F–N* Curves

Other *F–N* curves reported in the literature have been added to the results shown in Figures 1 and 2. Data were also available from an intercity corridor risk analysis carried out by the Health and Safety Executive in the United Kingdom (*7*). These results have been modified for comparison with Canadian conditions, such that:

	Assumptions	*Health and Safety Executive Inputs*
Chlorine tanker capacity (tonnes)	90	29
Route distance (km)	274	101
Average corridor population density (persons/km^2)	600	300

As shown in Figure 1, the *F–N* curves associated with the analysis of chlorine shipments are in general agreement with the results of the Health and Safety Executive (*7*). For LPG shipments, it was only possible to obtain comparative *F–N* curves for rail. Significant differences between North American and U.K. transport environments occurred even after the adjustments were made. Moreover, the U.K. results are based on a more sophisticated model with better data. Nevertheless, the comparison suggests that the two independent results are similar and representative of the risks involved.

The analysis of chlorine and LPG shipments by road and rail yielded the following expected fatality rates:

Substance	*Rate per million tonne-km*
Rail:	
Chlorine	0.0035
LPG	0.000015
Average rate	0.0018
Road:	
Chlorine	0.0108
LPG	0.00062
Average rate	0.0057

For a total shipment volume of 180 million tonne-km/year on each mode, these rates predict an average of 0.68 fatalities per year, assuming a mix of chlorine and LPG shipments and a 50-50 mode split.

COMPARISON WITH OBSERVED DATA AND TIME INTERVAL ESTIMATION

This section compares the model predictions as represented in the *F–N* curves from Figures 1 and 2 with observed data on dangerous goods incidents and fatalities. *F–N* curves ideally represent the full spectrum of risks involving the transport of dangerous commodities, from high-frequency, low-consequence events to low-frequency, high-consequence events. Observed risks can be extracted from the available data and compared to statistical risks as estimated from the *F–N* curve for each type of dangerous commodity. Furthermore, it is possible through the application of Monte Carlo simulation techniques to obtain expected interval times between consequent events (i.e., fatalities) on the basis of the underlying *F–N* relationship.

Comparisons with Observed Risks Reported in the Literature

An *F–N* curve established by Glickman and Rosenfield (*8*) from observed dangerous goods releases in the United States was compared to the statistical relationship established in this analysis for chlorine. Because the basis of the Glickman and Rosenfield *F–N* curve is observed data for all dangerous goods shipments, it fails to reflect values at the high fatality range of the risk spectrum. These points would represent rare events that would not be included in the current data base. Statistical *F–N* curves, on the other hand, are not subject to the same restriction on the range of consequent damages, because points can be established for events that have not yet taken place. In comparison with the results for chlorine and LPG, the *F–N* curves observed by Glickman and Rosenfield (*8*) for all dangerous commodities tend to overcompensate for frequencies in the low number of fatality range and to undercompensate for frequencies in the high number of fatalities range.

Ormsby and Lee (*9*) compiled data on the transportation of chlorine and LPG in the United States by all modes of transport for the period 1976–1986. For the purpose of comparison, the Ormsby and Lee values were modified to account for the assumed base level of shipment under consideration in this analysis, that is, 180 million tonne-km. The results are shown in Figures 1 and 2 for chlorine and LPG, respectively.

For chlorine, only one observed point was available, and this value appears to be in close agreement with the model estimates and with the values reported by Purdy (*7*). Because this comparison is based on a single observation, it may be subject to further adjustment in frequency depending on the outcome of future events. For example, if with time no further chlorine-related fatalities take place, then the value of the frequency corresponding with this observed point would be reduced. For LPG, a more representative distribution of observed fatalities was available. As shown in Figure 2, the predicted *F–N* curve lies above the observed points for road and below the observed points for rail. Both modes, however, reflect *F–N* values that are close to observed values.

Estimating Interval Times for Fatalities Through Simulation

The basic purpose of this exercise is to estimate interval times between fatalities for incidents involving chlorine and LPG. The *F–N* curves in Figures 1 and 2 can be used to obtain a simulated number of fatalities for road and rail shipments over designated periods of time. This process permits an analysis of risks for incidents whose frequency of occurrence extends beyond the feasible time frame reflected in the available data bases.

The spectrum of cumulative risk probabilities for selected numbers of fatalities are presented in Tables 6 and 7 for rail and road transport of chlorine and LPG, respectively. These cumulative values were obtained directly from the *F–N* relationships in Figures 1 and 2, and are based on an average exposure measure of 180 million tonne-km/year carried by each mode for each commodity type.

Cumulative probabilities for the shipment of dangerous commodities by road and rail provide a target against which randomly sampled probabilities can be mapped. The technique is referred to as Monte Carlo simulation. Random sampling can be used to create a pool of events that are linked to real-time occurrence.

Application of Monte Carlo simulation to the cumulative *F–N* curves for chlorine and LPG yielded interval time periods in years between any designated fatality level. In Canada, total annual shipments of LPG amount to 1,877 million tonne-km by rail and 564 million tonne-km by road (*10*). The risk of fatalities associated with road and rail shipments has been adjusted in this analysis to account for actual LPG volumes for the base value of 180 million tonne-km (Figure 2). For chlorine, the 180 million tonne-km of bulk shipments per year was assigned exclusively to rail.

The results of this analysis suggest one-fatality intervals of 150 years for incidents involving chlorine and 250 years for incidents involving LPG. For more catastrophic events, for example, at-least-50-fatality events, the estimated interval time for chlorine may be as high as 500 years, well beyond the time frame of current data bases anywhere in the world. Plots of the interval time against different release fatalities are provided in Figures 3–6 for chlorine and LPG transport on rail and truck. These estimates of interval times assume a uniform population density of 600 persons/km^2. Because much of the

TABLE 6 *F–N* CURVE CUMULATIVE PROBABILITIES FOR RAIL SHIPMENTS OF CHLORINE AND LPG

Rail Chlorine		Rail LPG	
Fatalities	Cumulative Prob. (10^{-4})	Fatalities	Cumulative Prob. (10^{-5})
10000	0.1	100	0.10
1000	2.6	60	0.10
100	12.3	30	0.23
10	24.6	10	2.00
9	24.6	9	2.30
8	24.6	8	2.80
7	25.1	7	3.20
6	25.5	6	3.70
5	27.0	5	4.10
4	28.0	4	4.70
3	29.5	3	5.00
2	30.5	2	5.40
1	31.4	1	6.40
0	10000.0	0	100000.00

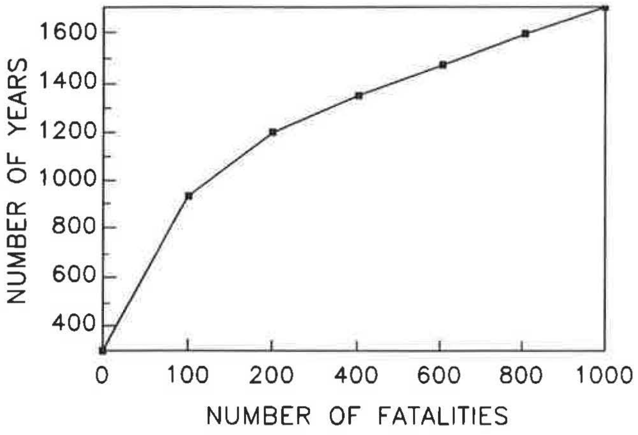

FIGURE 3 Simulated time intervals for fatalities for chlorine transport on rail.

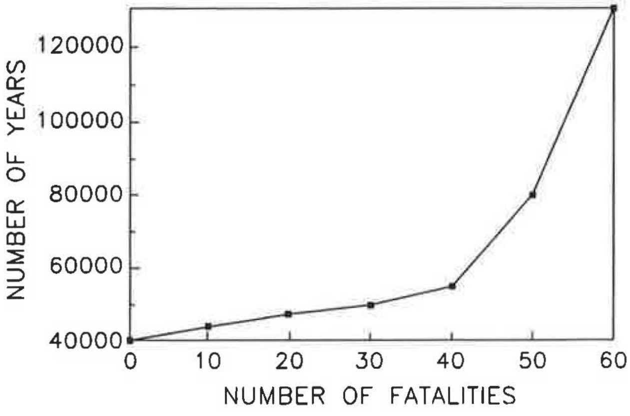

FIGURE 4 Simulated time intervals for fatalities for LPG transport on rail.

TABLE 7 *F–N* CURVE CUMULATIVE PROBABILITIES FOR ROAD SHIPMENTS OF CHLORINE AND LPG

Road Chlorine		Road LPG	
Fatalities	Cumulative Prob. (10^{-4})	Fatalities	Cumulative Prob. (10^{-4})
1000	1.4	30	2.10
500	2.0	20	3.10
100	10.8	10	4.20
50	20.0	9	4.20
10	43.2	8	4.70
9	45.7	7	4.80
8	48.2	6	5.00
7	49.9	5	5.60
6	50.7	4	6.10
5	51.5	3	8.00
4	53.2	2	17.00
3	54.9	1	34.00
2	56.5	0	10000.00
1	58.2		
0	1000.00		

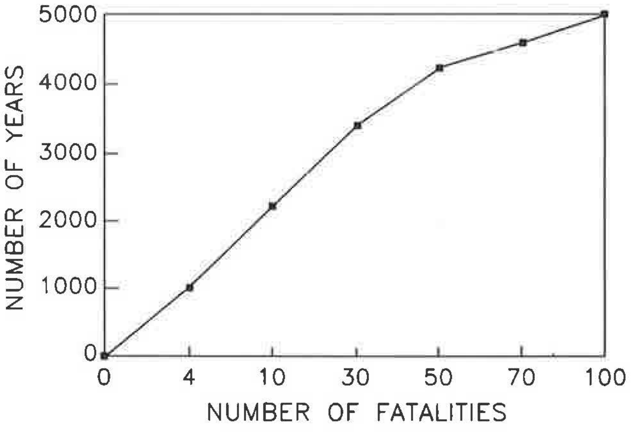

FIGURE 5 Simulated time intervals for fatalities for chlorine transport on road.

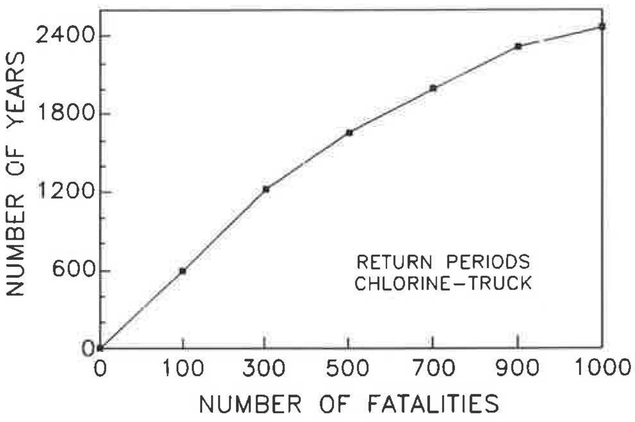

FIGURE 6 Simulated time intervals for fatalities for LPG transport on road.

road and rail network in Canada traverses sparsely populated areas where densities are considerably below assumed values, the interval times for these areas could be several times greater than the values reported here.

DISCUSSION AND CONCLUSIONS

The credibility of current risk analysis models has been questioned as a result of wide discrepancies between predicted and observed risks for incidents involving the transport of dangerous commodities. The two estimates of risk are representative of the same underlying phenomenon. Rather than reflecting a lack of reliability in the risk analysis process, the absence of verification in the data actually reflects the low-frequency, high-consequence nature of the risk spectrum as applied to the transport of dangerous commodities.

High-consequence, low-probability risks are best represented in terms of $F-N$ curves for each shipment situation. The $F-N$ curves obtained from an application of a risk analysis model to the road and rail transport of chlorine and LPG have produced results for actual transportation corridors that are in general agreement with risks reported elsewhere in the literature.

A novel way of looking at risks, essentially the expected time intervals between designated consequences, is presented. These time intervals were obtained by applying Monte Carlo simulation techniques to the $F-N$ curves calibrated for each shipment situation. This approach appears to have special relevance in the communication of statistical risks, because problems of data verification are absent. Risk analysis must be able to communicate the entire risk spectrum. The simple use of expected value, which is common in many risk analysis studies, fails to provide a level of understanding of expected risks that is both comprehensive in its application and supportable by experience.

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DISCUSSION

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This discussion has been prompted by the use in this paper of risk results for the transport of dangerous goods in Britain obtained from published papers. It is suggested that the manner in which the British results have been adjusted to allow them to be compared with those Canadian is invalid. Given the great differences between the risk models used by the authors and the risk models developed for the British studies, conclusions based solely on the risk results are of doubtful value. It is concluded that Figures 1 and 2 of the report do not adequately represent the predicted risks from the transport of chlorine or LPG, respectively, in Britain.

There is growing concern in Europe about the risks to members of the public from the transport of dangerous goods. This concern is leading to increased scrutiny by government regulatory authorities and calls for further controls.

In Britain, the risks from static major hazard installations have been extensively reviewed by an advisory committee who, in their third report (*1*) recognized the growing concern over transportation of hazardous goods and suggested that many of the controls the U.K. Health and Safety Commission had recommended for fixed installations could be applied to transportation. The U.K. Health and Safety Commission responded by setting up a subcommittee comprising nominated experts from industry, trade unions, the emergency services, and independent academics. The author of this discussion is responsible for much of the hazard and risk analysis that will form an important part of the information the committee will use to come to conclusions on the present levels of risk and the need for, and possible nature of, any additional controls. This work was carried out while the author was employed by the Health and Safety Executive (HSE), and later as an independent consultant.

HSE and industry in Britain would wish to have the fullest understanding of the nature of the risk, its magnitude, and major components before reaching any decision for the need for further controls. Great care has been exercised in building the risk models to ensure that

- They realistically represent the consequences and impact of a release on a human population taking into account mitigation and population characteristics;
- They give reasonable, accurate results, are robust, and are not unduly sensitive to simplifying assumptions;
- They are flexible, allowing a realistic range of conditions and circumstances to be represented with easy sensitivity testing; and

- They are transparent, so that the assumptions made and the manner in which the calculations are carried out can be seen and understood by the user of the results.

An important part of the process has been to subject the work to close and searching review, principally by an independent working party, the members of which have made a major contribution to the work. We have also sought external peer review by the publication of a limited number of papers (*2–4*) and by direct contact with other workers such as those at Waterloo University. The full report of this work is likely to be published later this year.

The authors make many valuable points in their paper with which I concur. However, I have a major concern over how they have used risk results drawn from my past papers. The manner they have used and transformed my results and the comparisons they have made do not adequately represent the work that has been carried out in the United Kingdom and could lead others to draw incorrect conclusions about the level of risk from the transportation of dangerous goods in the United Kingdom. The representation on their Figures 1 and 2 is of most concern.

There are two considerations here—first the manner in which they have scaled and shifted the societal risk results for transport on the U.K. system, in U.K. tankers and tank wagons, to represent 180 million tonne-km of chlorine or LPG transported on Canadian systems in Canadian tankers and tank cars. Although the *F–N* curves can, with care, be adjusted vertically to reflect changes in the total mass of material transported, the scaling horizontally to reflect changes in population density, population classes, and size of possible events is not easy, if at all possible, without rebuilding the risk models used to calculate the original results. For example, a 45.1-kg/sec continuous release following the puncture of a 29-tonne rail car will continue for up to 11 min, whereas that from a 90-tonne rail car will last for up to 33 min. As this event contributes significantly to the overall risk levels, you cannot just factor up the results.

We have estimated that if 180 million tonne-km of chlorine or LPG were transported in British rail tank cars on the British rail network, we would obtain risk results some half to one order of magnitude lower for chlorine and one to one and one-half orders of magnitude lower for LPG than the results shown as Rail Purdy on Figures 1 and 2, respectively.

The second and more serious consideration is whether the results from two sets of risk models should be compared in this way at all. We have strived to be realistic and adopt a best estimate approach in building our risk models. We believe that the models being used by the authors of this paper are simpler and may, overall, underestimate the true levels of risk. The difference seems to lie mainly in the areas of consequence and impact modeling. For example, it would seem that for LPG the authors may not include escalation from minor events to a BLEVE (boiling liquid evaporating liquid explosion); we have found that this event, although unlikely, nevertheless makes a major contribution to the risk. In the case of gas cloud dispersion, the Waterloo workers use a simple gaussian model to predict the dispersion of the dense gases chlorine and LPG, whereas we have used more appropriate dense gas models. Gaussian models do not predict the initial slumping and cross-wind spreading that is found with dense gases and as a consequence, will underestimate the area affected and hence the expected number of fatalities. We also feel that simple blanket assumptions on mitigation, such as that all people indoors will survive a chlorine incident, are optimistic and will lead to the risks being underestimated.

All these factors suggest that the comparison of results from such dissimilar studies may be of doubtful value and that great care is needed when drawing conclusions. Unfortunately, results displayed as in Figures 1 and 2 could be taken by others out of context; they suggest that the risks in the United Kingdom from the transport of chlorine and LPG are much higher than in Canada or North America. The historical record does not bear this out.

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AUTHORS' CLOSURE

Purdy's discussion is a welcome addition to the ongoing development of reliable risk analysis models for the transport of hazardous materials. In his commentary, he makes two valid points:

1. Need for great care in building reliable, robust risk models.
2. Difficulties in carrying out an objective comparative analysis of risks using other published sources.

Although we agree with his general premise, we also feel it is useful and instructive to compare results from various studies on the basis of a typical corridor application.

Risk is a complex phenomenon that requires information about a number of constituent events:

- Incident or accident occurrence;
- Failure probabilities in the physical containment system, given a prior incident or accident occurrence;
- Relating release rates and volumes to corresponding failure modes;
- Dispersal relationships and hazard area development for different damage levels; and
- Relationships that reflect the distribution and exposure of targets for various hazard areas (population distribution densities, shielding, evacuation, etc.).

Given the multiplicative nature of risk (probability times consequence), it would be difficult indeed to obtain reliable measures of risk exposure, when any one of these components has not been fully developed.

The Health and Safety Executive (HSE) in the United Kingdom has been instrumental in developing robust consequence and hazard area models for incidents involving selected hazardous materials. We don't wish to get into a detailed technical discussion of the advantages or disadvantages of dense gas versus Gaussian relationships for heavier-than-air gas dispersal. Both relationships have been used by various researchers in the field. The major issue, however, is whether robust development of hazard areas produces in itself robust estimates of risk. It is our contention that it doesn't make much sense to discuss: "How many angels can dance on the head of a pin?" when we are unclear as to the size and shape of the pin head. Despite their focus on the consequence side of risk, we contend that the HSE analysis of risks is based on a more cursory accident-incident analysis. For example, the use of average accidents and release rates from observed data, which fail to account fully for statistical variations in the accident environment, or release probabilities that fail to reflect the mechanistic nature of the tanker containment system, which result in component failures for a given accident situation. The result is risk estimates with significant uncertainties.

Purdy seems to suggest that a focussed analysis of risk consequences yields more accurate estimates of larger risk exposure. Unfortunately, in the absence of a more thorough development of all the constituent components of risk, this assertion may be at best premature.

At the Institute for Risk Research, we have attempted to develop estimates of risk that address these various constituent components. Our work on incident-accident analysis has involved a thorough statistical analysis of route and traffic control factors affecting significant variations in vehicle accident rates (*1–3*). Our analysis of release failure was based on some initial fault tree structures developed by Battelle Laboratories in the early 1980s. These fault trees were modified and specified for the Canadian experience to yield conditional release probabilities for different tanker components in an accident situation (*3–5*). Our dispersal models do not involve the level of detail carried out at the HSE. When uncertainties in the rest of the risk formulation are considered, our analysis does produce estimates of risk that are useful for the purpose of comparison.

Purdy notes that much of the work at the HSE has been overseen by a panel of advisors and experts. We feel that given the controversial and sometimes subjective nature of this type of work, such checking and validation is critical to the exercise. Failure to carry out these checks would be irresponsible, and this underscores the need to publish results as they become available. In our own work, we have frequently drawn on results and advice from the HSE as well as others working in this field.

To make the comparison more meaningful from our Canadian corridor perspective, the HSE results were adjusted as indicated in the paper. We concur with the argument that a more detailed modeling exercise would produce different results for the United Kingdom. Purdy suggests that the risks for LPG might be 1½ orders of magnitude lower and for chlorine 1 order of magnitude lower than the *F–N* curves reported in our paper. It should be noted, however, that this would not invalidate the results of the comparison, mainly that the predicted risks from our analysis are in the correct order of magnitude both in relation to observed data and the HSE model estimates.

The basic purpose of our paper was to address the issue of risk measurement, *F–N* curves versus the more common measure of expectation. We wanted to demonstrate how a more complete representation of risks in terms of *F–N* curves can produce time interval estimates between consequent events that are much larger than measures of normal life expectancy. The problem is the very low frequency, very high consequence, nature of risks associated with the transport of hazardous materials. Purdy's results were included to indicate the general band of risk estimates from various sources. It was not our intention to suggest that our estimates were better or worse than Purdy's values, but to show that some discrepancies exist, and these discrepancies need to be addressed in future work. Given the complex nature of risk estimation, however, the differences were not very large.

We feel one aspect of this debate is important. This aspect relates to the need to compare work undertaken by various researchers using different sources of data and methodologies. Such comparison can be undertaken adjusting for underlying assumptions in the original work. We do not share Purdy's assertion that one cannot adjust *F–N* curves horizontally to reflect changes in population distributions or densities, as we feel that making comparisons between predictions is an essential element in gaining confidence in the results. We agree that such comparisons should be undertaken considering the full range of prediction errors. Given the level of development in recent years on risk modeling for the transport of hazardous materials, the time may be opportune to bring these studies together in some comparative format. Given the focus of our paper, it would be highly premature to suggest that we have carried out such a comparative analysis. Accordingly, we don't feel that our results should prejudice Purdy's future report in any way.

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Developing an Impact Analysis System for the Transport of High-Level Nuclear Waste

MARK D. ABKOWITZ, MOSES KARAKOUZIAN, AND JAMES A. CARDLE

The question of when and where to build a permanent repository for storing high-level nuclear waste has created considerable interest in assessing the impacts associated with transporting these wastes from their generation site to the repository. Inherent issues are addressed for design of a comprehensive transportation impact analysis system and for the practical aspects of implementing the system in support of policy analysis. The focus of discussion is the current development of a transportation management information and analysis system (TMIAS) for the state of Nevada. Issues related to methodological approach, impact definition, system analysis capability, data requirements, transportation policy alternatives, system interaction, and development schedule are described. Because of the complex nature of high-level nuclear waste shipments, the discussion provided should be transferable to analyses of other hazardous materials shipments and more traditional transportation applications because these scenarios are likely to focus on a subset of the issues presented.

The disposal of high-level nuclear waste entails a continuing debate over when and where to build a permanent repository. Yucca Mountain, Nevada, has been selected by the U.S. Department of Energy (DOE) for site characterization. This choice has generated considerable concern on the part both of Nevada state officials and officials of potential corridor states concerning the impacts of transport operations to the repository site.

The objective is to identify system elements and interrelationships in building a comprehensive impact analysis system to evaluate these effects. The focus of the discussion is the design of a transportation management information and analysis system (TMIAS) for the state of Nevada for addressing high-level nuclear waste transport. The decision to implement TMIAS has been identified as an essential and immediate need for the state government in its evaluation of alternative transportation plans for shipping high-level nuclear waste to Yucca Mountain.

An operational impact analysis system for high-level nuclear waste transport in Nevada is predicated on development and implementation of a system by which a multitude of transport policy alternatives involving high-level nuclear waste shipments can be represented and analyzed. Issues related to high-level nuclear waste transportation will be examined and their consequences understood to support Nevada's position with respect to the DOE transportation planning process.

Important issues are discussed related to TMIAS development and implementation. This discussion includes methodological approach, definition of impacts, analysis capabilities, data requirements, transportation policy alternatives, and system interaction.

METHODOLOGICAL APPROACH

Identification and quantification of impacts involving high-level nuclear waste shipments require in-depth studies that describe the current or anticipated state or condition of many transportation-related elements, including

- Transportation infrastructure and use in the state of Nevada,
- Transportation regulation and inspection programs affecting the state of Nevada, i.e., federal, state, and local,
- Characteristics of the population and environment adjacent to the transportation corridor,
- Emergency preparedness capabilities within the state of Nevada,
- Shipment characteristics and routes of transport under consideration, and
- Plans for DOE waste shipment schedules and transportation operating procedures.

Impact analysis must begin with an initial (baseline) characterization of the current transportation system to create a reference point for evaluating repository transport policy alternatives and to establish model validity. The analysis of impacts and the effectiveness of impact minimization policies and actions can subsequently be investigated by altering existing parameters—routes, modes, road and rail quality, emergency preparedness capabilities, etc. For each set of parameters, the impacts to the welfare of Nevada (e.g., mortality, morbidity, and economic) can be surmised. The results, when compared to baseline conditions, isolate the impacts associated with locating a repository at Yucca Mountain.

Converting this conceptual approach into a tractable mathematical framework involves the use of sizeable amounts of data and mathematical formulations. Data bases are needed that describe the transportation system and system use, the population around each transport segment, and the geo-

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graphic characteristics of the area through which each segment passes. The problem must also address both highway and rail shipments of nuclear waste and the unique operating characteristics of each mode. Also, flexibility must be established to support independent studies of statewide versus national issues.

A transportation impact analysis system at the most fundamental level must consist of four basic components—definition of the transport policy alternatives under consideration; collection, translation, and management of essential data (i.e., data base management); application of models that accept data inputs and perform problem solving; and display and evaluation of forecasted impacts associated with the specified transport policy alternative. The schematic in Figure 1 shows a generalized approach to transportation impact analysis that has been selected for the Nevada development effort.

The process begins with definition of transport policy alternatives under potential consideration. Each DOE option under current or future consideration must be captured in such a way that TMIAS can predict its impacts. Consequently, capability and flexibility must be provided to represent the multitude of shipment and operational characteristics that could be included in a policy under examination.

Data collection, translation, and data base management refer to the broad category of gathering relevant information and managing its use in impact analysis. Some data collection involves gathering source data directly from agencies that maintain this information. For example, the transport network and segment attributes of distance, geometrics, travel usage, accident history, etc., would be considered source data because these data can be collected directly from such organizations as the Nevada Department of Transportation.

Other information needed to support policy definition and impact analysis must be generated from source data. For example, source data on residential and employment population are needed to create measures of impacted population residing within specified distances of a transport segment. Similarly, radiological risk attributes are typically created from source information that includes shipment characteristics and elements of the transport network. Models that accept source data and create generated data are referred to in Figure 1 as "generating models." Source data and generated data constitute the full set of inputs required to define a particular transportation policy alternative and to prepare pertinent information for analysis use.

Formal analysis (or problem solving) is performed using algorithmic models. These models must have the capability to accept large quantities of information and use efficient solution methods. In general, the algorithms are designed to operate on large-scale networks in which transportation problems are traditionally defined, and perform such functions as optimization, simulation, and evaluation. The algorithms are often mathematically complex and are typically developed by individuals with a strong background in the field of operations research.

When the problem-solving process is complete, several measures associated with the forecasted outcome are compiled. These measures are subsequently used to generate impacts for the policy alternative under study. An example of one element in this process might be the derivation of economic impacts. A measure traced through the solution process might be shipment-miles, which, in turn, could be used to generate transport operating costs. Impacts are typically presented in the form of a summary table to enable overall comparisons to be made. Segment-specific impacts can also be generated in support of more localized analysis.

Clearly, many potential impacts and impact variables must be accounted for in structuring an effective system design. Some impacts, particularly nontravel-related economic impacts, are difficult to represent in a transportation modeling envi-

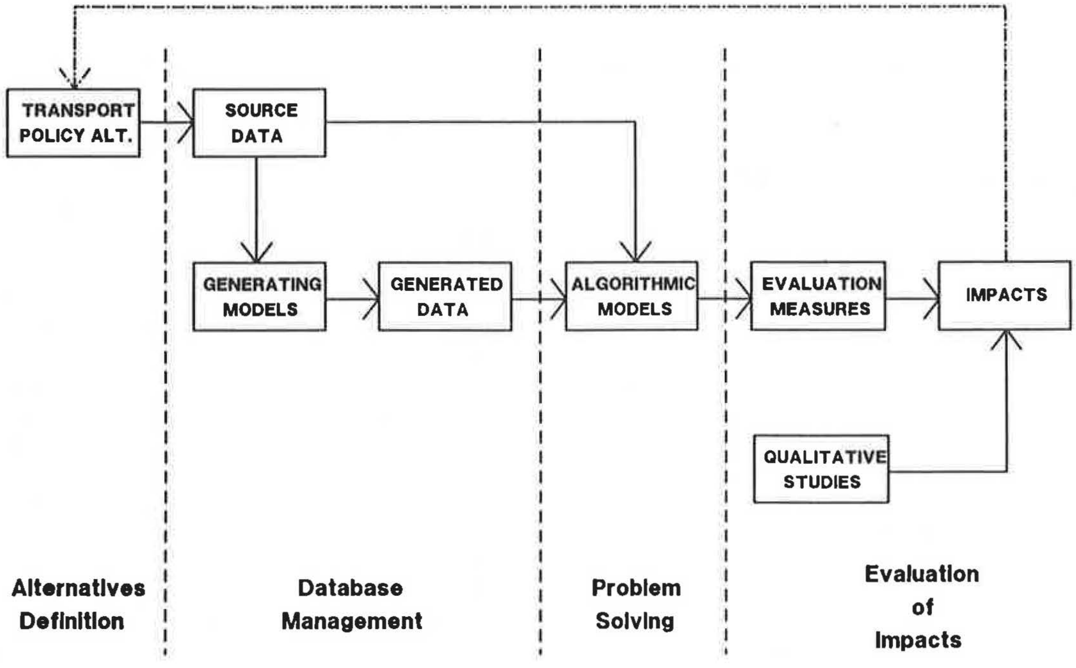

FIGURE 1 Generalized approach to impact analysis.

ronment. The administration of surveys may be a more effective course of action to characterize these impacts. The portion of the schematic shown in Figure 1 referred to as "qualitative studies" is designed with the intent of providing support for this type of impact measurement.

Figure 1 also displays a dashed line connecting impacts at the end of the analysis cycle back to transportation policy alternatives at the beginning of the process. The recursive nature of this connection is included to show that often the results of a particular impact analysis may suggest modifications to the initial policy that warrant the conduct of a subsequent impact analysis. For example, evaluation of a specific alternative may indicate that infrastructure problems are evident in certain locations. A subsequent alternative could also be defined that includes provisions for infrastructure improvements, and a need to forecast the economic and safety impacts of the new alternative.

From prior review of transportation issues related to the movement of high-level nuclear waste and an awareness of previous impact modeling efforts that have been undertaken in the field of transportation, it is apparent that the state of Nevada must adopt a systems approach to impact analysis that is built around a transportation network model orientation. By capitalizing on recent advances in geographic information system (GIS) technology, availability of Nevada data bases, integration of existing data and models, new model development, and state-of-the-art display graphics and user-friendly menu operation, Nevada has the opportunity to forge a pioneering effort that will exceed any current capability elsewhere in addressing nuclear waste transport impact analysis. With TMIAS in place, however, this system can also prove to be extremely useful for managing a multitude of other everyday transportation concerns within the state, such as road and bridge repair, traffic management, regulation of other hazardous materials shipments, and emergency response planning.

In discussing issues related to impact analysis, it is often useful to follow a backwards logic approach through the analysis process so that it is understood what system components are needed and how they interact to address the impacts of interest.

TRANSPORTATION IMPACTS AND ASSOCIATED MEASURES

The full range of potential transportation impacts associated with locating a repository at Yucca Mountain can be generally classified into two basic categories—safety and economic. Each of these categories includes a number of more detailed considerations as explained in the following subsections.

Safety Impacts

Safety impacts include both nonradiological and radiological impacts for normal transportation and from accidents (see Figure 2).

Impact Type Scenario	Radiological	Non-Radiological
Accident	✓	✓
Non-Accident	✓	

FIGURE 2 Relevant safety impacts considered in TMIAS.

Radiological impacts result from occurrences where there is a release of radiological materials. One such occurrence can take place during nonaccident (incident-free) transport during which some radiation is emitted through spent fuel casks. The rate of material emitted, its dispersion pattern and toxic effects, and local demographics are among the many variables that affect the overall radiological impact of this type of occurrence.

Situations in which a vehicular accident or incident causes a container failure and subsequent radioactive release have the potential for causing more serious harm to the population and the environment. In these instances, large quantities of nuclear material may release, causing more concentrated and widespread exposure. The radiological effects from such an occurrence will be related to factors that include the rate of release, shipment size, dispersion characteristics, toxic effects of the material, local demographics, and the response times and capabilities of emergency management personnel.

Radiological impacts are formally created in the modeling process by estimating radiation exposure and predicting the consequences in terms of death (mortality) and injury or illness (morbidity). Although some impacts are immediately apparent, long-term health effects can be subtle in their onset and ghastly in their result and are the subject of great public concern. Death and injury also take on different social and economic value because of heightened public concern about nuclear waste shipments and the long-term suffering associated with radiation exposure. A nuclear waste release is thought to be a low-probability, high-consequence event that is of great concern to the public. Risk estimation methodology must be carefully structured to permit a thorough, unbiased analysis of these potential effects.

Nonradiological impacts are considered those caused by the forces of the accident itself and typically consist of injury and death to vehicle occupants or people in the vicinity of the transport segment (e.g., pedestrians), damage to the vehicle and cargo, and other property damage caused by the vehicle involved in the accident. It can be argued that these impacts are reflective of the size and weight of the vehicle and not the material being carried. However, in studying these impacts, the volume and weight of the proposed nuclear waste shipments should be taken into account as well as the likelihood of increased accident frequency caused by growth of repository-related transportation.

There may be some nonaccident, nonradiological safety impacts associated with repository transportation, such as additional air and noise pollution generated by increased truck and rail activity. However, in relative terms, these impacts are considered of diminished importance, and have not been explicitly treated as a safety impact in TMIAS.

Economic Impacts

Economic impacts associated with nuclear waste transport involve capital and operating costs to use and maintain the transportation system infrastructure. These impacts are felt directly and indirectly. Direct costs include the cost of maintenance and improvements to the road and rail infrastructure to ensure safe passage, as well as expenditures for transportation services associated with using the transportation network such as operating costs tied to shipment-miles, ton-miles, cask-days, etc. Direct economic impacts are also associated with the costs of developing and implementing regulatory policy, inspection and enforcement, and emergency response (including clean-up) programs.

Indirect economic impacts include traffic congestion and delay associated with daily traffic patterns of the general population caused by increased transport activity, as well as traffic disruption or rerouting because of increased accidents. Although travel-related impacts may be considered relatively benign, they influence a broader constituency in the state; and several minutes' delay to each affected individual, multiplied by all affected parties, can represent a considerable productivity loss.

Additional indirect impacts include both positive and negative effects on the perception of the state and individual communities as desirable residential, business, and tourist attractions. Property values, particularly along designated transport routes; effects on tourism and business relocation; impacts on production in other sectors of the economy; insurance costs; secondary purchases generated by nuclear waste shipments, such as in the service economy; effects on noise and air quality; and potential improvements to emergency preparedness would all be considered indirect economic impacts.

ANALYSIS NEEDS AND MODEL DEVELOPMENT

TMIAS must have the capability to perform certain analysis functions that typify the policy issues that might be considered by DOE as related to repository transportation. In this section, each major functional capability is identified and described, including special features that could be made inherent to the TMIAS structure to accommodate specific analysis restrictions that might accompany certain policy alternatives.

Analysis Capability

Five major functions have been identified that would be highly desirable for TMIAS to perform for analysis capability.

- Route optimization (preferred route selection),
- Evaluation of a predefined route,
- Stochastic simulation of a nuclear waste incident,
- Prescribed simulation of a nuclear waste incident, and
- General management information system (MIS) functions.

These functions are explained in the following discussion.

Route optimization involves identification of the preferred (best) route for transporting nuclear waste according to the user's selection of appropriate decision criteria (e.g., risk and cost), the importance the user associates with each criterion, and the user's risk preferences (i.e., risk-averse, risk-neutral, or risk-prone). These three factors define, in optimization terms, what is known as the objective function. These factors are emphasized because the selection of a preferred route is highly sensitive to the criteria applied, and DOE may advocate a particular routing strategy that is based on applying different criteria than what the state of Nevada may feel is justified. Thus, the model must be capable of predicting the consequences of such varying assumptions. In route optimization, the preferred route is found by searching across any number of candidate routes to find the optimal (or preferred) solution.

The evaluation of a predefined route is a variant of route optimization. There is a desire to evaluate a specific route, regardless of whether it might emerge as a preferred route, under certain operating assumptions. The need to do so arises in cases for which shipments are planned for, or are currently being made, on a designated route; and there is an interest in comparing the impacts of moving nuclear waste on a designated route versus transporting it on an optimal route as defined by an objective function. The application would likely be used in situations where the state would want to compare the impacts of DOE-recommended routes with those based on Nevada's routing criteria.

The ability to simulate a nuclear waste incident is desirable for understanding the consequences of events should an incident occur somewhere in Nevada. This ability would have important implications both in terms of evaluating the magnitude of morbidity and mortality that could occur, and for the development and implementation of emergency preparedness programs (relative to the siting of response units and level of capability desired).

Two different types of simulation activities are envisioned—stochastic and prescribed. A stochastic simulation recognizes that there is a distribution of incident severity depending on the type of event that might occur. Consequently, because of uncertainty involved in incident severity and consequence, a probabilistic approach is taken. The simulated event is based on a sampling from a distribution of possible incident scenarios to arrive at a generalized or expected risk impact. A prescribed simulation is one for which the user defines the event parameters as an input, and the simulation forecasts the impacts in a deterministic rather than probabilistic fashion. The outcome is specific to the defined incident and not to the likelihood that such an event could occur.

The state could benefit from the availability of both functions. The prescribed simulation is clearly necessary when the impacts of a particular type of event must be known, such as a worst case scenario. The stochastic simulation can be used as an important input in defining risk for different transport segments as an attribute in determining preferred routing.

The final area, general MIS functions, refers to the ability to access a rather substantial data base that is necessary to support TMIAS. This information can be used separately from impact analysis to generate reports and file management documents as a decision support function to several agencies in the state. For example, reports on pavement condition ratings for each highway segment in Nevada could be used by the Department of Transportation to schedule preventive maintenance activities. Similarly, traffic congestion levels at various times of the day could be generated to examine potential delays in areas of high growth.

The functions described should not be misconstrued as the only ones that are important. All other analysis requirements can also be handled within this structure.

Special Features

Within the model structure, two special features have been identified that can significantly enhance the flexibility and sophistication of impact analysis.

The first, link and node inclusion or exclusion, refers to the ability to require a shipment to pass along a given transport segment or through a particular junction, or, conversely, to avoid a segment or junction. There are several situations for which either inclusion or exclusion requirements may apply. Inclusion applies in the cases in which shipments are required to use a particular route when passing through a community because of local ordinance, to access a safe haven, or perhaps to stay within the range of qualified emergency response personnel. Examples of exclusion include situations in which a shipment must avoid routes near an environmentally sensitive area (e.g., a heavy population concentration, or location of schools, hospitals, or water supplies), or where routing ordinances prohibit such use. Exclusion can also be applied for interim periods of time where construction activities on a transport segment temporarily remove certain segments from routing consideration.

The other special feature, referred to as "hot spot" identification, allows the user to specify threshold values for characteristics of transport segments, that if exceeded, could result either in identification of these sites for further analysis consideration (e.g., as high-risk locations) or the exclusion of these segments from subsequent routing consideration. Hot spot identification can be used in routing impact analysis or for MIS functions in which certain outliers such as roads with adjacent population densities exceeding some value can be identified.

DATA REQUIREMENTS AND DATA MANIPULATION CAPABILITIES

The information required to support TMIAS capabilities can be classified into the following categories:

- Transportation network,
- Social and demographic factors, and
- Other geographical considerations.

Each of these categories is described separately in the following discussion. In terms of system connectivity, social and demographic factors and other geographical considerations become part of the transportation network definition for reasons that will become clearer as the discussion proceeds.

Transportation Network

Transportation network considerations consist of physical dimensions and geometrics of the transportation system and associated utilization. For TMIAS, highway and rail networks must be characterized. The following highway link or node attributes are resident in the system with editing capability provided:

- Physical coordinates;
- Distance;
- Average annual daily traffic (AADT), by truck and time-of-day, if possible;
- Functional classification;
- Number of lanes;
- Surface type and condition;
- Lane and shoulder widths;
- Bridge and tunnel clearances;
- Accident rate;
- Median type;
- Temporary restrictions (because of construction, weather, etc.);
- Rest areas;
- Curvatures and grades;
- Passing lanes and sight distances;
- Operating speed and stop times;
- Regulatory restrictions; and
- Number of at-grade crossings (controlled and uncontrolled).

The following rail link or node attributes are resident in the system with editing capability provided:

- Physical coordinates,
- Distance,
- Accident rate,
- Track condition,
- Track class,
- Bridge and tunnel clearances,
- Track density,
- Number of tracks and sidings,
- Ownership,
- Yards and transfer points,
- Temporary restrictions,
- Operating speed and stop times,
- Number of at-grade crossings (controlled and uncontrolled),
- Curvatures and grades, and
- Sight distances.

Highway Network

Each highway link (segment) and node (intersection) must be defined by physical coordinates. The most appropriate convention is the use of latitude and longitude, which can be integrated with other geographical information that typically uses latitude and longitude mapping convention.

Highway geometric information should include the physical distance of the segment—number of lanes, lane width, passing lanes and sight distances, location of rest areas, presence of shoulders and medians, surface type, curvature and grade, and whether the segment includes a major bridge or tunnel (along with clearance considerations). The geometric characteristics are important in defining each segment in terms of permissible traffic. For example, certain shipments may be restricted from passage on roads without a sufficient lane width. Geometric characteristics are also used to classify roads into categories for subsequent analysis (e.g., accident severity may vary by median type).

Information on highway use corresponds to the movement of traffic across the road facility and the quality of service provided. One of the key characteristics, AADT, identifies the amount of traffic that typically uses the roadway being studied. AADT can be used as an indicator of congestion by relating traffic volumes to the road's design capacity. Congestion has a direct effect on operating speeds and stop times. The extent to which the information can be disaggregated by vehicle type and time-of-day will determine the precision with which truck shipments can be evaluated in the model. Accident rate is also an important use measure and truck accident rates are preferred to general vehicular accident rates. Functional classification corresponds to road location and its function in the overall road system (e.g., as rural feeder or urban Interstate). This classification is helpful in determining how future travel patterns distribute onto the roadway collection, line-haul, and distribution network. Surface condition is a measure of the quality of the road and relates to safety as well as economic considerations concerning roadway maintenance and infrastructure improvement. Finally, the presence of regulatory and temporary restrictions may affect routing decisions during an interim period of time.

Rail Network

The rail system is characterized similarly to the highway system. However, different features are pertinent to rail operations and rail node definition takes on greater significance. Rail network considerations also consist of geometrics and use. Track class parallels functional classification on the roadway system, while track density is similar to AADT for roads.

Unique features of rail networks include track ownership, yard and transfer points, and the presence of sidings. Track ownership can be an important issue because most railroads often try to maximize the use of track that they own. Consequently, the tradeoffs between operating strategy and what is preferred from a systemwide standpoint must be understood. Yard and transfer points are node characteristics that are important in determining where delays and incidents can occur because of rerouting trains and where legitimate transfers between railroads can take place. Finally, siding location identifies points where trains can pull off the main line either to permit another train to pass or as a resting place.

Social and Demographic Factors

Interactions between the transport facility, adjacent land use, and environment are classified as social and demographic factors. These factors include (a) residential and employment population within varying distances of the transport segment, (b) response time from the nearest first (and ultimate) responder and associated response capability, and (c) distance to schools, hospitals, water supplies, and other ecologically sensitive areas.

Knowledge of the location of the residential and employment populations relative to the transport facility determines the impacted population at varying times of the day who are exposed to accident and nonaccident radiological risk. The distance from the transport segment has implications on the level of exposure depending on the release quantity and rate.

The response time from the nearest response unit and the ultimate response capability is an indication of how quickly an incident can be reacted to and controlled should one occur at a given point in the Nevada transportation system. An important distinction must be made between first response, on-scene arrival, and ultimate response (the capability to control the release). Both responses are important. However, first response is directed more at responding to the immediate consequences of the incident, whereas ultimate response focuses on containing the source of the problem.

Proximity of schools, hospitals, water supplies, and other sensitive areas identifies the presence of sensitive locations and their impact distance from the transport facility. This may prove particularly important in the determination of routing criteria as well as in the development of emergency preparedness and evacuation planning.

Social and demographic factors will be generated from GIS data describing the surrounding land use, and this information will be overlaid on the transportation physical coordinates, allowing appropriate measures for each transport segment to be derived by using geometry and other mathematical computations. The considerations, in essence, are derived by computer and are subsequently appended to the transportation network data base.

Other Geographical Considerations

Other geographical considerations can be instrumental for modeling capability as TMIAS is expanded. Information on weather, topography, and geology, which are all available through a GIS, could also be overlaid on the transportation and social and demographic systems to permit a more precise assessment of radiological impacts, particularly in an accident release scenario. Important weather considerations include wind direction, wind speed, and temperature. Weather considerations help determine release dispersion as well as the likelihood of cloud cover that might shield radiation effects. Topography adjacent to the transport facility constitutes an important factor in dispersion. Geological characterization of the surrounding country also has important implications on ground and surface water transport should a release occur.

It is expected that measures of social and demographic considerations would be derived from GIS data and appended to the transportation network as segment level descriptors.

TRANSPORTATION POLICY ALTERNATIVES

A multitude of transportation policy alternatives must be considered to represent current and anticipated plans that DOE may investigate. Generally, any such policy would comprise two sets of features—shipment characteristics that specify the scale of spent fuel movement, vehicle configuration, timing, etc.; and operation considerations that indicate manpower needs, presence of escorts, legal and regulatory issues, etc. Legal and regulatory issues impact the system by constraining the feasibility of alternative transportation policies. However, the results of impact analysis can also create a two-way interaction that leads to consideration of future modifications to the existing institutional environment.

The following discussion outlines the more important elements to consider in TMIAS to ensure that adequate capability is provided for characterizing specific transportation policy alternatives.

Shipment Characteristics

Shipment characteristics describe the spent fuel program to be defined for impact analysis. Because there are so many assumptions that can be considered, and given that DOE is constantly modifying the types of scenarios being contemplated, the TMIAS design calls for characteristics to be defined by the user each time a new impact analysis is desired. This process permits the model to select a preferred or optimal route for each shipment scenario and creates an opportunity to compare preferred routes under different scenarios in order to identify the preferred scenario. Therefore, cask size, modal mix, and other operating issues can be explicitly addressed by the model.

The shipment characteristics proposed for TMIAS inclusion at this time, which are defined by the user for each point of entry, are the following:

- Beginning of repository operation;
- Mode and vehicle configuration;
- Cask type, shielding, and capacity;
- Casks per shipment;
- Number of shipments;
- Shipment time-of-day; and
- Spent fuel type (PWR or BWR), consolidation, and age.

Because shipments may be entering the state from several points that may vary for each DOE scenario (including whether monitored retrievable storage facilities exist), it is expected that information will be identified separately by point of entry. The beginning date of repository operation identifies how far in the future to project growth conditions in Nevada in forming a prerepository base case for comparative analysis of repository transportation impacts. Modal mix and vehicle configuration refer to the level of rail and highway use as well as the type of truck (e.g., overweight or convoy) or train (e.g., unit or special) under consideration. The cask type, shielding, and capacity are important in establishing release probabilities and maximum release amount in order to characterize accident and nonaccident radiological risks. The number of casks per shipment and total number of shipments define the magnitude of individual and collective movements at each point of entry. Spent fuel type, consolidation, and age also help assess the dangers associated with a release should one occur. The time-of-day when shipments enter the state can be used to set a clock that triggers time-of-day modeling as the shipment travels within Nevada until it reaches the repository site.

Operations

Operations are an extension of shipment characteristics because they define special provisions that are associated with the shipment once movement within the state begins. The presence of (a) escorts, (b) physical protection, (c) shipment tracking system being used, (d) number of drivers and workers assigned to the shipments, (e) in-transit inspection and enforcement programs, and (f) legal and regulatory matters including future ordinances would all be considered members of this group. As for shipment characteristics, the user is expected to define these conditions as model inputs before executing the analysis.

SYSTEM INTERACTION

In previous sections, individual system components have been identified and their role in the analysis approach has been defined. This section focuses on the activities required to integrate these components into a single, functioning modeling system. The logic embedded in the integration process involves the tracing of independent pieces of information through a four-step process from policy alternative definition to impact evaluation.

The previous discussion identified several modeling features and information needs that must be addressed and represented in a comprehensive transportation impact analysis methodology for Nevada. Figure 3 shows the modeling process envisioned to meet project objectives. Care has been taken to distinguish those steps in the process that are user defined from those that are derived by computer. User-defined steps permit the user to modify input values to represent alternative scenarios under consideration. However, the user need not enter the entire file of information manually. Rather, a data base can be maintained resident to the system that the user may edit, as appropriate.

Three primary inputs support the analysis environment: (a) the transport network and its related attributes, (b) shipment characteristics to describe shipment options, and (c) operational considerations. The transportation network data base is shown in its expanded form once social, demographic, and other pertinent geographic attributes have been generated and appended to the network data base.

These three components support the functional capabilities previously described, namely, routing analysis, event simulation, and MIS applications. For routing analysis, if optimization is selected, the user must also be queried to supply the explicit criteria under consideration, weights to be assigned to each criteria, and the risk preference (e.g., risk-averse) assumptions that should apply. In the case of event simulation, when a stochastic analysis is selected, a release distribution must be specified. However, this requirement could be contained in a resident data base that is accessed during the analysis. MIS applications are expected to emanate principally from the information contained in the expanded transportation network data base and may take the form of several different standard reports that focus on the extraction and sorting of resident information to support various functions carried out by Nevada state agencies.

When routing analysis is performed, it is expected that accident nonradiological, nonaccident radiological, accident radiological, and economic impacts will be experienced. In the case of event simulation, the emphasis is on release impacts. Consequently, only accident effects, both radiological and nonradiological, can be expected. In some instances, translation tables must be developed as an intermediate step in

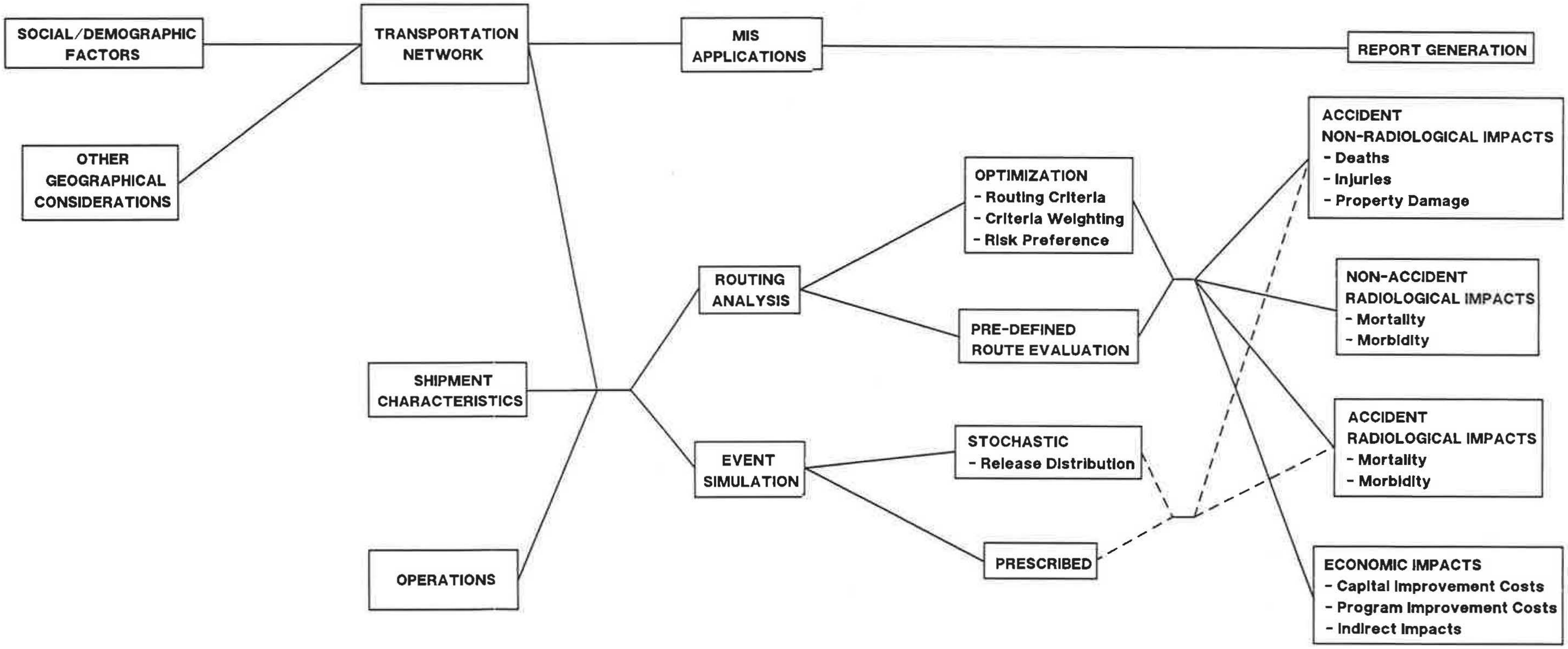

FIGURE 3 Schematic of TMIAS design specification.

converting analysis outputs into impact measures. Such would be the case with shipment duration, distance, and typical analysis outputs that need to be linked to economic formulas to provide measures of shipment cost (economic impacts).

SYSTEM DEVELOPMENT SCHEDULE

A number of desirable features to be contained within TMIAS have been identified. To accomplish these objectives, an ambitious, time-staged development schedule has been implemented that partitions TMIAS into divisible tasks and establishes the priority among tasks. A guiding principle in this effort is the requirement to build a first-generation impact analysis model and use it for preliminary impact analysis within the coming year.

Implementation of TMIAS involves the development of a comprehensive impact analysis system that captures all of the issues raised in this system design specification. These activities will involve the integration of existing works (one–five), whereas others will focus on new methodological development that may require source data collection efforts.

The development schedule for full-scale TMIAS capability is envisioned as a 3- to 5-year effort due to the sophistication of certain modeling elements. It is also expected that as policymakers become more familiar with TMIAS capabilities from their use of the first-generation model and subsequent iterations, needs will arise that require model enhancements for future transport applications, both nuclear and nonnuclear in nature.

CONCLUSION

Analyzing the transport of high-level nuclear waste requires a comprehensive approach that encompasses many facets of the transport operation and a wide range of associated impacts that can potentially arise. Design issues inherent in developing a system and practical aspects of implementing the system in support of policy analysis were addressed. Because of the complex nature of high-level nuclear waste shipments, the discussion should be transferable to other hazardous materials shipments and more traditional transportation applications, as these scenarios are likely to focus on a subset of the issues presented.

ACKNOWLEDGMENT

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Improved Delivery of Airport Emergency Services

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A new methodology to improve delivery of emergency airport services is described. Important goals of airport response planning are to simultaneously maximize mobility and payload, and minimize arrival time. The Waterways Experiment Station of the U.S. Army Corps of Engineers has developed the Army Mobility Model and Transportation Model. These models were adapted for use at airports by the U.S. Department of Transportation, Research and Special Programs Administration, Transportation Systems Center. A case study was performed that demonstrates that the airport-specific methodology can be used to assess and improve delivery of emergency services. Combining the two models with airport-specific geography creates a situation in which it is possible to quickly investigate travel time sensitivity to changes in factors such as weight, gear ratio, or tire pressure. This experience indicates that properly applied geographic colocation can lead to integration of transportation models with models from other fields.

The time to develop and implement an emergency plan is long before an incident occurs. As Figure 1 shows, emergency response planning is separated into two elements—readiness planning and delivery planning. Readiness planning consists of emergency preparations that can be made in advance of an accident. Readiness planning is a deliberate long-term process designed to ensure availability of resources and development of procedures for coordination during an emergency. Examples of the readiness process are purchase of equipment; training of personnel; and establishment of mutual aid agreements with local hospitals, fire, police, and volunteer organizations. Delivery planning focuses on the time-critical and event-specific efforts by rescue and firefighting personnel to save lives and mitigate the impact of an accident. Examples of delivery planning actions are preselecting travel routes to potential airport accident sites and conducting periodic emergency drills.

Figure 2 shows a typical delivery process with the following sequence of events: after an alarm is received, personnel and equipment are mobilized; ground vehicles transport emergency resources to the scene; rescue and firefighting (RFF) services are deployed at the accident scene. Thus, the time needed to respond includes mobilization time (in practice, RFF vehicle and payload are ready to roll at all times, thus mobilization time occurs seconds after the alarm sounds); travel time (this period is often minutes rather than seconds); and deployment time (because the window of opportunity for rescuing victims, suppressing a fire, and mitigating the impact of an accident is short, deployment must occur immediately on arrival).

ALL-TERRAIN RESPONSE

The challenge of providing for public safety at an airport is unique because the airport seeks to provide all-terrain emergency response both for unpaved areas that often constitute a large portion of an airport and for paved areas such as those found near passenger terminals. Significant response factors to be considered include timeliness (which for aircraft incidents requires that RFF help must arrive within seconds) and payload (which requires that RFF vehicles must transport adequate quantities of water, chemicals, equipment, medical supplies, and personnel).

Timeliness

There is ample evidence that, when rescue and fire fighters arrive quickly, they are more effective in saving lives and reducing damage. Thus, all other things being equal, the faster the emergency response, the better. Current airport response planning is concentrated on procedures, training, and practice sessions for (a) rapid mobilization at a station, (b) on-pavement transport, and (c) resource deployment at an accident site. Until recently, no systematic method was available for analyzing the unique problems of rapid off-pavement response or to provide for timely payload delivery and pertinent training of personnel for this circumstance.

Payload

Because the standard method of transporting an airport emergency payload is by ground vehicle, timely payload arrival

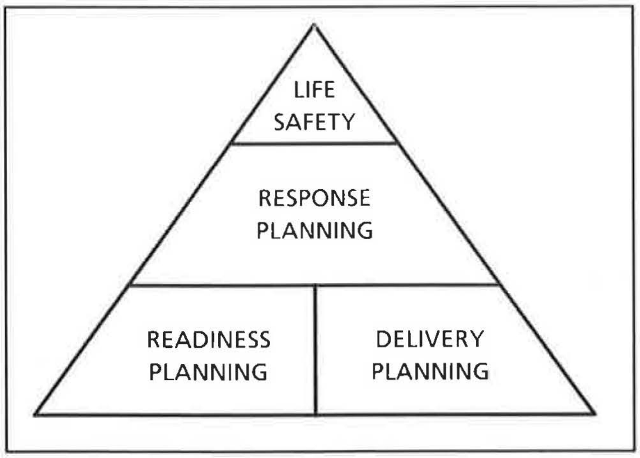

FIGURE 1 Emergency response planning.

Research and Special Programs Administration, U.S. Department of Transportation, Kendall Square, Cambridge, Mass. 02142.

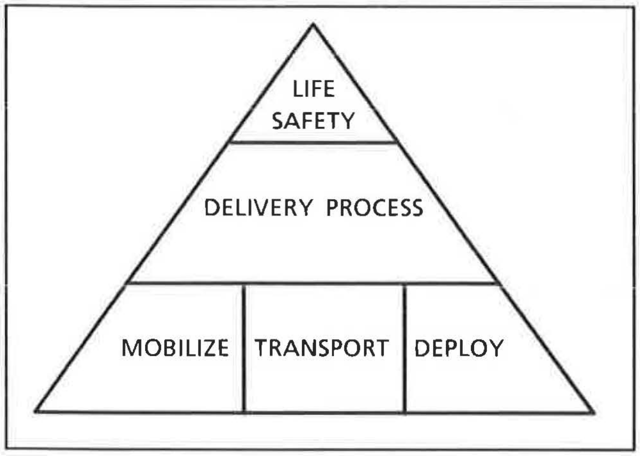

FIGURE 2 Typical delivery process.

should be determined from an analysis of vehicle performance. Unfortunately, most vehicle statistics are limited to on-pavement performance, which does not adequately predict payload arrival for airport conditions. In addition, airports are faced with the paradox that improving vehicle performance may not improve public safety levels. For example, one method of improving vehicle performance is to decrease vehicle weight by reducing the payload. This in turn means fewer resources (water, chemicals, equipment, medical supplies, and personnel) available to ensure safety. All other things being equal, when lives are at risk, having more resources is better than having less.

Mobility

Mobility is defined as the capacity for movement, that is, the speed at which a vehicle moves under various environmental conditions. Because rapid arrival of an adequate payload is key to mitigating accident severity, important goals of airport response planning are to maximize mobility, maximize payload and minimize travel time. Solutions to this complex problem can best be found with analytical models.

Since 1946, the U.S. Army Corps of Engineers, Waterways Experiment Station (WES), has performed research on and modeling of vehicle, terrain, and operator interactions under a variety of environmental conditions. This work included development of techniques for quantifying the effects on vehicle mobility of grade, slope, vegetation, obstacles, linear features, human factors, and seasonal conditions. The primary focus for WES has been to evaluate vehicle performance using the single-patch Army Mobility Model (AMM). Recently, WES developed the Transportation (T-) Model, which quantifies travel time over a sequence of patches.

Army Mobility Model

Conceptually, the AMM sums the physical forces affecting a vehicle's motion as it moves at constant speed over a single patch of ground. The Army applies the AMM to military problems of ground movement in a particular region of the world (e.g., tank movement in Europe). Each region is represented by patches (Figure 3) with large and small features typical of that area (e.g., urban, mountain, farm, and rocky). The model then computes average vehicle speed and fuel consumption per patch and provides a set of diagnostic data for each type of patch. A typical set of computations performed by this model requires less than 50 min. The same set done by hand would require approximately 50 man-years.

FIGURE 3 Global regions and patches.

Transportation Model

Conceptually, the T-Model sums the times used as a vehicle moves from an origin over a route to a destination. Usually, an origin-destination pair is connected by a network of intermediate nodes and route segments as shown in Figure 4. Travel time along a single route is calculated by dividing speed along each segment of the route into each segment length and summing over all the segments in one route.

AMM and T-Model Colocation

When the AMM patches and T-Model network are superimposed, a relationship is established between variables from the two models. The superimposition shown in Figure 5 was created by colocating network nodes and patch center points. For this geometry, segment length (T-Model) is equal to the distance of a patch side (AMM), and speed per segment (T-Model) is equal to average speed per patch (AMM).

Adaptation for Airport Use

With WES assistance, the models have been adapted for use at airports by the U.S. Department of Transportation, Research

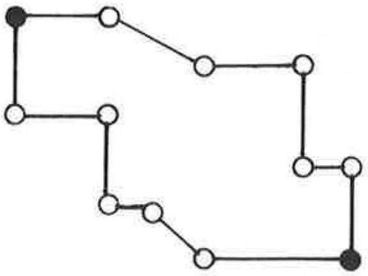

FIGURE 4 T-Model network.

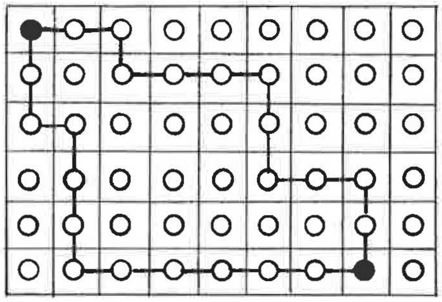

FIGURE 5 Geometry of AMM and T-Model colocation.

and Special Programs Administration, Transportation Systems Center (RSPA/TSC). The resulting capability is the new methodology to improve delivery of emergency airport services (IDEAS). It can be used in (a) siting fire stations, (b) siting fire lanes, (c) estimating RFF response time, (d) diagnosing problems that could delay or disrupt emergency response, (e) developing safety improvement strategies, (f) identifying alternative methods to implement a strategy, and (g) evaluating safety improvement implementation costs and benefits.

Adaptation included the following:

1. For airport use, the ranges allowed for AMM parameters were adjusted to emphasize the high-speed travel required for an RFF vehicle and to deemphasize the low-speed movement of military convoys.
2. Because an airport, unlike the Army, has unilateral control over airport grounds, technical applications were extended to include impact analysis of changes to the landscape; for example, elimination of obstacles, grading rough areas, filling in ditches, or adding fire lanes.
3. An estimate of all-terrain response is accomplished by calculating travel time from the airport fire station (origin) to all potential destinations. For data presentation, travel time is plotted in contours. In Figure 6, each contour represents an additional 30 sec of travel time.
4. The relationship established between the models by colocation was made airport-specific by superimposition over airport geography, producing a tri-location. The airport was partitioned into 15-foot-square sections. Then, each section had an AMM patch superimposed on it and a T-Model node located at the center point. Partition size was chosen because it is simultaneously proportional to (a) changes in airport features that could affect delivery, (b) size of the RFF vehicle, and (c) aircraft accident conditions.

The following list developed by RSPA/TSC includes commercial and field options for improving airport emergency services.

VEHICLE

- Vary tire pressure,
- Change tire width,
- Use radial tires,
- Use chains and paddles,
- Use additional wheels, and
- Modify suspension system.

ROUTE

- Use emergency routes,
- Plan preposition locations,
- Map airport, and
- Install fire lanes.

ENVIRONMENT

- Study impact of wind,
- Study ground congestion,
- Grade terrain,
- Fill ditches,
- Improve drainage, and
- Mark ground obstacles.

HUMAN

- Train vehicle operator.

The IDEAS method is site-specific. It depends on actual airport topology and weather history, actual RFF vehicle configuration, and airport safety policy. Therefore, a case study is presented as an aid to understanding and to demonstrate IDEAS capability.

Case Study

In 1988, RSPA/TSC completed a case study of IDEAS with the cooperation of the General Mitchell International Airport at Milwaukee, Wisconsin. It investigated one specific approach to reduce arrival time of a payload and considered the costs and benefits of several implementation alternatives.

This aircraft rescue and firefighting (ARFF) Index D airport covers approximately 2,200 acres (6 mi^2). Formerly farmland, the soil contains a high percentage of clay and the terrain is generally flat, with a forested hillock on the approach to Runway 1L.

In 1986, soil samples, aerial maps, and terrain data were gathered by WES and RSPA/TSC with the assistance of air-

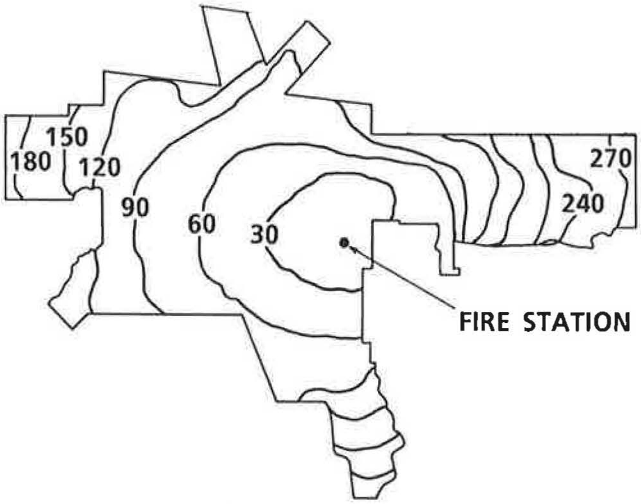

FIGURE 6 Time contour concept, scale 1:36,000.

port personnel. The data were digitized and entered into the ARC/INFO geographic information system data base. The resulting airport data base contains information on approximately 1,422,000 fifteen-foot-square patches of airport terrain with an equal number of center point nodes. Figure 7 is a map of the airport that identifies airport features such as runways, control tower, fire station, railroad, highway, ditches, fences, ponds, parking lots, fire lanes, urban, and wooded areas. The fire station is to the right of the tower, which is located near the center of Figure 7.

After reviewing weather data for the past 10 years, two weather conditions were chosen for analysis: best condition—no rainfall (dry ground), which occurs 61 percent of the year, on average; worst condition—excessive rainfall (wet, slippery ground), which occurs 6 percent of the year, on average.

Data for one specific vehicle were then entered into the data base. Typical vehicle data are weight, center of gravity, clearance, number of wheels, power, gear ratio, tire width and pressure, and tread type. The specified vehicle is designed to carry a relatively large payload of 3,000 gal of water, 500 lb of Halon 1211, 360 gal of aqueous film-forming foam (AFFF), 55 gal of fuel, and a crew allowance of 350 lb—a total payload of approximately 31,000 lb.

The case study addressed three scenarios, as follows:

- Scenario 1—Vehicle on dry ground,
- Scenario 2—Vehicle on wet ground, and
- Scenario 3—Modified vehicle on wet ground.

For analysis purposes, each scenario included the vehicle, weather and ground condition, airport features, and one set of soil measurements.

First Estimated Time-of-Arrival Computation

The first step in the analytical sequence was to use the AMM and the airport geographic and vehicle data bases to calculate speed for each patch. Speed per network segment was then set equal to speed per patch; these data were then entered into the T-Model. Travel times from the fire station (origin) to all potential destination nodes were calculated, and plotted as estimated time of arrival (ETA) contours. Figure 8 is an ETA plot for Scenario 1. The less regular contours reflect variations in off-pavement speed caused by grades, rough terrain, and obstacles. Each succeeding contour represents an additional 30 sec of time.

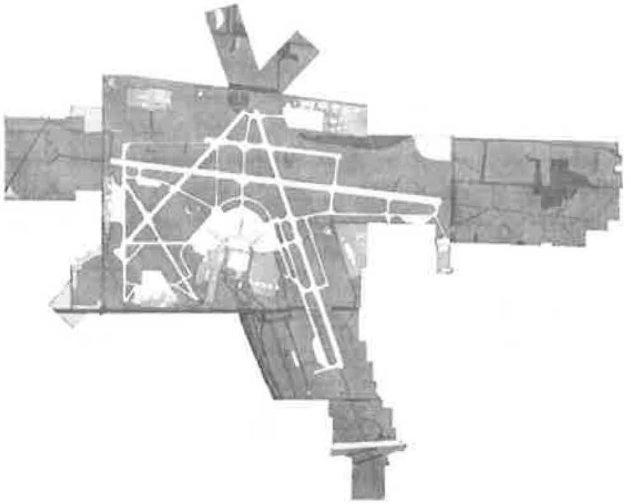

FIGURE 7 General Mitchell International Airport surface feature map, scale 1:36,000.

On the basis of a review of larger plots than can be shown here, Figure 8 predicts that the payload can be delivered everywhere on the airport fairly rapidly, coverage is not limited, but speed off of the pavement is slower than speed on the pavement.

Figure 9 is an ETA plot for Scenario 2. In the black areas, speed is zero; the vehicle cannot transport its payload, and deployment cannot occur. Although the vehicle complies completely with current federal emergency response requirements (14 Code of Federal Regulations, Part 139), it cannot perform under these conditions.

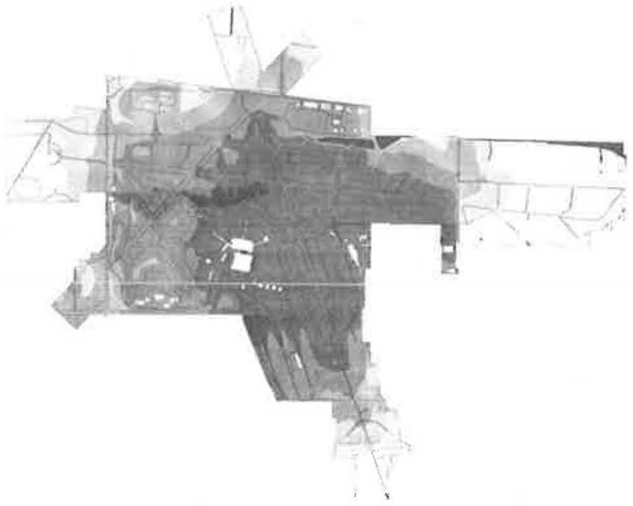

FIGURE 8 Existing Scenario 1—ETA for the vehicle on dry ground, which occurs 61 percent of the year on average, scale 1:36,000.

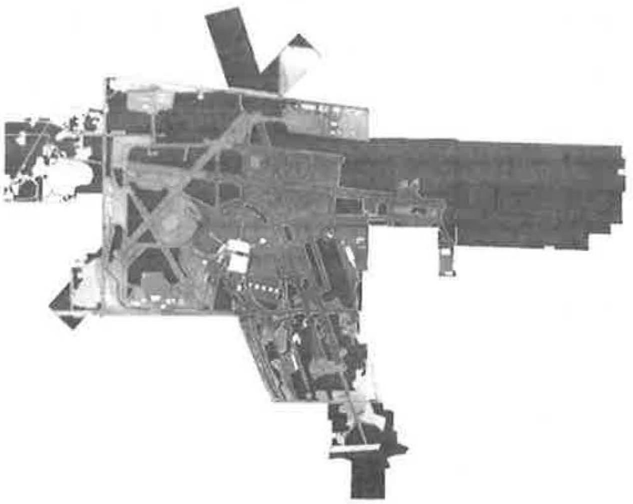

FIGURE 9 Scenario 2—ETA for the vehicle on wet ground, which occurs 6 percent of the year on average, scale 1:36,000.

Scenario 1 Diagnostic

Figure 10 is a plot of the major factors per patch diagnosed by the AMM as the major reason speed is limited in Scenario 1. Most of the light-grey patches refer to speed reductions caused by poor ride quality. Ride quality forces are measured in terms of continuous absorbed power, that is, vibration in the vertical direction. Results of Army field tests indicate that for short periods of time under high stress human tolerance can be as high as 15 Watts of vertical absorbed power. The AMM uses this information to predict operator loss of control because of excessive vibration. It reacts to poor ride quality by reducing vehicle speed until the cab vibration is reduced to tolerable levels.

Airport Evaluation

On reviewing this plot, the airport fire chief and ground maintenance manager indicated that some areas at the airport retained furrows from previous farming activity. Describing the physical problem led almost immediately to suggestions for a better suspension system and better landscaping. There was universal appreciation that these improvements could improve timeliness of arrival.

Scenario 2 Diagnostic

The major AMM speed-limiting factor for Scenario 2 is shown in Figure 11. Most areas, especially those at the ends of runways, are impassable, because the vehicle sinks into the muddy clay soil. This problem had another somewhat more complex solution.

Second ETA Computation

Although Figure 11 shows that arrival time is adversely affected by weather-related ground conditions, to change the soil is not feasible or economical. Instead, an increase in the vehicle's footprint was investigated in the hope that distributing the vehicle's weight (more than 60,000 lb) over a larger area would decrease the tendency to sink.

The large-footprint approach was modeled by changing the computer's data base of vehicle parameters, all other factors being held constant. AMM calculations for average speed per patch were made using the new data. T-Model predictions were also recalculated. After several possible alternatives were tried, Scenario 3 was created and the ETA contours shown in Figure 12 were plotted. Figure 12 shows that many areas (black), formerly predicted by the models as inaccessible, could now be reached by the vehicle. This result shows that the proposed strategy will indeed reduce arrival time and extend emergency response coverage.

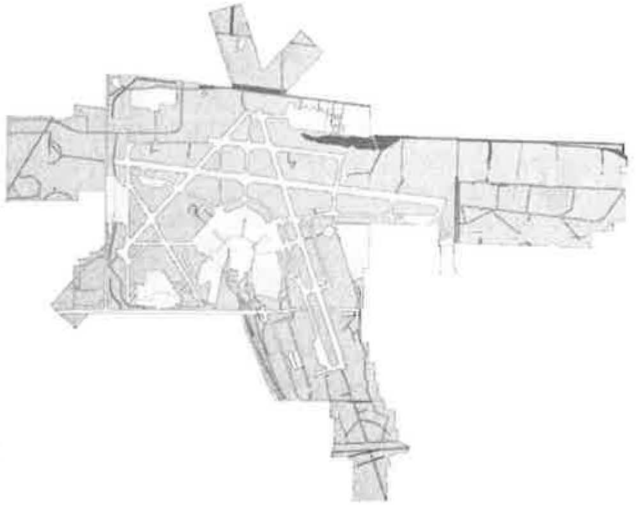

FIGURE 10 Scenario 1—diagnostic plot for the vehicle on dry ground, which occurs 61 percent of the year on average, scale 1:36,000.

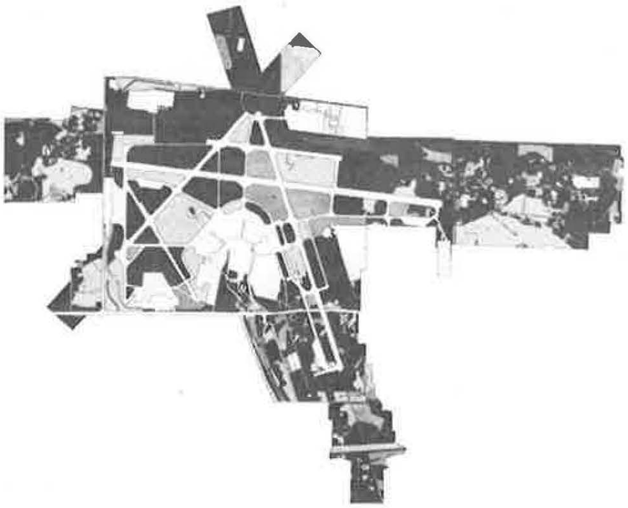

FIGURE 11 Scenario 2—diagnostic plot for the vehicle on wet ground, which occurs 6 percent of the year on average, scale 1:36,000.

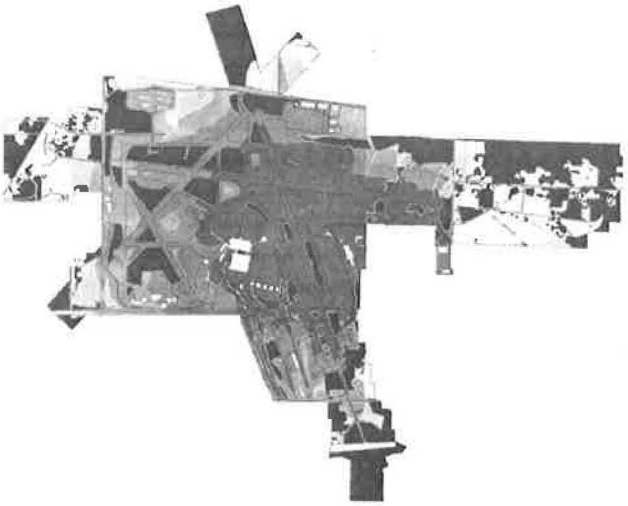

FIGURE 12 Scenario 3—ETA for the modified vehicle on wet ground, which occurs 6 percent of the year on average, scale 1:36,000.

Working from the list of proposed safety options and from tire experts' recommendations, three large-footprint implementation alternatives were identified:

1. Reduce tire pressure manually. This option is not recommended. However, when all else fails this approach might help.
2. Install tires rated for low pressure operation and add a bead retention system to clamp the tires to the rims. This option is recommended for consideration because of its low initial cost, relative ease of maintenance, and reliability. Driver training is also recommended because a large footprint alters the vehicle's handling characteristics.
3. Install tires rated for low-pressure operation and an automatic inflation-deflation system. This option is also recommended for consideration. Because the vehicle operator can adjust tire pressure according to situational requirements (e.g., full inflation when on pavement and lower inflation off the pavement), this solution could provide the best overall response capability. Retrofitting the specified vehicle is feasible, but more complex and expensive than the other alternatives.

CONCLUSIONS

On the basis of the work reported, IDEAS is a useful adaptation of the models developed by WES. The case study demonstrates that airport-specific methodology can be used to assess and improve delivery of emergency services. In addition, combining the two models with a specific geography creates a situation in which it is possible to quickly investigate travel time sensitivity to changes in factors such as weight, gear ratio, and tire pressure. This experience indicates that properly applied geographic colocation could lead to integration of transportation models with models from other fields.

ACKNOWLEDGMENTS

The authors would like to express their sincere gratitude to Bertrand Ruggles, FAA, Office of Airport Standards, Safety and Criteria Division, for funding and contributing his expertise to this work. Thanks are also extended to the General Mitchell International Airport staff for their cooperation and to the WES Mobility Systems Division staff for their technical contributions.

Transportation of Dangerous Goods in the Province of Ontario

JULIUS GORYS

Transportation of dangerous goods has recently been the subject of considerable scrutiny. In general, little is known about the quantity of such substances produced and moved or the degree of risk that exists for the transporters and the general public. The amount of dangerous goods movement, the modal share distribution, the principal issues associated with its transport, the relative frequency of incidents, and the degree of societal risk involved are examined.

The issue of dangerous goods and their transportation has received a great deal of public attention because of the transportation-related incident at Mississauga and the plant-related incidents at Bhopal and Chernobyl. The subject is now frequently in the news.

The principal interest of the Ministry of Transportation in such matters relates to its on-highway safety and regulation mandate. Its involvement is much greater than this, however, given its participation in the recent federal (Gilbert) Task Force on the Movement of Dangerous Goods by Rail in the Toronto area, and its ongoing monitoring and analysis of trends. In addition, the ministry's enforcement strategy includes educating shippers and carriers and ensuring general compliance.

In contrast, the federal government of Canada is responsible for the three other modes, and for shippers and manufacturers. Municipal police form an extension of provincial on-highway enforcement, and are the first responders in the event of an incident.

Dangerous goods can be described as any commodity or product that presents a danger to the environment or to people coming into contact with it. The legal definition of dangerous goods provided in the *1980 Transportation of Dangerous Goods Act* is any product, substance, or organism included by its nature, or by the regulations in any of the nine classes listed in Schedule 2 of the regulations.

On the order of 3,500 products are listed in the Act. Some have technical names such as chlor-tetra-fluoro-ethane; others have common names—paint, petroleum, chlorine. Dangerous goods are divided into classes and divisions, according to the type of hazard involved. There are nine major categories:

1. Explosives,
2. Gases,
3. Flammable liquids,
4. Flammable solids,
5. Oxidizing substances,
6. Poisonous and infectious substances,
7. Radioactive materials,
8. Corrosive substances, and
9. Miscellaneous products.

DANGEROUS GOODS QUANTITIES AND TRANSPORT

Substantive statistics on the quantity of dangerous goods produced or transported in Ontario Province are scarce. Much of what exists is derived from federal statistical or monitoring and regulatory agencies and is not necessarily compatible. Inferring from this data, on the order of 39 million tonnes of such goods are transported annually to, from, and within Ontario, and they have a value between $30 and $40 billion.

Data from Statistics Canada and Transport Canada suggest that the quantity of dangerous goods being moved has been increasing, commensurate with the economy. Commercial trucking tonnage of such products within Ontario has increased by about 15 percent per year since the end of the recession, while rail tonnage of such commodities has risen by 5 percent per year. The value of Ontario trade in dangerous goods has also been increasing about 15 percent per year (Figure 1).

It is estimated that about 63 percent of the dangerous goods tonnage in the province—some 25 million tonnes—is being hauled by trucks. The rail and marine modes transport 23 and 14 percent of all such tonnage, respectively, while the air mode handles about 1 percent (Figure 2). Transport Canada estimates that for the nation, trucks also transport about 63 percent of all tonnage, compared to only 11 percent for rail.

Within the province, it is not known with certainty whether one mode is assuming greater importance in the overall movement of dangerous goods relative to another. However, a review of federal statistics on Ontario imports and exports suggests that the transportation of dangerous goods is increasingly being handled by trucks.

Import and export data presented here are derived from Statistics Canada's International Trade Division's computer files (informal communication) in Ottawa. In 1977, the truck/highway mode handled 37 percent of the transported export value of dangerous goods moved from the province of Ontario. By 1985, it increased its share to 46 percent, at the expense of the rail mode. In 1977, the truck/highway mode handled 56 percent of the transported import value of dangerous goods moved to the province of Ontario. By 1985, it had also increased its share, to 59 percent (Figure 3). For the nation, Transport Canada estimates that the tonnage share held by trucks increased from 55 percent in 1981 to about 63 percent in 1989.

Although trends suggest a shift in modal share, there is probably an upper limit to how much dangerous goods cargo

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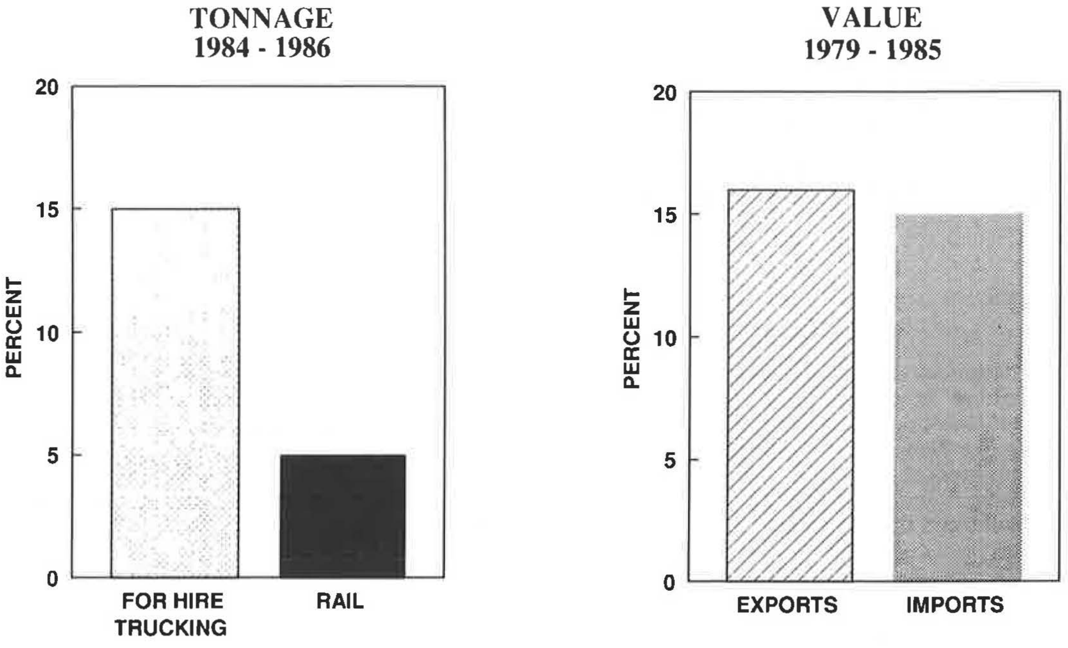
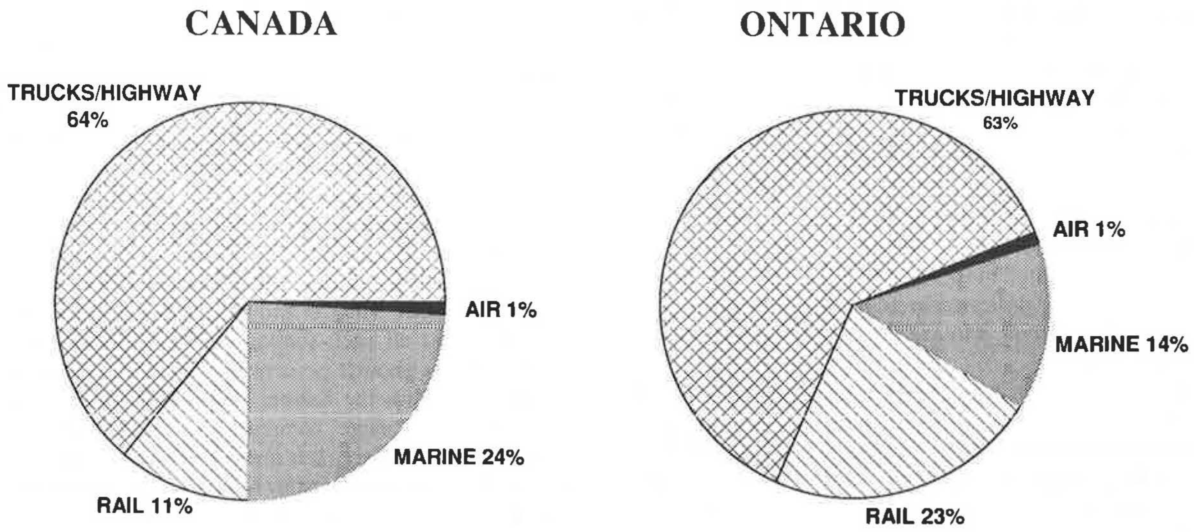
Municipal Transportation Policy/Planning Branch, Ontario Ministry of Transportation, 1201 Wilson Avenue, 3rd Floor, West Tower, Downsview Ontario, Canada M3L 2E4.



SOURCE: Statistics Canada

FIGURE 1 Increases in dangerous goods quantities for Ontario.



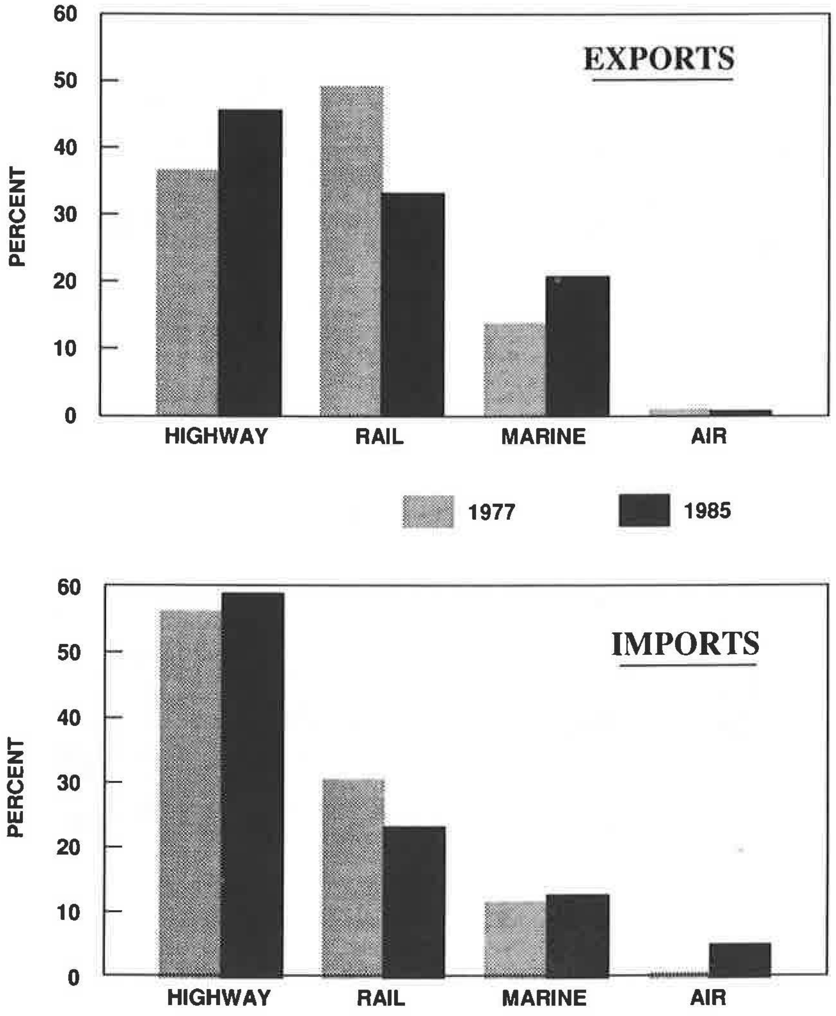
SOURCE: Ontario Ministry of Transportation, Transport Canada

FIGURE 2 Dangerous goods tonnage estimated modal shares, 1989.

can be hauled by truck. For example, compressed bulk gases are now predominately, and more safely, transported great distances by rail. This assertion was partially supported by the findings of a recent (1988) analysis of U.S. DOT data, which concluded that, at least for rail tank cars and for-hire tank trucks (which tend to travel greater distances than their private truck counterparts), the release accident rate for rail was lower than that of its principal long-distance competitor (*1*). However, preliminary information from the Canadian Ministry of Transportation's 1988 Commercial Vehicle Survey suggests that even for commodities such as compressed gases, there is increasing use of trucks to haul it.

The present modal share relationship should not change appreciably in the near future. As such, the rate of change in modal share in dangerous goods transport between rail and truck has been less, and in the short term is anticipated to continue to be less than for all other commodities.

For example, in the movement of all of Ontario's imports and exports to the United States, the rate of modal shift in favor of the truck/highway mode recently has been quite pro-



SOURCE: Statistics Canada

FIGURE 3 Modal shares in 1977 and 1985.

found. Between 1977 and 1987, the proportion of the value of Ontario's imports transported by truck/highway mode increased from 71 to 86 percent, while the export value handled by the truck/highway mode increased from 59 to 70 percent (Figure 4).

Dangerous goods are estimated as constituting approximately 18 percent of all truck tonnage in Ontario. This amount is equivalent to just over 1 million truckloads a year or some 4,100 truckloads a day in the province. But, in many instances, dangerous goods form but a small part of a larger general cargo movement—for example, a box of butane lighters as part of a large shipment of goods being delivered to a convenience or department store. Thus, the number of trucks that are actually hauling dangerous goods is much larger.

The principal commodity hauled by each mode varies. In terms of shipments, medicine is by far the most frequently transported dangerous good shipment by truck, followed by corrosive liquids, flammable liquids, paints and varnishes, and ethanol, in that order. In terms of tonnage, about 63 percent of the dangerous goods transported by truck is flammable liquids, such as gasoline, fuel oil, or ethanol; the largest components of the remainder are fertilizers and corrosive liquids. In contrast, three quarters (74 percent) of what is hauled by rail are compressed gases (Figure 5). Flammable liquids are also the most prominent (84 percent) dangerous good hauled by the marine mode (*2,3*, and Transport Canada's Dangerous Goods Directorate, Evaluation Analysis Division, informal communication).

The majority of dangerous goods truck movements in Ontario (63 percent) are intraprovincial in nature (Figure 6), and close to 40 percent of all trips involve a location in the greater Toronto area itself.

In 1988, a major goods movement study was completed for metropolitan Toronto. In its cursory analysis of dangerous goods movements, the Metropolitan Toronto Goods Movement Study found that the characteristics of dangerous goods transport was not altogether different, in terms of trip pattern and frequency, than all other forms of truck movement (*4*).

During the course of that study, firms were surveyed as to the nature of the commodities they shipped. It was determined that although close to one-quarter of firms surveyed shipped dangerous goods, less than 5 percent of their loads were dangerous goods. In addition, although the total quantities of dangerous goods being transported could not be measured

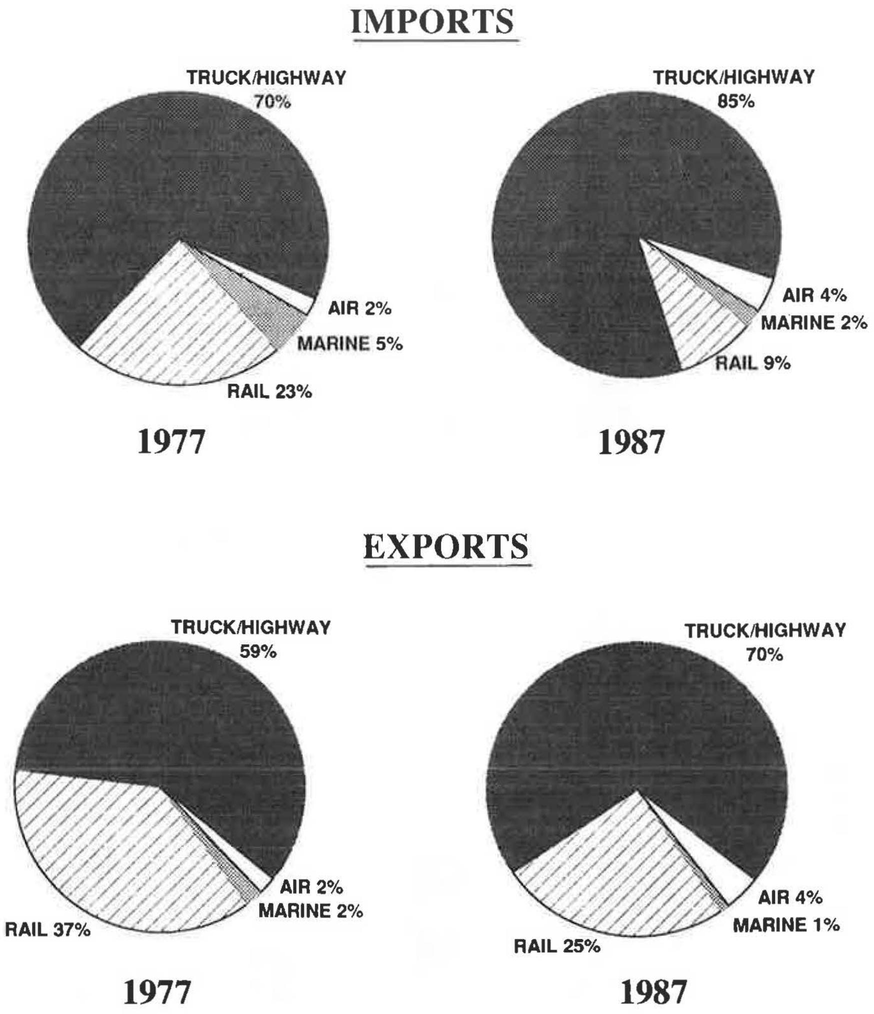


FIGURE 4 Ontario-United States trade relationship—modes used to cross customs for 1977 and 1987.

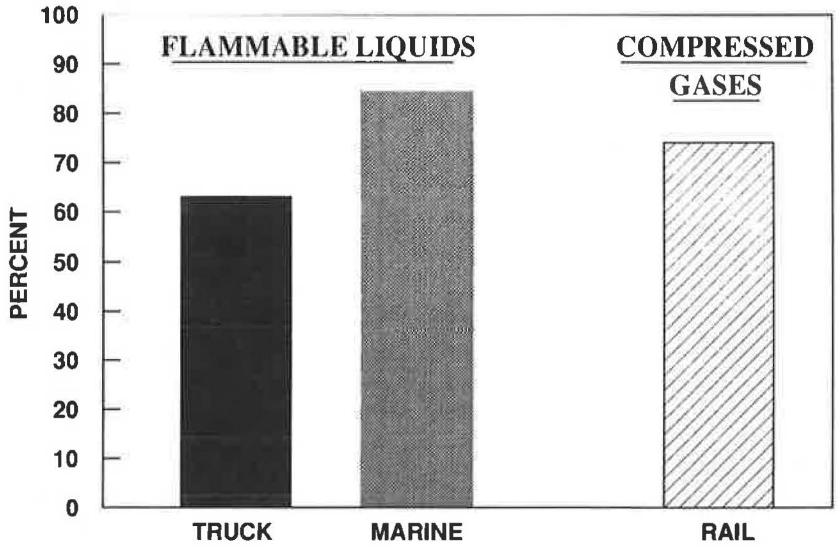


FIGURE 5 Principal quantities hauled by major transport modes, 1986.

with certainty, commodity and trip information revealed that at a minimum, there were 18,000 movements per day of chemicals in the Toronto area alone.

In the Canadian Ministry of Transportation's periodic commercial vehicle surveys was found a greater amount of international movements of dangerous goods compared to such trips for all other commodities. Some 20 percent of dangerous goods truck movements in 1983 were to the United States; consequently a higher proportion of truck traffic near border areas was related to dangerous goods. The value of trade in dangerous goods between Ontario and the United States was on the order of $5.6 billion in 1985.

In terms of how dangerous goods were hauled by truck, the ministry's 1983 Commercial Vehicle Survey established that generally larger vehicles were used (Table 1), and there were greater private fleet involvement and use of vehicles not registered in Ontario (*2*, Chapter 4). Those findings were confirmed by preliminary information supplied by the ministry's 1988 Commercial Vehicle Survey.

Because of concerns about dangerous goods rail transport incidents, a federal government task force was established in 1986 to inquire about

- The feasibility of rerouting or relocating rail traffic carrying dangerous goods in the Toronto area, and
- Any additional requirements governing the safe transportation of dangerous goods by rail.

The Gilbert Task Force included Provincial Transport Ministry representation; final reports were published in 1988.

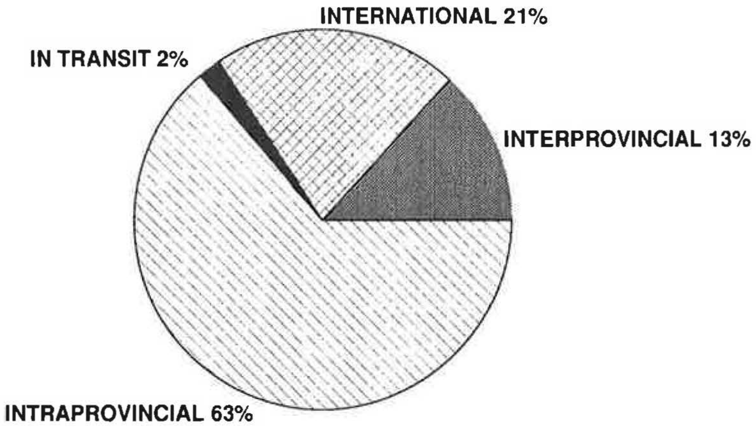


FIGURE 6 Origins and destinations of dangerous goods movements, 1983 (*2*).

TABLE 1 DANGEROUS GOODS TRUCK TRIP CHARACTERISTICS, 1983 (*2*)

	GENERAL TRUCK POPULATION	DANGEROUS GOODS CARRIERS
USE OF NON-ONTARIO REGISTERED VEHICLES	16%	22%
INTRAPROVINCIAL MOVEMENTS	62%	60%
AVERAGE TRIP LENGTH (kms)	345	335
PRIVATE TRUCK HAULAGE	55%	64%
REGISTERED GROSS VEHICLE WEIGHT (kilogram average)	37,200	44,100

From information submitted to the task force, it was found that for long distance moves, generally more than 400 km in length, rail was the predominate means of transport for dangerous goods. For example, in contrast to the truck mode, 42 percent of dangerous goods movements by rail in Ontario was interprovincial (Figure 7), whereas only one-third was intraprovincial.

Given the nature of the existing rail infrastructure, a lot of rail traffic in urban areas is through movement (Figure 8). Information supplied to the task force by Canada's national railways noted that 53 percent of the 67,000 rail carloads in the Toronto area containing dangerous goods were merely passing through Toronto to another destination (*3*).

ISSUES AND CONCERNS

There are four principal issues or concerns related to dangerous goods:

- The safety levels of each transport mode;
- Risk minimization;
- Incident management adequacy; and
- Cost effectiveness of enforcement, regulations, and movement restrictions.

The objective of federal and provincial legislation is to protect the public. The regulations require safety marks and documentation, enabling incidents to be dealt with safely and quickly. In addition, diligent enforcement ensures greater compliance with the regulations. Enforcement for on-highway activity is carried out by ministry enforcement officers, municipal police departments, and the Ontario Provincial Police (OPP).

The key areas of compliance are

- Proper and complete documentation,
- Appropriate safety marks (labels and placards), and
- Certificate of training for the driver.

Much more work is still necessary in this area. For example, a major U.S. truck carrier manually audited every hazardous material freight bill for a week and found that 62 percent of its shipping customers was providing improper information or was in some way violating regulations (*5*).

On-highway enforcement is still the predominant means of ensuring compliance. Since 1985 in Ontario, the ministry and the OPP have laid over 2,000 charges, and the courts have levied fines ranging from $100 to $2,000. In addition, occasional checks are made of the containers hauling dangerous goods by enforcement personnel. The experience of enforcement staff and the trucking industry is that the greatest risk of spills and the cited violations for the general freight carrier were in damage to or failure of drums and pails containing liquids.

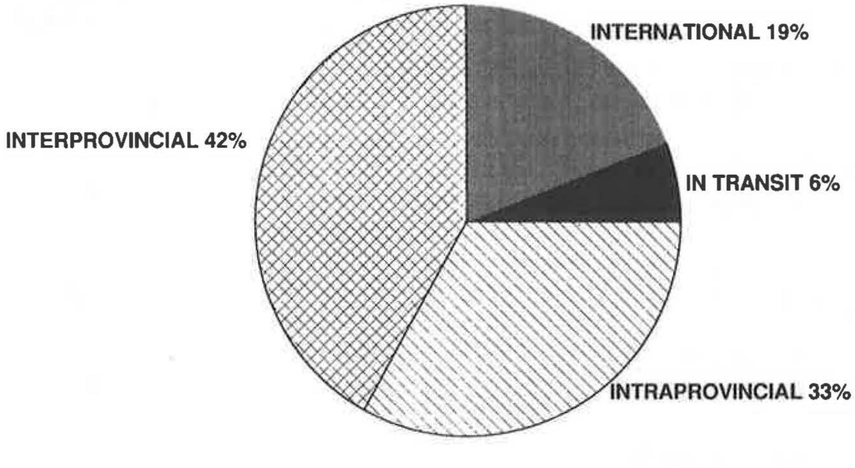
INCIDENT EXPERIENCE

Although dangerous goods movements are frequent and accidents do occur from time to time, few accidents are significant enough to result in the release of dangerous goods, and fewer result in injuries or fatalities. The destruction of the James Snow overpass on Highway 401 near Milton in 1986 was the result of a dangerous goods incident that was initiated by a drunk driver. It was contained with the loss of only one life that occurred from the accident itself, not the dangerous good. The 1979 Mississauga derailment of toxic and chemical cargo, despite the temporary evacuation of 240,000 persons, did not involve a single fatality.

For the most part, in the event of an incident, the type and amount of commodity transported would impact system operating personnel rather than the general public. Any harm would largely be contained within the immediate right-of-way. However, exposure may be relatively high in certain instances, and there may be sufficient justification to rationalize the transportation network, in order to spread the risk.

In the United States, over 900 million tons of dangerous goods is moved over the nation's highway system annually. Since 1981, the country has averaged about 5,400 incidents, 12 deaths, and 200 injuries per year (*5*).

In Ontario, only one-third of the reported dangerous goods spills occur while the commodity is being transported. Thirty



SOURCE: Statistics Canada

FIGURE 7 Origins and destinations of rail tonnage for Ontario, 1986.

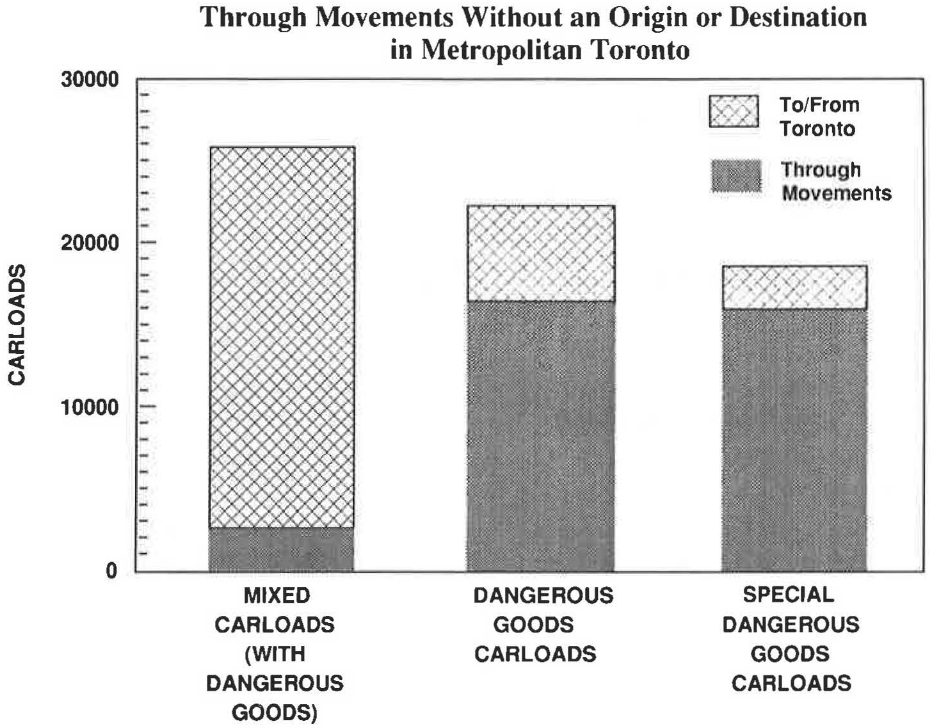


FIGURE 8 **In-transit dangerous goods transport by rail, 1988 (*1*).**

percent of spills were attributed to processing mishaps whereas a further 25 percent were related to storage (Transport Canada, Dangerous Goods Directorate, unpublished data) (Figure 9). The number of incidents that occur on the road network annually has averaged about 130 over the past few years, about one-half being related to tank trucks (Figure 10).

Driver error was the most predominant reason for such a road transport related incident (26 percent), twice that for equipment failure (13 percent); inclement weather was a more infrequent reason for the occurrence of an incident (4 percent).

A review of Ministry of Environment dangerous goods spills summaries from 1981 to 1984 found that the highest proportion of spills occurred in northeastern Ontario (29 percent), while the highest percentage of tank truck incidents occurred in central Ontario (29 percent). There was no discernible explanation for this spatial distribution (*6*).

The number of accidents involving dangerous goods has declined nationwide from 1986 to 1988 (Transport Canada, Dangerous Goods Directorate, informal communication). The highest proportion of dangerous goods accidents—just over one-third—occur each year in Ontario (Figure 11). Alberta and Quebec are the next most frequent locations for dangerous goods accidents. Ontario levels are higher because of the larger volume of dangerous goods movement and the larger number of vehicle-miles traveled in the province. Also, the accident rate of major transportation modes during this time frame decreased considerably (Figure 12).

Between 1986 and 1988, however, an average of 15 persons were killed and 165 persons injured annually in dangerous goods accidents in Canada. Although one-half of the injuries could be directly attributed to the dangerous good, on average only two of the deaths each year were the result of the dangerous good (Figure 13).

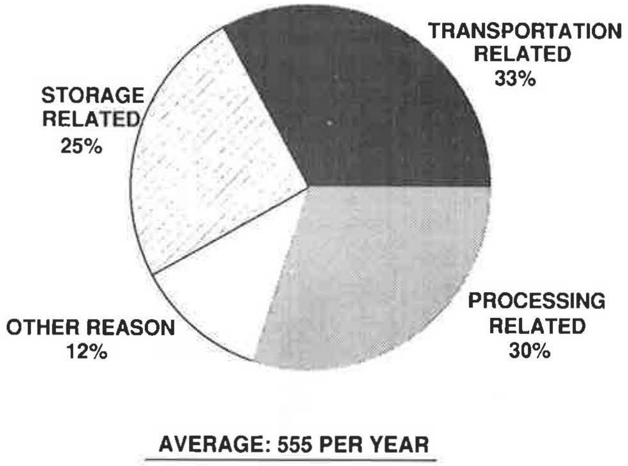


FIGURE 9 **Dangerous goods incidents by type for Ontario, 1977–1985 (*7*).**

Evidence conflicts as to what constitutes the safest mode for dangerous goods transport between cities. Theoretically, because the rail mode has its own right-of-way and can carry a larger quantity of such goods, the potential for an incident could be assumed to be less for this mode than for more frequent truck travel required to carry the same volume of a commodity.

The potential for an incident to affect a larger area or population would be greater for the rail mode, given the larger volumes of goods involved. The 1988 U.S. analysis also suggests that the estimated accident release rate for rail was in excess of that found for all trucks.

A cursory review of Transport Canada data would seem to support that conclusion simply on the basis of the number of accidents per tonne transported. Between 1986 and 1988, the

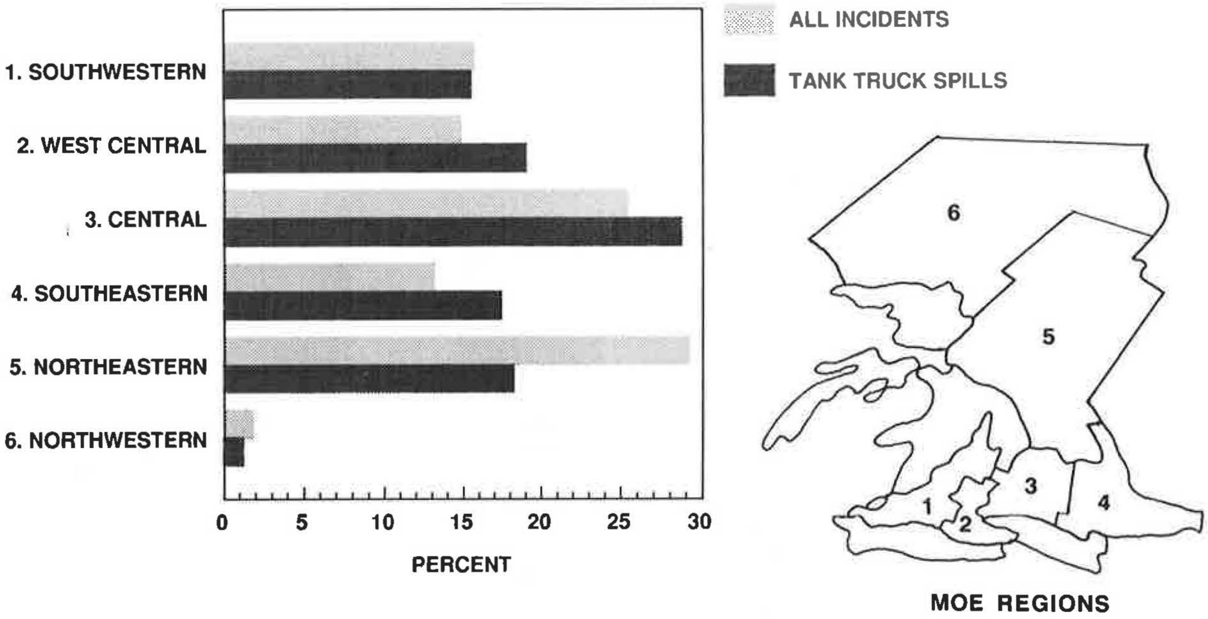


FIGURE 10 Dangerous goods incidents and tank truck spills by MOE region, 1981–1984.

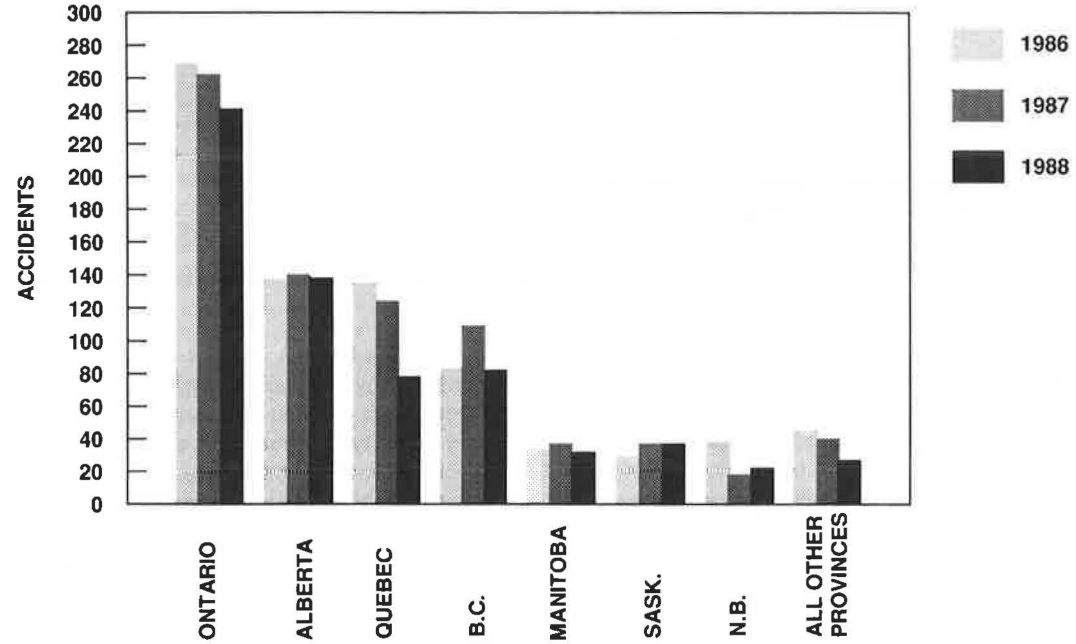


FIGURE 11 Dangerous goods accidents by province of Canada, 1986–1988.

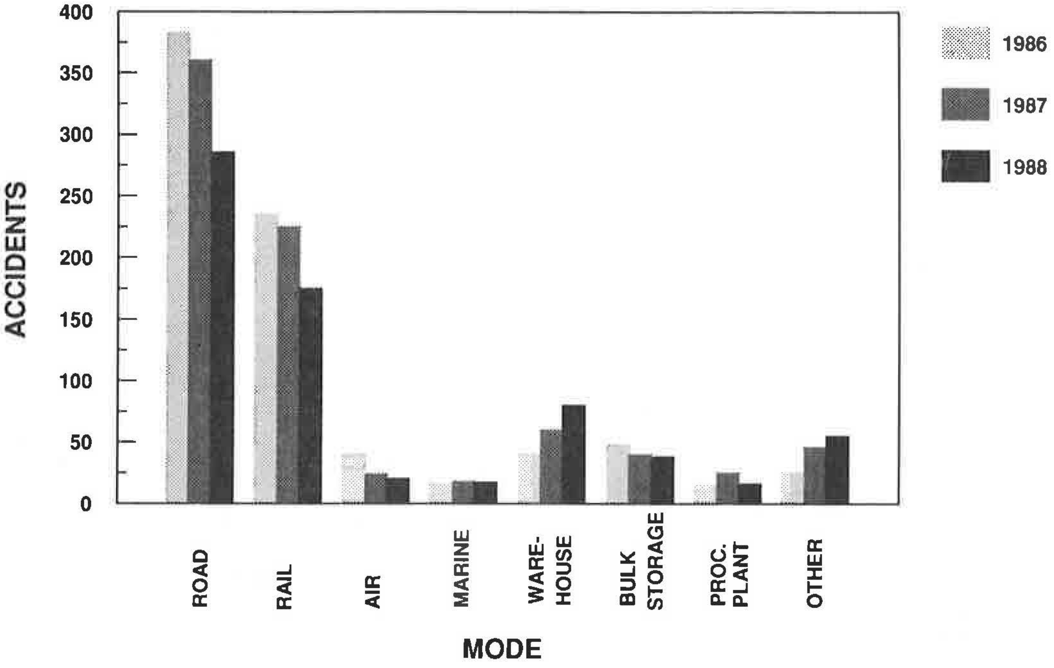
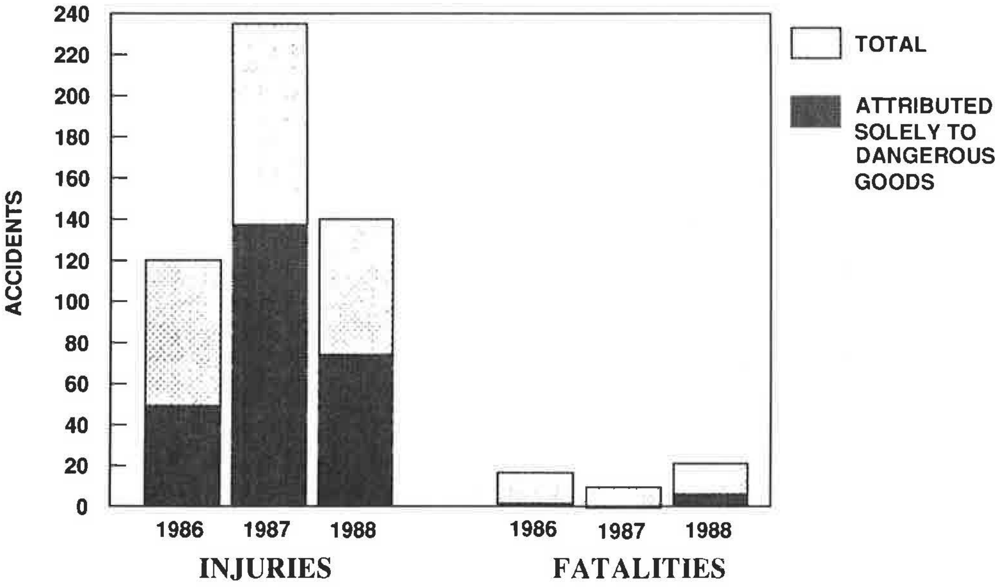


FIGURE 12 Dangerous goods accidents by mode for Canada, 1986–1988.



SOURCE: Transport Canada

FIGURE 13 Dangerous goods accidents for Canada, 1986–1988.

rail mode accounted for about 11 percent of the dangerous goods tonnage moved (Figure 2), but more than one-third of the accidents related to dangerous goods (Figure 12) among the various transport modes, while the truck/highway mode accounted for 63 percent of the tonnage moved and 57 percent of the accidents.

However, considering the differences in volume and capacity between rail and truck cargo tanks, and the distance traveled for that cargo, inverse conclusions may well be drawn using other measurement units.

SOCIETAL RISK ASSESSMENT

In spite of a seemingly large number of dangerous goods incidents, the likelihood of an incident's causing death at a given location is remote. The probability of an annual occurrence of an accident involving death is on the order of 1 in 100 million. Information presented at the Gilbert Task Force indicated that the societal risk involved from the rail transport of dangerous goods is quite low—roughly equivalent to that from earthquakes and lightning (Table 2).

Although the level of public risk with the existing system under current operating conditions has been estimated as being 4 to 5 per year on average, the rail mode has experienced no deaths because of dangerous goods accidents across the entire country of Canada over the past 10 years.

The likelihood of 10 fatalities resulting from a dangerous good rail mishap was estimated at being 1 in 100 years (Figure 14). Thus, much of the risk associated with an incident at a particular location is more perceived than real. However, clearly events have and will continue to occur, and possible outcomes must be addressed.

Public concern, as well as constructive actions by government, shippers, and carriers, has resulted in

- Mandatory placarding of dangerous goods vehicles in excess of a certain weight (1985 in Ontario);
- Institution of dangerous goods truck routes in certain communities (Edmonton, Alberta);
- Lower train speeds for trains handling such products through major populated areas (Toronto, Ontario);
- Rerouting of rail traffic away from some residential areas (Vancouver, British Columbia);
- Provision of specialized training by and for shippers and carriers and emergency response personnel; and
- Development of programs such as the Transportation Emergency Assistance Plan.

POLICY IMPLICATIONS AND OPPORTUNITIES

The transportation of dangerous goods raises many issues, among them: At what price is such transport truly safe? What level of enforcement is enough? and What degree of compliance is acceptable? For example, the pattern of land use and community development in Ontario and the cost of additional infrastructure make it impractical to construct dangerous goods bypass routes throughout the province.

TABLE 2 SOCIETAL RISK CAUSED BY VARIOUS HAZARDOUS EVENTS (*3*)

	Societal Risk (fatalities per year)
Motor vehicle accidents	**4,238**
Falls	**1,829**
Poisoning +	**665**
Dwelling Fires	**487**
Excessive cold	**121**
Cataclysmic storms	**13**
Earth movements	**5**
Lightning	**3**
Rail Transport of Dangerous Goods (TDG) in the Greater Toronto Area (baseline risk based on existing system)	**4.1***

*This is the estimated societal risk in "statistical" fatalities per year as determined by risk assessment. All of the other societal risk numbers are "actual" fatalities recorded Canada-wide. (Source: Statistics Canada, 1985, "Causes of Death," Publication #84203)

+ Includes accidental poisoning due to poisonous and other substances, surgical complications and misadventures to patients.

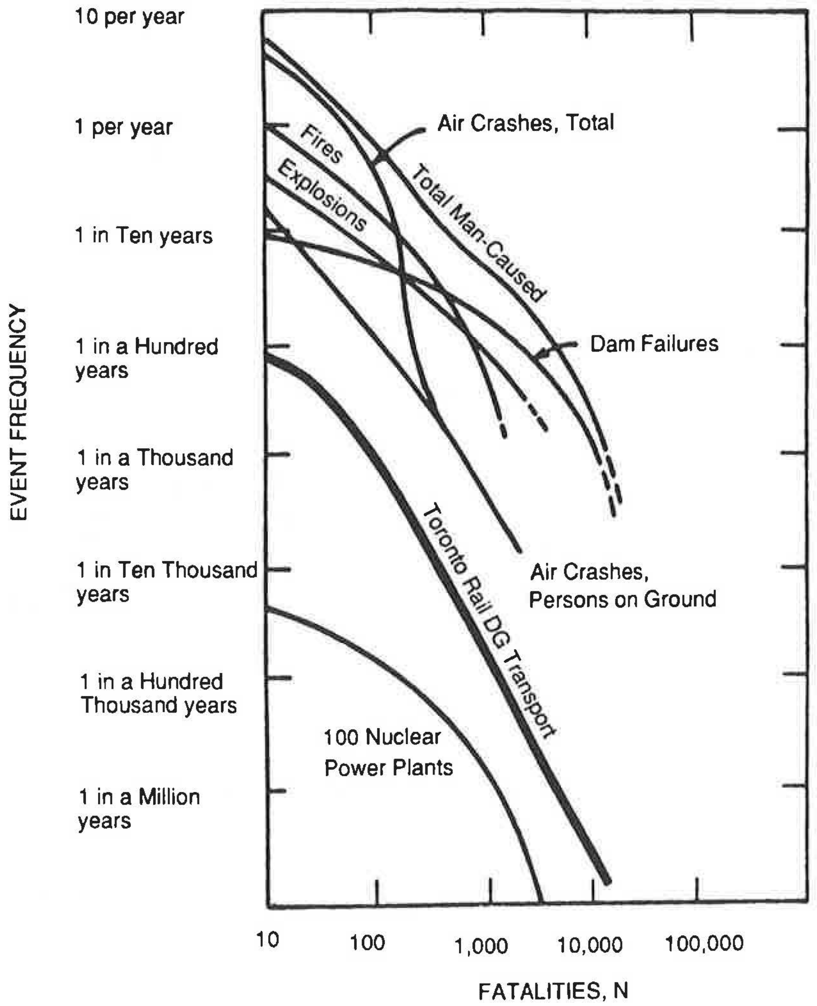


FIGURE 14 Risk assessment (*3*).

For the most part, routing restrictions, such as the superimposing of dangerous goods truck routes in an existing community, merely transfer risk and enhance the potential for a more severe incident by increasing the number of vehicle-kilometers that have to be driven. Also, the effect of concentrating, in a restricted area, the movement of commodities that are even more dangerous when mixed in an incident must be considered.

The practicality of such restrictions is questionable when the multitude of destinations for dangerous goods products—hospitals, retail paint and convenience stores, corner gasoline stations, etc.—is considered.

Time-of-day restrictions affect delivery schedules, and may result in the clustering of placarded vehicles parked along the side of a road or highway during banned hours.

The position of the Ontario Ministry of Transportation is that the movement of dangerous goods should not be unnecessarily hindered between shippers and receivers. Additional fees or restrictions can place a considerable economic burden on goods movement, whether assumed by the public or private sector.

For example, reducing risk to public safety from movement of dangerous goods at a regional level either by rerouting dangerous goods rail traffic through operational changes or by relocating dangerous goods rail traffic by developing new rail lines north of Metropolitan Toronto was evaluated by the Gilbert Task Force. The estimated costs of such an undertaking ranged from a low of $60 million (capital and operating cost) to a high of $1.7 billion, depending on the alternative chosen (Figure 15).

CONCLUSION

The subject of dangerous goods movement in the province of Ontario is quite complex. Minimizing the risk to the public from occasional incidents has been achieved with regulations, voluntary compliance, and enforcement. Many groups have contributed to safety—shippers, carriers, and all levels of government. As such, the level of public risk is quite low, but further improvement is possible.

If decision makers are of the opinion that the existing risk level is still too high, alternative actions can be contemplated. These actions would have to be evaluated in terms of societal risk, community impacts, effects on the natural environment, and economic ramifications.

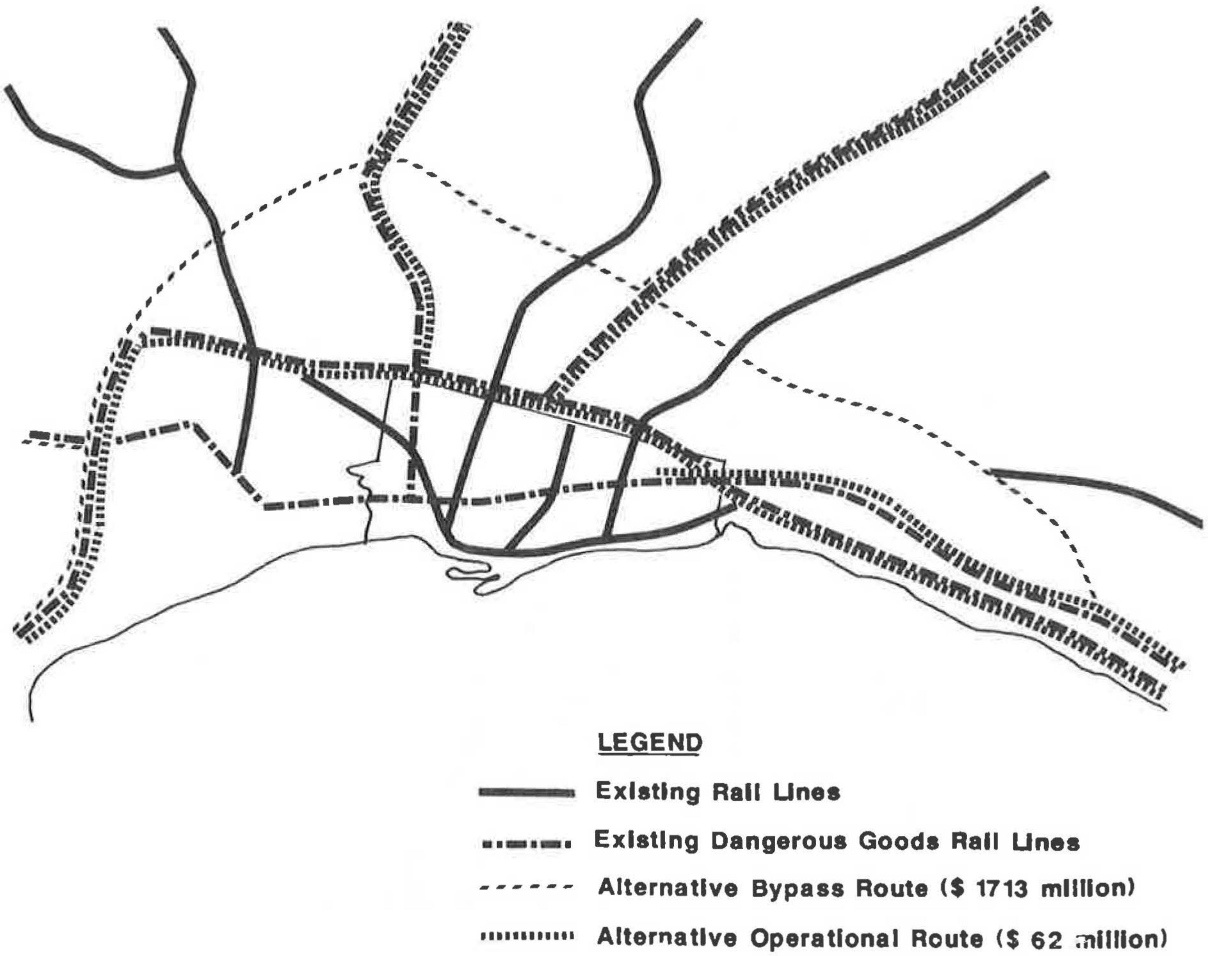


FIGURE 15 **Alternative bypass route concept (*3*).**

Whatever action is taken has to be achievable, effective, and enforceable. As always, value judgment on the appropriateness of each alternative can only be made by the broader political process.

ACKNOWLEDGMENTS

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The opinions expressed in this paper are solely those of the author, and in no way reflect the position of the Ontario Ministry of Transportation.

Restricting Hazardous Materials Routes on the Nation's Railroads: Some Considerations for Regulatory Analysis

THEODORE S. GLICKMAN

Regulating the routing of trains carrying hazardous materials is considered. Possible regulatory approaches, insights from past accident experience, status of related research, estimating population exposure, and determining preferred routes are described. Some major conclusions are as follows: (a) Regulation can be accomplished by route designation or by setting routing standards, but speed reduction and time-of-day restrictions should also be considered. (b) Experience shows that only about one out of three accidents is track-related and that although routing to avoid such accidents would reduce their total number, the proportion of costly equipment-related accidents and high-severity derailments would increase in the absence of speed reduction or time-of-day restrictions. (c) Localized population exposure cannot be estimated with confidence using the leading national network models in their current form because of geographical inaccuracies and the high level of link aggregation. (d) Better data on track conditions and economic impacts are needed, along with better methods for preferred route determination that would consolidate the advances in risk assessment modeling with those in developing efficient routing algorithms.

With the exception of certain radioactive shipments, hazardous materials are generally routed in the same way as other railroad freight. Track quality is sometimes taken into account when routing hazardous materials, but testimony given at the 1987 congressional hearings on DOT oversight of defense-related shipments of toxic chemicals indicates that the railroads do little or no risk analysis. During those hearings, a spokesman for one of the nation's most safety-conscious rail carriers testified that his company does not assess the risks of the various routes that are proposed to shippers. Later on, the executive director of the FRA testified that the government does not require them to, because there are no federal guidelines for the routing of rail shipments of hazardous materials.

Contemplation of regulations for restricting the routes of trains carrying hazardous materials entails the considerations that follow. The discussion is organized into five parts: possible regulatory approaches, insights from accident experience, review of related research, population exposure estimation, and preferred route determination. Although the emphasis is on the last three parts, where specific matters of data, models, and algorithms for evaluating regulatory options are discussed, the earlier parts give rise to two significant conclusions of a more general nature: (a) speed reduction and time-of-day restrictions should be considered in addition to (or in lieu of) regulations that would otherwise be limited to the designation of permissible routes or the prescription of standards for route selection, and (b) the benefits of regulations that would simply divert traffic to better track would be limited by the fact that most accidents are not track-related and that accidents on better track tend to be more severe.

POSSIBLE REGULATORY APPROACHES

If the federal government were to regulate the routing of rail shipments of hazardous materials, net societal benefit (or disbenefit) and whether that would be the most cost-effective way to achieve further safety, are uncertain. Some reasonable conjectures about possible regulatory approaches can be made, however, on the basis of experience in the highway mode. DOT Docket HM-164 led to the rules that trucks carrying highway route-controlled quantities of radioactive shipments are restricted to the Interstate highway system (or to minimum-risk routes identified by states) because those roads are generally safer than others, and that beltways must be used whenever possible to avoid going through urban areas. Docket HM-203, which is in the stage of proposed rulemaking, considers the possibility of extending restrictions such as these to other hazardous materials.

By analogy, FRA's track class system for regulating train speeds would be convenient for restricting the routes of trains carrying certain hazardous materials shipments (the classes are numbered 1 to 6, ranging from worst to best), although certain nontrivial difficulties must be overcome. Better information is needed to estimate the denominators (i.e., traffic volumes) of accident rates by track class; there is only a limited public record of which track is in which track class; and track class changes over time as track conditions change. Yet, none of these obstacles is insurmountable, and a regulatory approach can be envisioned in which the most hazardous shipments would be restricted to the highest available class of track on the set of plausible routes between every origin and destination. Of course, this approach assumes that higher classes are substantially safer than others when the FRA speed limits are obeyed, which may not be the case (depending on how safety is defined), considering that the original intention of the track class system was to achieve equal safety across all classes. Moreover, such an approach would not by itself discourage routing through urban areas—it might actually encourage it—and compliance would be far more difficult than in the highway mode because of a host of operational

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complications related to train scheduling, car blocking, and interlining between railroads.

Minimum population exposure would be another possible basis for restricting routes, but even apart from an earlier observation made by Glickman (*1*) that this criterion would in some cases result in an increase in risk because of longer distances associated with more circuitous routes and higher accident rates associated with diversion to lower-quality track, there is a conceptual pitfall that must be avoided: an exposure of 10,000 persons/mi over 10 mi on one route from A to B is not the same as an exposure of 1,000 persons/mi over 100 mi on another route, even though both routes have the same total population exposure of 100,000 persons. The reason is that the number of expected fatalities caused by an accidental release depends on the population density.

Generally speaking, use of any single-risk factor such as track class or population exposure is insufficient, because the combination of multiple factors matters. Whether the regulatory approach is to designate which routes must be used, declare which routes are prohibited, or let the transporters select their own routes as long as they follow certain procedures or meet certain standards in the process of doing so, all pertinent factors must be taken into account.

Another regulatory approach that could be pursued in addition to, or instead of, route restriction is mandatory speed reduction. The degree to which such a measure would reduce the probability that an accident will occur is unknown, although accident reports show that the number of cars damaged or derailed in a mainline derailment—which is an indication of accident severity—tends to increase as the reported speed of the train increases. This number was found to be roughly proportional to the square root of the train speed in the report by Nayak et al. (*2*). To determine from the existing statistical evidence what the overall benefit of a speed reduction policy would be does not appear possible; more extensive engineering analysis is warranted, probably involving the use of simulation models to relate train dynamics to track conditions.

The 1979 near-disaster in Mississauga, Ontario, not only drew a lot of attention, but it also spawned a good deal of research about railroad operations in the Toronto area and elsewhere in Canada, some of which has addressed the speed issue. Speaking on behalf of CP Rail, Kelsall (*3*) cited a study that showed that schedule losses would increase by 174 min for a speed reduction from 35 to 25 mph, creating ripple effects on throughput and marshalling operations elsewhere in the system. Although the report of the Toronto Area Rail Transportation of Dangerous Goods Task Force (*4*) did not advocate such action, the consultant's input to that report provided by Delcan (*5*) recommended that speeds be reduced to the range of 35 to 45 mph.

A federally imposed slow order on certain hazardous materials trains in the United States would be relatively simple to enforce, but whether it would make sense in terms of costs and benefits and whether it would keep risks in urban areas down to an acceptable level have not been determined. Other dimensions of the speed reduction argument that would have to be considered are the operational complications and safety implications of having reduced-speed trains that carry hazardous materials share the same track as normal-speed trains. Unless this situation were avoided by judicious scheduling or by slowing all trains down on the affected routes, the need for additional passing maneuvers might introduce associated risks.

INSIGHTS FROM ACCIDENT EXPERIENCE

Historical accident experience provides some insight into the way that routing restrictions would be expected to affect the frequency and severity of accidents involving hazardous materials. The following observations are based on previously published statistics that are repeated in the accompanying tables.

Track defects are the largest single cause of train accidents, but even if that cause could be totally eliminated by rerouting or other measures, the decline in the number of accidents would be limited to 37.3 percent, and the decline in the level of damages to railroad property to 31.8 percent, according to 1985 FRA reports, as presented in Table 1. The decline in the number of mainline derailments involving releases, amounting to 43.6 percent on the basis of all reports from 1978 to 1986, as presented in Table 2, would exceed the decline in the total number of accidents. Equipment failures, which account for 16.3 percent of all accidents and 33.4 percent of mainline derailments with releases and cause the most damage per accident, would still remain. These statistics indicate that even under the most optimistic scenario, the process of rerouting trains to better track would not be a panacea for concerns about rail safety.

The statistics in Tables 3–5, which present accident experience by track class, provide additional insight into the effects of rerouting. Table 3 indicates that diverting traffic to better track (higher track classes) would create a higher proportion of accidents caused by equipment failures (37.5 percent on Class 4 and 55.1 percent on Classes 5 and 6), which according to Table 1 tend to cause the most damage per accident. Table 4 indicates that the average damage per accident due to all

TABLE 1 TRAIN ACCIDENTS BY CAUSE, 1985 (*6*)

	Track Defects	Equipment Failures	Human Factors	Other Causes	All Causes
Number of Accidents	1,280	559	999	592	3,430
(% by Cause)	(37.3)	(16.3)	(29.1)	(17.3)	(100.0)
Total Damage ($M)	59.7	47.6	46.6	34.1	188.0
(% by Cause)	(31.8)	(25.3)	(24.8)	(18.1)	(100.0)
Damage per accident ($K)	46.6	85.2	46.6	57.6	54.8

TABLE 2 MAINLINE DERAILMENTS BY CAUSE, 1978–1986 (*7*)

	Track Defects	Equipment Failures	Human Factors	Other Causes	All Causes
Percent with Releases	43.6	33.4	7.3	14.8	100.0

TABLE 3 TRAIN ACCIDENTS BY TRACK CLASS AND CAUSE, 1985 (*6*)

	Track Defects	Equipment Failures	Human Factors	Other Causes	All Causes
Accidents in Track Class 1	678	125	545	226	1,574
(% by Cause)	(43.1)	(7.9)	(34.6)	(14.4)	(100.0)
Accidents in Track Class 2	208	66	154	93	521
(% by Cause)	(39.9)	(12.7)	(29.6)	(17.8)	(100.0)
Accidents in Track Class 3	153	151	93	123	520
(% by Cause)	(29.4)	(29.0)	(17.9)	(23.7)	(100.0)
Accidents in Track Class 4	76	151	77	99	403
(% by Cause)	(18.8)	(37.5)	(19.1)	(24.6)	(100.0)
Accidents in Track Class 5 & 6	6	27	9	7	49
(% by Cause)	(12.2)	(55.1)	(18.4)	(14.3)	(100.0)

TABLE 4 TRAIN ACCIDENTS BY TRACK CLASS, 1985 (*6*)

	Track Class							
	1	2	3	4	5	6	Unknown	Total
All Accidents	1,574	521	520	403	49	10	353	3,430
(% by Track Class)	(45.9)	(15.2)	(15.2)	(11.7)	(1.4)	(0.3)	(10.3)	(100.0)
Damage per Accident ($K)	26.1	51.5	103.9	128.1	138.6	36.6	21.0	54.8

TABLE 5 MAINLINE DERAILMENTS BY TRACK CLASS, 1976 (*2*)

	Track Class				
	1	2	3	4	5 & 6
Number of Derailments	830	1084	1346	672	157
Billion Gross Ton-Miles	15.6	62.8	241	1,140	187
Derailment Rate (per BGTM)	53.2	17.3	5.6	0.6	0.8
Number of Cars Releasing per Hundred Derailments	1.00	2.55	4.13	4.61	6.21

causes tends to increase in higher track classes (amounting to $46.6K in Classes 1 to 3, and $128.2K in Classes 4 to 6). Table 5 indicates that the average number of hazardous materials cars that release per derailment also tends to increase in higher track classes.

The disadvantages of the higher severity of accidents on better track that are demonstrated by these results need to be considered relative to the advantages of lower accident rates. This tradeoff is immediately clear in the case of derailments, where Table 5 indicates that the rate per billion gross ton-miles (BGTM) tends to decrease in higher track classes. If the BGTM estimates by track class in Table 5 are applied to the accident frequencies in Table 3 and the damage statistics in Table 4 (a rough approximation, given that the data are from different time periods), the rate of accidents per BGTM and damage per BGTM also tend to decrease in higher track classes, as presented in Table 6.

In summary, any regulation that encouraged or required hazardous materials traffic to be diverted to better track, where trains are generally permitted to go faster, would tend to reduce the total number of accidents and the associated total damage to track structures and equipment, but would also tend to increase the average number of cars releasing hazardous materials dramatically.

REVIEW OF RELATED RESEARCH

The consequence of a transportation release accident is commonly estimated by sizing up the expected impact area and using a population exposure estimate to determine the expected number of fatalities or injuries in the area. On a given route segment, the risk of an accident can then be determined simply by multiplying the probability that an accident will occur (based on statistical evidence, tempered where appropriate by expert judgment) by the expected consequence if it were to occur. In more elaborate analyses, the risk is expressed instead not as a point estimate but as the estimated frequency distribution of all the different possible magnitudes of the consequence, which is customarily displayed as a risk profile in complementary cumulative form. Either way, the route segments risks can be combined to obtain the risk for the entire route by doing the appropriate calculations.

Risks were expressed both as point estimates (the expected number of fatalities per year) and risk profiles (stressing the annual frequency of high-fatality accidents) in the derailment risk analysis done by the Transportation Systems Center (TSC) in the early 1980s [as described by Glickman and Rosenfield (*8*)], in which catastrophic risks were the principal concern. Consequences were estimated in that analysis by combining the data base of linkwise population densities (constructed in the manner described in the next section) with the expected size of the lethal impact area (assumed to be circular) on any given link in the event of a release of any given type of non-radioactive hazardous material. These estimates were then factored into the risk calculations, which showed that there was a 95 percent chance of no fatalities in a derailment release accident and less than a 1/100,000 chance of 100 or more fatalities. The individual risk of death in a year was found to be about 1 in 32 million, assuming that the entire U.S. population was exposed.

The routing impact study that accompanied this analysis, referred to in the comments on minimum population exposure in the preceding section, used a simpler approach to estimate the expected annual number of casualties (fatalities plus injuries) associated with any given population avoidance scenario. The conclusion was reached that rerouting to minimize population exposure could reduce the annual expected number of casualties by almost 50 percent nationwide (from 240 to 124) if radical changes in traffic patterns were made, but that some urban areas might suffer at the expense of others, especially if traffic were diverted to poorer track having higher accident rates.

The most detailed analysis of hazardous materials train routing through a localized area was performed by the Toronto Area Rail Transportation of Dangerous Goods Task Force (*4*). The work involved a variety of contractors who spent 2 years looking at many different aspects of the situation. Eleven different candidate routes for through trains were selected and their risks and costs were compared. The conclusion was reached that rerouting was not warranted on the grounds of risk reduction. Nevertheless, on the basis of the observations that were made about the influence of train speed on risk, the Canadian transport minister decided to lower the speed limits on four high-risk track segments. The report also recommended that in the long term, compatible-use buffer zones should be defined and redeveloped adjacent to hazardous materials routes. The shorter-term recommendations include the notions of establishing a nationwide, publicly known track class system that would take nearby population density into

TABLE 6 APPROXIMATE ACCIDENT RATES AND DAMAGE RATES BY TRACK CLASS

Track Class	Accidents	Damage* ($M)	BGTM	Accidents per BGTM	Damage per BGTM
1	1,574	41.1	16	98.4	2.6
2	521	26.9	63	8.3	0.4
3	520	54.0	241	2.2	0.2
4	403	51.6	1,140	0.4	0.05
5 & 6	49	7.2	187	0.3	0.04

*(number of accidents) x (damage per accident)

account, and instituting an accelerated program of track improvements (concrete ties, direct fixation fasteners, and continuous welded rail) in densely populated urban areas.

Other developments in the application of risk analysis to railroad problems outside the United States are also relevant to the assessment of routing options. These include, in reverse chronological order, the British Health and Safety Executive's comprehensive study of chlorine, liquefied petroleum gas (LPG), and ammonia routes using probabilistic risk assessment, which began in 1985 and is still ongoing; the study done for industry by Saccomanno et al. (*9*), which closely examines the statistical basis for accident rates in Canada and includes a case study for LPG; and the extensive study of the risks of chlorine and ammonia transport in the Rijnmond region of the Netherlands, sponsored by the Ministry of Housing, Physical Planning, and Environment (*10*).

Three recent American developments involving the rail transportation of nonradioactive hazardous materials are the route-specific analysis of LPG and chlorine transportation that was performed for the FRA and summarized by Raj and Glickman (*11*), the transportation risk analysis capability developed for the Chemical Manufacturers Association by Pickard, Lowe, and Garrick, Inc. (*12*), and the study of LPG and natural gas liquids by truck and train that was performed by Arthur D. Little, Inc. (*13*), for Santa Barbara County in California. But most of the recent activity related to train routing in this country has dealt with spent nuclear fuel and high-level radioactive waste, typically relying on the INTERLINE model of the U.S. rail network to find the most direct route or the least-exposure route, and the most recent version of the RADTRAN model to calculate the associated point estimate of risk. This approach is illustrated by the study of the national transportation impacts of the commercial radioactive waste management program done by Cashwell et al. (*14*). The two models reside at Oak Ridge National Laboratory (ORNL) and Sandia National Laboratories, respectively.

Some recent advances in computer systems may improve the ability to analyze and weigh the issues involved in routing hazardous materials trains to reduce risk. The digital cartographic data base being incorporated into FEMA's Integrated Emergency Management Information System (IEMIS) contains geographic information taken from large-scale, high-resolution maps, including the 1:100,000 scale TIGER file. The system also has map editing features, meteorological aspects, graphics software, and expert system capabilities, all of which may help to improve the analysis of rail routing scenarios. Some of the same information has already been incorporated elsewhere into new geographic information system software developed specifically for transportation systems analysis at TSC and by a number of commercial vendors.

A powerful workstation capability has also been developed by the International Institute for Applied Systems Analysis (IIASA) in Vienna for processing and displaying high-resolution geographic information. With support from the Dutch government, this system has been enhanced with a hazardous materials data base, a transportation network generator, and a risk assessment module based on the SAFETI software package, which takes in meteorological information, land use data, and other risk factors, and produces sophisticated graphics displays that superimpose risk contours onto detailed location maps. A recent report from IIASA (*15*) documents how the system is being used to analyze the risks of chlorine transportation on railroads in the Netherlands.

POPULATION EXPOSURE ESTIMATION

Population exposure is obviously a major consideration in analyzing the risks of hazardous material train routes. Even low levels of radioactive exposure cause great public concern because of health effects such as latent cancers and genetic defects, and in the case of many nonradioactive hazardous materials, a release that results in a fire, explosion, or toxic vapor cloud can expose a large segment of the general public to immediate harm. High concentrations of residential and working populations are the primary focus in most accident scenarios, but motorists, students, shoppers, and others can also be exposed to risk, depending on the time, location, and severity of the accident.

The TSC derailment and routing studies pioneered the notion of systematically combining census data with the attributes of a transportation network model for the purposes of hazardous materials risk assessment. Residential population counts from the 1970 U.S. Census were updated to produce 1976 estimates for every enumeration district in the 48 contiguous states. Then the population within a mile-wide band centered on each of 17,000 links of the railroad network model was estimated following the method of Haaland and Heath (*16*), in which the centroid of every enumeration district was assigned to the appropriate cell of a national latitude-longitude grid. The network model was superimposed on this grid and, for each link, the populations in the cells within or incident to the surrounding band were accumulated. The result was then divided by the corresponding area to yield an estimate of the population density. The same general approach for estimating population exposure, in which rail network models similar to the TSC one are used, has been used by ORNL and ALK Associates of Princeton, and by researchers at Vanderbilt University who are concerned primarily with highway applications. ORNL and ALK were recently engaged by the U.S. Department of Energy to analyze the routing of rail shipments of radioactive debris from Three-Mile Island to the Idaho National Engineering Laboratory. For a discussion of this experience, see the review conducted at TSC by DOT's Research and Special Programs Administration (RSPA) (*17*).

In their more localized study of the risks on two highway routes and one rail route that are used to transport LPG through Toronto, Saccomanno et al. (*9*) estimated population exposure in much finer detail. Using land use maps based on aerial photographs of the area, they estimated the population in each of the buildings adjacent to roads and railroad lines, distinguishing among single-family dwellings, apartment buildings, townhouses, industrial and office buildings, commercial buildings, and schools, thereby producing estimates of the exposed residential population (which they assumed to be constant throughout the day and night) and the exposed employment population (which they assumed to be daytime only).

In the highway mode, the nonradioactive routing guidelines of FHWA, as described by Barber and Hildebrand (*18*), suggest that census tract maps be used to determine population exposure and that employment exposure also be taken into account. Similar suggestions were made in the guidelines for routing radioactive materials on highways that are published by DOT's Research and Special Programs Administration (*19*). An illustration of an application of the FHWA approach to the Dallas-Fort Worth area was provided by Kessler (*20*).

Of course, the estimate of risk on a route segment is only as good as the information that goes into its calculation, and the method for estimating population exposure using the TSC/ORNL/ALK models has some critical deficiencies originating in the fact that the original FRA network model was not intended for hazardous material routing and risk analysis. One problem is that the network links and nodes do not always line up well with the actual locations of tracks and junctions; in fact ORNL has indicated that the level of precision is only about 10 km [see Committee on Government Operations (*21*, p. 201]. Another problem is that the practice of using a single number to represent the estimated population exposure on each link masks significant variations in the exposure level over the course of the tens or hundreds of miles of a link's length. Unless the links are disaggregated to follow the shapes of the actual routes more closely (to intercept the correct census districts and to avoid the masking effect), serious distortions in the measurement of population exposure can arise. For example, if link A is long and passes through mostly rural areas except for one large urban area, whereas link B is short and passes through a number of small urban areas, then the calculated population density may be lower on link A because so much of its length has a low population. Clearly, each of these links should be split into urban and nonurban segments.

A similar problem is created by the nonuniformity of accident rates on links. Accidents depend on the nature of the track structures and grade and curvature features, along with other factors that contribute to operating hazards. If these characteristics vary substantially from one part of a link to another, then they cannot be adequately represented by a single average value for the accident rate. Therefore, if either track class or speed limit is used as a surrogate for operating conditions, its value needs to be ascertained along each segment of the links on the routes of interest.

Another refinement would be to make the size of the surrounding bandwidth that influences link-by-link population exposure estimation depend on the hazardous material and on the volume of the containment vessel, because the size of the impact area is a function of these factors. The importance of this consideration was demonstrated by Chin and Cheng (*22*) who showed that the ORNL national highway network model produces significantly different minimum-population routes between Hoboken and San Diego, depending on whether the band around each link is 1, 3, or 5 mi in width.

The need to address time-of-day variations in population exposure was demonstrated by a study of weekly traffic patterns in Washington, D.C., which found that the population in business districts increased by a factor of as much as eight from night to day, while the population in residential districts increased by a factor of as much as two-and-a-half from day to night (*23*). Thus, the advisability of operating on a particular route can depend on the time of day at which the shipment is made. If time-of-day variations are ignored because residential census data alone are used, then it is conceivable that the following kind of error could be committed: the safest route appears to be one that goes through a busy commercial area in which few people live, and therefore a hazardous materials train is routed through that area during the busiest hour of the workday, even though the exposed population is actually high.

Time-of-day population variations also need to be taken into account because temperatures tend to be cooler and atmospheric conditions tend to be more stable at night, so that the behavior of a gas cloud emanating from a release will depend to a large degree on when the release takes place. In many cases, it will be better if the cloud is blown away by the wind, as long as this process does not result in a highly toxic vapor being sent into a highly populated area that would otherwise be spared. Yet another reason to be concerned about time-of-day variations is that the consideration of curfews as an alternative to, or in addition to, routing restrictions requires that population exposure be estimated as a function of the proposed curfew periods.

Unfortunately, the only apparent source of comprehensive employee population statistics at the federal level is the manufacturing census, and only about one of every five American workers is employed in the manufacturing sector. Thus, only broad-brush attempts to account for the effects of time-of-day population variations on risk may be possible when large regions of the country are being investigated, and more specific treatments of these effects may have to be limited to localized routing studies in which land use data and other local information are available.

A final observation on population exposure estimation has to do with the importance of basing routing decisions on the combined influence of risk factors rather than on their individual magnitudes alone, a point that was raised earlier but which is worth reiterating in the context of this discussion. Measures of individual factors such as minimum total population exposure that contribute to risk should not be used as a sole criterion for routing because it is important to know whether locations of high population exposure coincide with locations where accident rates are high, and it is impossible to tell whether this is the case on the basis of an average value that creates the potential for distortion by smearing the variations in population exposure along a route.

PREFERRED ROUTE DETERMINATION

There are basically two ways to determine the most favorable routes for hazardous materials shipments: (a) identify the candidate routes and compare them according to some criterion, and (b) identify the criterion of interest and generate the optimal route that best satisfies it. If safety is the only concern and only one aspect of risk is of interest (e.g., fatal accidents), then a single criterion will suffice. But if there are other concerns such as cost, some of which may be in conflict with the primary concern or with each other, or if other aspects of risk are also of interest (e.g., nonfatal accidents), then there may be no single best route and the process of comparing or generating routes will have to be repeated for each different point of view.

Unless there are many candidate routes—a condition that is not likely to hold over shorter distances or in regions where the rail system tends to have a tree structure, with only one path between any pair of nodes—and unless other complications such as scheduling requirements are introduced, the first way will generally be satisfactory; that is, simply enumerate the routes, calculate the risk for each one, and compare the results. The second way requires estimating the risk on every link of a network model and then using a pathfinding (shortest-path) algorithm to find the combination of links that, when they are strung together, constitutes the least risky way to get through the network.

Pathfinding algorithms are easy to program on a computer and run fast even on large networks. Because they are insensitive to what the numbers on the links indicate, the algorithms can be used to find an optimal path on the basis of any criterion for which the link numbers are additive. (Point estimates of risk are usually additive, as are cost estimates.) Such algorithms provide the most efficient means of finding the best route for a long trip through a complex network. Pathfinding algorithms have been used extensively with the TSC/ORNL/ALK models to estimate actual routings of cross-country and regional movements of chemicals, petroleum products, high-level nuclear waste, and other freight. The numbers on the links in these applications are their actual lengths adjusted by a factor that makes mainline links more attractive (shorter) than branchline links, A-mainline links more attractive than B-mainline links, and A-branchline links more attractive than B-branchline ones. These models may not truly simulate actual routing decisions, which are in reality based on a complex combination of considerations such as operating efficiency, scheduling requirements, freight rates, and train make-up. Although their accuracy has never been scientifically validated, they are useful nonetheless.

The research related to the determination of preferred routes that has been published in the technical literature can be divided more or less into two groups: (a) risk assessment procedures that could have been used in conjunction with route enumeration or generation, but were not, and (b) theoretical route generation methods that could have been used in conjunction with risk assessment, but were not. The first group is represented by the Battelle Pacific Northwest Laboratory studies performed for the U.S. Department of Energy (DOE) on propane and chlorine transportation by rail, as documented by Geffen et al. (*24*) and Andrews et al. (*25*), respectively. The second group is represented by Batta and Chiu (*26*), who describe a relatively abstract approach for dealing with variations in population exposure when finding least "obnoxious" routes by means of a shortest-path algorithm, and by Turnquist (*27*), who proposes a hybrid simulation and shortest-path scheme that accounts not only for multiple criteria and for uncertainties in their measurement, but also for scheduling considerations.

Multiple-criterion pathfinding algorithms have the advantage of reducing the computational effort that is required when a number of different measures of effectiveness are of interest. Algorithms such as the one described by Henig (*28*) are capable of efficiently identifying the set of Pareto-optimal solutions to the routing problem, that is, those solutions with the property that if one of the measures could be improved by changing routes, then another one has to be worsened. Knowledge of this set of routes provides a clear understanding of the tradeoffs that exist among alternative routes. The entire set of Pareto-optimal solutions could be identified instead by successive applications of a single-criterion algorithm, but not necessarily by using a weighted sum of the individual objectives (as in the case of the TRANSNET at Sandia National Laboratories), an approach that also suffers from the fact that it is difficult at best for decision makers to articulate in advance the values of the weights that reflect the relative importance (to them or to society) of the various criteria.

Available techniques for preferred-route determination are preferable. However, risk assessment models should be integrated into the process of applying these algorithms. Ideally, such models would be computationally straightforward yet sensitive to variations in the major factors that affect risk. When supplied with adequate data and accompanied by an appropriate network model, these analytical tools would produce credible benefit-cost estimates for evaluating the options for potential regulatory action.

CONCLUSION

A complex combination of factors contributes to the risk of hazardous materials transportation, including (but not limited to)—on the probability side—track defects, equipment failures, and human factors, and—on the consequence side—meteorological factors, population exposure, and deficiencies in emergency preparedness. Some factors such as train speed could affect both the probability and consequence of an accident. Research on the advisability of regulating railroad routes to achieve risk reduction—whether by designating a system of preferred routes or by promulgating a set of guidelines for route selection—has to give due consideration to all these factors and their interactions, as well as to the direct cost implications and indirect economic effects of any proposed regulations. The importance of this observation is demonstrated by the possibility that routing based solely on population avoidance could result in higher risks in some locations, and that diverting traffic to better track without reducing train speeds would likely result in fewer but more severe derailments.

If the regulatory objective is to designate a system of preferred train routes for certain hazardous materials, then on the basis of the discussions in the preceding sections, the following research requirements should be met: (a) a national network model should be developed that is sufficiently accurate and detailed enough to reflect important locational variations in population exposure and operating conditions; (b) a corresponding data base reflecting track class or other link-by-link measures of track condition should be established; (c) improvements in the methods for determining the corresponding population exposure estimates, including a practical way to account for time-of-day variations, should be made; (d) existing models for estimating probabilities and consequences of average-severity and high-severity accidents should be reviewed and, if necessary, modified or replaced; (e) the functional relationship between reduced operating speeds and accident causation needs to be better understood; and (f) a methodology for estimating the economic effects of potential routing regulations should be established.

Alternatively, if the regulatory objective is to establish standards and associated guidelines for selecting preferred routes (as has recently been proposed for the highway model in proposed bill H.R. 3520 in conjunction with reauthorizing the

Hazardous Materials Transportation Act), then a less ambitious research effort needs to be undertaken to identify the soundest set of principles for routing. By means of a series of case studies of carefully selected situations that are representative of the range of possibilities that might be encountered, a number of analyses could be performed to determine the relative effectiveness of different types of guidelines. Items (d)-(f) would still be required in their entirety, but items (a)-(c) could be scaled back and produced only for the selected situations, thereby reducing the data collection requirements considerably. Although not as comprehensive as a designated route system, this approach does have the virtue of being more flexible and more reflective of localized conditions.

In either case, it is clear that the analysis of regulations that would reroute railroad cars laden with hazardous materials is far from a simple task, and that it must be performed judiciously because of the potential public safety implications and economic ramifications.

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Projecting Hazardous Materials and Wastes in Transportation: Conceptual and Methodological Factors and Application

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Future quantities and routings of hazardous materials shipments were projected for the year 2000, on the basis of the results of previous Arizona transportation surveys. Projections were made of internal shipments of gasoline, propane, and acids. Interstate shipments, hazardous waste, and nonbulk shipments were also projected. Routing maps of Arizona depicting the projected shipments were then created. A data base information system was developed to store hazardous waste shipment data for the year 1986, and information from this data base was used to project volumes and routings of these shipments. Despite the uncertainties, the effects of new regulations and waste minimization activities were incorporated. Similar projection routing maps were developed for hazardous materials. The results provide a picture of future hazardous materials transportation on Arizona highways and a basis for conducting risk analysis. Methodological issues and data availability problems are addressed to model projections at the state level.

Approaches used to project hazardous materials shipments and routing patterns in the state of Arizona are described. The projections are based on a 1985 study (*1–3*) of the movement of hazardous materials in Arizona, and further analysis of available transportation data subsequent to the initial study. However, the 1985 statistics serve as a baseline for the projection of shipments in the year 2000.

States have been increasingly interested in developing an understanding of the volumes and types of dangerous substances that are transported within their jurisdictions. Some of this interest is related to the need for information to enhance hazardous waste management. Also, this interest reflects the need for information to help in more effective planning in the area of hazardous materials transportation accidents. Several states and cities have recently undertaken surveys of hazardous materials transportation patterns to conduct risk analysis for routing decisions.

Projections of hazardous materials shipments and routing are difficult, and are based on assumptions with high levels of uncertainty. First, for most states the available data bases are not comprehensive for the entire road network nor do they include the full range of hazardous materials. Second, the available data bases are derived from sample surveys that may have serious projection limitations, because of dubious generalizability. The additional problem of many of these surveys (including the 1985 Arizona survey) is that they do not provide trend data; the data characterize hazardous material shipments for one point in time. As a result, projections, by necessity, depend on indirect methods (such as using regression analysis that indicates a relationship between hazardous materials volume and projected growth within a sector of the economy).

Although several studies have attempted to estimate current shipment levels of hazardous materials, no other investigations have been found that try to develop an approach that characterizes the full range of shipments on a route-by-route basis, that is, of statistical significance that can be generalized to the state as a whole. Forecast assumptions for each category of hazardous substances in transportation—hazardous waste, through-traffic interstate shipments, intrastate bulk chemical shipments, and hazardous materials entering the state—are also developed. A systematic approach is used that is comprehensive in scope, that has attempted to reduce the uncertainties identified, and that can serve as a model for other states' hazardous materials shipment forecasts.

Projections of hazardous materials shipments were accomplished by examining assumptions in four distinct areas of hazardous materials transport. The first area consisted of examining the intrastate shipment patterns of bulk hazardous goods, which included gasoline, propane, and acids. Based on the 1985 baseline study and changes to date, assumptions were developed for each bulk product and projections made for the year 2000. For each group of hazardous material, projected routing patterns were determined.

The second component of hazardous materials shipments for which projections were undertaken was the through-traffic shipments. These shipments refer to vehicles that enter the state, do not unload their cargo, and exit the state. Over 50 percent of hazardous materials shipments that enter Arizona are through-traffic shipments. The third component involves the nonbulk hazardous materials shipments that enter Arizona for industrial and agricultural processing. The expansion of this category is related to growth in the sectors of the economy that use these materials.

The fourth area of attention focuses on the pattern of transporting hazardous waste, which falls under the authority of the Resource Conservation and Recovery Act (RCRA). In projecting hazardous waste shipments, shipment data were collected for 1983 through 1986, including survey efforts.

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Three factors will significantly affect the volume of waste to be transported from the state in the future:

1. Continuous growth of the high technology industry in the state (which is a major generator of hazardous waste),
2. Efforts at hazardous minimization and recycling, and
3. Implementation of the small-quantity hazardous waste generator regulations.

A substantial amount of uncertainty is associated with these factors. Consequently, the projections of hazardous waste shipments were built around three scenarios of possible eventualities.

INTERNAL SHIPMENTS OF BULK HAZARDOUS MATERIALS: PROJECTION ASSUMPTIONS

The three major subclasses of bulk shipments are gasoline, propane, and acids. The sum of these three bulk commodities constitutes more than 80 percent of all the internal bulk shipments of hazardous materials on Arizona highways. The goal was to project the volume and routings of gasoline, propane, and acids on the major highway routes within Arizona for the year 2000.

Gasoline shipments originate in Phoenix and Tucson gasoline tank farms (to which gasoline is brought from neighboring states by pipeline and stored before distribution) and end at different gas stations inside the state. To forecast gasoline sales for the target year, correlation analysis of historical gasoline sales data with key socioeconomic factors was undertaken. Historical data of gasoline sales were obtained from the Motor Vehicle Division of the Arizona Department of Transportation (ADOT), and three socioeconomic variables—automobile registration, population, and employment data that were obtained from the Arizona Department of Economic Security (ADES). Data were secured for the county level and regression analysis was conducted separately for each of the three socioeconomic factors with gasoline sales data. The best relationship for gasoline sales was observed to be with population. Therefore, 15 linear regression equations were developed for the 15 counties in Arizona, and county population forecasts were used in these equations to project gasoline sales.

Gasoline shipments from Phoenix and Tucson to the various smaller communities in Arizona are done by 8,500-gal tank trucks. There are some Arizona border communities whose gasoline needs are met by out-of-state shipments rather than by shipments from the tank farms. These are basically the communities that lie on or near the major highway routes like I-40, I-10, and I-8, and the state's ports of entry. To incorporate this feature in the projection, the volumes of projected gasoline sales were adjusted by a factor derived from the population that will be served by the domestic tank farms. After this adjustment was made, projected gasoline volumes were converted from gallons to number of truckloads. Once the number of truckloads to each of the counties and communities was established, their respective routes from Phoenix or Tucson to those communities were defined. During the 1985 study, a survey of truck drivers was conducted to ascertain the preferred truck routes in Arizona. The results of this survey and engineering judgment were used in assigning the projected routes. Special care was taken for counties that are equidistant from Phoenix and Tucson. They were divided into regions, depending on proximity and accessibility from Phoenix and Tucson.

Propane is brought into Arizona mainly from Gallup, New Mexico, and partly from Anneth, Utah. Although some of the propane shipments to the in-state distribution centers are carried by railroad, most are by tank trucks on major highways originating in the northeast region. They are then distributed to the retail shops in smaller bulk shipments.

Propane suppliers were contacted for information on their monthly shipments. The number of shipments originating from out-of-state locations and destined to distribution centers in Arizona was identified. Furthermore, shipments originating from distribution centers and destined to companys' retail plants in Yuma, Chandler, Glendale, and other communities were also identified, including the primary routes over which propane shipments are transported.

Projected propane consumption data are not readily available. A report published by the Department of Energy (DOE) documented national energy pricing and consumption trends. The following facts, that have relevancy to the projection analysis, were noted from this report. The price of oil is expected to remain stable in the 1980s. After 1990, however, the price is expected to increase at the rate of over 4 percent per year. The price of natural gas is expected to follow the same trend as gasoline until the beginning of the 1990s. In the late 1990s, the price of natural gas will rise again and will increase every year at the same rate as oil. The history of natural gas in the United States shows a declining trend and is expected to decline rapidly from the late 1980s onward.

From this information, and by assuming that Arizona generally follows national trends in this area, the consumption of propane and other natural gases used by the residential, commercial, and industrial sectors is expected to increase (considering 1984 as the base year) slightly every year until mid-1990, and then decrease after the turn of the century. The consumption figures for gas in quadrillions of BTUs in the year 2000 is expected to be the same as in 1988. Thus, the volume and pattern of propane distribution in 1988 can be assumed to be the same as the projected propane volumes.

An indirect approach was used for the projection of bulk shipments of acids for the year 2000. Acids are generally used by the high-technology manufacturing industries, mining industry, and utilities. Because acids are not manufactured in Arizona, they are imported from outside the state and are stored in warehouses in the Phoenix and Tucson areas for further distribution to individual companies, or are transported directly to individual mines or large industries. For the purpose of projecting acid consumption in the year 2000, it was necessary to estimate the growth of these industries. Arizona has experienced a rapid growth in the area of high-technology industries. ADES periodically projects the employment level in various sectors of the economy such as manufacturing, construction, mining, and services. Figures 1 and 2 show the projections for the manufacturing and mining sectors. High-technology industries, which are included in the general group of manufacturing, can be assumed to grow in the near future at a high rate until at least the turn of the century. The mining industries, on the other hand, are expected to decline, and the utilities industries are expected to expand because of the projected growth in population of the state.

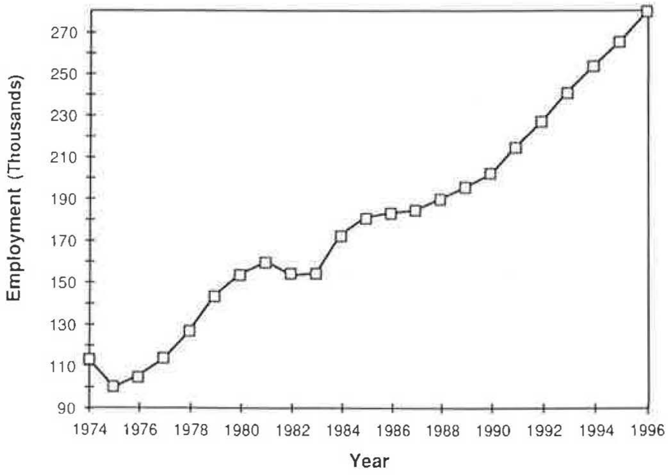

FIGURE 1 Projection of employment in Arizona in manufacturing.

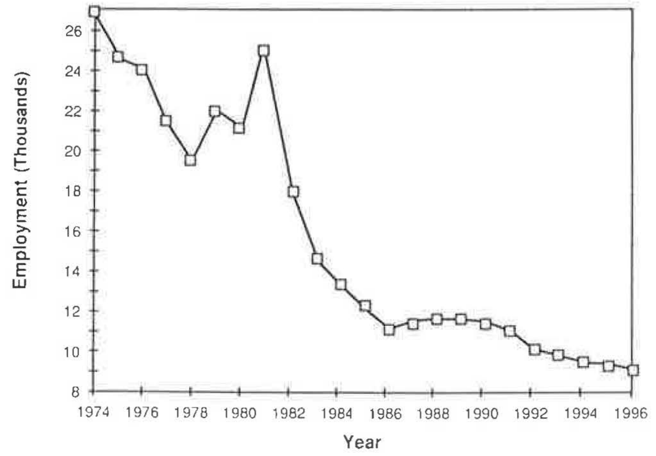

FIGURE 2 Projection of employment in Arizona in mining.

From the previous discussion, it can be assumed that the consumption of acids in the future is expected to grow, although not at as high a rate of growth as the manufacturing sector or the state population. The future volume of acids consumption can be studied under such circumstances by constructing a scenario using the trend data on economic variables. No major geographical shifts in concentration of population and industries are expected up to the year 2000. Therefore, the routings of acid shipments identified in the base year (1985) are not expected to change by the projection year.

ASSUMPTIONS FOR THROUGH-TRAFFIC AND NONBULK TYPE SHIPMENTS

Two surveys of hazardous materials carriers at the entry points into Arizona were conducted during the 1985 study (*3*). The results were used to determine the annual number of truckloads carrying hazardous materials entering Arizona. Information on the hazard class of the shipments and destinations was also collected. This information was used to estimate the number of trucks that enter but also exit without unloading, i.e., through-traffic type. Table 1 presents the statistics of that survey. However, the results depicted are not the typical ones, because during the time of the surveys the gasoline tank farms at Phoenix and Tucson were shut down and the demand for gasoline and related materials was met by imports by trucks from neighboring states. The flammable and combustible materials shipments disrupt the normality of the statistics. Under normal circumstances, most of the gasoline supply (approximately 80 percent) would have originated from the internal tank farms (some of the border communities are served by neighboring states). Table 2 presents the hazardous materials shipment figures, after adjusting for the gasoline shipments. The results show that 56 percent of the trucks that enter Arizona also exit directly without unloading.

Because almost all entering or through-traffic materials are used by the industrial sector of the economy, these volumes

TABLE 1 THROUGH-TRAFFIC HAZARDOUS MATERIAL TRUCKLOADS BY HAZARD CLASS, 1985

Hazard Class	Entering Arizona	Through-traffic	Unloading	Percent Remaining
Flammables and combustibles	82,940	27,248	55,692	67.2
Oxidizers	3,796	2,964	832	21.9
Corrosives	22,048	13,260	8,788	39.8
Poisons	3,900	2,652	1,248	32.0
Radioactives	572	572	0	0.0
Explosives	5,876	4,992	884	15.0
Total	119,132	51,688	67,444	56.6

are expected to grow in the future at approximately the same rate as the industries that use them. Assuming an annual industrial growth rate of 4 percent for the region (based on ADES forecasts) and taking the 1985 shipment data as the base, the hazardous materials volumes should grow by about 1.8 times by the year 2000. The projected annual hazardous materials shipments by hazard class are presented in Table 3. The projected nonbulk-type shipments, i.e., oxidizers, explosives, radioactives, and poisons, are also presented in Table 3.

Final results of the gasoline shipments routing allocation were drawn on a route map of Arizona (Figure 3). This projection map shows the number of gasoline shipments in tank trucks on various segments of Arizona's highway system network. Projected volumes of propane and its shipment routings are shown in Figure 4. Using projected volumes and routings of acid shipments, a similar projection map was prepared (see Figure 5). Projections of shipment routings of nonbulk-type hazardous materials, i.e., oxidizers, poisons, explosives, flammables, combustibles, and radioactives, were also developed.

PROJECTIONS OF HAZARDOUS WASTE SHIPMENT

The movement of hazardous wastes is monitored by a manifest system that requires generators and transporters to report

TABLE 2 THROUGH-TRAFFIC HAZARDOUS MATERIAL TRUCKLOADS AFTER ADJUSTMENTS FOR GASOLINE SUPPLIES, 1985

Hazard Class	Entering Arizona	Through-traffic	Unloading	Percent Remaining
Flammables and combustibles	55,940	27,248	28,692	48.7
Oxidizers	3,796	2,964	832	21.9
Corrosives	22,048	13,260	8,788	39.8
Poisons	3,900	2,652	1,248	32.0
Radioactives	572	572	0	0.0
Explosives	5,876	4,992	884	15.0
Total	92,132	51,688	40,444	43.8

TABLE 3 PROJECTED THROUGH-TRAFFIC HAZARDOUS MATERIAL TRUCKLOADS BY HAZARD CLASS FOR YEAR 2000

Hazard Class	Entering Arizona	Through-traffic	Unloading
Flammables and combustibles	100,100	48,450	51,650
Oxidizers	6,850	5,350	1,500
Corrosives	39,700	23,900	15,800
Poisons	7,000	4,750	2,250
Radioactives	1,000	1,000	0
Explosives	10,600	9,000	1,600
Total	165,250	92,450	72,800

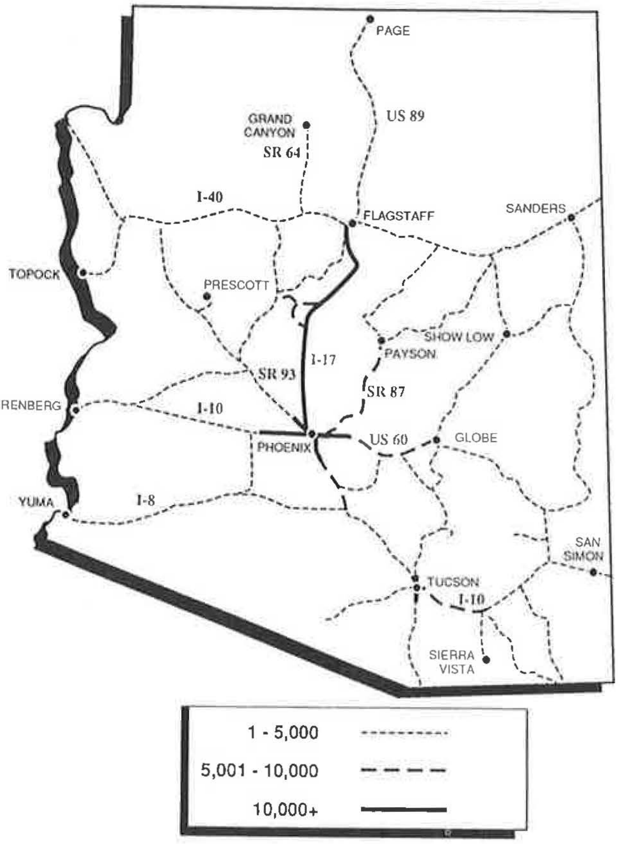

FIGURE 3 Annual truckloads of internal shipments of gasoline in Arizona for the year 2000.

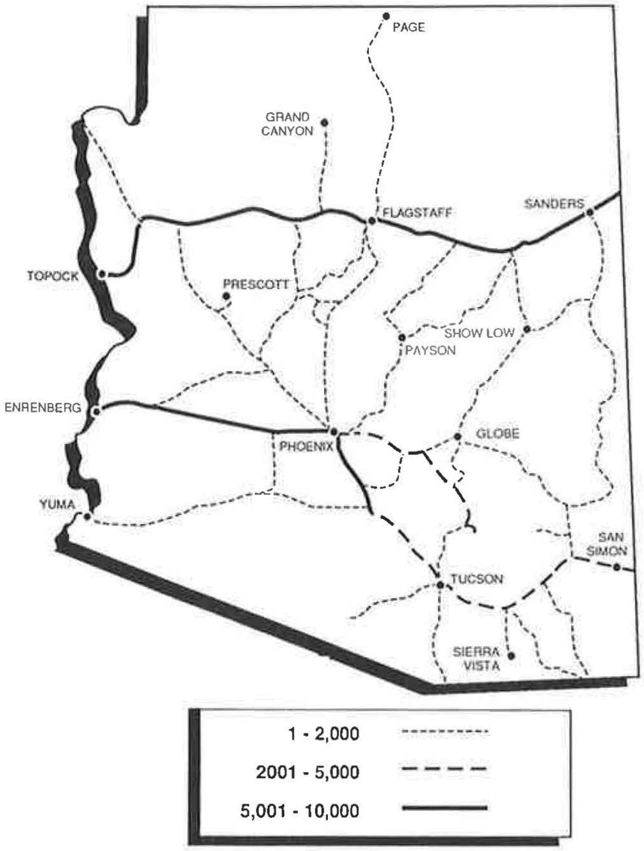

FIGURE 5 Annual truckloads of acid shipments in Arizona for the year 2000.

FIGURE 4 Propane shipments in Arizona for the year 2000.

information. This information includes the amount and type of wastes, and U.S. Environmental Protection Agency (EPA) identification numbers of the generators, transporters, and final destination sites.

In the state of Arizona, the manifests are sent to the hazardous waste section of the Arizona Department of Environmental Quality (ADEQ) after they are completed by the transporters and generators. Most of the hazardous waste generators are concentrated in and around the urban areas of Phoenix and Tucson. The disposable wastes are typically transported to nearby states that have disposal facilities, such as California, Texas, Nevada, and Utah, as there are no disposal sites presently in Arizona. Three land disposal sites in California, one in Nevada, and one in Utah are most used by Arizona's generators and transporters. A large percentage of waste is first sent to storage and treatment facilities in Arizona before being shipped outside the state. Most of the transporters are based in Arizona or are branches of multistate corporations.

The amount of hazardous wastes transported has been on the increase in the last decade. Also, the costs of handling, storage, and disposal have increased significantly. The regulations have now become stringent regarding the types and amounts of wastes generated and disposal procedures. In addition, many generators are now compelled to reuse wastes or change the industrial processes and raw materials involved to achieve lower volumes of hazardous wastes (*4*).

The 1985 study (*1–3*) conducted for ADOT was used as a base for hazardous waste projections. For the purposes of this study, information on all of the hazardous waste shipments for the years 1983 and 1984 was collected from the RCRA manifests filed with ADEQ, compiled, and stored in a data base management system in a dBASE III environment. This type of data base was the first of its kind in the United States and is helpful for studying such characteristics as the types and amounts of hazardous wastes usually produced, the major generators, transporters, and final destinations. Also conducted during this study was a survey of truckers, requesting them to answer questions regarding preferred routes from various origins to destinations. This aided in identifying the major routes of hazardous waste shipments.

Waste Generation Minimization and Recycling

Hazardous waste management has become a national issue and managing hazardous wastes to avoid adverse effects on health and environment is a complex problem. There are several strategies available today to prevent and reduce exposure to hazardous wastes. One strategy involving waste reduction was assessed by the National Research Council (*4*). Two reduction measures that are pertinent to this study are reduction in waste generation at the source, and recycling of wastes for energy or as raw material, or both. Reliable estimates on future shipments of hazardous wastes will be based on understanding the extent of waste reduction over the next decade.

Factors affecting hazardous waste reduction can be put broadly into two groups—nontechnical (institutional) and technical. The former factors include access (or lack of access) to information on how to reduce the generation of hazardous waste, access (or lack of access) to funds for capital investment in new equipment, predictability (or lack of it) of government regulation, and economic goals that determine the actions of industrial companies. The latter includes using different raw materials, modifying production processes, or redesigning products. There are a number of industrial processes generating waste and the technical approaches to hazardous waste generation reduction are many and varied. Numerous case studies are currently available that document the implementation and attendant benefits of such techniques by industries in the United States. The term "hazardous waste reduction" refers not only to in-plant process modifications that reduce the volume or degree of hazard of the waste generated, but also to reuse or recycling of the waste. Although reduction of hazardous waste generation is almost always possible, the amount of waste generated that can be avoided is, unfortunately, not known because of difficulties in obtaining reliable data.

Small-Quantity Generators in Arizona

In the United States, the RCRA obligates every hazardous waste generator to report the quantities of hazardous waste generated and shipped. Only small-quantity hazardous waste generators were exempted from this reporting procedure. The process of designation of small-quantity generators has seen some changes in this decade. In 1980, the EPA promulgated the small-quantity generator exemption for industries generating less than 1,000 kg/month. This action was followed by nationwide opposition because of the dangerous properties of the substances involved. Congressional hearings and legislation resulted in a law in November 1984 that reduced the limit to 100 kg/month. This regulation resulted in the need for additional disposal capacity on the part of the generators and created greater volumes of hazardous waste for transport to disposal sites.

In 1984, a survey of generators was conducted in Arizona (*5*) regarding the amounts and types of small-quantity hazardous wastes, on-site and off-site handling, and storage and disposal methods. The total number of individual firms in the survey was 4,332 and 16 percent of the total (698) were selected for the survey. Of these 698, only 409 (50 percent) reported generating hazardous waste. Some of the major industrial groups were printing and publishing, automotive repair shops, automotive paint shops, gasoline service stations, laundry and cleaning establishments, medical products, petroleum and rubber products, and electrical and communication equipment. The hazardous waste generated by these industries range from halogenated solvents, waste oils and paints, ignitable and reactive wastes, to pesticides, waste ink, and heavy metals. Four major groups of industries were found to be consistently producing hazardous waste at an average rate of more than 100 kg/month each. They were automotive repair shops, automotive paint shops, metal stamping, and gasoline service stations. It was estimated that around 3,385 firms in Arizona were producing hazardous wastes and about 1,424 of them (42 percent) fell in the four groups mentioned.

Data Collection and Analysis

To project the hazardous waste volumes and shipments, it was necessary to have a clear picture of the present situation. A few changes have evolved since the 1985 study (*1–3*). First, the lower limit amount of hazardous waste generated per month allowed for exemption from regulation has been lowered. This change results in greater volumes of hazardous wastes that must be transported to disposal sites. Second, some chemicals classified as hazardous waste have now been declared forbidden, i.e., they cannot be dumped at disposal sites. Third, the cost involved in handling, storage, and disposal of hazardous wastes has increased. The result is an unprecedented increase in waste minimization and recycling activities. This trend is expected to continue as regulations become more stringent.

Because the new laws regulating the types and amounts of hazardous wastes were passed in late 1984, it was expected that their effects would be noticeable from 1986 onwards. Therefore, it was decided to include hazardous waste shipment data from the RCRA manifests for the year 1986 (the most complete year available) to study the present hazardous waste transportation characteristics. The data gathered from the manifests were transferred to a dBASE III data base management system environment similar to the one developed during the 1985 study (*1–3*). Once the data were stored, a main program and set of programs in dBASE III language were developed that allowed the user to request selective information from or edit the data base of hazardous waste shipments of 1986. These programs were used for calculating the shipments in terms of volumes and number of shipments by hazard class. The same set of programs was then altered to obtain similar information from the hazardous waste data bases of 1983 and 1984. The percentages of total number of waste shipments for each hazard class were estimated and are presented in Table 4.

The total volumes of hazardous waste transported for the years 1983, 1984, and 1986 are 44, 40, and 30 millions of pounds, respectively. The number of shipments in 1986 increased over the numbers reported in the years 1983 and 1984. However, the results also indicated that there has been an overall decrease in the total volume of hazardous wastes transported. The increase in the number of shipments results from the new regulations regarding the lowering of the monthly limit of hazardous waste generation for small-quantity generators. The increase in total shipment volume because of the inclusion of the waste from small-quantity generators is much smaller than the decrease resulting from hazardous waste minimization, recycling, and the use of alternative industrial processes. There is an expectation of a decreasing trend in hazardous waste transportation in the near future. Tables 5 and 6 present statistics on the applications of hazardous waste generation minimization programs in Arizona.

Projection of Hazardous Wastes

The number of hazardous waste shipments in the near future may be lowered because of recycling and waste minimization efforts. The EPA is expected to be regularly passing new

TABLE 4 PERCENTAGE OF TOTAL NUMBERS OF HAZARDOUS WASTE TRUCKLOADS BY HAZARD CLASS, 1983, 1984, AND 1986

Hazard Class	1983	1984	1986
ORM-E	28.3%	29.2%	28.1%
Flammables and combustibles	37.6%	40.7%	36.2%
Corrosives	19.7%	14.3%	12.8%
ORM-A	10.9%	11.5%	15.1%
Poison	2.8%	2.6%	5.2%
Oxidizers	0.6%	1.1%	1.5%
Explosives	0.0%	0.0%	0.2%
ORM-B	0.0%	0.1%	0.1%
ORM-C	0.0%	0.4%	0.6%
ORM-D	0.0%	0.0%	0.0%

Note: The values have been rounded off to the nearest 0.1.

TABLE 5 AVERAGE AMOUNT OF HAZARDOUS WASTE GENERATED

Reporting Year	Average Amount of Hazardous Waste Per Reporting Generator (Tons)
1982	371
1983	456
1985	344
1986	125
1987	120

Source: Arizona Department of Environmental Quality.

TABLE 6 TOTAL WASTE RECYCLED AS PERCENT OF TOTAL WASTE GENERATED

Reporting Year	Percent
1982	14
1983	44
1985	34
1986	38
1987	62

Source: Arizona Department of Environmental Quality.

regulations that will forbid the disposal of some chemicals that contribute to the waste generated from industrial processes. This action will lead to even further technical advances in the area of hazardous waste minimization, recycling, and the search for alternative raw materials and industrial processes. But again, the amount of hazardous wastes generated that can be avoided is still not precisely known, although some of the firms in Arizona have claimed in their annual reports to the ADEQ to have reduced the volume of wastes significantly. Given these uncertainties, it would be prudent to study the future hazardous waste transportation system under different projection scenarios, i.e., holding the 1985 hazardous waste study shipment amount as the base and projecting it for the year 2000 under different assumptions of waste generation.

First, if the waste generation rate is assumed to equal the rate of growth of the manufacturing industries (i.e., if the new law regarding small-quantity generators and the waste-reduction techniques are not taken into account), the hazardous waste volume projection may be similar to Curve 1 in Figure 6. But the fact is that since the mid-1980s, when stricter laws were passed regarding disposal of hazardous wastes and the costs of treatment, storage, and disposal escalated, minimization of hazardous waste and recycling came into the picture. This process resulted in an overall reduction in hazardous waste volume. In fact, in 1984 and 1986 a reduction of almost 12 percent in generated amounts was observed. This rate of reduction, though, is not expected to be constant and will begin to decrease because of limitations in applications of waste-reduction techniques while greater amounts of wastes will be generated because of industrial growth. This scenario is shown by Curve 2 in Figure 6. Finally, as of 1985, small-quantity generators were mandated by the law to report and dispose of their hazardous waste. This procedure will lead to an increase in volume of hazardous waste. From previous studies, the growth rate for this waste is expected to be about 7 percent annually. Noticeable effects of this new law are expected to be observable from reports of 1987 onwards. However, although small-quantity generators were not reporting disposal activities until recently, shipments may have occurred. The level of such activity versus on-site storage or disposal with regular solid waste is unknown. The effect of this new feature is shown by Curve 3 in Figure 6, which was used in projecting future hazardous waste shipments in this research. The future rate of growth of hazardous waste will be lower than that of manufacturing industries for a few years after 1985. Later, the slope of growth will start getting steeper.

According to the projections of ADES, the Phoenix and Tucson metropolitan areas are expected to remain the centers of population and industrial concentration until the year 2000 and beyond. Therefore, the patterns of hazardous waste shipments will be similar to the ones identified in the 1985 study. Hazardous waste shipments and routings on Arizona's highways were calculated and added to bulk and nonbulk hazardous materials shipments to produce Figure 7. Hazardous waste

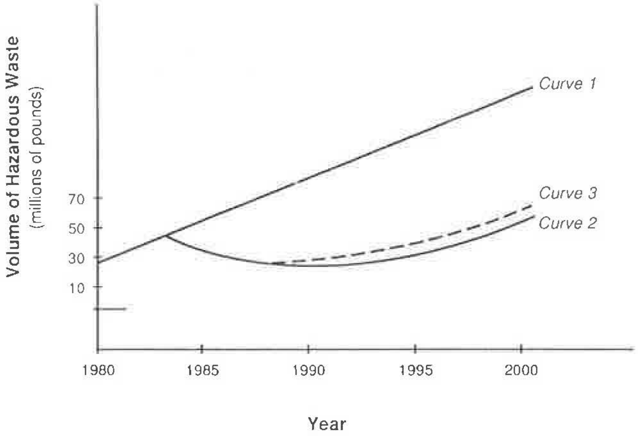

FIGURE 6 Growth in hazardous waste volumes.

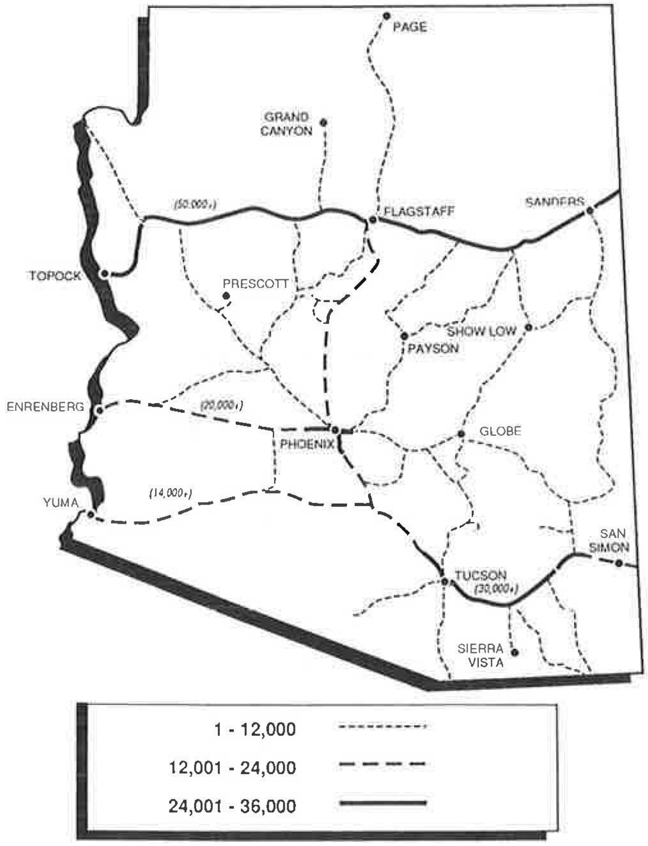

FIGURE 7 Map for hazardous materials and hazardous waste shipments in Arizona for the year 2000.

shipments represent a small fraction of the total hazardous materials and hazardous waste shipments combined.

CONCLUSION

The volume of hazardous materials transported on Arizona highways is expected to almost double by the year 2000. Flammables and combustibles will continue to form a major part of the hazardous materials shipments.

Among internal shipments being handled in Arizona, gasoline transport is expected to increase whereas propane and acids shipments will stay more or less constant. The through-traffic and nonbulk type shipments are expected to increase about 1.8 times. Rapid growth in intraurban shipments is expected to continue in the Phoenix and Tucson areas. The major routes for hazardous materials shipments will be I-40 and I-10 between Tucson and Phoenix and between Tucson and San Simon, respectively. Moderately high levels of hazardous material traffic are expected on I-10 between Phoenix and Ehrenberg and on I-8.

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