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

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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.

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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

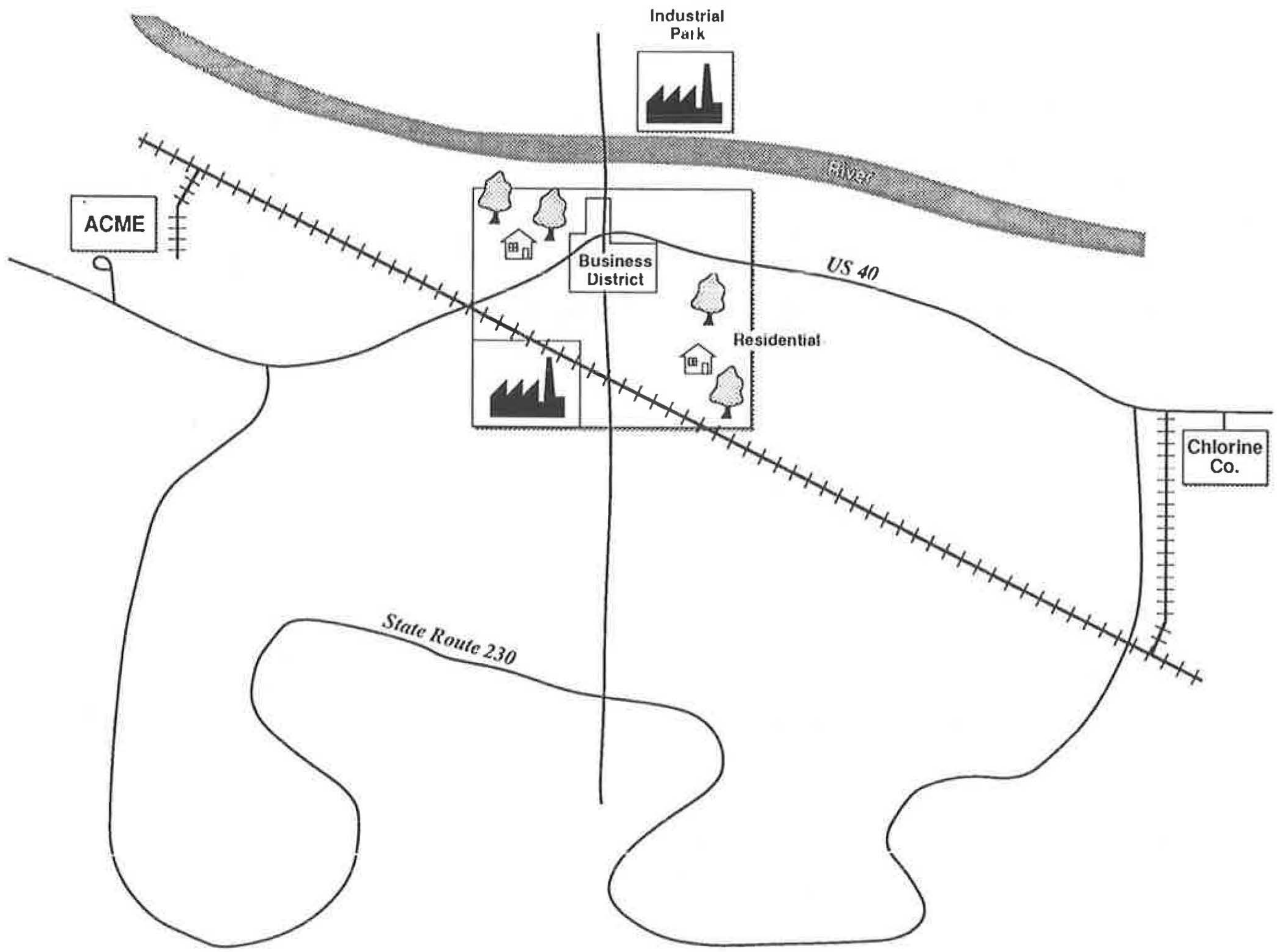

FIGURE 1 Route and mode alternatives.

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
Highway Mode Only				
Truck-Suburban	Worst	Worst	Worst	Best
Truck-Urban	Best	Best	Best	Worst
Rail and Hwy Modes				
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.

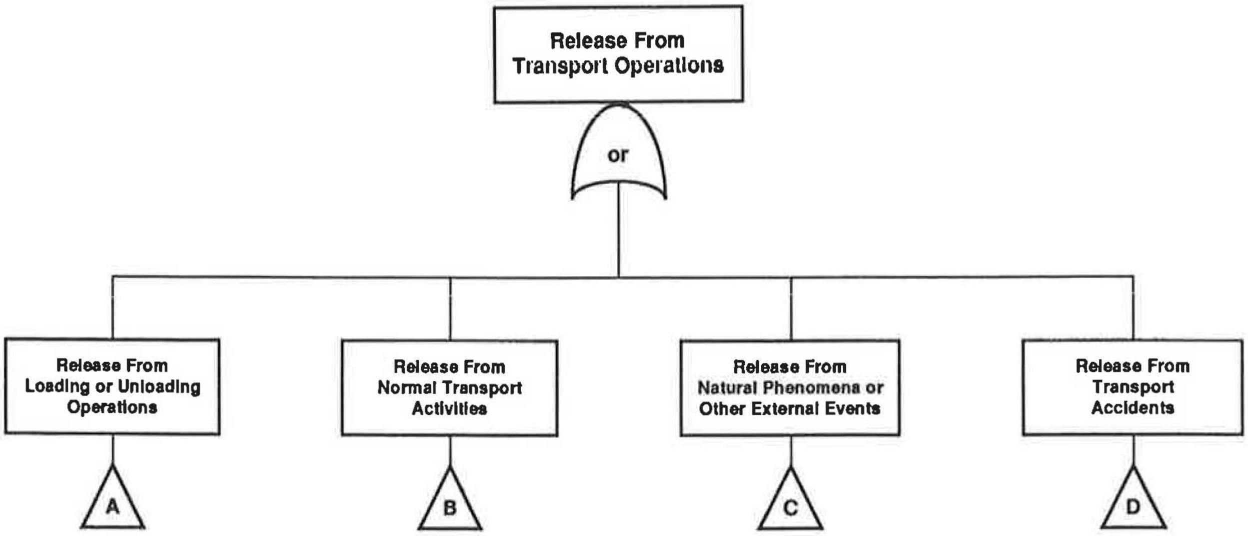

FIGURE 2 Fault tree for releases from transport operations.

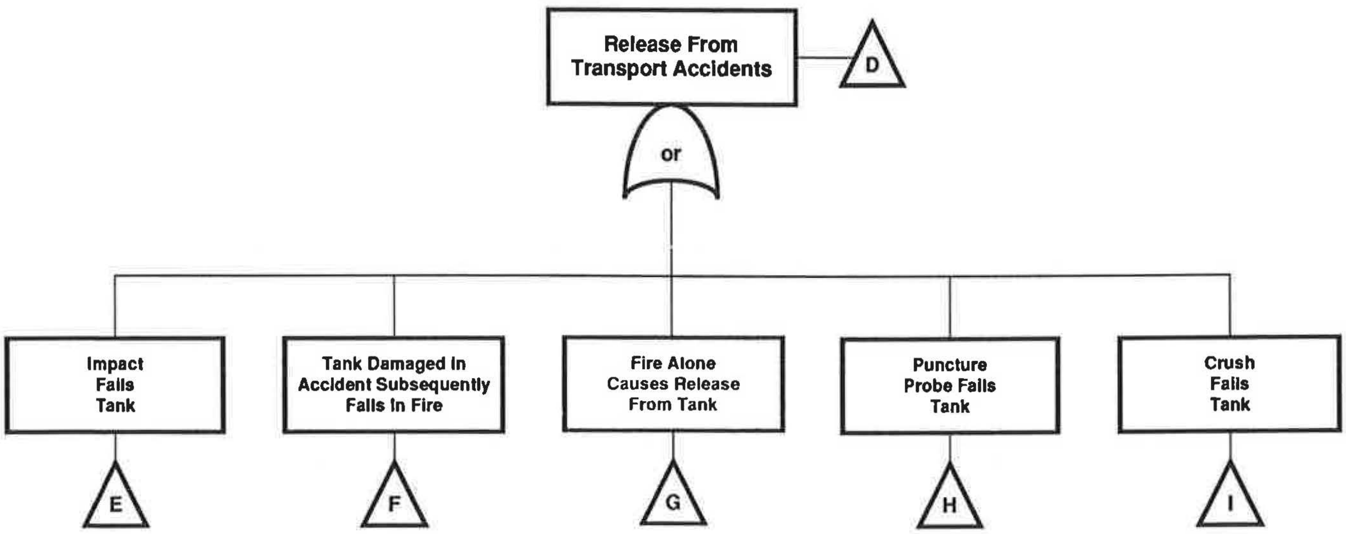

FIGURE 3 Fault tree for releases from transport accidents.

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/km² for the first 4 km² affected, 1,300 persons/km² for the next 14 km², and 400 persons/km² thereafter. For the residential zone, the population density is 1,300 persons/km² for the first 20 km² and 400 persons/km² 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

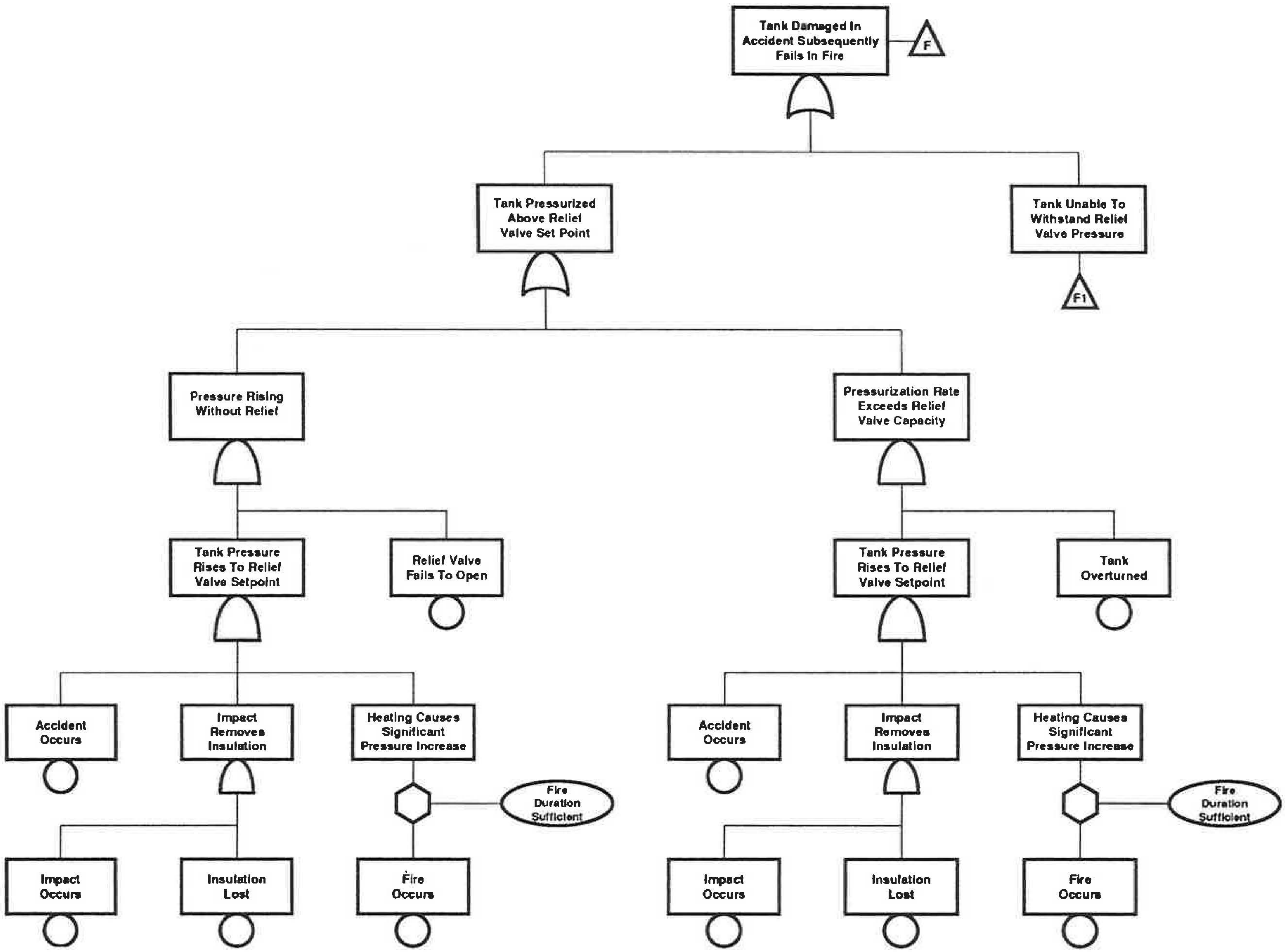

FIGURE 4 Fault tree for failure of tank by mechanical and thermal forces.

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

[a] Per truck mile.
[b] R is the truck accident rate.
[c] Based on $R = 5 \times 10^{-6}$/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.

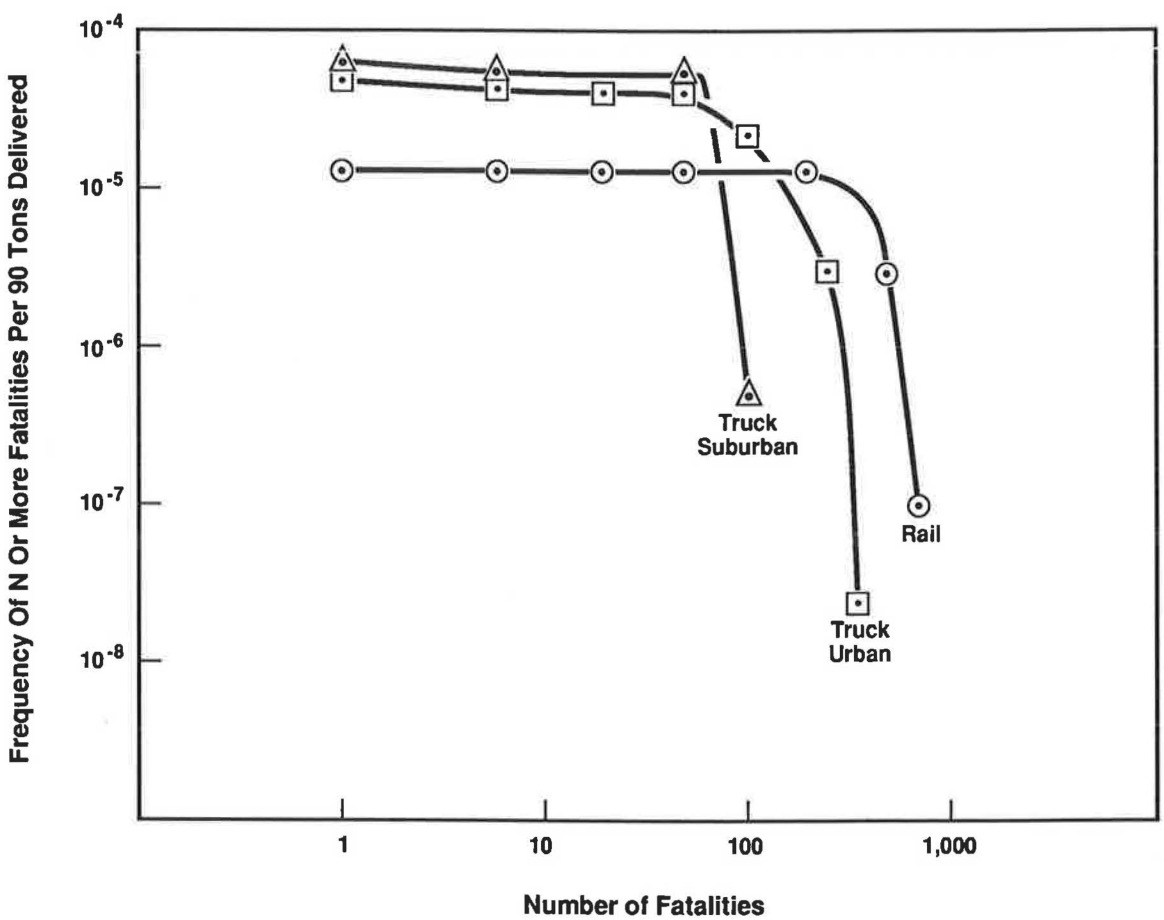

FIGURE 5 ***F*–*N* curves for different transportation options.**

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:

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

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:

$$R = \Sigma R_i \quad (3)$$

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:

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

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:

$$\text{Compare } F_1^x M^x N^x \text{ and } F_1^y M^y N^y \quad (5)$$

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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