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A Risk Assessment Study on the Transportation of Hazardous Materials over the U.S. Railroads

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Development
Washington, D.C. 20590

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16. Abstract

A comprehensive and generic risk assessment model has been developed for evaluating the risk to the public from the transportation of hazardous materials (Hazmat) on rail over specified routes. The model considers the various operational and Hazmat property parameters. These include the make-up of the freight trains, annual volumes of transport of particular Hazmat, train accident statistics both on main line and in yards, effect of leak prevention devices such as head shields and shelf couplers, population density distribution and the behavior of the chemicals in the environment after release.

The model developed was utilized to evaluate the risks posed in transporting LPG, chlorine and sulfuric acid on two (alternative) routes between the same origin-destination pair. Historical main line and yard accident data together with the current volumes of transportation of the specified Hazmats were considered. The results are presented in the form of risk profiles. These results indicate higher risk from chlorine on both routes compared with that due to LPG or sulfuric acid. The sulfuric acid risk is in order of magnitude, smaller than either the LPG or chlorine risk. Safety measures, such as head shields and shelf couplers, seem to reduce, substantially, the annual frequency of high casualties but seem to have less impact on the low casualty end of the risk profile. A similar positive effect in risk reduction is seen from emergency response action following an accident. Sensitivity of the risk profiles to various other parameters were also investigated.

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

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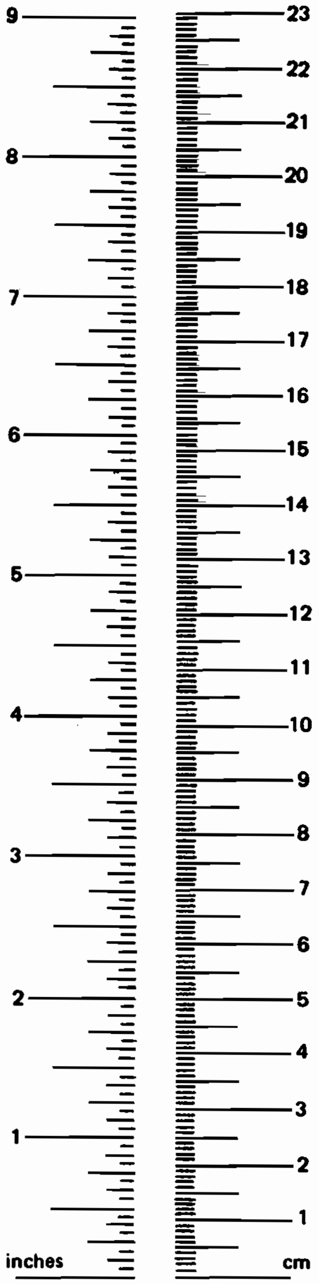
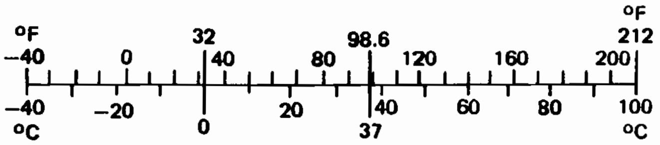
*1 in. = 2.54 cm (exactly). For other exact conversions and more detail tables see NBS Misc. Publ. 286. Units of Weight and Measures. Price $2.25 SD Catalog No. C13 10 286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	36	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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EXECUTIVE SUMMARY

Considerable volumes of hazardous materials are transported on the U.S. railroad systems. These hazardous materials include chemicals which, when released into the environment, behave in several differnt ways and pose significantly different levels of of hazards to the population that may be exposed to these chemicals. Development of rational decisions concerning risks associated with hazardous material transportation will have to take into account several different types of parameters, including operational parameters, chemical specific properties, historical data on the accidents, effects of tank car safeguards and safety devices, population density, etc. Risk analysis procedure synthesizes the influence of the various parameters and represents their effects in a mathematically tractable way.

The principal purpose of this study was to develop a comprehensive and generic risk assessment model applicable to the evaluation of risks in transporting specified chemicals on designated routes. Such a model will be useful in calculating not only the absolute risks inherent on a specified route from the transport of a hazardous material ("hazmat") but also the relative risks of transporting the same or similar hazmat on an alternative route. In addition, a comprehensive risk assessment method could be useful for testing the effectiveness of improvements in both operational procedures and equipment. Also, the effects of increased traffic and variations in train speed on existing tracks could be easily evaluated.

A generalized risk analysis model was developed in this study. This model, described in Chapter 2, consists of evaluating the stochastic (probabilistic) aspects of accidental releases of hazmat from train accidents as well as the definitive consequences in terms of hazard areas. The various conditional probabilities of occurrence of accidents, derailments, hazmat releases, etc, on a given segment of the route are calculated using the historical accident data correlations, traffic volumes, and physical models. The primary data considered and used in the risk analysis model are based on train accident data. That is, non-train accident related releases of chemicals (from human error, overfilling, etc.) are not included in our analysis. The detrimental consequences of hazmat releases are evaluated using physical models that describe the behavior of the chemical released into the environment, and noting the type of hazard of interest and the population density within the hazard area. The spectrum of accident sizes, their probabilities of occurrence, and the range of associated casualties are expressed in the form of a risk profile. The risk profile indicates the annual probability of occurrence of accident events that can lead to casualties in excess of a specified number on the route of interest.

For the purposes of illustrating, the model development and its applicability is applied to evaluating the risks in transporting three different chemicals of considerably different properties and shipment volumes between an origin and a destination within the United States. Four pairs of origin-destination points were considered and one pair was chosen for detailed study. The choice was based on a set of criteria which included (i) the availability of alternate routes between the origin and destination, with the routes being sufficiently different in characteristics; (ii) the high volume of chemical traffic on the routes; (iii) the availability of traffic and accident data for the routes, etc. The details of the route characteristics and other data for the two routes selected are indicated in Chapter 3. These routes are designated as Route 1 and Route 2. Each route was further subdivided into segments, and all data such as track class, train speed, freight volumes, hazmat traffic, population density, etc., were collected for each segment. The segmentation of the routes in our study was on the basis of the county lines across which the tracks passed.

Three hazardous materials were selected for study. These were (i) chlorine, (ii) liquefied petroleum gas (LPG), and (iii) sulfuric acid. These chemicals have considerably different physical and chemical characteristics. The behavior in the environment of each is different from that of the other. Also, the annual volumes of transport of these chemicals over the national railroad system are significant.

This report is sectioned to correspond to the determination of the various parameters that are required to exercise the model. The historical accident data is analyzed in Chapter 4. The details of various release scenarios and the associated hazards from rail accidents involving these chemicals are given in Chapter 5. In addition, the physical models which are used in determining the hazard areas are also described. The results obtained from exercising the risk model are indicated in Chapter 6 and discussed.

Historical Accident Data

In this study, the data and other statistics on accidents and chemical releases used refer to only those caused by "train accidents:. These do not include incidental hazmat releases from such incidents as failure of bottom outlet fittings, tank corrosion, etc. (unrelated to train accidents). It is the experience of a major railroad that the hazmat releases from non-train related incidents are comparable or even more than the total of hazmat releases from train accidents (O'Driscoll (36)). It is uncertain, however, whether this is true industry-wide. Train accidents over the past years show a steady decline throughout the industry. The number of non-train related release incidents, on the other hand, may not have changed over the years. The risk assessment procedure and model presented in this report have to be, therefore, viewed in the perspective of the above data consideration.

In general, all accident data necessary for the exercise of the risk model were collected from both public sources and non-public sources. The U.S. national statistics on railroad freight transportation accidents between the years 1979-82 were collected from the Federal Railroad Administration, References 1 through 3. Also, the annual volumes of shipment of hazardous materials over U.S. railroads, number, types, causes of accidents and releases involving hazardous materials were obtained from the publications of the Association of American Railroads(4). In addition, several important route specific data related to the general freight traffic and the hazardous material traffic over the selected route segments were gathered from a cooperating railroad.

It is seen from the data collected that the main line accident rates for freight trains in the U.S. varies between 82.4 per million gross ton miles for Class 1 track to 0.17 per million gross ton miles for Class 6 track. The comparable accident rates for the routes chosen in this study vary between 14 for Class 1 track to 0.2 for Class 6 track. The railroad operating on the routes chosen uses a more stringent set of criteria for (internal) reporting of "accidents" compared to the FRA accident reporting requirements. The national average yard accident rate is 8.54 accidents per million car classifications compared with 6.6 accidents per million car classifications on the yards along the two routes chosen. In effect, the national average accident rates and those for the routes chosen are comparable in magnitudes.

Hazmat Traffic Volumes

The hazardous material traffic volumes varied from segment to segment on the routes chosen. Exact traffic volumes for those selected chemicals on the chosen routes were not available. For purposes of risk analysis, we calculated the individual chemical traffic volumes on each major segment of the routes using the hazardous material class traffic volumes provided by the cooperating railroad and the national average traffic data for each of the chemicals. That is, the calculated traffic of, say LPG, on a given segment of the route bears the same ratio to the total traffic of all chemicals of its class on the segment, as is the LPG traffic volume nationwide to the nationwide traffic of compressed flammable gases. The traffic density of each of the chemicals of interest to this study on the two selected routes is expressed in the form of average number of tank cars of the chemical in each freight train on the route. The national average LPG traffic is 0.344 tank cars per freight train. We note here that among hazardous materials transported on rail, LPG ranks number 1, nationally, in the annual volume transported. It is found that over a number of segments of the two chosen routes, the chemical traffic volume does not vary. We have divided the routes into sectors over which there is significant variation in the traffic of the chemicals. On this basis, it is found that LPG traffic on Route 1 is 0.832 cars per train in Sector 1; 0.089 in Sector 2, and almost no traffic in Sector 3. Similar variation is found for Route 2 also. Chlorine and sulfuric acid traffic volumes on the routes chosen are comparable. The (estimated) mean number of chlorine cars on Route 1 varies between 0.141 and 0.045; the national average value is 0.139. Sulfuric acid traffic is between 0.16 cars per train, to 0.05 cars per train; national average is 0.142 cars per train.

Hazmat Release Probability

One of the interesting items in the data collected is the fraction of derailed rail tank cars that release their contents subsequent to main line derailment/collision accidents. This fraction has progressively decreased from about 25% in 1978 to about 7% in 1983. While the direct cause of this decrease cannot be found in the data, we infer that the decrease is a consequence of the use of head shields on tank cars and shelf couplers between tank cars and other operational safety measures instituted by railroads. Unfortunately, detailed data on the quantity of material released or their relationship to hazardous material class, severity of accident, and tank car material strength were not available. We have modified (in light of the above data) a correlation, developed in an earlier work by Nayak, et al(5), relating the probability of release from a tank car (irrespective of hazmat class) to the train speed. This modified correlation is used in the risk model, with a variable coefficient, to evaluate the sensitivity of risk values to release probabilities.

Hazard Areas

The hazard areas arising from the release of the chemicals have been obtained utilizing the state-of-the-art physical models which describe the behavior of the selected chemicals in the environment. The following assumptions were made in calculating the hazard areas:

- Entire tank car contents are released,
- Release can occur in any one of the many different scenarios associated with the particular chemical,
- Most unfavorable weather condition exists, which gives maximum hazard area,
- Multiple releases, if any, occur in such a way that the hazard areas are multiples of one tank car release area.

The effective hazard area is calculated by summing the individual hazard scenario areas weighted with the probability of occurrence of the release scenarios. These probability values are obtained from published data on releases during the 1978-83 period, (AAR - Bureau of Explosives(6)).

It is seen that the expected hazard area for chlorine releases is substantially larger than that for either LPG or sulfuric acid. This is because the safe concentration limit (threshold limit value) for chlorine is in the 10's of parts per million.

For a large cloud of chlorine vapors to be diluted to this concentration, a substantial volume of air has to be mixed. Because of the higher than air density of chlorine vapor, the cloud dispersal is slow and stratified, requiring large distances for dilution. The hazard distance for very rapid release of the entire tank contents of a rail tank car of chlorine is estimated to extend to about 2 km downwind and the cloud is calculated to be about 1.2 km wide, resulting in a total hazard area of 1.8 km^2. However, the expected hazard area is 0.57 km^2 because of the 10% conditional probability of this type of release occurring, given that a chlorine car releases its contents.

The expected hazard area for LPG releases is calculated to be 0.06 km^2, even though in very rare cases the detonation of a dispersed LPG vapor cloud could give a hazard area of 3.8 km^2.

The hazard area resulting from one tank car full of sulfuric acid is estimated to be 0.02 km^2. No fatalities are expected to result from sulfuric acid spills. For the purpose of risk assessment, the area of spread of the spilled liquid was considered to be the hazard area.

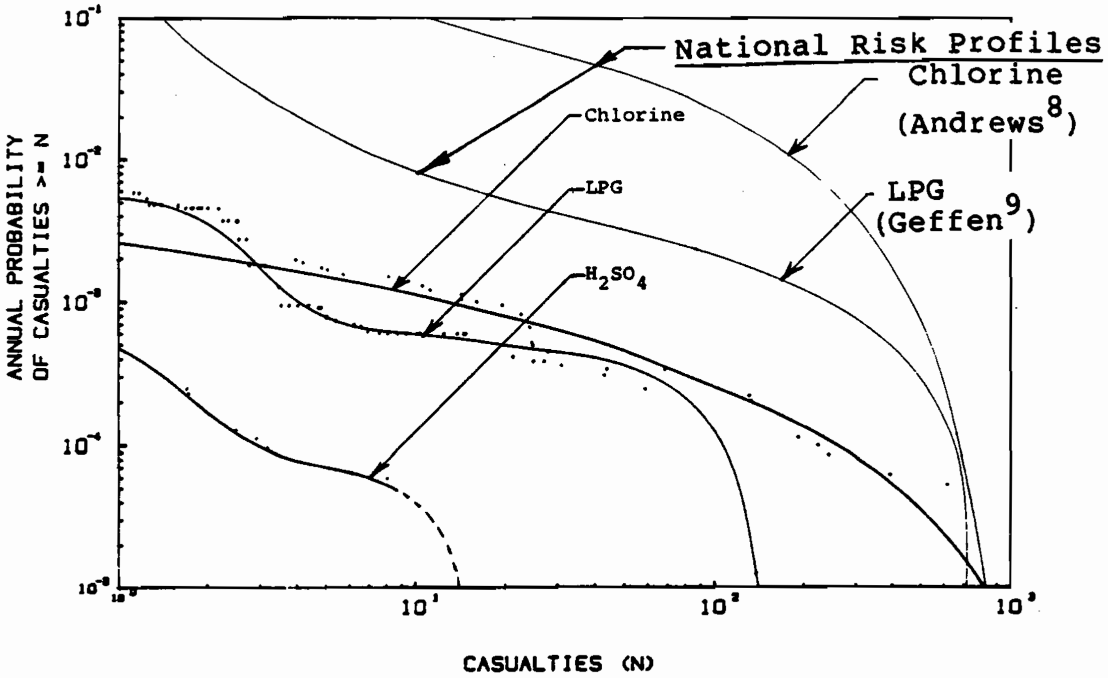
Population Density

The consequences of hazardous chemical releases are expressed in terms of casualties to the exposed population. The expression "casualty" used in this report is the product of hazard area and the population density within the hazard area. In general, the hazard areas are calculated on the basis of severe injury or fatality criteria. Actual casualties may be significantly less than the calculated values because of the protection provided by buildings or as a consequence of emergency response action. None of these potential risk reducing factors have been considered in our calculations. Hence, the casualty numbers evaluated may be overstated.

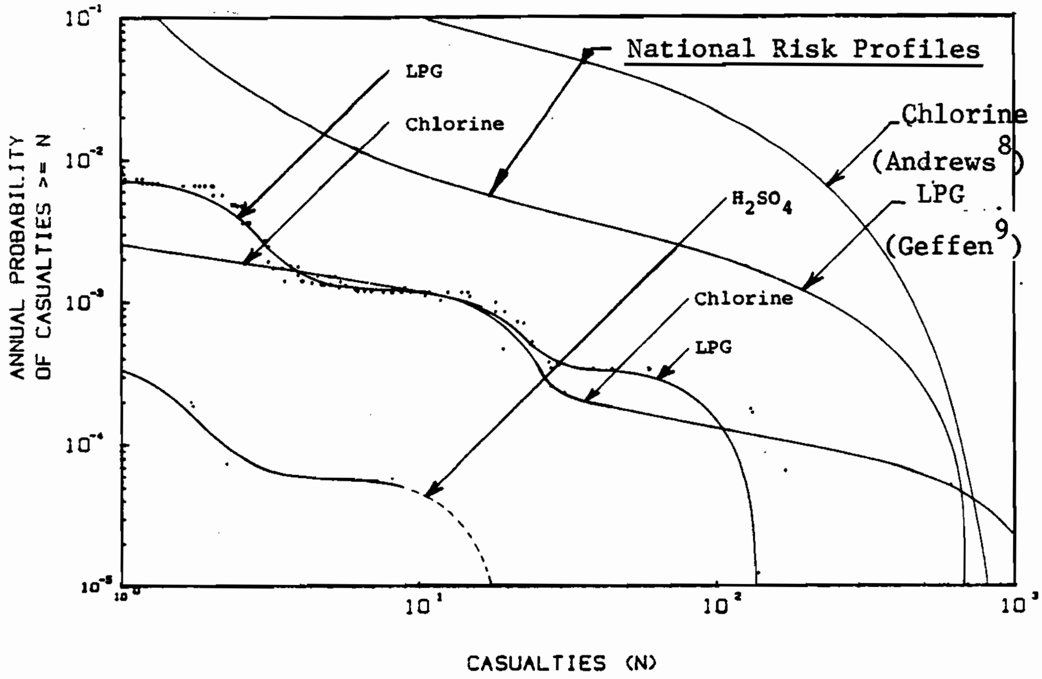
The density of population we have used is the county averaged, census population density. These data were obtained from the Census Bureau Publication(7). The county population densities, especially in metropolitan areas, are significantly higher than can be expected in the neighborhood of railroad tracks. Because of the use (in our risk analysis calculation) of the county population density data, the actual population that may be exposed to a potential hazmat release from a rail accident may be highly exaggerated.

Risk Profiles

The risk profiles obtained for the three chemicals for the two routes are shown in the accompanying figures. These results have been obtained for "base case" values of the parameters. The values in the base case are based on 1983 traffic volumes in the respective segments of the routes (both freight as well as hazmat traffic). Accident rates specific to the routes are



Comparison of the Chlorine, LPG, and Sulfuric Acid Risk Profiles for Route 1



Comparison of the Chlorine, LPG, and Sulfuric Acid Risk Profiles for Route 2 used. The tank puncture/release probability is consistent with the national average value for the period 1978-83 (i.e., 11.6% of derailed tank cars release contents). Also shown in the figures are the national risk profiles developed by Andrews, et al(8) for the transportation of chlorine over the U.S. railroads and by Geffen(9) for LPG transportation over the entire United States.

Results

The following major observations are made from the results generated:

- Chlorine releases have a potential for causing large casualties ($>$ 100) compared with either LPG or H_2SO_4 releases. However, the annual probability of exceeding 100 casualties is very low, of the order of 10^{-4} per year. That is, such a catastrophic accident may occur once in 10,000 years.

- There is little difference between the risk profiles for the same chemical on Route 1 and Route 2, even though during selection of the routes it was assumed that their characteristics were considerably different. It is likely that the variation in traffic volumes and population densities result in such close risk profiles. In addition, we note that both Routes 1 and 2 share a common sector, initially. It is from this sector that the large casualty results arise.

- The LPG and chlorine risk profiles are similar for lower casualty values. However, for casualties larger than 100, the difference in the profiles is considerable.

  The reason for the agreement at lower casualty values is that the LPG traffic volume is larger than that of chlorine, and the hazard area is large. The combination of the two effects result in similar profiles for low casualty values.

- The risk from sulfuric acid transportation, on both routes studied, is almost an order of magnitude smaller than that of either LPG or chlorine. From the casualty perspective, sulfuric acid related casualties is calculated to be no more than 10.

- The expected number of casualties in a year, arising from the transport of chlorine, LPG and sulfuric acid, in each of the two routes, is indicated in the accompanying Table. These values, extrapolated to national values, are compared with the results obtained by other researchers for the national risk.

EXPECTED NUMBER OF CASUALTIES PER YEAR DUE TO RAILROAD ACCIDENTS INVOLVING DIFFERENT CHEMICALS

CHEMICAL	This Study Base Case		NATIONAL EXPECTED CASULATIES			Reference
			Extrapolated Value from This Study		Result from other Studies	
	Route 1	Route 2	Route 1	Route 2		
Chlorine	0.088	0.073	11.4	11.4	9.4	Andrews(8)
LPG	0.043	0.055	3.6	4.2	0.5	Geffen, et al(9)
Sulfuric Acid	0.001	0.001	0.2	0.23	Not Available	

The route specific expected casualty values are extrapolated to the national level on the assumptions that, (i) the population density along the route is representative of the national average and (ii) the expected value of casualty in each route is directly proportional to the loaded tank car miles of the particular chemical in the route. The results from the above Table indicate that the extrapolated values are somewhat higher than the values for the expected casualties calculated by other researchers, for the U.S. as a whole. This is a surprising result because of the excellent quality and maintenance of the tracks (class 6) on the routes chosen. In addition, the operational standards on the selected routes are very strict. Therefore, we expect the overall risk along the routes chosen to be far lower than the national average.

Our explanation for the above dicrepency is that the population density along the routes chosen is substantially higher than the national average value because of the inclusion of several metropolitan areas within the 600 miles of the routes studied. Secondly, certain of the models used by the previous researchers underestimate the extent of hazard areas. Other differences that contribute to the different results are discussed in Chapter 6.

We argue, therefore, that a simple extrapolation of risk results from a route specific risk assessment to the national risks (or vice versa) cannot be performed . The various parameters interact in such a complex fashion that only a route specific risk assessment can indicate the true risks arising from the transportation of a specified chemical on a given route.

Sensitivity analysis was also carried out to determine the effect of variation in some of the important parameters. The parameters varied included (i) probability of release given a tank car of the chemical is derailed; (ii) population density (reduction) due to emergency evacuation; (iii) accident rate; (iv) use of national data instead of route specific data.

The results indicate that a reduction in release probability by a factor of 10 decreases the annual probability of casualty exceeding 1 also by about a factor 10 in the case of LPG but only by a factor of 3 in the case of chlorine. However, the benefit of decrease in release probability is most pronounced in the large casualty situations, where reductions of factors of 10 or more in the number of casualties (at 10^{-4} annual probability) are obtained. Therefore, strengthening the tank car appurtenances and prevention of tank punctures can provide substantial to moderate benefit depending on the chemical.

It is also found that emergency evacuation and protection provided by buildings, etc., reduces the risk markedly. That is, any plan that has the effect of reduction in the effective population density within the potential hazard area can lead to significant reduction in overall risks. The effect of this parameter, as in the release probability case, is more pronounced at the higher casualty end of the risk profile.

We have also investigated the material specifications currently used on tank car materials and how these specifications affect tank car puncture probabilities in accidents. At present, there are no known procedures by which the results from material strength tests can be incorporated directly into either predicting the puncture probability or used in the risk analysis.

The following is the set of recommendations resulting from our study presented in the report. We point out that while the risk results have been generated for the transportation of the chemicals on the routes chosen, the assessment of the acceptability of these risks and other decisions related to the transportation were beyond the scope of this study.

RECOMMENDATIONS

Based on the results of the risk analysis study presented in this report we recommend that:

1. The risk analysis model developed in this study be improved by incorporating several additional features which will provide better risk estimates. We recommend that, at the very least, the following features be included in the revised model.

    o Evaluation of individual hazard scenario occurrence probability and the area of hazard for the scenario, consequent to a hazmat release. At present only an expected hazard area is used in calculating the overall casualties.

    o Integration of the effects of emergency response operation. A sub-model should be included to consider the beneficial aspect of emergency response and the resulting reduction in casualtites.

- Evaluation of effect of time of day variation in population density. This should be included at least for the urban and industrial areas through which the freight traffic may pass through.

2. More detailed data be collected regarding the population type and density near the railroad right-of-way, when specific route risk analysis is to be performed.

3. The risk model be improved to take into account, explicitly, the risks to railroad employees and emergency response personnel in addition to the risk to the general public.

4. Testing procedures currently used for evaluating the tank car material properties be modified to take into account the process of rupture that occurs in a railroad accident that involves a tank car. Also to be considered in the test procedure modifications should be the effects of scale of the accident.

5. A rational method be developed to consider the tank car material properties in risk assessment. Specifically, this should include mathematical modeling to represent the accident severity in terms of dynamical parameters.

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Over the past 10 years, considerable improvements have been made in the handling and transportation of hazardous materials on U.S. railroads. New regulations have been passed whose implementation has reduced the number of hazardous material ('hazmat') release incidents. Technical solutions (required by the Hazardous Materials Regulations) involve the retrofitting of head shields on tank cars carrying selected (high hazard) chemicals, installing shelf couplers, and providing thermal protection on tank cars carrying flammable compressed gas such as LPG. These technological improvements, together with operational changes, have contributed to the reduction of potential exposure of population along the rail corridors to detrimental effects from hazmat release caused by rail accidents.

The degree of reduction of risk to population has not been determined. This is because, at present, there does not exist a comprehensive risk assessment method applicable to railroad transportation of hazmat which can be utilized to evaluate, quantitatively, the effects of the various (risk reducing) parameters and safety systems. In addition, improvements in safety are achieved by instituting better operating procedures in transporting hazmat, training the railroad personnel, and by timely emergency response action in case of an accident. For allocating resources to each of these types of safety improvements, it is necessary to be able to measure the effectiveness of each parameter, in a quantitative way, on the reduction in overall risk to the population. Therefore, there exists a need to develop the necessary mathematical tools of risk analysis which quantify the above safety systems and which can assess the effect of each parameter on risk.

One other method by which overall safety in rail transport of hazmat can be improved is to route the shipments through alternative, less risky routes. In order to aid in making appropriate decisions on rerouting, it is necessary to be able to evaluate route specific risks. Questions regarding the tradeoff between reduction in mainline risks and increased risk due to additional handling of tank cars in yards have to be considered if an alternate route is to be used which may have better tracks but involves considerably more travel distance or has more switching operations in yards. Such an evaluation can be done only by considering all factors that contribute to risk increase or to its reduction.

The Office of Research & Development of the U.S. Federal Railroad Administration recognized the need for developing a comprehensive and route specific risk assessment methodology. Therefore, it sponsored the research described in this report. The research effort was undertaken by Technology & Management Systems, Inc., (TMS).

1.2 PURPOSE OF THE STUDY

The purpose of the study was to develop a methodology for risk assessment which would use both historical accident data and scientific analysis of accident conqequences involving the release of hazmat. The metholology was to be applicable to specific route segments so that this risk analysis tool could be utilized by the railroad industry (for internal decision making) and other agencies.

In addition, the purpose of this study was to develop appropriate risk assessment models which could be used to test the sensitivity of the risk results to variations in operational parameters, properties of chemicals and improvements in materials technology and emergency response actions, all related to hazmat transport on rail. A secondary purpose was to apply this model to the transportation of three specific chemicals, between a set of origin and destination points, on alternate routes with very different tracks, population densities and other characteristics.

1.3 CONCEPTS OF RISK

The concept of "Risk" needs to be defined quite clearly. Unfortunately, there are many definitions of the term, all meaning different things and which are appropriate in different contexts. The principal difficulty is due to the imprecision in describing intrinsic human values on which decisions are based; while, the resulting decisions are often expressed in explicit, objective terms that belie the subjectivity of the value judgments employed in arriving at them (Rowe(10)).

"Risk" is defined, very broadly, as a measure of the uncertainty regarding the occurrence of an undesirable event or the resulting detrimental consequences arising from an industrial or other societal activity. Figure 1.1 shows the different attributes and classification of risks. The individual risk arises from a deliberate activity that an individual takes (or is exposed to) as opposed to societal risk in which segments of society (without being concerned with who within that society) are subjected to potential detrimental events. Examples of the former are the "risks" an individual takes in driving an automobile, smoking a cigarette or swimming. Risks to society can arise from wars, environmental pollution or transportation of hazardous goods within the given "society". The nature of risk can be voluntary, i.e., the segment of population (individual, or a group) undertakes an activity which, historical data may point out, would have some undesirable effects. Again driving, flying, smoking, etc. are examples of these. Involuntary risk is imposed if the potential detrimental activity is imposed on an individual (or a segment of society) without the individual affected knowing about it or participating in the decisionmaking. This type of risk to which populations may be exposed is very much the focus of the work presented in this report. In the case of transportation of hazmat on rail, the population along the shipment corridor may be subject to involuntary risk. In the context of hazmat transport on rail, the railroad workers including the personnel on the train and the emergency response personnel may be categorized as taking a voluntary risk. The scope of the work presented in this report is limited to the evaluation of involuntary societal risk.

Various quantitative measures are used in expressing the size of "risk" (See Figure 1.1). For example, in the transportation of hazardous materials the detrimental effects of accidental releases can be expressed in the size of the hazardous area formed. Sometimes the average consequence area, obtained by the summation of different hazard areas for different spill quantities weighted by the probability of spill of the given quantity is also used as a representation of the risk. However, these types of representations of risk do not capture the details of its dependence on different influencing parameters to the degree that is needed to make informed judgments. A "Risk Profile", on the other hand, does. The risk is expressed in terms of annual probability or frequency of exposing a given **number of people to the detrimental consequences. A histogram of this annual probability of exposure vs. the number of people gives the risk profile. The advantage of expressing the risk in the form of a profile is that the "activity" can be compared with other risks to which the society is exposed. This aids in the formulation of decisions based on informed judgments. Secondly, the effect of variation in parameters can be readily (and graphically) observed. For example, the variation in a parameter value may not affect the probability of occurrence very much but may affect the consequences to a significant extent or vice versa. In this project the methodology is developed for representing the overall risks in transporting hazmat in the form of risk profiles.**

1.4 RELATED PREVIOUS INVESTIGATIONS - A BRIEF REVIEW

Assessment of risks to the public arising from the transportation of hazardous materials is a subject of great interest, worldwide, and therefore has received attention in the literature. There have been several studies, both in U.S. and in Europe on the movement of hazmat on rail and the potential dangers they pose. Andrews, et al(8) have analyzed the risks of transporting chlorine on rail. The methodology used by Andrews, et al(8) is very detailed and evaluates the release scenarios and release probabilities by the method of "event tree". This is a sophisticated analysis and the results are expressed in risk profiles. However, because of its complexity and use of U.S. averaged traffic statistics, its use for specific route segments may be of limited value.

Glickman(11) has researched into the rates of derailment accidents, probabilities of hazmat releases and general consequences of hazmat releases. This study developed a risk model which takes into account the accident probabilities on the mainline, probabilities of different types of chemicals being released, the distribution of quantities of chemicals released

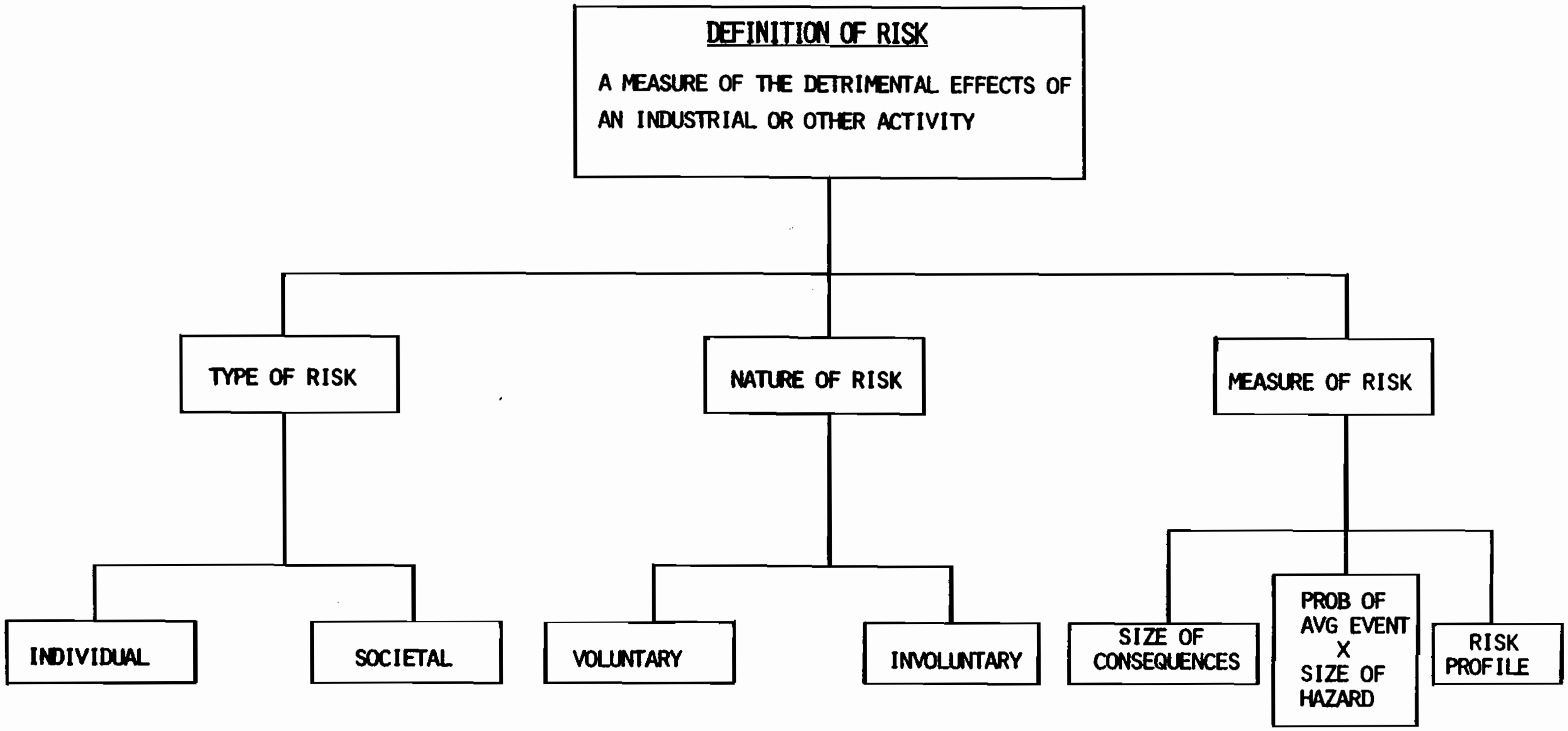


FIGURE 1.1 SCHEMATIC REPRESENTATION OF THE DIFFERENT ATTRIBUTES OF RISK

given that an accident has occurred and other statistics related to track class, train speed, etc. In other words geographically disaggregated values of the major factors which influence, in a quantifiable way, the frequency and severity of rail accidents in which hazmats are released are considered. Using these accident and release probabilities the expected fatalities, nationwide, from several classes of chemical releases are quantified and integrated to obtain an overall public fatality risk profile. The details of this model has been published by Glickman & Rosenfield(12).

The approach taken by Glickman(11) is very broad because of the need for the applicability of the model to the whole country. For example, the results indicate that the risk of fatality to an individual (anywhere in U.S.) is about 1 in 32 million (using 1976 statistics) and this is lower than expected risk of fatality to a person on the ground from plane crashes. On a national basis there is a 99% probability (almost a certainty) that in a year there will be one or more fatalities directly attributable to hazmat transport on rail. However, such a broad statement may not be very applicable to specific scenarios of transporting a named chemical from point A to point B nor does it help in determining optimal shipment strategies.

Some parts of this risk model were modified by another study (Raj(13)) to take into account the realistic impacts of mitigative actions generally undertaken by emergency response personnel. In addition, the areas impacted by the release of different quantities and types of chemicals have been determined with more recent and appropriate models. Also taken into account are the variations in population density in urban, suburban and rural areas with time of day. With these modifications the risk model predicts values for the fatality risks to the general public which are very close to those observed in the 1976-77 time period.

Nayak, et al(5) have developed accident rate and other correlations based on data relevant to rail transport of hazmat. While their study is not a risk analysis study, the information presented in their report is useful for performing a formal risk assessment. Both mainline and yard historical train accident data for 1975 thru 1977 were analyzed and accident rates for both derailment and collision accidents were presented. Correlations were also developed for the probability of release in a train accident and the amount of chemical released per car given that an accident has occurred. These correlations were based on 1975 - 1977 FRA derailment and collision data and on the 1971 through 1977 Research and Special Programs Administration data on the number of hazardous material releases, types and quantities of chemicals released, etc.

This report also calculated the hazardous areas expected to occur for various quantities of release of hazmat and the type of hazmat.

Glickman(14) has investigated the population avoidance rerouting policies that can be implemented for transporting hazmat on U.S. railroads. This study considered the effects of upgrading track quality, effect on cost by rerouting and risk reduction to population by rerouting. Approximate flow patterns throughout the U.S. of hazardous materials were generated using a national network model. The study results show that for some metropolitan areas a simple rerouting would reduce expected casualties by over a factor of 3, whereas in some other metropolitan areas, rerouting, together with track upgrading, will be necessary to reduce expected fatalities by the same factor.

A study on developing special routing of spent radioactive fuel on railroads from the generation plants to waste depositories has considered the approach of risk analysis (Berkowitz, et al(15). Because of the nature of the commodity, special requirements and regulations apply. Also, the quantities shipped annually are small compared to the quantities shipped for other hazardous industrial chemicals. Finally, the behavior in the environment and the nature of hazard posed by the nuclear materials are vastly different from that posed by industrial chemicals. Therefore, the results of this study cannot be directly utilized for assessing the risks from the chemical hazmat.

A simplified risk assessment procedure for determining the "least hazardous route" for shipping large quantities of radioactive materials on the U.S. highways has been illustrated in a DOT document(16). This procedure is very similar to an "expected risk index" evaluation approach. In this method, the total "system" risk is the sum of all subsystem release consequences weighted by the probability of occurrence of a scenario. The procedure does not take into account many of the details which are essential for comprehensive risk analysis needed for decision-making.

The probability of derailment of a tank car in a freight train depends on many factors including (a) the speed of the train, (b) the nature and condition of track, (c) the serial position of the tank car in the train and (d) the weight distribution in the train, the weight of the tank car itself, etc. No systematic study is available which has evaluated the optimal position for hazmat tank cars in a train from the point of view of minimizing the derailment probability. An unpublished report has evaluated the accident data for 1975-77 period purely on a statistical basis and has concluded that, among the 4 quarters of a freight train, the middle two quarters pose the higher derailment probabilities for tank cars irrespective of train speed, weight distribution and track class. This is a conclusion based purely on statistics, and it is uncertain whether the accident statistics sample considered was adequate for such a generalized conclusion. Also, there is no physical model to justify such a conclusion. The location of a hazmat tank car in the train has considerable economic and safety implications. If for example, a certain region of the train is determined to be "safer", from a derailment point of view, would the increased handling of tank cars in a switch yard (to locate the cars in the desired positions in a train) lead to an increased overall risk? Also, more handling necessarily means higher operating costs. What therefore are the overall risk and economic effects? These questions have not been studied to any extent.

Finally, there are a number of models to describe the behavior of hazmat chemicals in the environment [The USCG's CHRIS, EPA models, etc.]. However, there are very few models that address the question of spill of chemicals on various conditions of land (as may occur next to a railway line) and under various environmental conditions - porous soil, wet soil, soil covered by snow, flat ground, sloping ground or culverts and various soil temperatures. Each one of these conditions, together with the specific property of the released chemical (such as vapor pressure, liquid density), may cause different levels and areas of hazard. A systematic study of the behavior on land of most commonly transported chemicals on the railroads has not been performed; only a theoretical analysis of some of the situations has been developed (Raj(17)). Also, no detailed rank ordering of hazmat chemicals - from the point of view of public risks from railroad transport - has been developed.

It is with a view to study the effects of some of the important local parameters and specific route parameters on the overall hazmat transportation risk that the present study was undertaken.

1.5 SCOPE OF STUDY

The scope of the present study included the following:

- Development of a risk analysis methodology for evaluating the potential risks posed to the public from the transportation of hazardous materials on the railroad.
- Selection of a specific origin-destination combination with alternative routes and representative hazardous materials for a detailed case study.
- Collection of relevant historical railroad accident data, demographic or other data for the routes chosen to perform a risk analysis.
- Evaluation of credible release scenarios of chemicals in railroad accidents, their behavior upon release and review and analysis of physical models used for determining the hazard areas. Also, the development of additional chemical behavior models, where necessary, to supplement or modify existing models.
- Analysis of sensitivity of the transportation risk values to changes in operational and other parameters.

The Scope of Work did not include the detailed determination of failure modes or accident modes during the transport of hazmat on rail nor did it include considerations of detailed demographic breakdowns, in terms of urban, rural populations and time of day variations in population densities. Also, the demographic data used was more representative of the "county average" population densities rather than the densities close to railroad right of way.

The releases of hazmat during transportation on rail may arise due to human error caused accidents, track related causes or rolling equipment malfunctions or failures. The investigation in this report does not attempt to segregate the cause and effect relationships but considers only those parameters that are (traditionally) thought to be the principal operational parameters on which train accident rate correlations are based.

CHAPTER 2

RISK ANALYSIS MODEL

2.1 ELEMENTS OF RISK ANALYSIS

A general risk assessment consists of two broad categories of calculations, viz: (i) the determination of the probability of occurrence of the event(s) and (ii) the evaluation of the nature, type and extent of hazard posed to the public. In the Risk Analysis Model discussed in this Chapter we have considered several elements which determine the accident occurrence probability and the extent of hazards posed.

Shipping of hazmat on railroads between an origin and a destination involves several important steps any one of which, if not properly executed, may result in release of hazmat into the environment. These steps involve loading of the hazmat into tank cars, movement of the tank car in an industrial yard, on main lines, at classification yard(s), on the industrial yards at the receiving terminal and unloading of the tank car. Leak of hazmat at loading can occur from a number of causes including overfilling, pressure or other relief valve opening, significant increase in ambient temperature relative to loading temperature, metal or valve failures, etc. During the transportation traffic accidents such as derailments, collisions and sideswipes, tank punctures or appurtenance failures can result in and lead to releases. Depending on the nature of the chemical and the quantity of hazmat involved, the result of such releases can be minimal or significant (with large fires or toxic vapor cloud generation and its dispersion).

The parameters considered in our risk assessment model described below include (i) the length of freight train expressed in number of cars, (ii) the number of hazardous material cars in a given train and their frequency of use, (iii) track class, track type and train speed, (iv) puncture/leak occurrence probability given an accident, (v) physico-chemical properties of the chemical and (vi) population density variations by counties and other parameters of significance. The details of the model are described below.

In this study, the data and other statistics on accidents and chemical releases used refer only to those caused by "train accidents". These do not include incidental hazmat releases from such incidents as failure of bottom outlet valve, tank corrosion, etc. (unrelated to train accidents). It is the experience of a major railroad that annual volumes of hazmat release from non-train related incidents are comparable to or even more than the total volume of hazmat releases from train accidents (O'Driscoll[36]). Nation wide, train accidents over the past years show a steady decline. The number of non-train related release incidents, on the other hand, may not have changed over the years. The risk assessment procedure and model presented in this report have to be, therefore, viewed in the perspective of the above data consideration.

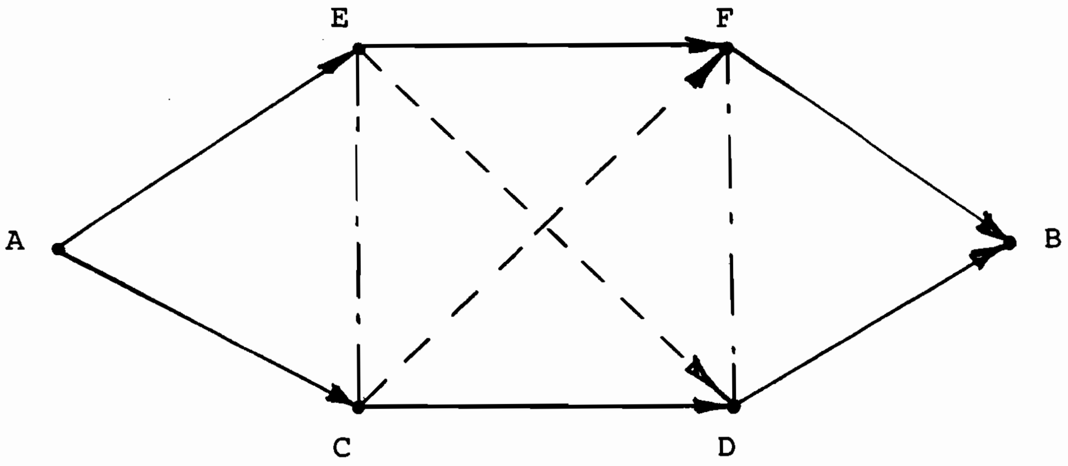
2.2 MODELING PRINCIPLE & APPROACH

Consider the transportation of hazardous materials from an origin point (A) to the destination point (B). It is very likely that between points A and B the quality of track and allowable speeds are different in different sections, the type of population and the population density varies over the route and a number of classification yards are encountered. In the classification yards the makeup of the freight trains are changed because of the different destinations of cars and the different volumes of flow of traffic to different destinations. The possible routes are schematically indicated in Figure 2.1.

The difference in the "make-up" of the freight trains implies variation in several key parameters all of which have an effect on the safety of hazmat transport. These include: (i) the length of train expressed in number of cars, (ii) number of loaded cars, (iii) number of hazardous material cars in a train, and (iv) number of cars containing a specified hazardous material. These parameters vary from train to train, and from segment to segment within the route A-B. In a generalized risk assessment methodology the effect of each of the above parameters needs to be considered.

The most reasonable and accurate approach in modeling the hazmat transportation, which includes the effect of all of the above parameters, is to subdivide the route into several segments, within each of which certain characteristic parameters can be considered to be invariant. These characteristics may be the track quality and allowable speed, traffic density, type of population, population density, or some other geographic boundary such as the county lines. A classification yard can be considered as a segment by itself. We have used this approach of dividing the routes(s) into distinct segments. The basis of division is the county line (i.e., the segment borders and the county borders coincide) because, in most cases, the quality of track was the same within each county and population density data were readily available on a county basis (See Chapter 4).

The annual probability of release of the specified chemical in a given route segment is then calculated. The approach we have used in obtaining this probability is to consider the release of 1 or 2 or 3 ··· (i.e., integral numbers of) tank car full of chemical and calculate the probability of occurrence of the release from all possible combinations of train make-up and other parameters. The hazard area is then calculated using the hazard assessment models (See Chapter 5). The casualty rate is then calculated using the local population density. Thus, the probability of release of 1 car per year on a given segment and the corresponding number of casualties are calculated. Similar calculations of probability of 2 car release per year on the segment and its corresponding casualties, 3 cars per year, etc., are calculated.



Route 1: ACDB
Route 2: AEFB
Route 3: ACFB
Route 4: AEDB
Route 5: AECDFB
Route 6: ACEFB

Yards are: A, B, C, D, E, F.

FIGURE 2.1 SCHEMATIC DIAGRAM SHOWING DIFFERENT ROUTES AND YARDS BETWEEN AN ORIGIN(A) AND DESTINATION(B)

These calculations give a range of annual probabilities and the corresponding expected casualties. The calculations are repeated for all segments in the transportation route and for the classification yards enroute. The results obtained are then sorted in decreasing numbers of casualties, and, by summation of appropriate segment probabilities, a total picture of the risk profile is then obtained. The summation of segment probabilities is performed because the probability of occurrence of incidents anywhere in the route is to be evaluated. The frequency of n cars releasing per year depends, for each value n, on a number of parameters as explained below.

The single most important calculation in the model is the annual probability of release (of entire tank contents) of 1 or 2 or 3,··· etc. tank cars in each segment. Release of a specified chemical over the specified route segment is dependent on the occurrence of a sequence of events, each of whose occurrence itself is stochastic in nature. For example, release of, say, 1 tank car full of chlorine on a segment "N" can only occur if all of these events occur.

(i) At least one train accident should occur over the segment N in a year;
(ii) Accident should be of sufficient magnitude to cause derailment of several cars;
(iii) The train has at least one chlorine car;
(iv) The set of derailed cars should contain at least 1 chlorine car;
(v) The derailed chlorine car should be punctured to such an extent that the entire tank car content is released.

It is clearly seen, therefore, that the overall release probability is dependent on a number of conditional probabilities.

Similarly, the hazard area resulting from the release (See Chapter 5) depends on the type of hazard scenario that occurs subsequent to the release. The common scenarios include fire, explosion, and toxic vapor dissemination in the atmosphere. A probability is associated with each scenario (depending on the chemical). The area of hazard depends not only on the release condition and hazard type, but also on the weather conditions and the hazard level (index). These elements of the risk analysis are mathematically formulated in the following Sections.

2.3 MATHEMATICAL REPRESENTATION

2.3.1 Assumptions

The following assumptions are made in the derivation of the model below:

1. Accident events are random and are uncorrelated in both time and spatial location.

2. The accident events (within the designated route) are assumed to follow a Poisson process. The probability distribution function is represented by:*

$$P(N) = \frac{F^N e^{-F}}{N!} \tag{2.1}$$

where

P(N) = Probability that in a year exactly N accidents occur over the given route segment

F = Mean frequency of accidents over a year.

e = base of the natural logarithm (2.7183)

3. The mean frequency (in # of accidents per year) is numerically very small compared to 1. Hence, the probability that in a year one or more accidents occur is numerically equal to the mean frequency (a consequence of assumption 2).

4. An accident which results in chemical release will empty the tank car, that is, volumes of chemical released are integral **multiples of a full tank car.**

Consider the route, designated by an origin point A and a destination point B (See Figure 2.1). The route consists of "main line" segments and "classification yards". This distinction in segments will be made throughout the development of the risk calculation methodology.

2.3.2 Mainline Accidents

(i) Derailments

The frequency of derailments on a main line segment is estimated by (Nayak, et al, 1983)

$$F_D = Z_D * G * L \tag{2.2}$$

where

F_D = Frequency of mainline derailments in #/year

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* Symbols are defined in the nomenclature.

Z_D = Mainline derailment rate obtained from accident statistics (#/gross ton mile)

G = Traffic density on the given mainline segment (gross tons/yr)

L = Length of mainline track segment (miles)

(ii) Collisions

For mainline collisions, the frequency of accidents is given by:

$$F_C = Z_C * G^2 * L \tag{2.3}$$

where,

Z_C = Collision rate expressed in # of accidents per (gross ton)^2 mile

The data from which the values of Z_D and Z_C are obtained are discussed in the next chapter.

The total frequency of accidents on mainline is then given by:

$$F_M = F_D + F_C \tag{2.4}$$

2.3.3 Yard Accidents

It is uncertain what the "correct" correlating equation is for expressing the relationship between the frequency of accidents in yards and operational parameters such as the average speed of cars, number of cars handled, length of track within a yard, total volume of traffic in gross tons, etc. In addition, several types of hazmat cars (Poison A, for example) are not humped or cut loose in motion in a yard. Considerations of these operational variables in a generalized correlation for yard accident rates is very difficult. We recognize these difficulties in considering yard accidents in our risk analysis. However, the correlation we have used is due to Nayak et al (5):

$$F_Y = Z_Y * N_{C,Y} \tag{2.5}$$

where

F_Y = Mean frequency of accidents in a yard (#/year)

Z_Y = Rate of accident expressed in # of accidents per car classified

$N_{C,Y}$ = Number of cars classified annually (#/year)

2.3.4 Probability of Release of Chemical X from Tank Cars, In a Specified Segment

Consider the release of a designated chemical, say Chemical X, from railroad accidents on a specified mainline segment of length L.

Then, **

[The annual probability of release from exactly I_X cars, over the segment] = [Accident Frequency] * [Probability of release from I_X cars over the segment in accident] (2.6a)

i.e.,

$$P_R\,(I_X) = F_M * P_R\,(I_X \mid A) \qquad (2.6b)$$

where, $P_R\,(I_X \mid A)$ = Conditional probability of release given the occrrence of accident

We can express the above conditional probability in terms of other conditional probabilities that depend on train make-up parameters.

$$P_R\,(I_X \mid A) = \sum_{N_T = I_X}^{N_T^{Max}} P(N_T) \sum_{N_X = I_X}^{N_T} P(N_X \mid N_T) \quad P_R(I_X \mid N_X, N_T) \qquad (2.7)$$

where

$P(N_T)$ = Probability that the freight train involved in the accident has exactly N_T number of freight cars

$P(N_X \mid N_T)$ = Conditional probability that given a train of N_T total cars, exactly N_X of them carry Chemical X

$P_R(I_X \mid N_X, N_T)$ = Conditional probability of release from I_X cars given that a train has N_X cars of chemical X and N_T total freight cars.

N_T^{max} = Maximum number of cars in a train (generally set equal to the mean number of freight cars over the segment + 2 * standard deviation of N_T distribution).

The above conditional probability of release (left side of equation 2.7) depends on the number of cars derailing, the fraction of these derailing cars which are Chemical X cars,

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** All probabilities are annual probabilities.

number of cars that are punctured leading to release of the total contents of the cars. The conditional probability on the far right hand side of equation 2.7 can be written as:

$$P_R\,(I_X \,|\, N_X, N_T) = \sum_{N_D=I_X}^{N_T} P_D(N_D \,|\, N_T,\ U,\ \ldots\ldots)\ P_R(I_X | N_D, N_X) \qquad (2.8)$$

where

$P_D(N_D \,|\, N_T,\ U,\ \ldots)$ = Conditional probability of derailing of N_D cars in the train given that there are N_T cars and train speed is U

$P_R(I_X \,|\, N_D,\ N_X,\ N_T)$ = Conditional probability that I_X cars release given that a train with N_X cars of Chemical X derails and N_D of a total of N_T cars are derailed.

Equation 2.8 expresses the fact that I_X car **releases can occur** from a combination of number of cars derailing and a variable fraction of these derailed cars being the Chemical X cars. Since, all possible combinations by which I_X "release cars" can be formed are to be considered, the total probability (left hand side of equation 2.8) is the result of the sum of all other individual constituent event probabilities.

To calculate the release probability on the right hand side of equation 2.8, we assume that J_X number of chemical X cars are derailed and form part of the N_D total derailment. However, not all J_X cars will release. In fact, if

q_X = (binomial) probability of release of a derailed Chemical X car

then the number of cars releasing follows a binomial distribution and probability of release by I_X cars is given by:

$$\underbrace{P_R(I_X \,|\, J_X)}_{\text{Probability that exactly } I_X \text{ cars release given that } J_X \text{ cars of Chemical X have derailed.}} = \frac{J_X!}{I_X!\ (J_X - I_X)!}\ q^{I_X}\ (1 - q)^{(J_X - I_X)} \qquad (2.9)$$

Therefore the conditional probability $P_R\ (I_X \,|\, N_D, N_X)$ can be written as

$$P_R(I_X \,|\, N_D,\ N_X,\ N_T) = \sum_{J_X=I_X}^{J_X=N_X} P_D\,(J_X \,|\, N_D, N_X, N_T \ldots)\ P_R(I_X | J_X) \qquad (2.10)$$

where

$P_D(J_X \mid N_D, N_X, N_T)$ = Conditional probability of J_X cars of Chemical X derailing when there are N_X chemical X cars and N_D number of freight cars derail.

The set of equations 2.6 through 2.10 gives, when appropriate parameter values are substituted, the overall annual derailment and leak probability for I_X cars of Chemical X on the specific segment. However, before such a calculation can be made several of the conditional probabilities have to be obtained either from data correlations or from mathematical analyses using known parameters. The evaluations, mathematically, of some of these parameters are indicated below. The data correlations are discussed in Chapter 4.

In the above formulation of the equations we have used the terminology "derailment" and the derivations are strictly correct for true derailments. There is no easy way of considering exactly the mainline collisions for risk assessment purposes. We have simply assumed that the conditional probabilities that apply for derailments hold good for collisions also. Therefore, by multiplying the I_X car release probability (given an accident) as shown in equation 2.6a, by the overall frequency of accidents F_M (the sum of derailments and collisions - see equation 2.4), we have effectively taken into consideration both mainline derailments and collisions. We further note that main line collisions form a very small fraction of the total number of train accidents on main lines. That is, the term "derailment" used in the equations should be construed as encompassing both true derailments and collisions.

The set of Equations 2.6 through 2.10 forms the basis of the risk assessment calculations. The annual probability of releases of Chemical X from 1 tank car, 2 tank cars, 3···, etc., are calculated (using equations 2.6 thru 2.10) for each segment of the route. The consequences from these releases are calculated using hazard assessment models and population density information. These latter calculations are described in Chapter 5.

2.3.5 Casualty Calculations

The casualties (expressed in the form of numbers of injuries, fatalities or economic damage) are calculated by:

$$C_{N,X} = \overline{A}\,(V_X)\;\rho \qquad (2.11)$$

where

$C_{N,X}$ = Number of casualties that may result from the release of volume V_X of the Chemical X

$\overline{A}\,(V_X)$ = Expected area of hazard resulting from the release of Volume V_X of Chemical X

ρ = Density of population within the hazard zone.

In the above equation the value of A is obtained by taking into consideration (i) the quantity of chemical released, (ii) the type of hazard and its probability of occurrence after release, (iii) the hazard level for each type of hazard and (iv) the type of weather under which the hazard is occurring and the probability of occurrence of the given weather. These calculations are discussed, in detail, in Chapter 5.

2.3.6 Determination of the Conditional Probabilities

The evaluation of $P_R(I_X)$ (Equation 2.6b) involves the use of several conditional probabilities. The values of some of these probabilities are dependent on operational parameters and others are functions of the severity of accident, the physical characteristics of tank cars and their appurtenances. Calculations of these conditional probabilities are discussed below.

(i) Number of Freight Cars in a Train (N_T)

The average number of freight cars in an "average freight train" in the U.S. is estimated to be 69.1 in 1982 (AAR$^{(4)}$). This number varies over the different regions in the U.S.; from a low of 66.1 to a high of 71.9. It can be expected that even within a region the "average" number of cars in different sections vary depending on the freight traffic volume. To the best of our knowledge there is no published information on the statistical distributions representing the number of freight cars in a train. It can be anticipated, however, that this distribution will be close to a Gaussian with a low normalized standard deviation. Hence, the probability that a given train, in a specified segment, has exactly N_T cars can be written as:

$$P(N_T) = \frac{\exp\left(-\dfrac{(1-N_T/\overline{N_T})^2}{2\,s^2}\right)}{\left[\sqrt{2\pi}\;\overline{N_T}\;s\right]} \qquad (2.12)$$

where

N_T = Number of freight cars in a train

$\overline{N_T}$ = Mean number of cars in freight trains going over the specified segment

s = normalized standard deviation of the number of freight cars in a train (N_T) distribution. (Generally in the range 2 to 5%)

(ii) Presence of Chemical X Cars in a Freight Train

A freight train is made up of a number of cars containing various cargoes some of which may be hazardous materials. Depending on the segment of route under consideration and the total number of tank cars N_X of Chemical X in each train will vary and follow a particular distribution. There are, again, no published data describing the distribution representing N_X. The occurrence of Chemical X cars in a given freight train can be assumed to be represented by a Poisson distribution (which, in general, represents the probability of occurrence of infrequently occurring phenomena). Then we have,

$$P(N_X \mid N_T) = \begin{cases} 0 & \text{for } N_X > N_T \\ \dfrac{(\overline{N}_X)^{N_X} e^{-\overline{N}_X}}{N_X!} & \text{for } N_X \leq N_T \end{cases} \qquad (2.13)$$

[Conditional probability that a given train of N_T cars contains exactly N_X number of Chemical X cars]

where,

$\overline{N}_X$ = Mean number of Chemical X cars in a train on the segment of interest (Note: this can be a fraction)

The value of $\overline{N}_X$ has to be obtained from direct data, if available, on the make up of trains or indirectly from the annual volume of shipments of Chemical X over the segment. The data for determining the above mean number of Chemical X cars for different types of hazmat are indicated in Chapter 4 (see Table 4.11).

(iii) Probability of Mainline & Collision Derailments

One of the inputs required to establish the overall probability of Chemical X release is the probability of derailment of a given number of freight cars. Nayak, et al (1983) have analyzed in detail the available data for the 1975-77 period on derailments and the causes of derailments. They have concluded that:

- the number of cars derailing in an accident is strongly dependent on the train speed prior to the accident,

- the number of vehicles derailing is generally independent of the length of the train so long as the total number of cars is greater than 25,

- in relatively large number of collision accidents no cars are damaged. Quantitatively, only in about 54% of collision accidents was there damage to one or more cars,

- the number of cars derailed has the same dependence on the train speed irrespective of the track type (mainline or yard).

The correlations obtained by Nayak, et al(5), based on regression analysis of data, are expressible in the form:

$$\overline{N}_D = A * U^{0.5} \qquad (2.14a)$$

$$\sigma_{N_D} = B * U^{0.5} \qquad (2.14b)$$

where U is the train speed expressed in m.p.h., and the values of A and B, for use in the above equations, are indicated in the table below.

Parameter		Accident Type		
		Mainline & Yard Derailments (All causes)	Mainline & Yard Yard Derailments (Track causes)	Mainline & Yard Collisions
Value of 'A' to determine the mean # of derailed cars N_D	A	1.7	2.1	1.25
Value of 'B' to calculate the standard deviation of the # of cars derailed σ_{N_D}	B	1.64	1.64	1.52

Accident data in sufficient detail are not available to determine the probability distribution of the number of cars derailed as a function of train speed, track class, track type, etc. Nayak, et al(5) did not evaluate the probability distribution of number of cars derailed in an accident. They reviewed the data pertaining to the derailment of only hazardous material cars in accidents and showed that the derailments of hazardous material cars could be represented by a (discrete) Gamma distribution. We extrapolate this result from (only) hazardous material cars to a larger population including the derailments of all types of freight cars. That is, we assume that the probability density distribution of number of cars derailing in an accident is given by:

$$P(N_D \mid N_T, U, \text{Acc.}) = \frac{1}{\Gamma(a)\, b^a} \int_{x=N_D-0.65}^{N_D+1-0.65} x^{(a-1)} \quad e^{-x/b} \quad dx \qquad (2.15a)$$

where the left hand side parameter is the probability that exactly N_D cars derail, given that an accident occurs at speed U to a train containing N_T cars and ,

$$a = \overline{N}_D^{\,2} \,/\, \sigma_{N_D}^2$$

$$b = \sigma_{N_D}^2 \,/\, \overline{N}_D \qquad (2.15\ b)$$

Γ = The Gamma function

In the above equation for $P(N_D, \cdots)$ the probability that exactly N_D freight cars are derailed is independent of N_T the total number of cars in the train. Also, the constant 0.65 in the limits of integration is based on matching the value of the probability for "no derailment" of cars. The constants a and b in the above equation are evaluated for the given train speed by using the values of $\overline{N}_D$ and σ_{N_D} from Equations 2.14a and 2.14b.

(iv) Probability of Presence of Chemical X Cars Among the Derailed Cars

In a given mainline derailment accident if we assume that N_D cars derail then there is a finite probability that some of these cars may be the hazardous material cars carrying Chemical X. The evaluation of this probability is indicated below.

The conditional probability, $P(J_X \mid N_D)$, of J_X cars of Chemical X cars derailing, given that a total N_D freight cars have derailed in an accident, is dependent on the following parameters:

(i) The total number of cars (N_X) of Chemical X in the train and the total number of cars N_T in the train.

(ii) Distribution of these N_X cars in the train. That is, whether all N_X cars are blocked together, or distributed in several blocks, or are placed completely randomly in the train.

(iii) Position of the hazmat cars in the train (front quarter, last quarter, middle half, etc. within the train).

In Appendix A we have shown a simple model to evaluate the above probability for the case of all Chemical X cars being blocked together. Nayak, et al(5), have given an expression for the above conditional probability for the case of random distribution of hazardous material cars in a train in terms of hypergeometric series. Here we quote our results from Appendix A:

FOR $N_D > N_X$

$$P(J_X \mid N_D, N_X, N_T) = \begin{cases} \dfrac{2}{N_T} & \text{for} \\ \\ \dfrac{N_D - N_X + 1}{N_T} & \end{cases} \qquad (2.16a)$$

or

FOR $N_X \geq N_D$

$$P(J_X \mid N_D, N_X, N_T) = \begin{cases} \dfrac{2}{N_T} & \text{for} \\ \dfrac{N_X - N_D + 1}{N_T} & \\ 0 & \end{cases} \qquad (2.16b)$$

(v) Probability of Release and Volume of Chemical X Released from a Derailed Tank Car Carrying the Chemical

Depending on the severity of a derailment accident a derailed tank car may or may not leak. The accident may cause damage to the over-pressure relief valves, piping, tank shell, any one of which can lead to the potential release of the lading. The rate of release and the quantity of chemical released depend on the nature, location and size of the puncture.

It is shown from the examination of available liquid release data (Nayak, et al(5)) that the quantity released per car is dependent on the speed of derailment. Nayak, et al have, in fact, obtained a correlation for the mean quantity of hazardous material released ($\overline{Q} = 2000\ U^{0.5}$ gallons) and standard deviation ($\sigma_Q = 11{,}400$ gallons) only as a function of the speed of derailment. The number of data used to obtain these distribution parameters was very small (in fact, 12).

It is impossible to represent all hazardous material releases into one set of correlation because the quantity released depends to a large extent on the nature of the chemical as well. For example, in the case of a liquefied compressed gas, a hole in the tank car shell next to the vapor space will lead to a depressurization, liquid boil-off and release of significant fraction of the tank's contents, irrespective of the location of the hole. However, the same size hole in a tank car carrying sulphuric acid may not result in any significant volume being released.

Therefore, instead of using a correlation whose applicability to different types of hazardous material releases is questionable, we use the volume of an entire tank car's contents as the standard volume of material released, if it is assumed that a release has occurred. Such an assumption, in a risk analysis model, leads to the evaluation of the relative risks due to various types of chemical releases on an equal basis. In addition, the assumption is conservative.

Therefore, in our model the probability of damage leading to a puncture and release is identical to the probability that the entire contents of the tank car are released (given that a tank car has derailed). This conditional probability is assumed to be binomially distributed. The binomial probability of release from a derailed hazmat tank car is represented by q_X (see also Equation 2.9). The data from which the value of q_X is estimated are discussed in Chapter 4 (see Table 4.12).

2.3.7 Risk Calculation Procedure

The risk assessment model developed in this chapter consists primarily of two sets of calculations, namely: (i) calculation of the annual probability of spill of total contents of integral numbers of tank cars of the chemical being released over a given segment and (ii) the calculation of the consequence of release of the chemical. The consequence area calculations are indicated in Chapter 5. In this section, we summarize the procedure for obtaining the release probability and the development of risk profile.

The following is the sequence of calculation of the release probability on a given segment of the transportation route:

STEP #	Calculation Element	Symbol	Equation #
1	For the given segment the annual frequency of derailment & collision accidents is determined from the traffic and other data.	F_M F_Y	(2.4) or (2.5)
2	Average train speed, commensurate with the track class, is noted.	U	
3	A specific number I_X (= 1,or 2, or 3...) of tank cars is selected whose annual probability of release is to be determined.		

STEP #	Calculation Element	Symbol	Equation #
4	Average # of total cars in a freight train (N_T) is noted from data. Alternatively an integral number N_T is chosen in the range $\overline{N}_T$ (1 - 2 s_{NT}) to $\overline{N}_T$ (1 + 2 s_{NT}) and its probability of occurrence determined.	$P(N_T)$	(2.12)
5	Average number of Chemical X cars in a train (N_X) is determined from available traffic data (see equation 4.1a or 4.1b)		
6.	A number N_X is chosen in the range I_X to N_X^{max}. The maximum value is generally set equal to $\overline{N}_X + 5$.		
7	Probability of N_X cars being present in the train is calculated.	$P(N_X \mid N_T)$	(2.13)
8	Average number of cars derailing is $\overline{N}_D$		(2.14)
9	The number of cars derailing in an accident, N_D, is chosen in the range $\overline{N}_D - 2\sigma_{N_D}$ to $\overline{N}_D + 2\sigma_{N_D}$. The probability of N_D cars derailing is obtained.	$P(N_D \mid N_T ..)$	(2.15)
10	The number of cars of chemical X derailing, J_X, is chosen with a value between I_X and N_X.		
11	Probability of J_X cars of chemical X being derailed is calculated.	$P_D(J_X \mid N_X, N_T)$	(2.16)
12	The binomial probability of release from a tank car given that the car has derailed is obtained from data correlations (see Chapter 4).	q	
13	Probability of release from exactly I_X cars given that J_X cars have derailed is obtained from the equation.	$P_R(I_X \mid J_X)$	(2.9)
14	Results in Steps 11 and 13 are multiplied.		
15	Step 10 is repeated over the range of J_X values and running sum of result in Step 14 is determined. This gives the conditional probability of I_X cars releasing, given that N_D cars derail and train contains N_X cars of chemical X.	$P_R(I_X \mid N_D, N_X)$	(2.10)

STEP #	Calculation Element	Symbol	Equation #
16	Steps 9 thru 15 are repeated for different values of N_D. The value of conditional probability of I_X cars releasing given that the train has N_X cars is determined.	$P_R(I_X \mid N_X, N_T)$	(2.8)
17	Steps 6 thru 16 are repeated for different values of N_X, in the given range. The conditional probability of I_X release given that there are N_T freight cars is determined.	$P_R(I_X \mid N_T)$	(2.7)
18	Steps 4 thru 17 are repeated if necessary, for the range of (N_T), the total number of cars in a train. The total probability of release from I_X cars is determined.	$P_R(I_X \mid A)$	(2.7)
19	Overall release probability from I_X cars is determined.	$P_R(I_X)$	(2.6b)
20	For each I_X, the expected casualty area is determined (see Chapter 5).	$A(I_X)$	
21	Using the census population density data, the total number of casualties for given I_X car releases is determined.	$C(I_X)$	(2.11)
22	Steps 3 thru 21 are repeated for different values of I_X.		

The entire set of calculations (from Step 1 thru 22) is repeated for the different segments of the route. The results of these calculations will be a 2 column matrix of values of which one column will represent the annual probability of release of 1,2,3...tank cars full of chemical, and the other column will indicate the number of casualties. This matrix is then rearranged (without regard to the route segment) with decreasing number of casualties. For drawing the risk profile, the probability of exceeding a given casualty value, say C, is determined by adding all of the individual probabilities corresponding to casualty numbers in excess of the given casualty value C. A plot of the cumulative probability against the casualty value C gives the risk profile. The above sequence of calculations is shown in Figure 2.2 as a calculation flow chart.

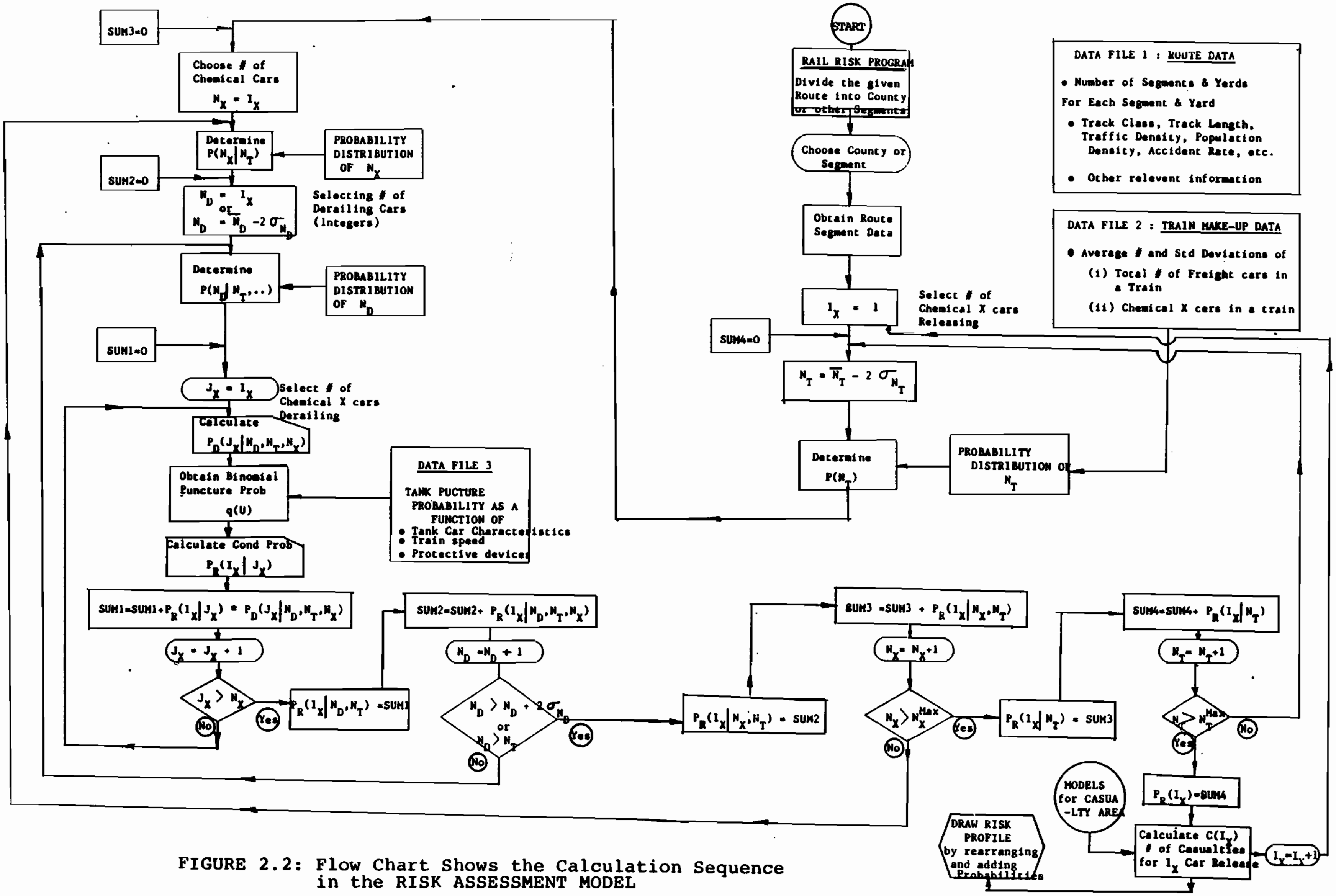

FIGURE 2.2: Flow Chart Shows the Calculation Sequence in the RISK ASSESSMENT MODEL

2.4 DISCUSSION

The model developed in the previous Section is useful for two purposes. First, the model can be utilized to determine the overall risks in the transport of a specified chemical on a given route between two points. These overall risk values can then be compared with magnitudes of other risks to which the population along the route would be subjected, even without the hazmat transportation. In this category would lie the risks posed to the public by natural phenomena, other involuntary risks due to industrial activity, etc. The comparison of risks due to rail transport of hazmat with other risks will indicate the degree to which the hazmat transport risk may be acceptable (especially if the increase in risk is marginal).

The second use to which the model developed can be put is for comparing the relative risks of transporting hazmat on alternative routes. In this case, the profiles of risks for the alternative routes can be developed and compared. Such a comparison, with the criteria for acceptability of hazmat risks spelled out a priori, will yield the least dangerous route for the transport (where such alternatives are available). The limitation of this use lies, of course, in the fact that the risk burden is shifted from one segment of the population to another.

The model indicated in Section 2.3 is very detailed, and requires several items of data, correlations, and other information. First, to the extent that the model assumes integral numbers of tank car volumes of chemical are released, risks may be overstated. This is because releases from tank car accidents follow a distribution (by volumes of spill). All releases do not result in the entire contents of the tank cars being released. However, this conservative assumption does not lead to significant errors when risk comparisons for alternative routes are made. Secondly, the model does not take into account either multiple chemical releases or secondary releases. Each release and damage to each tank car are treated as independent random events. It is very difficult to model multiple chemical release event scenarios. There are not enough data on multiple releases and their consequences. Therefore, a model development effort without the availability of sufficient data to determine key probabilities in the model would be futile. As to the effect of secondary releases, while they are important, we argue that because of the requirement of thermal insulation on several types of tank cars (49 CFR Part 179.105[17]) the incidence of secondary fire related releases may be so small as to have a negligible effect on the overall risk probabilities.

The application of the above model to a specific case is illustrated in the following Chapters. The details of the routes chosen and the criteria for selecting the particular routes for study are discussed in Chapter 3. The historical accident data statistics and correlations therefrom are indicated in Chapter 4. In Chapter 5, the hazard area calculation models are described, and casualty estimating is discussed. The application of the risk analysis model to the specific routes chosen and the results generated are discussed in Chapter 6. The sensitivity of the results to variations in parameter values are evaluated in Chapter 7.

CHAPTER 3

SELECTION OF COMMODITIES & ROUTE(S) FOR CASE STUDY

The risk analysis model developed in the previous chapter is applicable to the evaluation of rail transport risks associated with any specified chemical. In this chapter, selection of three representative chemicals for detailed transport risk study is discussed. The selection of the chemicals is based on a set of criteria which are indicated. Also discussed in this chapter is the selection of a set of origin and destination points for the transport of the selected chemicals for detailed risk assessment.

3.1 SELECTION OF CHEMICALS FOR STUDY

The selection of chemicals whose transportation risks were to be evaluated was based on three principal criteria. The first was that the three chemicals chosen be considerably different from one another. Second, that a chemical with high annual usage/transportation volume and ones with medium-to-low annual volume of transport be included. Third, the chemicals chosen be such that the areas of potential hazard extend from basically covering the railroad right-of-way to covering a large area. These criteria were utilized in selecting the three hazardous materials from commonly transported industrial chemicals.

3.1.1 Annual Volumes of Chemical Transport and Release Incidents

A large number of hazardous chemicals are transported on railroads in the U.S. The United Nations Committee of Experts has divided these chemicals into 26 main classes according to their physical and chemical properties. Generally, these different classes are defined in 49CFR, Part 173. These hazardous material classes and their corresponding United Nations Division Numbers (UN) are indicated in Table 3.1.

The annual volumes of shipment of those chemicals that form the industrial feedstock or energy fluids exceed the annual transportation volume of other chemicals by significant quantities on the U.S. railroad systems. Table 3.2 shows 25 chemicals ranked in the order of their annual volumes transported on rail in the United States for the years 1979 through 1983. It is seen that LPG (flammable compressed gas), caustic soda and sulphuric acid (corrosive materials), chlorine (nonflammable compressed gas), and fuel oil occupy the top ranks for the number of carloads shipped annually.

TABLE 3.1

Hazardous Material Classes and Their United Nations (UN) Division Numbers

United States Classifications	Corresponding UN Classifications	Reference in 49 CFR Subpart
Explosives (mass explosion hazard)	1.1	C
Explosives (with projection hazard)	1.2	C
Explosives (with fire hazard)	1.3	C
Explosives (no significant blast hazard)	1.4	C
Explosives (very insensitive)	1.5	C
Flammable gas	2.1	G
Nonflammable gas	2.2	G
Poisonous gas	2.3	H
Flammable and combustible liquids	3	D
Flammable solids	4.1	E
Spontaneously combustible	4.2	E
Dangerous when wet	4.3	E
Oxidizers	5.1	E
Organic peroxides	5.2	E
Poisonous materials	6.1	H
Irritating materials	6.2	H
Etiologic or infectious substances	6.2	H
Radioactive materials	7	I
Corrosive materials	8	F
Miscellaneous hazardous materials	—	—
Other regulated materials (ORM)	9	J
ORM A	9	K
ORM B	9	L
ORM C	9	M
ORM D	9	N
ORM E	9	O

TABLE 3.2

CAR LOADS OF CHEMICALS SHIPPED ANNUALLY IN U.S.

Commodity	1983 volume	1983 Rank	1982 Rank	1981 Rank	1980 Rank	1979 Rank
LPG	105,894	1	1	1	1	1
Caustic Soda	65,172	2	2	2	2	2
Hazmat FAK	57,532	3	4	4	3	3
Sulfuric Acid	42,911	4	5	5	6	7
Fuel Oil	40,750	5	3	3	4	4
Chlorine	37,918	6	6	7	7	6
Anhydrous Ammonia	37,126	7	7	6	5	5
Phosphoric Acid	23,991	8	9	9	9	9
Ammonium Nitrate	22,595	9	8	8	8	8
Methanol	20,063	10	11	11	12	14
Vinyl Choride Monomer	18,773	11	10	10	10	10
Hydrochloric Acid	11,259	12	12	12	13	15
Crude Oil	9,650	13	13	13	11	13
Gasoline	9,563	14	-	23	14	12
Carbolic Acid or Phenol	6,943	15	14	17	17	16
Petroleum Distillate	6,485	16	-	-	-	-
Carbon Dioxide	6,267	17	16	15	18	24
Adiptic Acid	5,793	18	-	-	-	-
Hexamethylene Diamine	5,699	19	19	18	23	20
Styrene Monomer Ihibited	5,591	20	22	23	22	19
Alcohol, n.o.s	5,515	21	-	-	-	-
Acrylonitrile	5,318	22	15	14	15	-
Petroleum Naptha	5,225	23	-	-	-	-
Ethylene Oxide	5,038	24	17	16	16	18
Propylene Oxide	5,025	25	18	19	34	21

FAK = Freight of all kinds

	1983	1982	1981	1980	1979
Total - Top 25	663,619	497,323	570,590	594,657	584,098
Grand Total - Haz. Mat.	827,303	720,685	818,411	847,299	848,852

Data Source: Reference 6
(Personal Communication from
Mr. Roy Holden of AAR, 1984)

Table 3.3 shows the number of leaking tank car incidents arranged by the class of the hazardous materials for the calendar years 1977 thru 1983. It is seen that consistently the largest number of leak incidents* occur in corrosive materials. The next high leak incidents are with flammable liquids. The third high release incidents occur in flammable gases and non-flammable (compressed) gases. The release of flammable gases and the non-flammable gases pose, however, larger areas of hazard than either corrosive materials or flammable liquids (when compared on an equal mass release basis). Therefore, from the point of view of assessing risks, the flammable compressed gases and the non-flammable toxic gases should be considered for study.

3.1.2 Risk Potential of Chemicals

The potential risk to the public from the transport of hazmat on rail is dependent on the exposure, i.e., the frequency or rate at which the public is likely to "encounter" the chemicals. That is, the risk depends on the volume of traffic. The area that may be affected, should a chemical be released, is dependent on the nature and physical state of the hazardous material. Therefore, any risk analysis study of hazmat transport on rail should include those chemicals that have high exposure and high consequence potential.

Using the above as the criteria for the selection of the candidate commodities in our risk assessment study, we have developed a subjective ranking table which is shown in Table 3.4.

This table is developed by considering the indices of exposure and hazard for each chemical and evaluating the product of exposure index and hazard index. The "Exposure Index" represents the potential for exposure of population in general, to a chemical. It can be argued that the larger the annual volume carried on the U.S. railroad system, the greater is the potential exposure to the population. Based on this premise, the Exposure Index is defined as indicated in Table 3.4. The "Hazard Index", on the other hand, is defined on the basis of expected hazard area for each chemical. Since the area depends on the volume of release, rate of release, nature of hazard, and the atmospheric conditions, we have used a uniform scenario condition of an accident (such as 1 tank carfull leakage, release of complete contents of a tank car, instantaneous release in very stable weather, etc.) to determine the hazard area. Where multiple scenarios of hazards exist, as in LPG, an average area, obtained by weighting the hazard area for each scenario with its probability of occurrence, is used.

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* For the data presented in Table 3.3, a leak incident is defined as an event in which some quantity of the material escapes out of the tank car from any one of the following causes (i) over fill, (ii) safety relief device venting, (iii) valve malfunction and (iv) accidents in transit involving fitting failures or shell puncture.

TABLE 3.3 LEAK INCIDENTS BY HAZARDOUS MATERIAL CLASS IN VARIOUS YEARS (LEAKING TANK CARS)

	1977	1978	1979	1980	1981	1982	1983
Nonflammable Gas	74	95	124	110	132	144	140
Flammable Gas	141	108	139	177	109	110	128
Flammable Liquid	134	214	222	283	250	230	253
Combustible Liquid	40	47	42	73	85	79	84
Flammable Solid	3	4	10	4	9	5	4
Oxidizer	10	16	7	16	18	15	16
Organic Peroxide	0	0	0	1	1	1	0
Poison A	0	0	6	0	0	1	0
Poison B	7	19	9	9	9	12	9
Corrosive Material	348	347	357	370	457	349	344
Unassigned	7	15	80	27	27	19	10
TOTAL	764	865	996	1070	1097	965	988

Note: Leak incidents include all release incidents from train accidents and those caused by unintentional releases due to car failures (fitting leaks, corrosion, etc.)

Source: Reference 6

TABLE 3.4

Ranking of Candidate Commodities for Consideration in the Risk Assessment Study

#	1 Hazardous Material	2 Hazmat Class	3 Exposure Index	4 Hazard Area Index	5 Combined Index
1	LPG	Flammable Gas	12.8	6.4	81.9
2	Caustic Soda	Corrosive	7.9	0.65	5.1
3	Sulfuric Acid	Corrosive	5.2	1.00 **	5.2
4	Fuel Oil	Combustible Liq.	4.9	0.41	2.0
5	Chlorine	Non-flammable Gas	4.6	56.7*	260.8
6	Anhydrous Ammonia	Non-flammable Gas	4.5	50.0*	225.0
7	Phosphate Fertilizer Solid	Oxidizer	2.9	1.7	4.9
8	Ammonium Nitrate	Oxidizer	2.7	1.7	4.6
9	Methanol	Flammable Liquid	2.4	2.3	5.5
10	Vinyl Chloride Monomer	Flammable gas	2.3	2.3	5.3

$$\text{Exposure Index} = 100 \times \frac{\text{\# of Commodity Tank cars shipped in 1983 in U.S.}}{\text{Total \# Hazmat cars shipped in U.S. in 1983}}$$

(Data from Table 3.2)

Hazard Index = 100 x Expected Lethal Hazard Area (in Km^2) for a worst case release (Ref: Nayak et al, 1983) of a tank car full of contents, under urban environments.

Column 5 = Column 3 x Column 4

** Technology & Management Systems, Inc. estimate for 13,350 gallon spill (see Section 5.5).

* Technology & Management Systems, Inc. estimate for 90 ton releases (see Table 5.2).

The procedure is similar to that indicated by Nayak, et al(5) . The Hazard Index definition is also indicated in Table 3.4.

It is seen from Table 3.4 that the top three commodities for inclusion in the risk assessment study are:

1. Chlorine and Anhydrous Ammonia
2. Liquified Petroleum Gas (LPG)
3. Sulfuric Acid (Oleum, or H_2SO_4)

The combined indices for caustic soda, sulfuric acid, methanol, and vinyl chloride are very close to each other; hence, any one of them can be chosen. Because of the high volume of sulfuric acid transported and its fuming characteristics, it is chosen for study.

Anhydrous ammonia and chlorine have about the same combined index value. The numbers of incidents of release of chlorine Cl_2 and anhydrous ammonia (NH_3) are comparable. Also, the physico-chemical properties are similar (see Table 3.5) and the behavior of their vapor clouds in the atmosphere are also similar. Therefore, either chemical could be chosen as a representative of toxic gas material for a risk analysis study.

We have elected to select chlorine (Cl_2) for study because of the following reasons:

a) Both Cl_2 and NH_3 have the same boiling temperature (239°K) at atmospheric pressure. However, the density of chlorine vapor at this temperature is 3.7 kg/m^3, whereas the density of ammonia vapor is 0.89 kg/m^3. While both materials when released from pressure, as in a tank car leak, will form a heavier than air, ground-hugging saturated vapor-liquid aerosol cloud (and the initial behavior of the clouds are similar) it can be argued that the chlorine cloud will be heavier both initially and during subsequent dispersion because of the higher molecular weight of chlorine and the non-reactivity of liquid chlorine with ambient moisture. Ammonia aerosols, on the other hand, will mix with ambient water vapor liberating heat of dissolution. This heat, together with the heat from the ground, may make the cloud of ammonia neutral or buoyant under certain conditions. In effect, the chlorine clouds are expected to hug the ground, spread laterally and downwind to larger extents than equivalent mass of anhydrous ammonia clouds.

b) Evacuation distances for chlorine releases are specified as 1 mile downwind and 0.7 mile crosswind width by the DOT (Emergency Response Guide Book(18)). The Bureau of Explosives(19) specifies an evacuation radius of 2500 feet (about 1/2 mile) for chlorine released from tank cars. The evacuation distances for anhydrous ammonia leaks are specified as 0.6 mile downwind and 0.4 mile wide. Therefore, the evacuation distances for chlorine are larger. This would imply that the hazard areas for chlorine releases are much larger than for anhydrous ammonia.

c) Chlorine vapors in air are dangerous to health (leading to possible fatality) at 50 ppm level when exposed for 30 minutes. The ammonia concentration level for the same effect over the same exposure time is 2400 ppm, i.e., almost two orders of magnitude higher than that for chlorine! This in itself indicates that chlorine is the more toxic of the two chemicals.

The above set of three chemicals provides a broad basis for risk assessment and comparing relative risks.

3.1.3 Properties and Behavior of Selected Chemicals

In this section, the physical and chemical properties together with the different types behavior of the chemical when released into the environment are discussed, for each of the three chemicals. Selected thermodynamic and physical properties of the chemicals selected are indicated in Table 3.5.

(i) Chlorine

Chlorine is transported at ambient temperature under pressure. An accident related release results generally in the formation of flash vapor and liquid aerosol cloud. Depending on the size of the hole in the tank car the size of the cloud formed may or may not be very large.

The principal hazard from a chlorine release arises from the toxic nature of the cloud. Because of the relatively low levels of concentration at which lethal hazards can occur, the hazard distances can be considerable. The ground level area within the hazard zone will depend on the atmospheric conditions and the accident related (release) conditions.

(ii) Liquefied Petroleum Gas (LPG)

LPG is a generic commodity name for a variety of liquid hydrocarbon gases. The mixture of LPG vapor and air of appropriate proportions is flammable and in a narrow range detonable. Several scenarios of fires associated with LPG releases are possible. These include: (a) torch jet fire for the case of vapor release from safety valve or a hole in the tank wall next to the vapor space, (b) pool fires from liquid spill onto ground, (c) BLEVE* from the sudden failure of the entire tank and the ignition of the whole mass of LPG released, (d) explosive and detonative burning of vapor-air mixture caused by delayed ignition of the vapor cloud from an ignitor far

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* BLEVE is an acronym for Boiling Liquid Expanding Vapor Explosion.

Table 3.5 Some Selected Physical & Thermodynamic Properties of the Selected Candidate Commodities

Candidate Commodity	Normal Bulk Rail Transport	Normally Used Tank Cars	Saturated Vapor Pressure - Temp. Relationship at		Saturated liquid Density at 25 C Kg/m3	Flamma-Bility Limit mol %	Short Exposure Lethal Toxicity ppm	Behavior in Environment	Property Data Reference
			Temp C	Vapor MPa					
Anhydrous Ammonia	Compressed Liquified Gas	105A300W 112S340W etc.	15 30 40	0.724 1.172 1.655	620	16 to 25%	2400	When released from pressure vapor and fine droplets of liquid aerosols form and disperse close to the ground. Large tank car size releases result in the formation of heavy ground hugging clouds of vapor that remain toxic for very large (several Km) distances. Small and slow releases from safety valves exhibit normal turbulent plume dispersion behavior.	Bennets, Feates, & Wilder (20)
Chlorine	Compressed Liquified Gas	105A500W 112J340W	15 30 40	0.59 0.91 1.19	1395	N/A	1000 ppm or 1000 ppm-min for > 35 ppm concentration		
Liquified Petroleum Gas (LPG)	Compressed Liquified Gas	112T340W 112J340W	15 30 40	0.724 1.103 1.379	509	2.15 to 9.6%	--	Highly flammable. Major releases result in the formation of a large combustible vapor which burns rapidly. Several types of burning of the released LPG is possible depending on type of release. Release of liquid thru a small hole in the tank car can result in either jet flame or a liquid pool fire on the ground. Heated tank car can lead to BLEVE.	NFPA(21)
Sulphuric Acid	Liquid at Ambient Pressure	103A, 103AW, 111A100W2	15 30 40	Pr in mm of Hg - - 0.00235	1820	--	--	Has very low vapor pressure. Fumes when released due to moisture absorption from the atmosphere. Hazard area is limited to site of spill.	Perry (22)

away from the point of release.** The detonation combustion and the BLEVE combustion affect a large area in the vicinity of the release site.

(iii) Sulfuric Acid

Concentrated sulfuric acid (greater than 95% H_2SO_4) is very corrosive and will burn skin, wood and other organic matter on contact. At ordinary ambient temperatures the vapor pressure is very low as to render evaporation inconsequential. However, sulfuric acid reacts with the ambient moisture and boils at the surface of the liquid pool. Released fumes of H_2SO_4 and fine droplets (aerosols) may result. In spite of this phenomenon the hazards due to a spill are usually confined to within a short distance (of the order of a few meters to few tens of meters) beyond the spread of liquid on ground.

If the acid meets water however, either because of wet ground or due to the presence of a water puddle from recent rain, or water from the hose of a fireman, copius quantitites of sulfuirc acid vapors will evolve and make the hazard distance significantly larger than the spill area.

3.1.4 Chemicals Selected for Study

Based on the analysis presented above, we selected the following 3 chemicals for consideration in the Risk Analysis study.

1. Chlorine
2. Liquefied Petroleum Gas (LPG)
3. Sulfuric Acid

** Detonation of an LPG vapor air mixture in the open, unconfined, situation requires the occurrence of several (low probability) events. These include passive ignition of a cloud, followed by flame acceleration due to presence of obstacles. Alternatively, if a detonation wave from a culvert or a sewer line exits into an open LPG vapor cloud, a detonation may be sustained if a significant part of the cloud is in the detonable concentration range. To the best of our knowledge, there is only one documented propane air detonation in the open (Burgess & Zabetakis(23)).

3.2: SELECTION OF ORIGIN-DESTINATION POINTS AND TRANSPORTATION ROUTES

In selecting the origin-destination points for the risk analysis study we formulated a set of selection criteria. These criteria included the following:

(1) The selected origin-destination points should be connectable through at least two separate routes.

(2) The principal route and the alternate route should have, if possible, significantly different characteristics. That is, the track quality and allowable speeds, number of yards, population density and types (residential, industrial, urban, rural, etc.) along the routes should be different.

(3) There should be a reasonably high volume of traffic of the selected chemicals between the two origin-destination points.

(4) Traffic and other relevent data for the routes chosen should be available in public or within cooperative agreements with the railroads along the routes.

Using these criteria, we have evaluated four different origin-destination point combinations and selected one set for detailed study. The details of these are discussed in the following sections.

3.2.1 Traffic Data

In order to apply a general risk evaluation methodology to the rail transport of specific chemicals, considerable amounts of data are needed on freight volumes, number of interchanges, number of switchings and yard operations encountered, etc. These statistics, especially for specific hazardous materials, are not easily available. The data which are readily available are in highly aggregated form, and are not applicable to even the DOT classes of Hazardous Materials. For example, the "Freight Commodity Statistics; U.S. Class 1 Railroads" published by the FRA (FRA-OPPD-80-9, Sept. 1980) gives data for freight tons originating and terminating by rail districts in the U.S. (East, South & West), and by major commodity groups such as "Chemicals and Allied Products, Petroleum & Coal Products", etc. These commodity groups are further subdivided by one or at best two further subcategories. However, no details are available on the specific locations from which or to which these commodities are transported. It may be possible, however, to run the FRA 1% waybill statistics computer tapes and get an idea of the "flow" of specific hazardous materials. Such an operation was beyond the scope and intent of this project.

Our approach to route selection was based on the review of readily available information. Table 3.6 shows the freight traffic data obtained from "FRA; Freight Commodity Statistics 1980" and from the "Railroad Facts" published by the Association of American Railroads.(4) Only two major commodity groups, within which fall most of the hazardous chemicals of interest to the project, are listed. It is seen that over 56% of chemicals and over 63% of petroleum products originate in the Western District. Western District includes the principal petro-chemical and chemical complexes in Texas and Louisiana. However, the consuming industries for these commodities are in the Eastern and Northeast corner of the southern region.

We selected four candidate origin-destination pairs for evaluation and selection of one pair for detailed risk assessment. These routes were in the following general geographical areas of the U.S.

	From	To
(i)	Gulf Port City	- Chemical complex in a Southeastern state
(ii)	Gulf Port City	- Midwestern industrial city
(iii)	Gulf Port City	- Mideastern chemical complex
(iv)	Gulf Port City	- Midwestern city

The origin-destination pair 1 has three alternative routes. The first alternative route consists of a well-maintained Class 6 main line, almost the entire way, and passes through several major cities. The second alternative route is mostly rural in character and does not pass through very large cities. The third alternate route is very similar to that of the second. Most of routes 1 and 2 are in a single railroad system, whereas route 3 goes through two railroad systems.

Detailed examinations of the nature and density of population along the route for origin-destination choices ii, iii and iv were not made. Only the major cities on the routes and the railroads encountered were noted. The principal reason for not conducting an in-depth study of these choices was due to the difficulty of obtaining reliable data on the traffic volumes and chemicals transported on these route choices.

3.2.2 Selection of the Origin-Destination Set for Study:

We have selected origin and destination combination #1 for in-depth risk analysis study for the following reasons (in the order of importance).

1. Considerable cooperation was received from a railroad system through which the routes pass. Traffic and other data were obtained from this railroad under a confidential agreement.
2. The routes under the choice of origin-destination carry significant volumes of LPG and acids, two of the commodities selected for study.

Table 3.6

Freight (originating) Traffic Data for Different Rail Districts for Two Commodities

From FRA Freight Statistics

STCC	Commodity		Eastern District		Southern District		Western District		U.S. Total		U.S. Total Bureau of Explosives Tons
			Carloads(1)	Tons(2)	Carloads	Tons	Carloads	Tons	Car-loads	Tons	
28	Chemicals & Allied Products	1979	240	15.7	428	31.2	757	59.8 (56%)	1426	106.7	93.6
		1982	-	-	-	-	-	-	-	-	91.2
291	Products of Petroleum Refining	1979	64.9	4.6	47.5	3.2	205	13.4 (63.5%)	317	21.1	21.1
		1982	-	-	-	-	-	-	-	-	15.1

Note:
1) Numbers in Carload Columns represent thousands carloads
2) Numbers in Tons columns represent millions tons
3) All numbers are for revenue freight originated
4) Adjusted from reported revenue tons for Petroleum & Coat products on the basis that 48% of this tonnage is made of products of Petroleum Refining.

Sources of Data: (i) "Freight Commodity Statistics, 1980"; Federal Railroad Administration
(ii) "Railroad Facts", Bureau of Explosives, Assoc. of American Railroads, '83

3. The chosen end points provide at least 3 alternative routes.
4. Each alternative route has considerably different characteristics than the other alternative routes. For example, alternate Route 1 goes through high population density cities and has several yard-handling operations. On the other hand, alternate Route 3 is predominantly rural in character.
5. The distances between the origin and destination are not very large (about 500 miles).

3.2.3 Details of the Routes Chosen

A line diagram of the various rail links between origin-destination pair #1 is indicated in Figure 3.1. There exist three alternate routes for transporting chemicals from the origin to the destination. For risk assessment purposes, we consider only two routes, designated TMS Route 1 and TMS Route 2 The same procedure can be utilized for assessing the third route.

The routes chosen are divided into number of segments. In our case, the track segment boundaries coincide with the county boundaries across which the routes pass. This is because the traffic volumes of the chemicals do not seem to vary very much over large sections of the route and that population density information is readily available on a county basis. Tables 3.7A and 3.7B give the following details for the two routes: (i) the county #; (ii) length of route track within the county; (iii) track class; (iv) annual volume of railroad freight traffic over the county; (v) population density (on a county average basis).

The historical railroad accident data collected from publicly available information sources (national averages) and those specific to the routes chosen for study are indicated in the next Chapter. Also presented in Chapter 4 are the numerical values for the various parameters used in the risk analysis model.

Table 3.7.A Track Details by Segment: Route 1

County #	Traffic Density million tons/yr	Track Segment Length (miles)	Maximum Train Speed* (mph)	Track Class**	County Population Density (#/sq. mile)	Average # of Chemical Cars in a Freight Train ($\overline{N}_x$)		
						Cl_2	LPG	H_2SO_4
1	17.7	18.9	30.0	6	2800	.141	.832	.160
2	17.7	21.3	45.0	6	127	.141	.832	.160
3	17.7	39.3	45.0	6	41	.141	.832	.160
4	17.7	20.0	45.0	6	48	.141	.832	.160
5	17.7	13.3	45.0	6	141	.141	.832	.160
6	17.7	32.4	45.0	6	89	.141	.832	.160
7	17.7	11.6	45.0	6	26	.141	.832	.160
8	17.7	20.0	45.0	6	51	.141	.832	.160
9	21.2	30.8	45.0	6	110	.141	.832	.160
10	23.1	27.8	45.0	6	19	.141	.832	.160
11	23.1	16.0	45.0	6	18	.141	.832	.160
12	23.1	21.9	45.0	6	23	.141	.832	.160
13	23.1	35.4	35.0	6	103	.141	.832	.160
14	42.7	38.0	30.0	6	602	.046	.089	.052
15	31.7	31.2	45.0	6	65	.046	.089	.052
15	31.7	24.5	45.0	6	196	.046	.089	.052
16	31.7	19.4	45.0	6	22	.046	.089	.052
17	31.7	18.8	45.0	6	65	.046	.089	.052
18	31.7	9.4	45.0	6	112	.046	.089	.052
19	21.3	18.8	30.0	6	268	.046	.089	.052
20	21.4	11.3	30.0	6	868	.046	.089	.052
21	29.5	14.1	30.0	6	1104	.045	.089	.051
22	37.7	4.2	30.0	6	1789	.045	.001	.051
23	35.5	7.3	30.0	6	1016	.045	.001	.051
24	35.5	23.9	30.0	6	113	.045	.001	.051
25	35.5	17.8	45.0	6	73	.045	.001	.051
26	35.5	17.8	45.0	6	37	.045	.001	.051
27	35.5	8.9	30.0	6	594	.045	.001	.051

* Based on the operating policy of the cooperating railroad for hazmat trains

** Data from cooperating railroad

Table 3.7.B Track Details by Segment: Route 2

County #	Traffic Density million tons/yr	Track Segment Length (miles)	Maximum Train Speed* (mph)	Track Class*	County Population Density (#/sq. mile)	Average # of Chemical Cars in a Freight Train ($\overline{N}_x$)		
						Cl_2	LPG	H_2SO_4
1	17.7	18.9	30.0	6	2800	.141	.832	.160
2	17.7	21.3	45.0	6	127	.141	.832	.160
3	17.7	39.9	45.0	6	41	.141	.832	.160
4	17.7	20.0	45.0	6	48	.141	.832	.160
5	17.7	13.3	45.0	6	141	.141	.832	.160
6	17.7	32.4	45.0	6	89	.141	.832	.160
7	17.7	11.6	45.0	6	26	.141	.832	.160
8	17.7	20.0	45.0	6	25	.141	.832	.160
9	21.2	30.8	45.0	6	110	.141	.832	.160
10	23.1	27.8	45.0	6	18	.141	.832	.160
11	23.1	16.0	45.0	6	18	.141	.832	.160
12	23.1	21.9	45.0	6	24	.141	.832	.160
13	23.1	35.4	45.0	6	103	.141	.832	.160
14	21.4	30.4	30.0	6	602	.141	.832	.160
15	19.4	32.1	45.0	6	83	.141	.832	.160
15	8.5	20.3	45.0	4	83	.001	.001	.051
16	8.5	6.8	45.0	4	98	.001	.001	.051
16	13.0	16.0	45.0	6	98	.047	.331	.054
17	13.0	2.5	45.0	6	23	.047	.331	.054
18	13.0	13.5	45.0	6	18	.047	.331	.054
19	13.0	28.7	45.0	6	54	.047	.331	.054
20	13.0	3.4	45.0	6	66	.047	.331	.054
21	13.3	38.8	35.0	6	125	.047	.331	.054
22	13.0	18.8	30.0	6	780	.047	.331	.054
23	9.7	15.0	45.0	6	17	.047	.331	.054
24	9.7	24.4	45.0	6	21	.047	.331	.054
25	15.9	2.8	45.0	6	23	.047	.331	.054
26	15.9	20.6	45.0	6	127	.047	.331	.054
27	15.9	10.3	35.0	6	594	.047	.331	.054

* Based on the operating policy of the cooperating railroad for hazmat trains

** Data from cooperating railroad

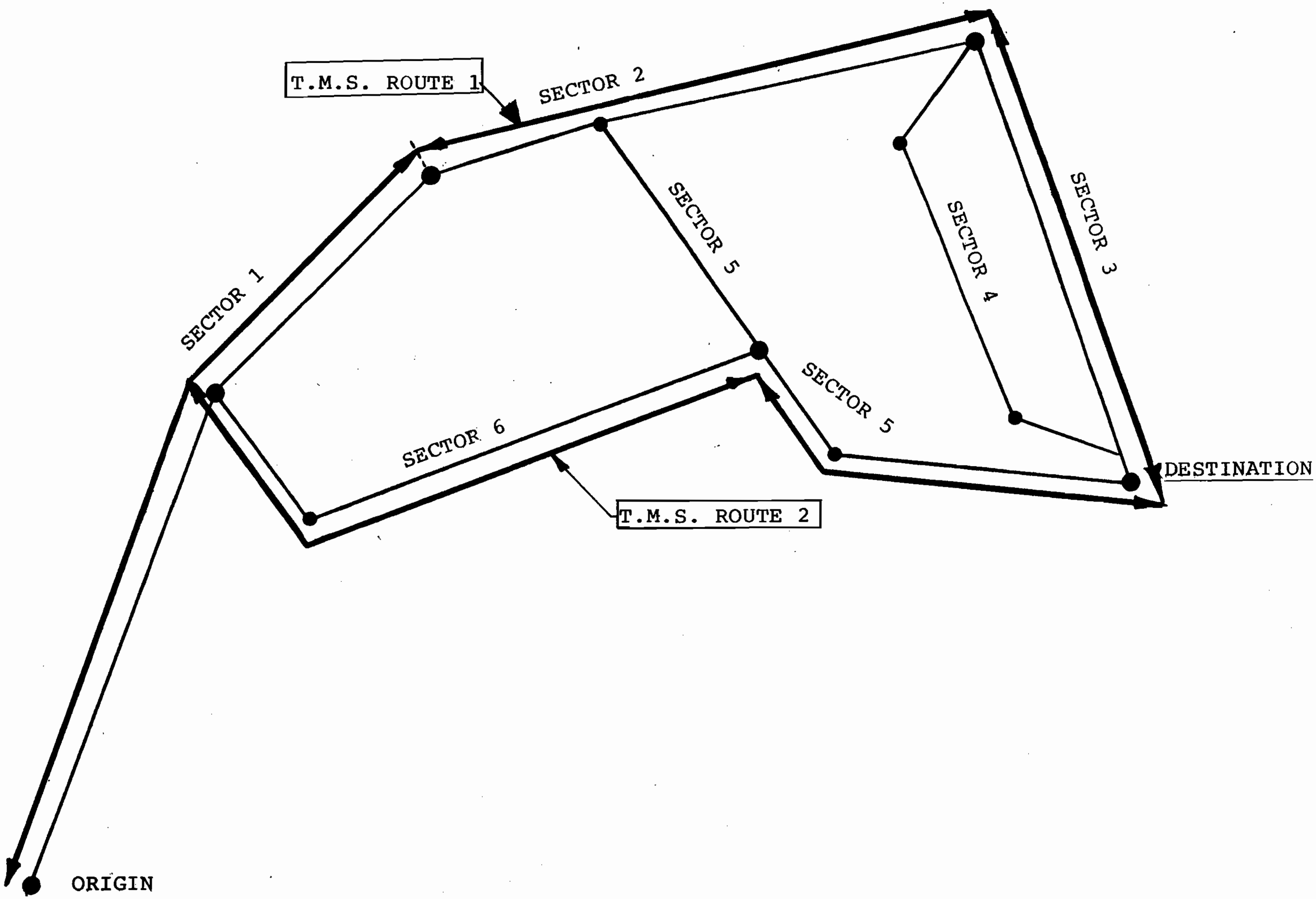

FIGURE 3.1 MAJOR SECTORS IN ROUTE 1 AND ROUTE 2 SELECTED FOR STUDY

CHAPTER 4

HISTORICAL RAILROAD ACCIDENT DATA AND VALUES OF OPERATIONAL & OTHER PARAMETERS

In this chapter, the various types of data collected and the values of parameters calculated from these data are indicated. The types of data required to perform the risk assessment are identified and the relevant data collected are indicated. The values of several of the conditional probabilities are developed from the data and the methodologies and underlying theoretical bases are described.

4.1 TYPES OF DATA NEEDED FOR RISK ASSESSMENT

The types of data which are necessary to utilize the risk assessment model described in Chapter 2 can be divided into 5 major categories. These categories and the data sets required in each category are indicated below. Where route specific data were available, they have been used. However, if route specific data were not available, region or even national average values were deemed acceptable. These are indicated in the sections that follow.

(i) Accident Statistics

- Rates of accidents and/or frequency of accidents derived from data on number of accidents, type of accidents, total freight traffic volume, track class, etc.

- Accident statistics classified by main line, yard, train speed, track quality, etc.

(ii) Train Make-Up Data

- Number of freight cars in freight trains and its distribution.

- Number of hazmat cars in freight trains or alternatively number of chemical-X cars in a freight train.

(iii) Route Specific Data

- Number of segments
- Number of yards encountered and annual traffic volume in each yard.

For each segment:
- Train speed or track quality or both.
- Annual freight traffic volume and annual hazmat traffic volume.
- Population density.
- Average number of chemical-X cars in each train.

(iv) Hazardous Material Releases

- Number of accidents per year and number of tank car releases.
- Statistics on volumes of materials released.

(v) Physico-Chemical Properties of Chemicals

The chemicals of interest to this study and their properties were indicated in Chapter 3. The route specific data for the routes chosen were also described in Chapter 3.

4.2 SOURCES OF DATA

Our primary sources of data include the publications by the FRA, AAR, and other public literature. We have also received some data of relevance from a cooperating railroad. The public literature from which we have collected data includes:

- "Accident/Incident Bulletins", Federal Railroad Administration, U.S.DOT, Washington, D.C. - For the years 1979 thru 1982 (both inclusive), Volume Nos. S148 - 151.
- "Yearbook of Railroad Facts", 83rd Edition, Association of American Railroads, Washington, D.C. 20036
- Bureau of Census Data - County Population Densities; U.S. Department of Commerce, 1982.
- Railroad Safety Statistics: Accident Locations/Hazardous Material Flows/Accident Rates", Federal Railroad Administration, Office of Safety, U.S.DOT, Washington, D.C., 1981 (Data from 1978 thru 1981).
- "Transport Statistics in the United States, 1982", U.S.DOT, Washington, D.C., (Data from 1978).
- Selected Data from the Accident Data Base maintained by Office of Safety, Federal Railroad Administration, Washington, D.C.; (Personal Communication, October 1984).

Tables 4.1, 4.2, and 4.3 indicate the specific data collected from or obtained from the different sources.

4.3 ACCIDENT RATES

4.3.1 National Data Averages

Table 4.4 shows the total number of collision and derailment accidents involving freight trains in the United States during the years 1979-82, arranged by track type and track class. It is seen that a significant number of accidents are of the derailment type and also that reduction in numbers between Class 4 and Class 5 tracks is dramatic.

TABLE 4.1

National Average Traffic and Accident Statistics

	Type of Data Being Collected	Source Where Data Are Gathered From
(i)	Number and type of accidents involving freight trains over different calendar years.	Reference 2
(ii)	Segregation of accidents by track class, track type (mainline, yard, industrial).	Reference 2
(iii)	Number of hazmat train accidents* in the given period.	Reference 2
(iv)	Total freight traffic and hazmat freight traffic (annual gross tons).	Reference 4
(v)	Segregation of hazmat traffic volume by different chemicals.	Reference 6
(vi)	Average number of cars in a train.	Reference 2
(vii)	Type and extent of accident damage to tank cars and probability of leaks (leak incidents)	Reference 6
(viii)	Physical & Chemical properties of chemicals of interest.	CHRIS**, Handbook of Physics & Chemistry.

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* Freight train accidents involving the derailment or collision of at least one hazmat tank car.

**CHRIS-- Chemical Hazard Response Information System, U.S. Coast Guard, Washington, D.C. 20590

TABLE 4.2

Traffic & Other Route Specific Statistics

	Type of Data		Source of Data
1)	Railroad Route Map	(i) (ii)	Rand McNally Railroad Map. Also, the participating railroad system map.
2)	Track quality on the various segments of the route	(i) (ii)	Information supplied by participating railroad. Evaluation from the freight train schedules provided by the railroad.
3)	Number and traffic density on the Yards along the route(s).	(i) (ii)	the different railroads. Report by Petracek et al(24), "Railroad Classification Yard Technology", FRA/ORD-76/304
4)	Annual freight volume on each segment of track.		Cooperating Railroad
5)	Traffic density (in tons/yr) by hazmat class		Cooperating Railroad
6)	Number of freight cars in a train: mean and standard deviation. Also number of hazmat cars in a train; mean and standard deviation.		Cooperating Railroad

TABLE 4.3

Certain Other Data Collected

	Type of Data	Source of Data
1)	Type of tank cars used for transporting a given chemical (say chemical X).	49CFR(17); part 173.272 and part 173.314
2)	Probability of release given a derailment at a certain speed and type of chemical.	Correlations from the Report of Nayak et al(5)
3)	Effect of head shields and shelf couplers on release probability.	Bureau of Explosives(6) (leak statistics for past 5 years).
4)	Quantity of material released given a puncture.	Correlations from the Report of Nayak et al(5)
5)	Population density variation along the routes chosen.	Bureau of Census data(7) (on a county population density basis).
6)	Population density variation with time of day in an urban commercial area.	Glickman(11)

TABLE 4.4

Summary of Train Accident Data for the Years 1979-1982

TRACK CLASS	TOTAL	TRACK TYPE			
		MAINLINE		YARD	
		COLLISION	DERAILMENT	COLLISION	DERAILMENT
1	14653	543	5569	1838	4410
2	4850	119	1987	401	1569
3	4355	68	1736	222	1375
4	2960	54	1036	180	821
5	357	6	125	23	98
6	25	1	4	4	4
Unknown	1364	62	489	217	388
Total	28564	853	10946	2887	8665

Source: FRA Accident Incident Reports(2), 1979-1982

Table 4.5 shows the types of accidents for each type of track. Again, the dominance of derailment type of accidents is clearly seen.

Table 4.6 presents the aggregated statistics on freight movement within the United States for the years 1979-82. The total gross ton miles is calculated since the number of derailment accidents is correlated with this parameter. The value of $(\text{gross ton})^2$ miles is also obtained because, according to Nayak, et al(5), the number of collision accidents is dependent on this parameter. The published data on the freight statistics are not segregated by track class. In order to assess the accident rates in different track classes, we have utilized the findings presented by Nayak, et al(5). These findings were based on a detailed review of the 1976, FRA 1% Waybill Statistics. It is seen that significant amount of freight transport occurs on Class 4 track. The haulage on Classes 3, 5 and 6 are comparable, but are a factor of 5 smaller than on Class 4.

Main Line Accident Rates (F_M)

The numbers of derailment and collision accidents for the same 4 year period (1979-82) are indicated in Table 4.7. It is noticed that a predominant number of accidents occur in Class 1 and Class 2 tracks. Data on the severity or the magnitude of the incidents are not easily available. The values of derailment accident rates and the collision accident rates calculated are also shown in Table 4.7. The accident rate values decrease as the class of the track increases. This is because of the lower number of accidents and higher gross tons of freight carried in higher class tracks, up to Class 4 tracks.

Yard Accident Rates (F_Y)

Data are available for the number of derailments and various types of collisions occurring in classification yards throughout the United States. The accident summary for all classes of tracks combined is presented in Table 4.5. While the numbers of accidents in each track class within yards are available, the total gross ton-miles of freight moved within yards, by track class, are not available. Therefore, the accident rate within the classification yards cannot be expressed in terms of the same parameters as were used for main line accident rates (e.g., gross ton miles and $(\text{gross ton})^2$ miles).

It can be argued that the number of accidents in classification yards should depend not on the total miles of track within the yard, but on the number of freight cars handled, irrespective of track class. For the purposes of analysis in this report, we use the number of cars classified as the accident correlating parameter for yard accidents.

Table 4.5

Accidents on All Classes of Track 1979-1982

	Main		Yard		Other	
Accident Type	No.	%	No.	%	NO.	%
Derailment	10946	78.7	8665	70.8	2062	85.7
Head-on Collision	58	---	193	1.6	15	---
Rear-end Collision	137	1.0	459	3.8	37	1.5
Side Collision	552	4.0	1863	15.2	148	6.1
Raking Collision	88	---	298	2.4	24	1.0
Broken Train Collision	21	---	68	---	0	---
Rail-Highway Crossing	871	6.3	0	---	0	---
Grade Crossing	8	---	0	---	0	---
Obstruction	122	1.0	68	---	0	---
Explosion/Detonation	2	---	0	---	0	---
Fire-Violent	384	2.8	213	1.7	41	1.7
Other	715	5.1	404	3.3	79	3.3
TOTAL	13903		12231		2406	

TABLE 4.6

FREIGHT STATISTICS (1979-82)

Year	1 Revenue Ton Miles (Billion)	2 Numbers of Cars Loaded (Million)	3 Originated Tons (Billion)	4 Avg Freight haul distance (Miles)	5 Gr Tons carried (Billion)	6 (Gr Ton)^2 = 10^{18} x	7 Gr Ton Miles (Billion)	8 (Gr Ton)^2 Miles = 10^{21} x
1979	913.7	23.9	1.5	608.3	2.936	8.62	1786	5.242
1980	918.6	22.6	1.49	615.7	2.848	8.11	1753	4.993
1981	910.2	21.6	1.45	616.4	2.750	7.56	1722	4.736
1982	797.8	18.6	1.27	628.7	2.382	5.67	1498	3.567
Total					10.916	29.96	6759	18.548

Source: "Railroad Facts", 1983, AAR

Notes:

1) Average freight hauling miles (column 4) = $\frac{\text{Revenue Ton Miles (Column 1)}}{\text{Originated Tons (Column 3)}}$

2) Gross tons = Originated tons + Number of cars loaded x 2 x 30

(30 represents the average tare weight of a freight car.
Factor 2 represents the two-way trip of a freight car.)

3) Column 7 = Column 4 x Column 5 ; Column 8 = Column 4 x Column 6

Table 4.7 Accident Rates For Main Line Track

Item #	Parameter	Class of Track					Total All track Classes
		1	2	3	4	5&6	
1	Number of Derailment Accidents	5569	1987	1734	1036	130	10456
2	Billion Gross Ton Miles*	67.6	256.8	986.8	4677.2	770.5	6758.9
3	Derailment Accident Rate (#1 billion gross ton mile)	82.4	7.738	1.757	0.222	0.169	1.547
4	Number of Collision Accidents	541	176	43	39	5	804
5	Collision Rate #1 $(\text{gross ton})^2$ miles	243.1×10^{-20}	29.7×10^{-20}	2.7×10^{-20}	0.304×10^{-20}	0.15×10^{-20}	4.335×10^{-20}

* The distribution of total gross ton miles and (gross ton)^2 miles into various track classes is based on the finding for 1976 from a review of 1% Way Bill statistics (Nayak, et al). These percentages in each track class are as follows:

Distribution of Items For Various Track Classes	Track Class					Total
	1	2	3	4	5&6	
Gross Ton Miles (%)	1	3.8	14.6	69.2	11.4	100
$(\text{Gross Ton})^2$ Miles	1.2	3.2	8.6	69.1	17.9	100

NOTE: Based on 1979-82 FRA Accident Data

The data on the number of cars classified in yards within the United States is given for the year 1974 by Petracek, et al[24]. It is seen that a total of 332 million cars were classified. Petracek, et al, conclude from an assessment of economic activity, improvements in technology, etc., that the rate of increase of the total volume of cars classified will be very small (about 0.33% per year) for the years 1974 thru 2000. Based on this assessment and projecting the total number of cars that will be classified in 1984 is assumed to be about 342 million cars.

Table 4.8 gives the details of the yard accidents for the years 1979-82 and the estimated number of cars classified each year. The desired accident rate values are also indicated.

4.3.2 Data Specific to the Routes Chosen

The two routes selected for study (see Chapter 3) lie principally within a single railroad system. We obtained detailed traffic and other operational data for these routes from this railroad under a confidentiality agreement. We have utilized these data, together with the Railroad Time Table, (to evaluate the average freight train speed) to determine the system-wide accident rates for derailments for 3 different track classes. The traffic data for 1983 were used. The number of accidents, the total gross ton miles, and the accident rates calculated using the data provided by the railroad for this system are presented in Table 4.9. We assume that these accident rates are applicable to each of the specific routes chosen.

The summary data and the calculated accident rates, both national averages and route specific averages, are indicated in Table 4.10. It is seen that the accident rate for Class 1 track on the route chosen is less than (by about 60%) the national average given in Table 4.7; however, the derailment rates of Class 4 and Class 6 tracks, for the routes chosen, are somewhat higher than the national average. This is because the definition of "derailment" used by the specific railroad system is significantly more stringent than that used for purposes of reporting to FRA. For internal management purposes included as a "derailment accident" is if any one of the wheels of a freight car leaves the track, irrespective of whether there is damage or not. The FRA reporting requirements for reporting a derailment is triggered "when the total equipment damage resulting from the accident exceeds $2,700 or when human injury or fatality results." In effect, therefore, in Tables 4.7 and 4.8, we may be comparing two different sets of data. We have used, however, both sets of accident rate values (summarized in Table 4.10) with risk assessment calculations.

TABLE 4.8

ACCIDENT RATES FOR CLASSIFICATION YARDS (1979-82)

		Year				
		1979	1980	1981	1982	Total for 4 Years
Number of Yard Accidents (All Track Class)	Derailments	1854	2651	1821	1340	7,666
	All Collisions	1061	887	582	394	2,924
	Total	3915	3538	2403	1734	11,590
Number of cars Classified (Millions)*		337.6	338.7	339.8	341.0	1357
Accident Rate in #/Million Cars Classified **		11.60	10.45	7.07	5.09	Average = 8.54

* Based on the projections by Petracek, et al(24)

** TMS estimates based on data obtained from "Railroad Accident/Incident Reports", 1979 thru 1982.

TABLE 4.9

MAIN LINE ACCIDENT STATISTICS FOR THE COOPERATING RAILROAD

(1983 Data)

MAIN LINE TRACK	TRACK CLASS CLASS 1	 CLASS 4	 CLASS 6 *
Total Accidents (Derailments)	22.0	36.0	73.0
Gross Ton Miles (Billions)	0.428	14.7	88.0
ACCIDENT RATE (In #/Billion Gross Ton Miles)	51.4	2.45	0.83

Source: Cooperating railroad, Personal Communication (1984).

* The threshold level of "accident" for internal reporting purposes within the cooperating railroad is considerably lower than that required by FRA regulations. Hence, Class 6 accidents for the railroad may be over-reported on this Table.

TABLE 4.10

SUMMARY OF ACCIDENT RATE VALUES
(National Average & Route Specific)

	Collision & Derailment Accident Rates (in # per Billion Gross Ton Miles) for Track Classes					Yard Accident Rate in (in # per Million Car Classifications)
	1	2	3	4	5 & 6	
National Data(1) (1979-82)	82.4	7.738	1.757	0.222	0.169	8.54
Cooperating Railroad (1983 Data)	14.0(2) 51.4(3)	- -	- -	0.41(2) 2.45(3)	0.2(2) 0.83(3)	6.56

Notes

1) The severity of collisions and derailments in the National Data is based on FRA Accident Reporting Requirement ($2600 in 1978, $2900 in 1979-80, and $3700 in 1981 damage per accident or injury or fatality).

2) Based on the number of severe accidents occurring in 1983. "Severe" accidents are those causing $45,000 or greater damage.

3) Based on all accidents on the railroad. The threshold for reporting is much stricter than FRA requirements.

4.4 STATISTICS ON THE NUMBER OF FREIGHT CARS AND CHEMICAL CARS IN FREIGHT TRAINS

One of the important sets of input parameters required for the Risk Analysis Model is the distribution of total number of freight cars in a freight train and also specific information on the expected number of a named chemical car (and the standard deviation) in the train. Given below are some of the data we have been able to collect.

4.4.1 Total Number of Freight Cars in a Train ($\overline{N_T}$)

The average number of freight cars in a train has been remarkably constant between 67 cars in 1978 to 69.1 cars in 1982 (AAR(4)). Of these, 56.2% in 1982 constituted loaded cars, and the remaining were empties. Statistics indicating either the probability density function or the standard deviation on the number of cars in a freight train are not easily available.

For the selected route, however, the total number of cars in a freight train (railroad system average) is found to be 88. We have used this number in our risk calculations, together with the assumption of 56.2% loaded cars.

4.4.2 Number of Cars of a Specified Hazmat in a Freight Train ($\overline{N_X}$)

In Chapter 2, it was argued that the probability distribution for the presence of a specified hazmat in a train can be represented by a Poisson distribution (see equation 2.13). The key parameter required to define this distribution is the mean value $\overline{N_X}$. This average number of chemical X cars in a train (note that this number can be a fraction) can be obtained from available traffic data using the equation(s):

$$\overline{N_X} = \frac{\text{Annual number chemical X cars loaded or traveling on the route segment.}}{\text{Annual number of freight trains on the same segment.}} \tag{4.1a}$$

OR

$$\overline{N_X} = \frac{\text{Annual tons of shipment of chemical X on the track segment}}{\text{Total freight shipment tons on the same segment}} \times \frac{\text{Gross tons of freight per train}}{\text{Gross tons of chemical X per tank car}} \tag{4.1b}$$

Annual number of freight trains (on a segment or nationally) can be estimated from the data published by AAR ("Yearbook of Railroad Facts") as follows:

$$\text{\# of Freight Trains per year} = \frac{\text{Total \# of freight car miles}}{\text{Average \# of cars per train}} \times \frac{\text{Fraction of car miles made by loaded cars}}{\text{Average distance of travel of loaded car}} \tag{4.2}$$

In 1982, the percent of car miles represented by loaded cars amounted to 56.2% (AAR$^{(4)}$).

Table 4.11 shows the value of $\overline{N_X}$ for the three chemicals of interest (LPG, chlorine and sulphuric acid) obtained from national data and also for the specific routes chosen. For the latter case, the data supplied by the cooperating railroad are used.

Table 4.11 shows a comparison of the average number of cars of each of LPG, chlorine, and sulfuric acid in a freight train. Both national average data and the route specific data are presented. The route chosen for study can be segmented into 6 distinct parts, the traffic characteristics of which differ substantially from one another. The mean number of the specified chemical cars in a freight train in each segment are also indicated in Table 4.11.

We notice that on the routes chosen for study there is a substantial variation in the traffic volumes of these commodities. In fact, the volumes of traffic can vary by 2 to 3 orders of magnitude. The highest rate of traffic (represented by the largest N_X value) in the segment is comparable to the national average values. However, it readily can be seen from this Table that use of national average values for specific route segments can lead to significant errors. In our risk analysis, we have used the route specific values as well as the national average values.

4.5 FRACTION OF DERAILED HAZMAT CARS WHICH RELEASE CONTENTS (q)

One other important parameter that has significant influence on the overall risk is the (binomial) probability of tank car puncture or contents release given that a tank car has derailed. The way in which this parameter is used in the risk model was indicated in Section 2.3.3 (see Equation 2.9) and discussed in Section 2.3.5.

Detailed data on specific hazmat car leakages following derailments are not available to evaluate the degree to which the protection devices are effective. It is conceivable that the protective devices, such as shelf couplers, head shields, and thermal insulations are effective in low speed derailments and that the probability of puncture increases as the train speed, prior to derailment, increases.

Nayak, et al[5] developed a correlation between the value of release probability and the train speed before derailment. This correlation was based on 1974-76 data and is given by

$$q(U) = 4.5 \quad U^{0.5} \qquad \begin{array}{l}\text{(q is in percent)}\\ \text{(U is in mph)}\end{array} \qquad (4.2)$$

Nayak, et al suggest the use of the same correlation for collision related releases also. However, since 1978, tank cars carrying certain hazardous materials (such as LPG, ethylene oxide, anhydrous ammonia, etc.) are required to have head shields, shelf couplers, and in some cases, thermal insulation (49 CFR: 179.105). Because these regulatory requirements are being met over a period of years, a greater fraction of the tank car fleet seems to be protected every passing year. This is being reflected in the statistics indicated in Table 4.12.

TABLE 4.11

AVERAGE NUMBER OF TANK CARS OF A SPECIFIED CHEMICAL IN A FREIGHT TRAIN

Chemical	National Data Averages		Route Specific Data (3) Mean Number of Tank Cars per Train ($\overline{N}_X$) on Different Segments of Route					
	Total # of Cars Loaded Per Year (1)	Mean Number of Tank Cars Per Train (2) ($\overline{N}_X$)	1	2	3	4	5	6
LPG	110,490	0.344	0.832	0.089	3.87×10^{-4}	6.7×10^{-3}	0.331	6.7×10^{-3}
Chlorine	44,580	0.139	0.141	0.046	0.045	2×10^{-4}	0.047	0.072
Sulfuric Acid	45,605	0.142	0.160	0.052	0.051	2.3×10^{-4}	0.054	0.081
All Hazmat (4)	900,860	2.805	2.23	0.51	0.292	0.01	0.743	0.476

Remarks:

Route 1 consists of Sectors 1, 2 & 3.
Route 2 consists of Sectors 1, 6 & 5.
(see Figure 3.1).

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(1) Data from AAR;(4) "Hazardous Material Statistics, 1982" with correction for 80% data capture.

(2) Based on total number of freight trains = 321178 (see Equation 4.2).

(3) 1983 traffic data from cooperating railroad, for the route segments.

(4) Assuming average hazmat net weight per car to be 80 tons (72.5×10^3 kg).

TABLE 4.12

PERCENT OF DERAILED HAZMAT TANK CARS SUFFERING PUNCTURE

(National Data)

Details of Incident	1978	1979	1980	1981	1982	1983	Average over (1979-83)
Number of Derailment Incidents	302	277	276	299	402	323	315
Number of Tank Cars Involved	822	666	702	670	906	623	713
Number of Tank Cars Losing Lading	211	92	126	66	63	65	82
% of Derailed Tank Cars Releasing Contents (Also the Probability of release given a derailment, q)	25.7	13.8	17.9	9.9	7.0	10.4	11.6
Train speed dependence factor "a" (see note)	4.61	2.47	3.21	1.77	1.25	1.86	2.07

NOTE: The conditional probability of release q(U) in % at any train speed U (mph) is given by

$$q(U) = a \quad U^{0.5}$$

Data Source: "Hazardous Materials Statistics 1983", Bureau of Explosives, AAR, 1984. (Reference 6)

This Table gives the fraction of derailed tank cars that have released their contents for the years 1978-83. These derived data are plotted in Figure 4.1. Also indicated in this Table are the values of a correlating parameter giving the relationship between release probability and train speed.

It is seen from Figure 4.1 that the fraction of derailed cars that release their contents has continually decreased since 1978 and may be reaching the lowest (perhaps constant) level in 1983 at about 7%. The ratio of the fraction of the number of derailed cars releasing in 1982 and in 1978 is about 0.28. We argue that this number represents the effect of protective devices. The slight increase in 1983 may be statistically insignificant.

The % of derailed cars releasing (the numbers in the last row in Table 4.12) also represents the overall conditional probability that a derailed tank car releases its contents. These reported values are not indicated as a function of the train speed prior to derailment. Assuming that a correlation similar to that indicated in equation 4.2 is valid for the most recent years also, we express the speed dependence of the conditional probability of release as,

$$q(U) = a \; U^{0.5} \qquad \text{(q in percent)} \qquad (4.3)$$

where q(U) is the conditional probability of release in % at given train speed U (mph). The database covered by Nayak, et al, includes train speeds from low values (below 5 mph) to high values (70 mph). Over the range of 0 to 70 mph speed the average probability can be shown to be

$$\overline{q} = 5.58 \; a \qquad (\overline{q} \text{ in percent}) \qquad (4.4)$$

The values of "a" factor obtained using the above formula and the average release probabilities for the various years are also indicated in Table 4.12. We assume that the above equations 4.3 and 4.4 are valid for all chemical cars, irrespective of the chemical.

Volume of Hazmat Released

Detailed data are not available on the sizes of releases following derailments and tank car punctures. The volume of hazmat released depends on a number of factors including (i) the nature of the chemical in the tank; (ii) the type of puncture, i.e., whether an appurtenance was sheared or whether the tank wall was punctured; (iii) the location of the puncture (in the liquid wetted wall or in the ullage wall), etc. If the chemical

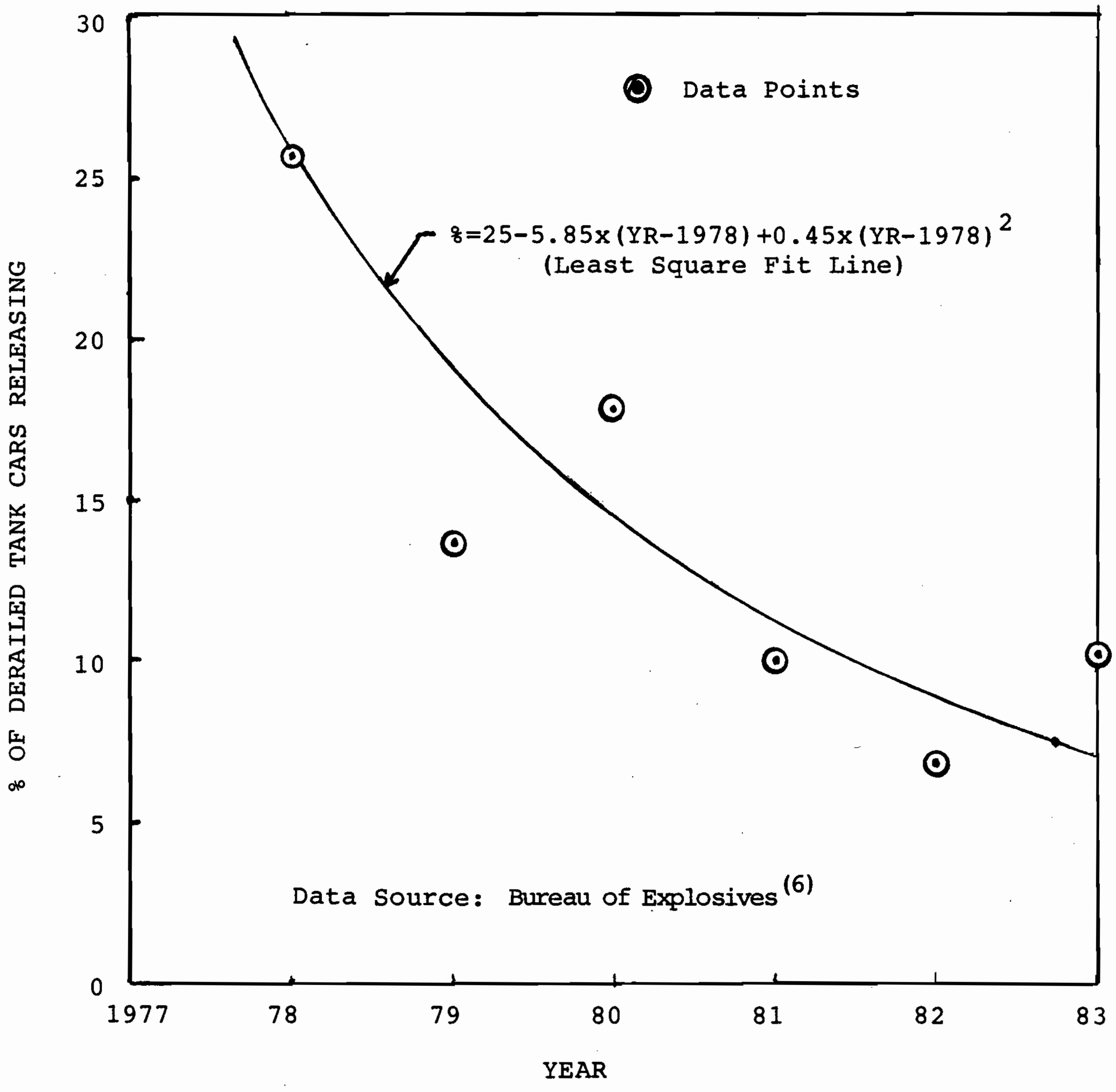


FIGURE 4.1 : PERCENT OF DERAILED HAZARDOUS MATERIAL TANK CARS RELEASING THEIR CONTENTS

is a liquefied compressed gas, then puncture of the tank wall will result in the release of most of the contents within the tank; whereas, if the chemical is a liquid with low vapor pressure at ambient temperature, only a limited volume would be released depending on the location of the puncture.

Nayak, et al, have reviewed the limited data (only 17 data items) on release quantities in rail accidents. The relationship developed by them for the volume released is:

$$\overline{V_R} = 2000 \quad U^{0.5} \qquad (4.4a)$$

and

$$\sigma_{V_R} = 11{,}400 \quad \text{gallons} \qquad (4.5b)$$

where V_R is in gallons and U is in mph.

Because of the limited sample size, the relationship developed for size of release would be of questionable accuracy. Furthermore, the relationship is not dependent on the nature and physical state of the chemical which, as discussed above, is quite important in determining the volume of material released. Therefore, in order to be conservative, we have, in our risk model, assumed that a leak results in the release of the total contents of the tank car.

The data presented in this Chapter are used in generating the values for the risks in transporting the commodities of interest over the routes chosen. The results are indicated in Chapter 6. In the next Chapter, the evaluation of the hazard areas and consequences of chemical release are discussed.

CHAPTER 5

HAZARD AREA CALCULATIONS

5.1 INTRODUCTION

In the previous chapters, we discussed the probabilistic aspects of risk analysis procedure. An equally important part of risk analysis is the determination of the consequences of hazardous material releases. The index used for measuring the consequences depends on the goal of the risk assessment. This index could be economic loss expressed in dollars, personal injury, and/or fatalities.

In general, where the consequence of interest is the health and safety of the public (i.e., injury or fatalaties from accidental chemical releases) the area of hazard is determined for specified types of hazards and for given threshold levels at which the hazardous effects of the chemical cause injury or fatality. The number of casualties is then evaluated by noting the density of population and the hazard area. Therefore, one of the primary steps in evaluating the consequences of hazmat releases is the calculation of the hazard areas. The various scenarios of hazards posed by hazmat are discussed, and the models by which the areas of hazard can be estimated are indicated.

5.2 HISTORICAL DATA ON RELEASE SOURCES

Releases of hazmat contained in tank cars can occur due to operational releases, equipment malfunction, tank material failure, accidents during transportation, environmental causes, or human errors. It is the general consensus in the railroad industry that the total annual volume of "non-train accidents" caused hazmat releases (from shell failures, bottom fitting leaks, etc.)is as much as, sometimes even larger than, train accident caused release volume. Hazmat releases caused by human errors or due to non-train accidents are not considered in our analysis because of difficulties in quantifying these causes for risk analysis purposes. However, we do wish to emphasize that future risk assessment efforts should attempt to quantify non-train accident related releases because the annual volumes of releases are perceived to be large and they may cause potential hazards to the public.

Several causes of potential releases from tank cars containing hazmat are indicated schematically in Figure 5.1, along with several possible hazard scenarios. Operational releases are caused by excess pressurization of tank cars due to increased ambient temperature and the action of the relief valve, or due to human error in overfilling the tank. While these types of releases are important for highly toxic or combustible materials, and their impacts have to be evaluated, it can be

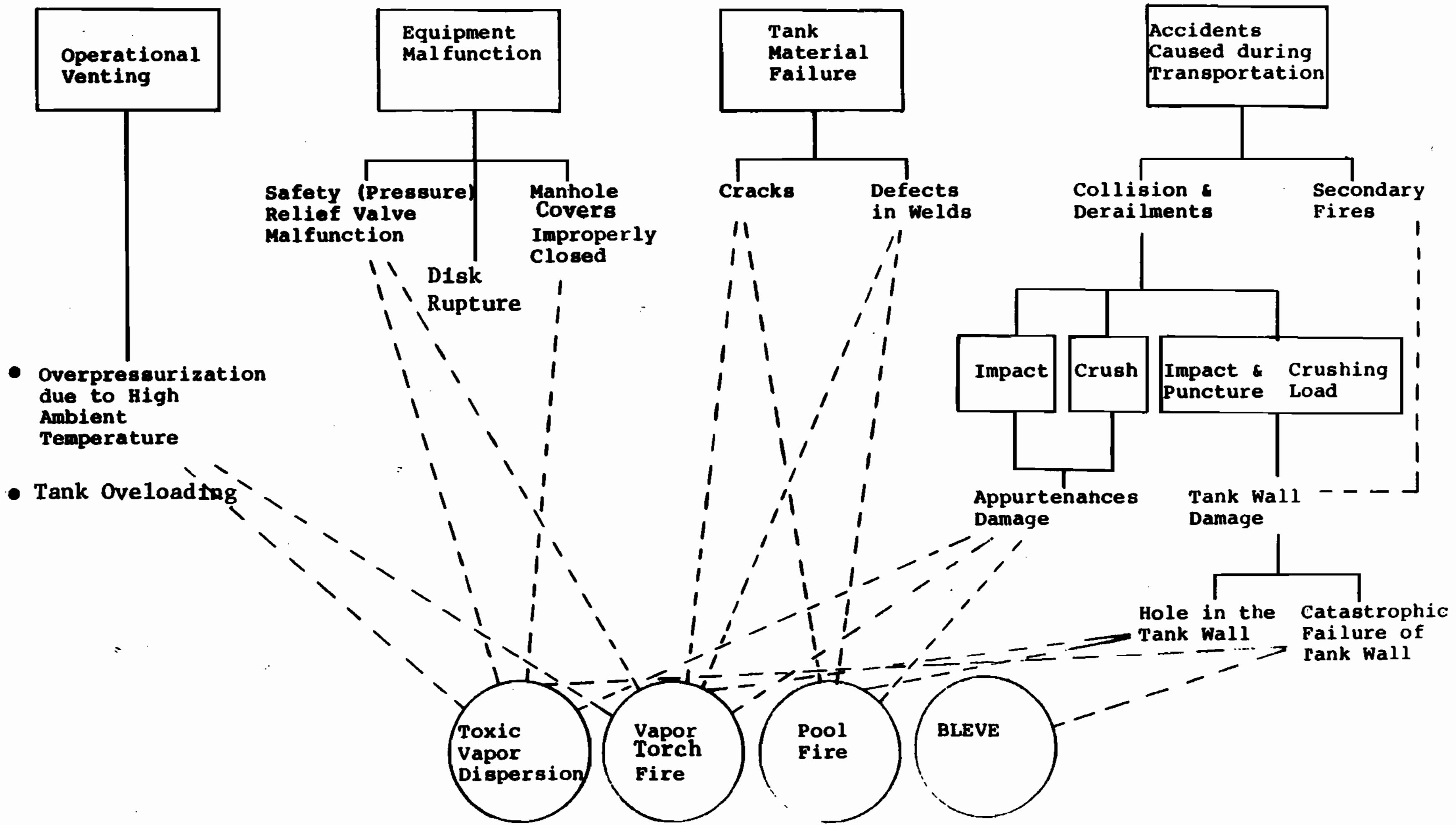


FIGURE 5.1 VARIOUS MECHANICAL CAUSES OF HAZMAT RELEASE FROM TANK CARS AND CONSEQUENCE SCENARIOS

anticipated that the quantities released would be small, therefore, the impact on the public, especially in an overall risk sense, would be small. The equipment malfunctions, such as stuck pressure relief valves or improperly closed manhole covers, can lead to continuous release of hazmat throughout the journey of the loaded tank car unless the leak is discovered and shut off. Tank car material failures, due to either material defects in the plates or in welds from normal usage of the cars, are extremely rare to nonexistent. With available data on hazmat releases from tank cars it is not possible to state definitively whether such failures have occurred or not; however, it can be anticipated, because of stringent regulatory requirements on tank car inspection and certification, that material failures (in non-accident situations) will not occur.

By far the most important hazmat release scenarios are associated with accidents occurring during haulage on main line or during handling in classification yards. Derailment and/or collision accidents can result in damage to or severance of appurtenances such as valves, pipes, manhole covers, etc., or result in the rupture of tank due to impact or crushing loads. Also, the tanks may be punctured. In all these cases, significant amounts of lading loss can be expected; the actual amount itself will depend on the size of hole, location of hole, orientation of tank car after the accident, and the nature of the chemical. Finally, release of a hazmat from a tank car can be induced by a fire on an adjacent car. The fire can cause over-pressures within the (undamaged) tank car, to weakening the shell due to high temperatures. In the latter case, the failure of the initially undamaged tank car is sudden (especially if there is internal pressure), and in many cases, all of the tank car contents are released into the atmosphere.

Andrews(8) has used the fault tree approach for determining the potential sources of releases and their probabilities of occurrence, using a chlorine tank car as an example. The result of Andrews' study indicates that while one can postulate a number of causes for releases, the bulk of leak sources contribute very little to the overall risk. The magnitude of the risk consequence is directly related to the volume of chemical release. In view of this finding, we have limited our consideration to large release volume sources.

Table 5.1 indicates the available data on the sources of release in tank car incidents. There seem to be two major types of releases, namely "passive leaks", and releases caused by derailment. It can be seen that there are a considerable number of "leak" incidents each year which (probably) result in small quantities of hazmat being released. Overheating of tank, overfilling or proper and improper relief valve operation, would result in leaks through top fittings, which, as indicated by the data, seem to be the predominant source of leaks. Also to be noticed is the relatively low percent of leak incidents (2%) attributable to shell or head sources. These are in contrast to the data indicated in Part II of Table 5.1 due to releases

TABLE 5.1

STATISTICS ON THE SOURCES OF RELEASES INVOLVING HAZMAT IN RAILROAD TANK CARS

	Percent of Total Number of Leaks Attributable to the Source						
Sources of Leaks and Releases	1978	1979	1980	1981	1982	1983	Average
I **LEAK INCIDENTS & SPLASH RELEASES** (1)							
Safety Devices (Valves, Discs)	29.0	24.1	25.6	32.2	28.4	27.9	27.9
Other Top Fittings	64.2	66.1	60.6	52.5	38.8	48.8	55.2
Bottom Fittings	28.8	17.7	20.4	15.6	17.2	18.4	19.7
Shell or Head	1.6	8.9*	2.9	2.8	1.7	1.3	2.1
Total # of Incidents	852	996	1070	1097	965	978	-
II **DERAILMENT & FIRE CAUSED RELEASES** (2)							
Safety Devices	6.9	6.9	7.4	12.5	9.5	10.7	9.0
Other Top Fittings	31.4	18.4	33.6	47.2	35.1	35.7	33.6
Bottom Fittings	21.5	10.3	11.4	8.3	18.9	12.5	13.8
Head	29.5	14.7	14.1	11.1	17.6	8.9	16.0
Shell	16.1	19.0	22.1	18.1	16.2	14.3	17.6
Fire Exposure	4.6	20.7	11.4	2.8	2.7	17.9	10.0+
Total # of Leaks	261	116	149	72	74	56	121
Total # of incidents Involving fires and derailments.	302	277	276	299	402	323	313

*This number not considered in the averaging process.
+This average value may not be meaningful because of considerable magnitude of standard deviation.

Source: "Hazardous Material Statistics" Bureau of Explosives, Apr., 1984.

Notes:
1) Leak incidents are those that result in releases, however small volume, of the hazmat. Splash releases are those in which a railroad worker is exposed primarily to a corrosive material.
2) These data include incidents which resulted in derailment, fire, death, or explosion. An accident that resulted in a hazmat car putting wheel on the ground is considered to be a derailment.

caused by derailments and fires. First, it is noticed that a number of leak incidents is generally a factor of 3 smaller than "passive incidents" of Part I. However, the percent of derailment/fire release incidents attributable to shell or tank head sources is significant (about 30%). Unfortunately, the dependence of the leaks on the derailment speed is not available.

The data indicated in Table 5.1 can also be interpreted as the conditional probabilities for the leak or release occurring from different sources, given that a tank car has derailed or has been subject to a fire and has released the contents. These data indicate that the precent of release incidents attributable to safety devices, to top fittings, or bottom fittings has remained more or less constant throughout the period 1979-83. This shows that no substantial improvements seem to have been made in these devices to reduce leak incidents. On the other hand, the percent releases attributable to each of the shell, head, or fire-caused sources shows a definite decreasing trend. We argue that this is a clear indication of the effects of shelf couplers and head shields being installed on tank cars. The values for an overall release probability given a derailment accident were indicated in Table 4.12, and the dependence on speed of train was discussed in Section 4.5. The determination of leak rates and quantities of materials released are discussed in the next Section.

5.3 HAZARD AREAS RESULTING FROM CHLORINE RELEASES

5.3.1 Volumes and Rates of Release

Release rates of hazmat from damages suffered by either the appurtenances on the tank car, or by the tank car structure itself, are dependent on the tank failure mode, size of holes, and the thermodynamic state of the chemical in the tank. It is extremely difficult to determine the rates of release for all possible scenarios of release. However, for risk analysis purposes, one needs to consider only those release magnitudes that have a potential for causing serious hazard to the public. Andrews(8), for example, has identified four major leak rates for the release of chlorine; these are perhaps applicable to releases of all chemicals in the liquefied compressed gas class.

Assuming that a fully loaded chlorine car carries 90 tons (81 x 10^3 kg) of chlorine, the release rates for various chlorine release scenarios are given as follows:

(i) A continuous release of chlorine vapor, at sonic velocity, from a relief valve at about 4 kg/s.

(ii) A continuous release of liquid chlorine from a stuck relief valve. Release rate is estimated to be about 10 kg/s.

(iii) Very rapid to instantaneous release of all of the tank car contents following shell or head puncture at normal transport temperature (294°K). Estimated fraction of the released mass that flashes to vapor is 17%, and the rest falls to the ground as saturated liquid at 240°K.

(iv) Instantaneous and catastrophic failue of tank following the heating and overpressurization after being subjected to a fire (for about 55 minutes with 90% of shell insulation intact). The temperature of liquid when the tank fails is calculated to be 333°K. The fraction of released mass (about 90 tons, which flashes directly to form a saturated vapor cloud at 240°K) is estimated to be 32%; that is, a mass of 26 x 10^3 kg of vapor is released instantaneously into the atmosphere.

5.3.2 Type of Hazard and Hazard Index

The principal hazard from chlorine releases is due to the highly toxic nature of the chemical. The gas phase chlorine presents toxic hazards to the public far from the site of release because of the atmospheric dispersion of vapors. The liquid fraction on the ground presents a local hazard from both burns on liquid contact and toxicity. The vapors of chlorine being heavier than air tend to disperse close to ground level, and could accumulate in low areas. Chlorine exposure symptoms vary from minor throat irritation, sneezing, and excessive salivation at low concentrations, to retching, vomiting, breathing difficulties, and death at high concentrations. The effects show a complex dependence on both concentration and dosage. Andrews(8) has reviewed the chlorine effects, and has concluded that exposure to 1000 ppm concentration is immediately fatal; exposure to a dosage of 1000 ppm/min above concentrations of 35 ppm are fatal to 50% of those exposed.

For the purposes of risk assessment in this study, we assume that the chlorine hazard can be calculated based on the following assumptions:

(i) The area of hazard is that contained within a ground level concentration contour of 1000 ppm

(ii) That all of the population within the hazard zone will suffer fatalities.

The latter assumption is extremely conservative. The physical models by which the hazard areas are calculated are described below.

5.3.3 Hazard Area Calculation Models for Chlorine

The models which are used to describe and calculate the extent of dispersion of heavier-than-air gases can be used to determine the chlorine vapor dispersion areas. This is because the saturated vapor of chlorine (which is released in tank car accidents) has about 3 times the density of ambient air. The released vapor mass spreads laterally due to its heaviness while it mixes with ambient air and moves in the downwind direction. There are a number of heavy gas dispersion models, some simple, and some extremely sophisticated. These models are reviewed by many researchers (see: VKI(25)). For the purposes of risk assessment, however, relatively simple models are adequate.

The details of the models applicable to determining the dispersion distances and hazard areas for chlorine are described in Appendix B. Also indicated in Appendix B are illustrative calculations. The results are presented in Table 5.2.

The results indicated in Table 5.2 can be compared to the results for downwind dispersion distances and hazard areas given by Andrews(8), and Nayak, et al(5). These two groups have used the neutral density gas dispersion models to describe the dispersion of chlorine vapors which are heavier than air. We believe their results are erroneous. For example, Andrews predicts a downwind hazard distance of 13 km and hazard area of only 0.62 km^2 for the case of entire tank content release in which 17% flashes to vapor and disperses in a stable atmospheric condition in a wind of 3.5 m/s. The maximum width of the cloud on this basis is only about 50m. These numbers are compared with our calculation results, which indicate the downwind hazard distance to be 1.7 km, maximum width of 1 km and hazard area 1.2 km^2; the last is twice the area predicted by Andrews. Our model describes the physics better, and gives more conservative (larger) hazard areas.

Nayak, et al(5) present hazard areas for the generic class of chemicals, namely, the non-flammable compressed gases. These results, in our opinion, are incorrect and cannot be applied for each one of the chemicals belonging to the non-flammable compressed gas class. First, the lethality index varies from chemical to chemical over such a wide range that a general "lethal area" of hazard is meaningless. Secondly, using concentration values from OSHA standards for an acute accident circumstance is not justifiable. For example, the OSHA limit for chlorine exposure over prolonged periods (8 hours) is 25 ppm. Nayak, et al, seemed to have used this criteria for establishing lethal zone for chlorine releases from tank cars. Because of this, their lethal hazard area for one tank car release of chlorine is 46.3 km^2, almost 2 orders of magnitude larger than either our value or that of Andrews. We, therefore, do not recommend the use of values of hazard zones indicated by Nayak, et al.

The hazard area results presented in Table 5.2 do not take into account the effect of emergency evacuation efforts or the effect of time of day population densities or the protection afforded by buildings and other enclosed spaces for short durations.

TABLE 5.2

SOURCE PROBABILITY AVERAGED HAZARD AREA FOR RELEASE OF CHLORINE FROM A SINGLE DERAILED TANK CAR*

	1	2	3	4	5	6	7
				Calculated Area of Hazard+			
Source Type	Conditional Probability of Source %	Type of Release	Released Amount	Maximum Downwind Distance (Km)	Maximum Width (Km)	Total Hazard Area $(Km)^2$	Probability Weighted Hazard Area $(Km)^2$
Pressure Relief Safety Valve & Top Fittings	44.2	Continuous Vapors Only	4 kg/s	0.35	0.02	5.5×10^{-3}	2.43×10^{-3}
Bottom Fittings and Stuck Relief Valve When Car is Upside Down	13.8	Continuous Liquid & Flashed Vapor	10 kg/s	0.60	0.032	15.1×10^{-3}	2.08×10^{-3}
Shell & Head Punctures	31.9	Very Rapid to Instantaneous Liquid & Flashed Vapor	13.8×10^3 kg	1.77	1.0	1.2	0.383
Fire Exposure Catastrophic Releases	20.0	Instantaneous Liquid & Flashed Vapor	26×10^3 kg	2.1	1.2	1.8	0.180
		Weighted Average Area of Hazard					0.567

Notes

Column 1 values are based on average values (for derailment and fire caused releases) given in Table 5.1

Columns 4, 5, & 6: Based on the following assumptions: (i) 3 m/s very stable "F" weather; (ii) lethal concentration is 1000 ppm; (iii) no reduction in hazard area to account for railroad right of way.

+ Hazard area is based only on the flashed vapor mass released and 1000 ppm as hazard index.

* A fully loaded chlorine car is assumed to contain 90 tons (81×10^3 kg) of chlorine.

These effects are reviewed in detail, the available data are presented, and the reduction in total area of hazard that can result from these mitgating phenomena are indicated in detail in a recent report (Raj$^{(13)}$. It is seen that emergency evacuation alone could result in a reduction factor of between 2 and 3 in the overall hazard area. On the other hand, depending on the type of locality (rural, urban, etc.), the actual population density could be anywhere from 0.7 to 5 times the census population density value. Neither of these effects is taken into consideration in our calculation of chlorine transportation risks.

5.4 HAZARD SCENARIOS AND AREAS RESULTING FROM LPG RELEASES

5.4.1 Types, Volumes, and Rates of Releases

The various scenarios of LPG release that can be postulated to occur as a result of rail tank car handling and railroad accidents are similar to those identified in the case of chlorine releases. Geffen et al (1980) have identified 7 major types of releases based on an extensive fault tree analysis of LPG tank car failure and release modes. These categories of releases include:

(i) Continuous slow leak of LPG as from an equivalent of 2.5 cm diameter opening. Release rates of 2.2. x 10^{-3} m^3/s (4 x 10^{-3} kg/s). Leakages from cracks in welds may lead to this release scenario.

(ii) Continuous release of vapor from an opened or damaged valve as a result of impact or puncture (no fire). Release is assumed to be equivalent to emanating from a 7.6 cm diameter equivalent opening. The rate of release is 1.96 x 10^{-2} m^3/s (3.6 x 10^{-2} kg/s).

(iii) The third release category is that of a small continuous leak with fire present in the vicinity. Estimated release rate is 10^{-2} m^3/s (1.8 x 10^{-2} kg/s).

(iv) Release from a safety relief valve in an accident where fire is impinging on the LPG tank car. Rate of release of vapor from an upright car is estimated to be 0.11 m^3/s (0.2 kg/s).

(v) The fifth category of release is due to a major mechanical failure of the tank. It is assumed that all of the contents of the tank car will be released in a very short time (order of seconds). While in a majority of cases these releases would be ignited, situations are also possible wherein ignition is delayed. Assuming that the initial lading temperature is 21°C, about 35% of released mass flashes directly to vapor.

(vi) The sixth type of release is the liquid release through the valve from an overturned car. The rate of release depends on the valve opening and this is difficult to estimate. For a 7.6 cm diameter equivalent opening (as in ii) the release rate is estimated to be 125 kg/s.

(vii) The last type of release corresponds to an explosive rupture of the tank, caused by overheating of tank wall by an impinging fire and internal overpressurization. This type of failure results in the BLEVE phenomenon. It can be assumed that all of the contents of the tank are released instantaneously. Temperature of lading before release (for an insulated tank car) is assumed to be 62°C. The percent flash for this temperature is 60%.

Current regulations for LPG cars require the use of insulation on, tank cars (HM-144; 49 CFR, Part 179.105-4). The provision of external insulation on tank cars has virtually eliminated the occurrence of BLEVEs. Therefore, it should be emphasized that the probability of occurrence of LPG tank car BLEVEs is extremely small (as to be negligible).

5.4.2 Hazard Scenarios and Hazard Indices

The principal hazard to both the public and the railroad emergency response personnel from LPG tank car accidents arises from the fires that result from leaks. Several different types of fires can result. Figure 5.2, taken from the report by Geffen, et al(9), illustrates schematically the various types of fires and hazards that can result from LPG releases. The types of fires range from torch fires, pool fires, vapor fires, unconfined detonation in dispersed vapor cloud to BLEVEs.

Discussed below are each of the fire scenarios and their effects. Details of hazard area calculation models and the magnitude of hazard areas for each fire scenario are presented in Appendix C.

Torch Fire These result from the ignition of relatively small leaks of LPG from cracks, stuck vent valves, or relief valves operating normally. When the tank is exposed to an external fire, torch fires pose danger to railroad and emergency response personnel, and to other tank cars on which the flames may impinge.

Pool Fires When an LPG tank fails catastrophically due to mechanical forces (large puncture or impact crushing), about 35% of the mass released flashes to vapor and the remaining 65% falls to the ground and spreads as a pool of liquid. In general, this liquid pool is ignited and forms a pool fire. The main hazard to people and property outside the fire is by thermal radiation.

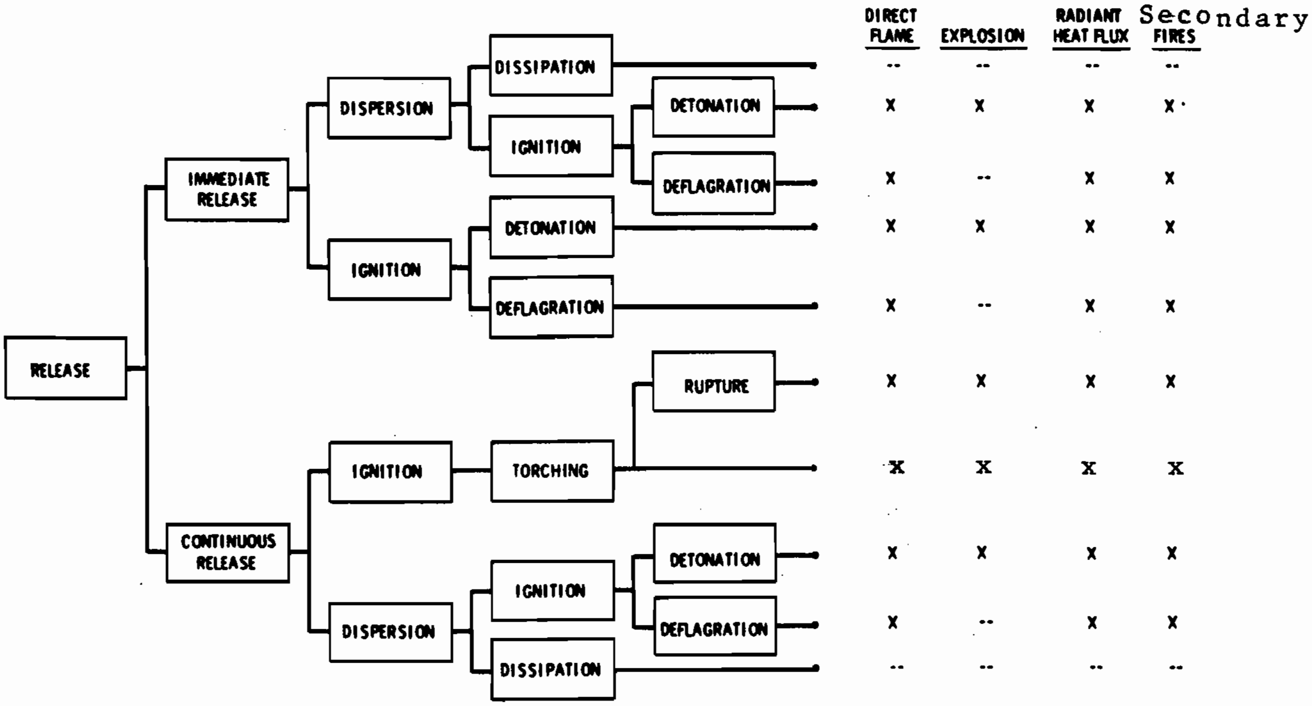


FIGURE 5.2 EVENT TREE FOR LPG RELEASE FROM A TANK CAR

Vapor Fire If the released LPG is not ignited immediately after release, the vapors are dispersed in the atmosphere due to prevailing winds and ambient turbulence. The dispersing cloud is flammable until the maximum ground level concentraton is below the lower flammability limit (2.1%). This cloud may be ignited by any downwind ignition source. In such a case, a burning propagating flame travels back through the cloud. This deflagrative burning is termed "vapor fire". The hazard area extends beyond the cloud dispersion area because of the thermal radiation hazard presented by the propagating fire.

Vapor Cloud Detonation A dispersed LPG vapor cloud ignited by an energetic source is known to detonate even in the unconfined geometry so long as the vapor-air mixture concentration is within the detonable range (see references 23, 25, and 26). Also, it may be possible for a deflagration burning of the vapor cloud to transit to detonation. The conditions under which such a transition may take place are not well known, nor are there documented cases of transition occurring in unconfined vapor clouds.

If the vapor cloud detonates, a pressure pulse travels radially in all directions from the vapor cloud. The magnitude of the peak over-pressure decreases with distance. A 10 psi over pressure is immediately fatal (Geffen, et al, 1980), and this value is used as the hazard index in our calculations.

Fireball - BLEVE Release As indicated earlier, the present regulations requiring the use of thermal protection on tank cars for the transportation of LPG on rail, are intended to preclude the occurrence of BLEVE and, therefore, "fireball" type of fire. Docket # HM-175, (amendments to parts 173 and 179 of 49 CFR), requires the use of high temperature thermal insulation(800° material) on all tank cars used for flammable gas or ethylene oxide service. The insulations are required to withstand 100 minutes exposure to pool fire and/or 30 minutes exposure to a torch fire. Retrofitting of existing cars was completed by the end of 1986.

While it is highly unlikely that BLEVE phenomenon can occur in railroad accidents involving LPG cars once all of the flammable gas carrying cars are retrofitted, we, however, consider in this risk assessment the possibility of such an occurrence; but as a very low probability event. Such a consideration takes into account the involvement of a non-retrofitted car in an accident and the remote possibility of a large area of thermal protection being ripped off in an accident and the bare metal being then exposed to a torch or pool fire.

The structural failure of an LPG tank after being exposed to fire results in the release of all of the contents, almost instantaneously. The failure time of an LPG tank car exposed to an intense fire can vary between 20 minutes for an unprotected car to 90 minutes for a thermally protected car. The "explosive" release that follows results in the rapid mixing of the flased vapor with air and ignition of the entire mixture. The result is the formation of an enormous fireball which subsequently lifts into the air as it burns.

The hazard from a fireball results from both fire contact and thermal radiation to objects outside the ball of fire. Contrary to popular thesis, the fireball phenomenon is not followed by an "explosion" or "detonation". The rapid failure of the tank and combustion of the released mass may induce fragmentation of the tank car structure which can be hurled a great distance from the position of the tank car.

Other Types of Hazards arise from the mechanical hurling of the structural pieces of tank cars (fragmentation) or the rocketing of reasonably intact tank cars. A direct impact on a person or a structure by any of the big-sized missiles may lead to serious injury, fatality, or property destruction. A set of empirical correlations, based on test observations, are indicated in Appendix C to evaluate the potential hazard zones. While these areas may be hazardous, they are far from being areas of complete fatality. However, for the purposes of conservative calcuation, we have assumed that these areas also constitute 100% fatality areas.

The hazard areas calculated for the release of one tank car containing LPG and resulting in different fire scenarios, are indicated in Table 5.3 Also given in the Table are the probabilities of occurrence of these fire scenarios. It is seen from this Table that maximum impact area results from fully developed and spread-out cloud detonations. However, the probability of such an event occurring is very, very low. The weighted average area is 6.4 x 10^{-2} km^2 which is about two orders of magnitude smaller than that for comparable mass of chlorine release (see Table 5.2).

5.5 HAZARDS FROM SULFURIC ACID RELEASES

Sulfuric acid is transported at ambient temperature in different types of non-insulated rail tank cars allowed by regulations (49CFR, Part 173.272 (i) (22)) such as DOT111A100W2. Nominal volume capacity of these tank cars is 13350 gallons (50.5 m^3). Relevant properties of sulfuric acid have been indicated in Table 3.5.

Leakage of sulfuric acid from tank cars caused by rail accident can occur either from damaged appurtenances or due to puncture of tank shell. Based on the AAR data(6), we estimate that given a derailment accident, the probability of releases from

TABLE 5.3

HAZARD AREAS FOR DIFFERENT SCENARIOS OF LPG RELEASE

Hazard Scenario	Scenario Conditional Probability (%)	Calculated Hazard Area Total $(km)^2$	Net Hazard Area Outside Right of Way $(km)^2$
Torch Fire	58.0	1.2×10^{-4}	0
Pool Fire	28.8	9×10^{-2}	8×10^{-2}
Vapor Fire	2.56	0.38	0.38
Vapor Cloud Detonation	0.64	3.8	3.8
BLEVE with Fireball	5.00	8.7×10^{-2}	7.7×10^{-2}
BLEVEd Car Rocketing	3.50	2.2×10^{-3}	0.0
Missile Debris Impact	1.50	1.2×10^{-2}	1.2×10^{-2}
Probability Weighted Hazard Area		6.4×10^{-2}	6.1×10^{-2}

Remarks:

Scenario probabilities are based on data in Table 5.1 for derailment accidents. Releases are attributable to 58% from safety valves and top/bottom fittings, 32% from shell and head punctures and 10% due to fire exposure. First type of releases are assumed to cause torch fires. Shell/head releases are assumed to cause pool fires 90% of the time and vapor dispersion 10% of the time. Vapor fire is assumed to occur in 80% of the vapor cloud ignitions and 20% ignitions result in cloud detonations. All "fire" induced releases are assumed to result in one form of BLEVE or other. Of these, BLEVE with fireballs are also assumed to occur in 50% of cases, 35% in BLEVE's result in cars rocketing, and 15% in missile impact.

In the light of the thermal protection systems, the probability of BLEVE occurring can be considered to be less than 1%. In such a case, the probability weighted hazard area (column 3 of the Table) is estimated to be 6.1×10^{-2} $(km)^2$. Because of the already low probability value for BLEVEs, the hazard area does not change significantly compared to that indicated in the Table.

various modes are as follows: top fittings 63%, and 37% from shell and head punctures. Release from exposure to fire is accounted for equally in the above two categories.

The maximum release rates are calculated to be as follows:

fittings and appurtenances (2" diameter) = 25 kg/s
shell or head punctures (12" diameter) = 1000 kg/s

At the latter rate of release, a tank car containing 92×10^3 kg will empty out in about 3 minutes if the puncture is at the bottom of the tank.

The principal hazard from the sulfuric acid leaks is due to the corrosive property of the acid. If a person comes in contact with the liquid, severe burning may result; fatality is quite remote. Inhalation of the fumes can also result in serious damage to lungs and breathing tracts. Because of the relatively low vapor pressure, the hazard area from fumes generated by the liquid spill will be limited in size.

For the purposes of hazard evaluation, we assume that the hazard distance is limited to the maximum radius of spread of the liquid on a flat ground. We estimate the maximum radius of spread of sulfuric acid (on ground surface normally found next to railroad tracks) when one tank car full of acid is released, to be about 60 m. The total hazard area is calculated to be 10^{-2} $(\text{km})^2$. However, when one considers the right of way (30 m wide) within which most of the hazard area will lie, the potential area of hazard to the general population is estimated to be 7.5×10^{-3} $(\text{km})^2$.

The hazard areas calculated in this Chapter for the release of the chemicals of interest are used in the risk model (see Equation 2.11), discussed in Chapter 2. The results obtained are indicated and discussed in the next Chapter.

CHAPTER 6

RISK ANALYSIS RESULTS

In the previous chapters were discussed the determination of the values of the various parameters from available data and mathematical modeling needed for performing a transportation risk analysis. These parameter values are used in the risk model described in Chapter 2. The 1983 traffic volumes are used in the analysis. The model has been coded into a computer program with the sequence of calculations following that shown in Figure 2.2 The results generated by using the model given in Chapter 2 are indicated and discussed below.

6.1 BASE CASE

We have evaluated the transportation risks associated with various chemicals on different routes and the senstivity of the risk values to variation in the magnitude of several other parameters. In order to compute these results and to draw proper conclusions, we have selected a "Base Case", represented by the set of parameters given below:

Base Case:

Routes:	Route 1 & (see Figure 3.1) Route 2
Route segment track and population density data:	Tables 3.8A, 3.8B
Annual traffic density:	Tables 3.8A, 3.8B
Accident rate:	Table 4.10; Route specific data
Average number of specified chemical cars in a train:	Table 4.11, Route specific data
Number of cars derailing:	Table 2.12; National data
Probability of tank puncture:	Table 4.12, National data
Hazard areas:	Tables 5.1, 5.2, 5.3

6.2 RISK RESULTS

The risks involved in transporting chlorine on Routes 1 and 2 for the conditions represented by the "Base Case" are shown in the form of a risk profile in Figure 6.1A. Similar risk profiles for LPG and sulfuric acid on Routes 1 and 2 are shown in Figure 6.1B and Figure 6.1C, respectively. The comparison of the relative risks for the three different chemicals on Route 1 is shown in Figure 6.2.

The risk results obtained by using the base case data and those obtained from using all national average values are indicated in Figure 6.3.A and 6.3.B for Route 1. The sensitivity of the results to variation in other parameter values are discussed in the next Chapter.

6.3 DISCUSSIONS

In Figure 6.1A, the risk spectra for chlorine transportation on two distinctly different routes are indicated. We see that the risk profiles exhibit the common characteristics of risk spectra in that the probability of low casualty accidents is high and the probability of high casualty accidents is low. The largest casualty number for a chlorine release is 613, with a probability of occurrence of 0.52 x 10^{-4} (or one such accident in about 20,000 years). This large magnitude of casualty is calculated to occur at the very high population density area (origin: a Gulf Coast city). Also, because of the relatively low annual shipment volumes of chlorine on the various segments of Routes 1 and 2 (see Table 4.11) we see from the risk model that the probability of two chlorine cars leaking in an accident is vanishingly small. In effect, the chlorine risk profiles shown in Figure 6.1A are due to release from one tank car in each accident.

The small difference in the risk profile probability values between Route 1 and Route 2 is primarily due to the chlorine shipment volumes on the two routes being comparable (see Table 4.11). On Route 2, the total freight traffic is slightly lower than that on Route 1; hence, a slightly lower probability of accidents. The probability of large size accidents on both Route 1 and Route 2 are very close (almost identical) because both routes share the yard at the origin and the first few segments of track, and these segments have high population densities. However, in the subsequent sections of Route 2, both the population density and the annual freight traffic volumes are, in general, lower than those in Route 1.

The risks in transporting LPG over Routes 1 and 2 are shown in Figure 6.1B. Results obtained by exercising the model indicate that the maximum casualty possible for the routes chosen is 276, with a probability of occurrence of 3 x 10^{-7} per year. This scenario occurs when LPG from four tank cars is released simultaneously and ignited at the location of higest population

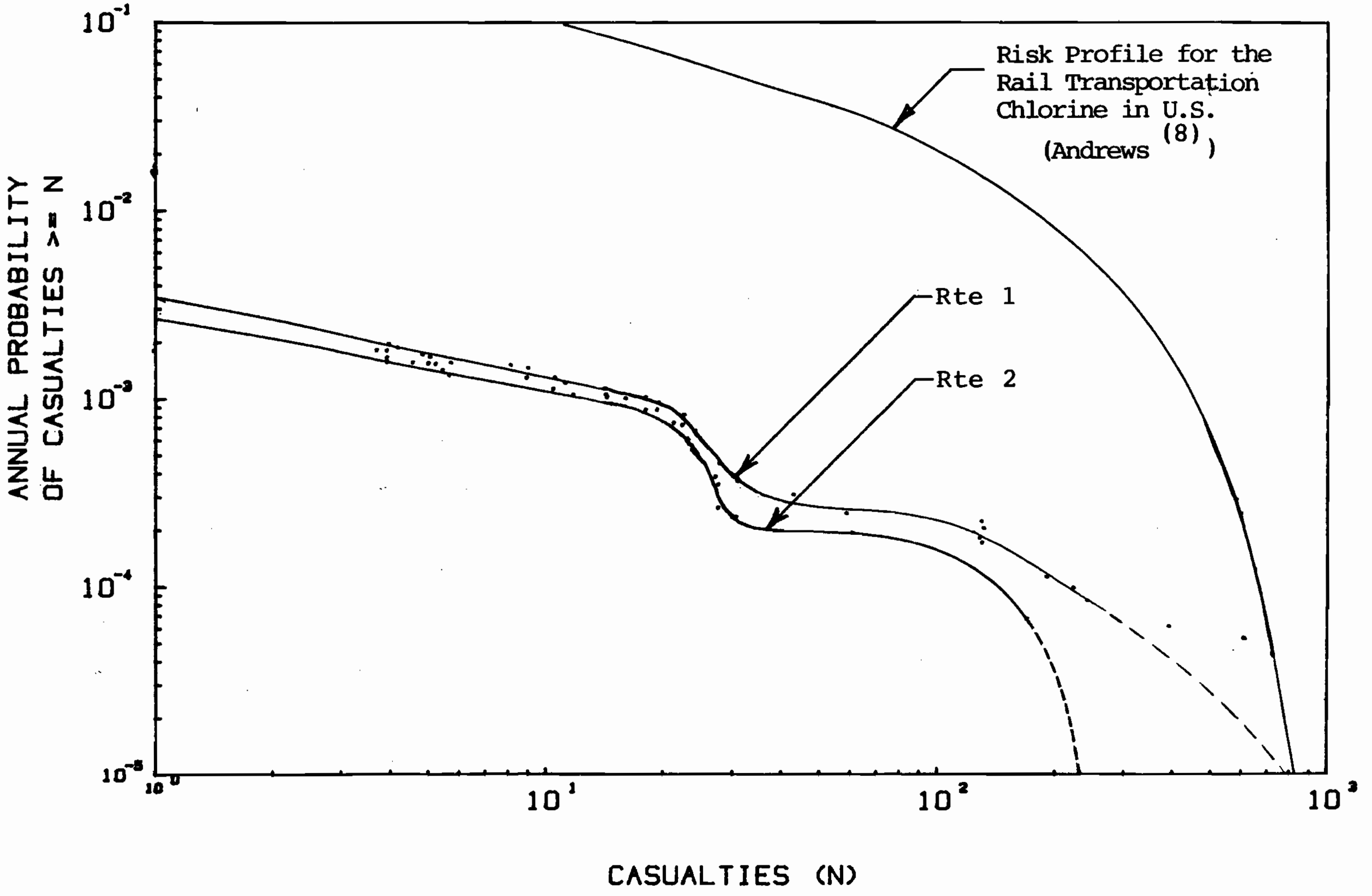


FIGURE 6.1.A Risk Profiles for Chlorine Transportation on Routes 1 and 2.

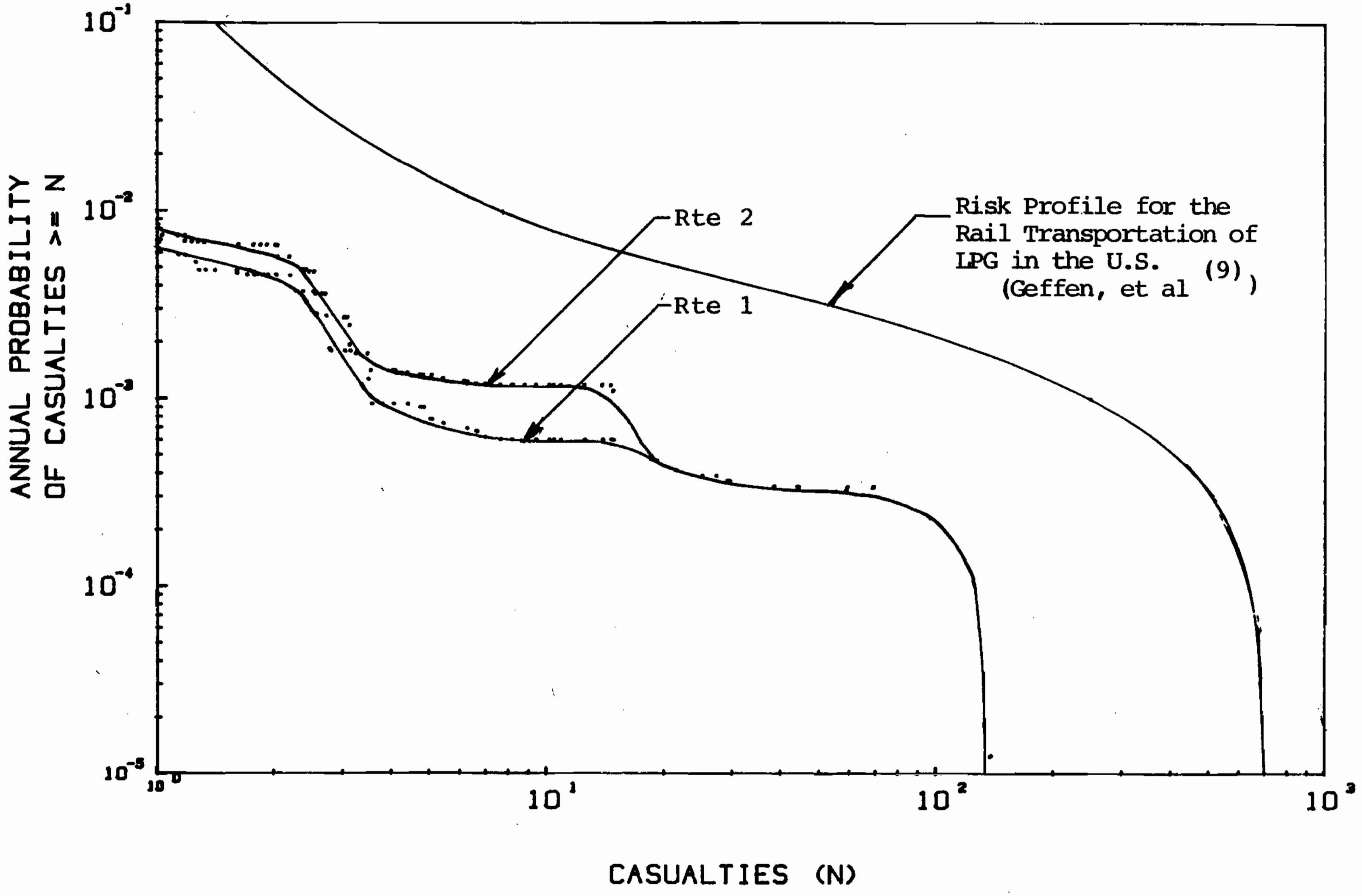


FIGURE 6.1.B Risk Profiles for LPG Transportation on Routes 1 and 2.

density. The largest casualty value with probability greater than 10^{-5} is 138. This figure also indicates that the LPG risk values (i.e., annual probabilities for given casualty levels to be exceeded) are comparable to those of chlorine for the same routes.

The LPG risk profiles for Route 1 and Route 2 are very similar. In fact, the risk values on Route 2 are slightly higher. This is a result of the higher volumes of LPG hauled on some segments of Route 2 compared to those on Route 1 (see Table 4.11).

The sulfuric acid risks are shown in Figure 6.1C. The principal feature of the result is that both the annual probability values and the casualty values are small, by an order of magnitude, compared to LPG or chlorine. On the routes chosen for study, the traffic volumes of sulfuric acid and chlorine are comparable; yet, the consequence values for the acid transportation are about 2 orders of magnitude smaller compared to chlorine at the same annual probability values. This is because (i) sulfuric acid hazard area is considerably smaller than that for chlorine; and (ii) the casualties from sulfuric acid arise only in the highest population density segments of the routes.

The risk profiles for all three chemicals on Route 1 are shown in Figure 6.2A. The relative magnitudes of risks for each chemical compared to the others can be easily noticed. It is emphasized here that these risks are the existing risks for the transport of the three chemicals at the present (estimated) volumes of haulage on the different segments. The LPG volume is about 3 times that of chlorine (on a national basis). Yet, the results indicate LPG risks are similar in magnitude to chlorine risks at the lower end of the casualty spectrum, and are considerably better (lower casualty values) at the high end of the casualty spectrum. This is simply a consequence of the lower hazard area of LPG - in spite of the spectacular accidents and the perception of higher hazard potential - compared to that presented by chlorine.

The risk profiles presented in this Chapter were generated using as much route specific data as were available from the cooperating railroad. Additional data that were needed but were not available were obtained by assuming the applicability of the national average parameter values. For example, the data that were avilable to us from the cooperating railroad included the annual volumes of traffic by broad categories of hazmat class. These were not segregated according to specific chemical. To obtain specific parameters for LPG, chlorine, and sulfuric acid (mainly the average number of tank cars per train), we used the national average data. It is uncertain whether the use of the "hybrid data" is appropriate or not. However, we conclude that the margin of error on the values of annual probabilities presented in the risk profiles in Figures 6.1 and 6.2 is within a factor of +/-3.

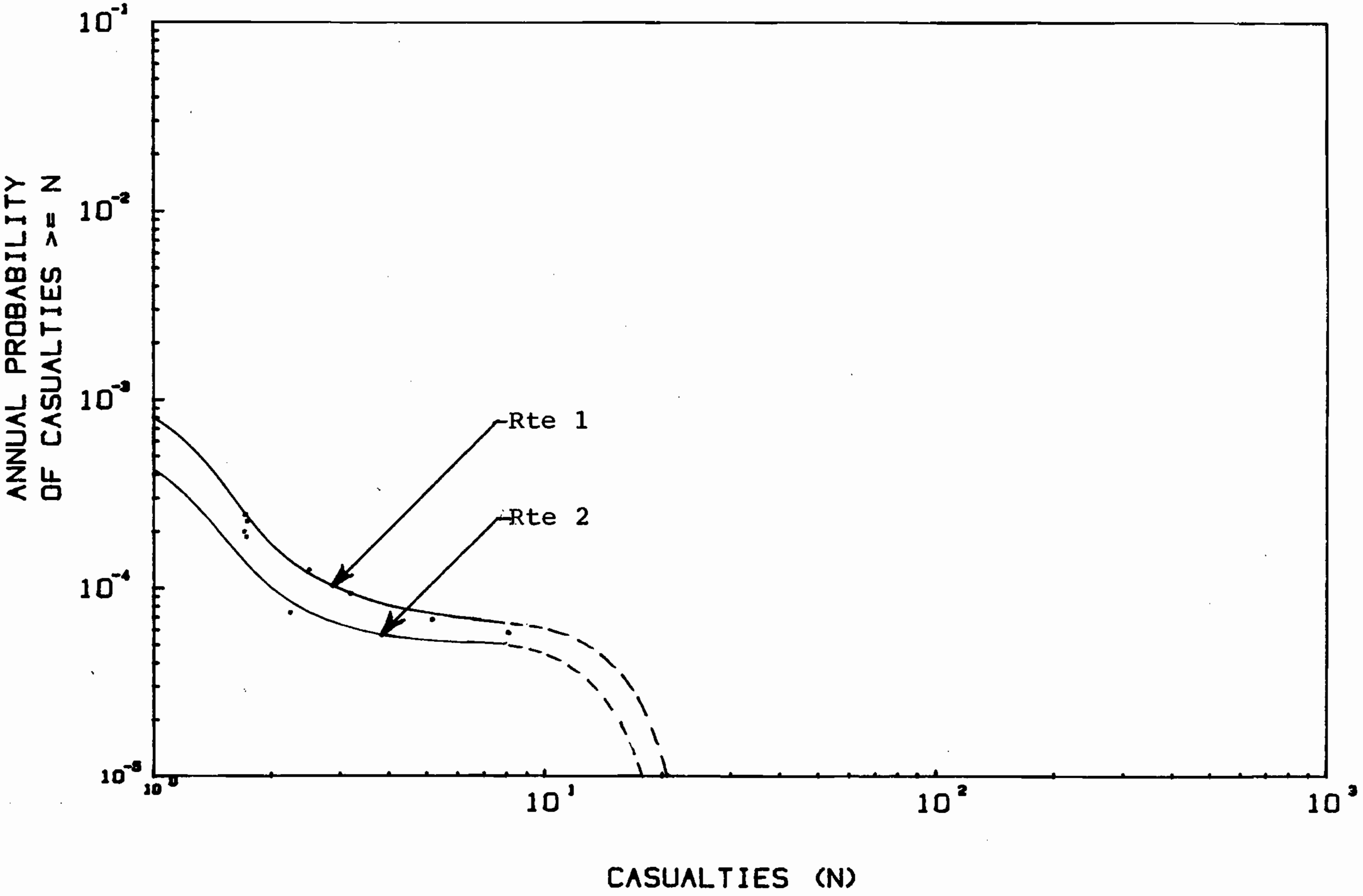


FIGURE 6.1.C Risk Profiles for Sulfuric Acid Transportation on Routes 1 and 2.

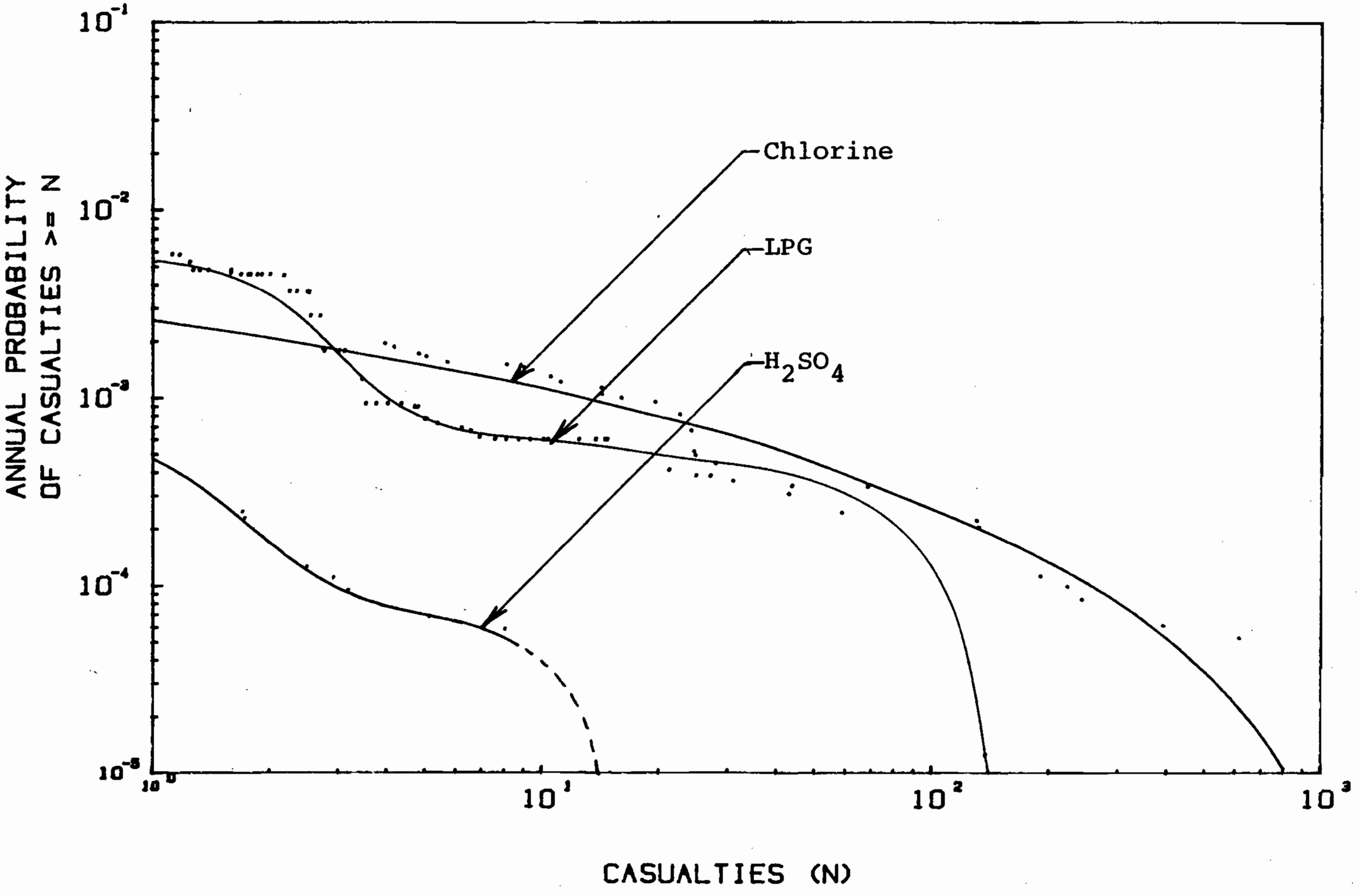


FIGURE 6.2 Comparison of the Chlorine, LPG, and Sulfuric Acid Risk Profiles for Route 1

The total number of different types of chemical cars loaded in the U.S. in 1983 were presented in Table 3.2. These data are modified to take into account 80% capture of information in the database presented. By assuming that the average distance of movement of a loaded car is 600 miles (irrespective of the chemical) and comparing the total number of car miles nationally and along the two routes studied, we developed the results presented in Table 6.1. This Table shows the fraction of the total national car miles (of the specific chemical of interest to this study) attributable to the route chosen. The results indicate that, for example, 1.2 % of the national LPG car miles can be attributed to traffic on route 1 of this study.

On the basis of the information presented in Table 6.1, we can now compare the expected fatality values obtained in this study with those predicted by other researchers for the U.S. as a whole.

The annual probabilities of exceeding specified casualties for chlorine indicated in Figure 6.1A are about 300 smaller, at the lower casualty end of the profile, than those calculated by Andrews(8), for chlorine shipments on rail throughout the U.S. This is in keeping with the fact that along the route studied, chlorine traffic is estimated to be about 0.77% of national traffic, and that the value we have used for the probability of puncture and release is about one-half to one-third of the value used by Andrews(8). The remaining difference lies, perhaps, in the distribution of population density along the route.

It is interesting to compare the national average fatality values calculated by other researchers for chemical transport on rail with values extrapolated from our route specific study. Table 6.2 indicates these comparisons. In order to present the results on the same basis for comparison, we have extrapolated the route specific expected fatality results (columns 2 & 3 in Table 6.2) to national values by assuming that expected casualty values are directly proportional to tank car miles on the segment. This assumption neglects the effects of quality of track, train speed, population density distribution along the tracks, safety measures instituted by the railroads on the route, etc. Therefore, the comparative results shown in Table 6.2 may be somewhat misleading and should be viewed in proper perspective.

The results shown in Table 6.2 indicate that nationally the expected fatality values for chlorine transportation (obtained from extrapolation of results of this study) are higher than calculated by Andrews(8). This does not, however, make the routes worse than the national average from a risk perspective. In fact, a review of the quality of the track on the two routes chosen for study indicates that they are very well maintained main line tracks. We explain the higher extrapolated national value as being, perhaps, due to two reasons. First, in our route specific calculations, several very high population density metropolitan areas were considered. This, together with the relatively short distance (600 miles) of track considered in the study, makes the effective population density along the route

TABLE 6.1

Percent of Total National Specific Chemical Tank Car Miles Attributable to the Routes Chosen

Chemical	Percent of Tank Car Miles on Route 1	Percent of Tank Car Miles on Route 2
LPG	1.20%	1.31%
Chlorine	0.77%	0.64%
Sulfuric Acid	0.52%	0.43%

TABLE 6.2

EXPECTED NUMBER OF CASUALTIES PER YEAR DUE TO RAILROAD ACCIDENTS INVOLVING DIFFERENT CHEMICALS

CHEMICAL	This Study Base Case		NATIONAL VAUES Extrapolated Value from This Study		Result from Other National Risk Studies	Reference
	Route 1	Route 2	Route 1	Route 2		
Chlorine	0.088	0.073	11.4	11.4	9.4	Andrews(8)
LPG	0.043	0.055	3.6	4.2	0.5	Geffen(9)
Sulfuric Acid	0.001	0.001	0.2	0.23	Not Available	

significantly larger than that for the nation as a whole. The effect of this, of course, is to increase the extrapolated national expected fatality value. The second factor is that in our study we used a more appropriate chlorine dispersion model which tends to predict larger hazard areas (than had been calculated by Andrews). These two factors combine to indicate a seemingly larger value for the extrapolated (from our route specific results) national expected fatality.

Table 6.2 further shows that for LPG transportation the national value for the expected fatality, calculated by Geffen et al(9), is almost an order of magnitude smaller than that obtained by an extrapolation of our route specific results. The effect of population density is much more pronounced for the case of LPG risks because of the relatively small expected area of hazard resulting from LPG accidents (see Table 5.3).

The comparative results shown in Table 6.2 and the above discussions clearly indicate the need to perform route specific risk assessments and not use the national results extrapolated (in any fashion) to the specific routes. The various operational and population density parameters interact in such a complex way that extrapolation of the results, in either direction, i.e., from the national risk analysis to the individual route or vice versa, will be meaningless.

The sensitivity of the risk profiles to variations in the parameter values is discussed in the next Section.

6.4 SENSITIVITY ANALYSIS

Both the probabilities of occurrence of accidents and the consequences depend on several operational and other parameters. In this Section, we present and discuss the results obtained from changing the values of some of the parameters. The parameters considered include:

- (i) Release probability
- (ii) Effect of emergency evacuation (for toxic gas releases)
- (iii) Accident rate
- (iv) Use of national average accident data.

6.4.1 Effect of Release Probability (q)

Release probability is dependent on the effectiveness of protective devices such as head shields, shelf couplers, thermal insulation, etc., and also on the tank car material properties. Also, the location and design of appurtenances have significant influence on the small volume releases. A discussion is provided in Appendix D on material specifications, material properties, their effects on release probabilities, etc. Also indicated in this Appendix are recommendations for further research to directly integrate tank car material property parameters in risk analysis.

A significant reduction in the release probability, by more than a factor of 2, is noticed between 1978 and 1983 (see Table 4.12). We have argued (in Chapter 4) that this reduction is a direct result of the provision of head shields, shelf couplers, and thermal protection sytems on tank cars.

The effect of this decrease in release probability on risk is shown in Figure 6.3A. The risk profiles for chlorine transporation on Route 1 are shown for three release probability values. The base case value is the average release probability value for 1978-83 period (Table 4.12). The other release probability values for which risk profiles are shown in Figure 6.3A include the 1978 value (which is about twice the base case) and 20% of the base case value - i.e. factor of 10 variation in the release probability values is covered.

The results indicate that the accident probability (for a given level of casualty) is almost directly proportional to the release probability, at the low casualty levels. That is, a twofold decrease in release probability leads to a twofold decrease in overall accident frequency at a specified low casualty. On the other hand, at the higher casualty end of the scale, reductions in overall frequencies of the order of 10 result in a twofold decrease in release probability. The latter effect is due to the sparcity of events that can lead to large casualties. Therefore, even a small decrease in release probability value (achieved by providing safety devices on tank cars) can decrease the potential for catastrophic accidents considerably.

Figure 6.3B shows similar comparisons of risk profiles for the transport of LPG on Route 1. The conclusions are similar as in the chlorine case; that is, substantial reduction in the catastrophic accident probabilities can be achieved by small decreases in the tank car release probabilities.

6.4.2 Effect of Emergency Evacuation

Figure 6.4 shows the risk reduction that can result if timely emergency evacuation is implemented in the case of toxic gas releases from railroad tank car accidents. In the Figure, the risk profiles for the base case and the case in which the effective population density is only 14% of the census population density are indicated for chlorine transporation on Route 1. The reduction in the census population density has been discussed in detail in a recent report (Raj(13)). For the case presented, it is assumed that (i) the population is representative of urban/rural population; (ii) the evacuation time is 1 hour; and (iii) that the entire contents of the chlorine car are released instantaneously, leading to the dispersion of flashed vapor cloud in a stable weather condition. The results shown in Figure 6.4 indicate, as can be expected, that the reduction in annual probability at the lower end of the casualty scale is directly proportional to the reduction in effective population density due to emergency evacuation. However, the significant benefit is seen toward the

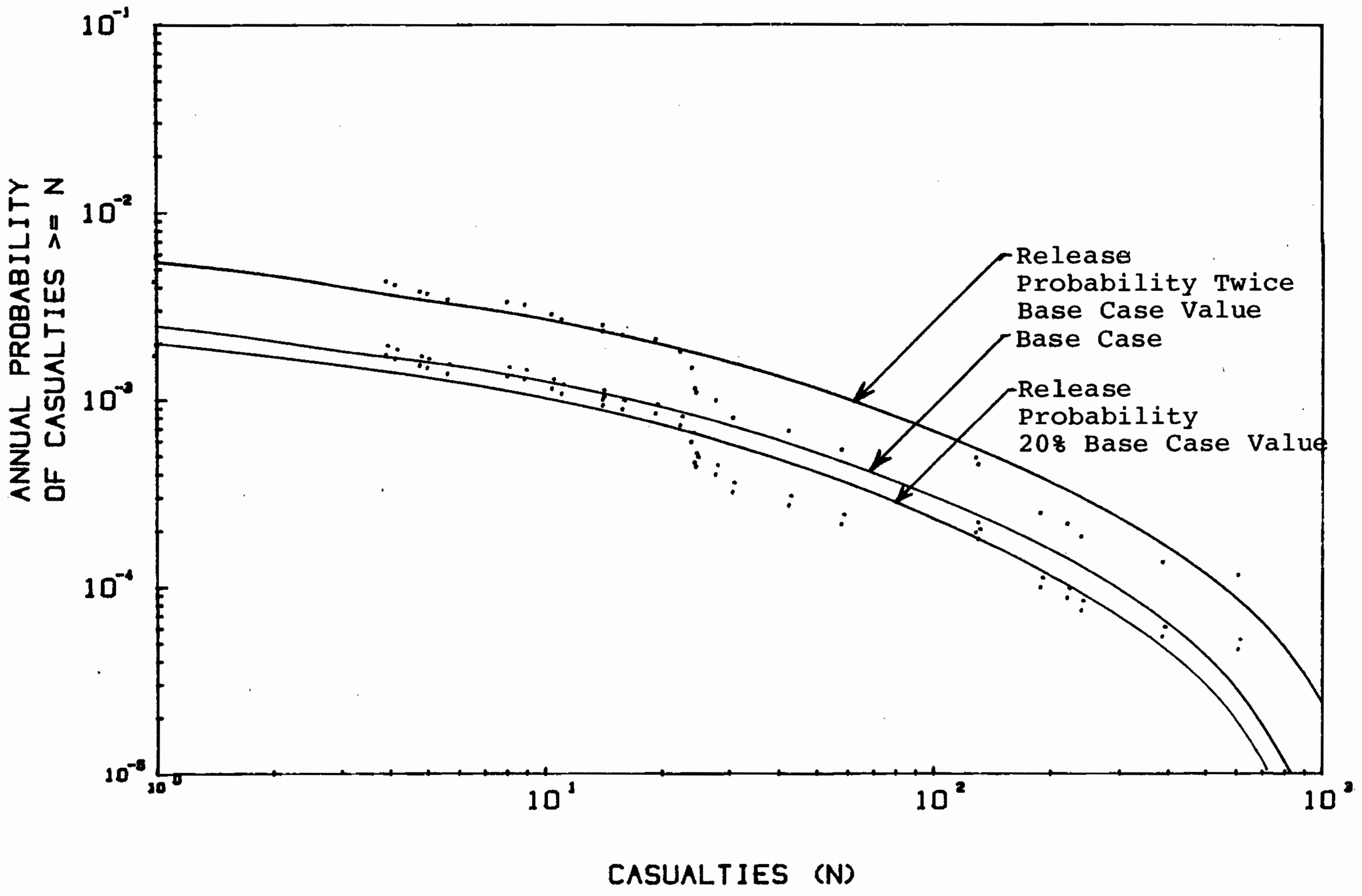


FIGURE 6.3.A Variation in Risks Due to Variations in Tank Car Release Probabilities: Chlorine on Route 1.

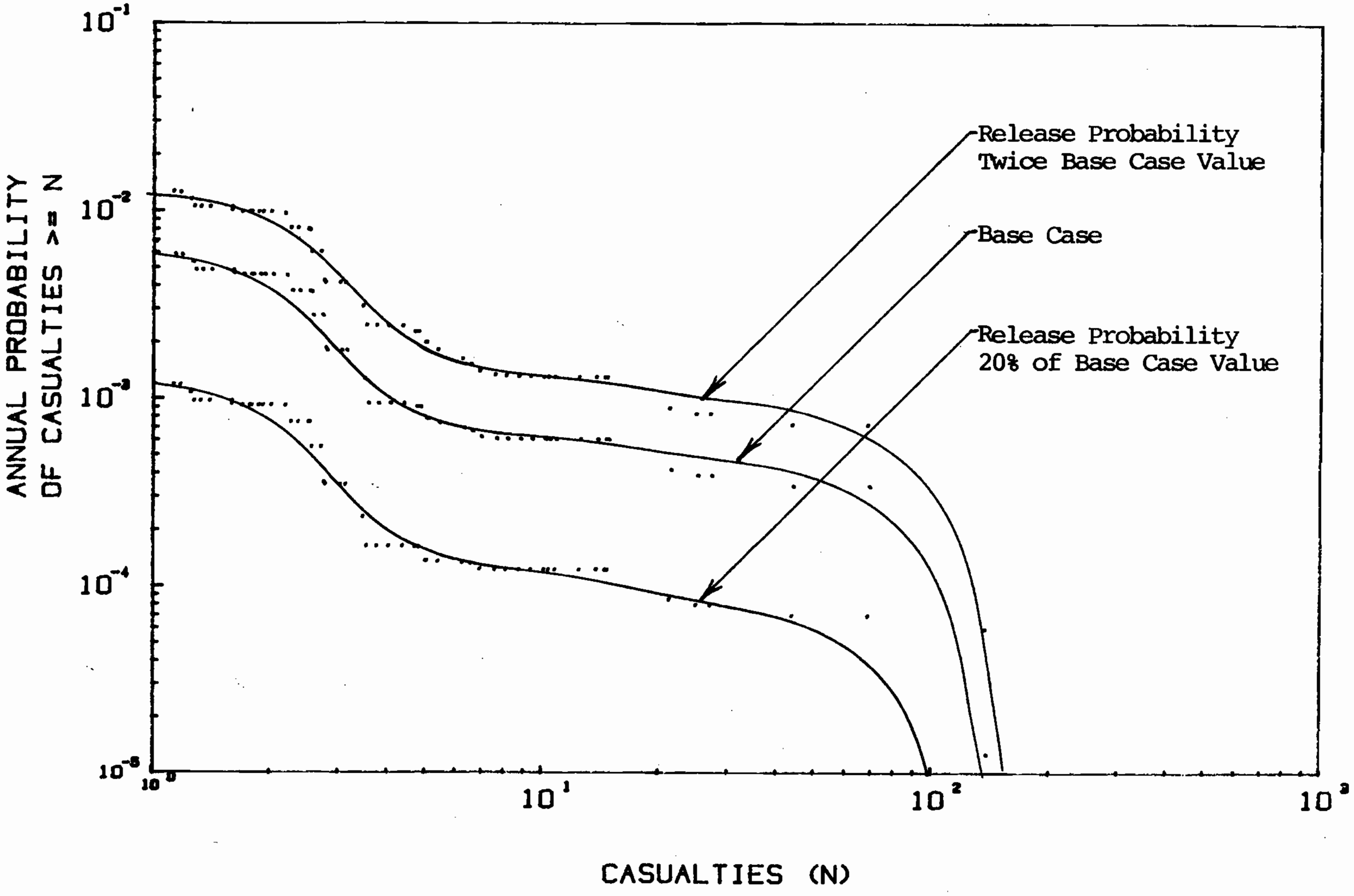


FIGURE 6.3.B Variation in Risks Due to Variations in Tank Car Release Probability: LPG on Route 1.

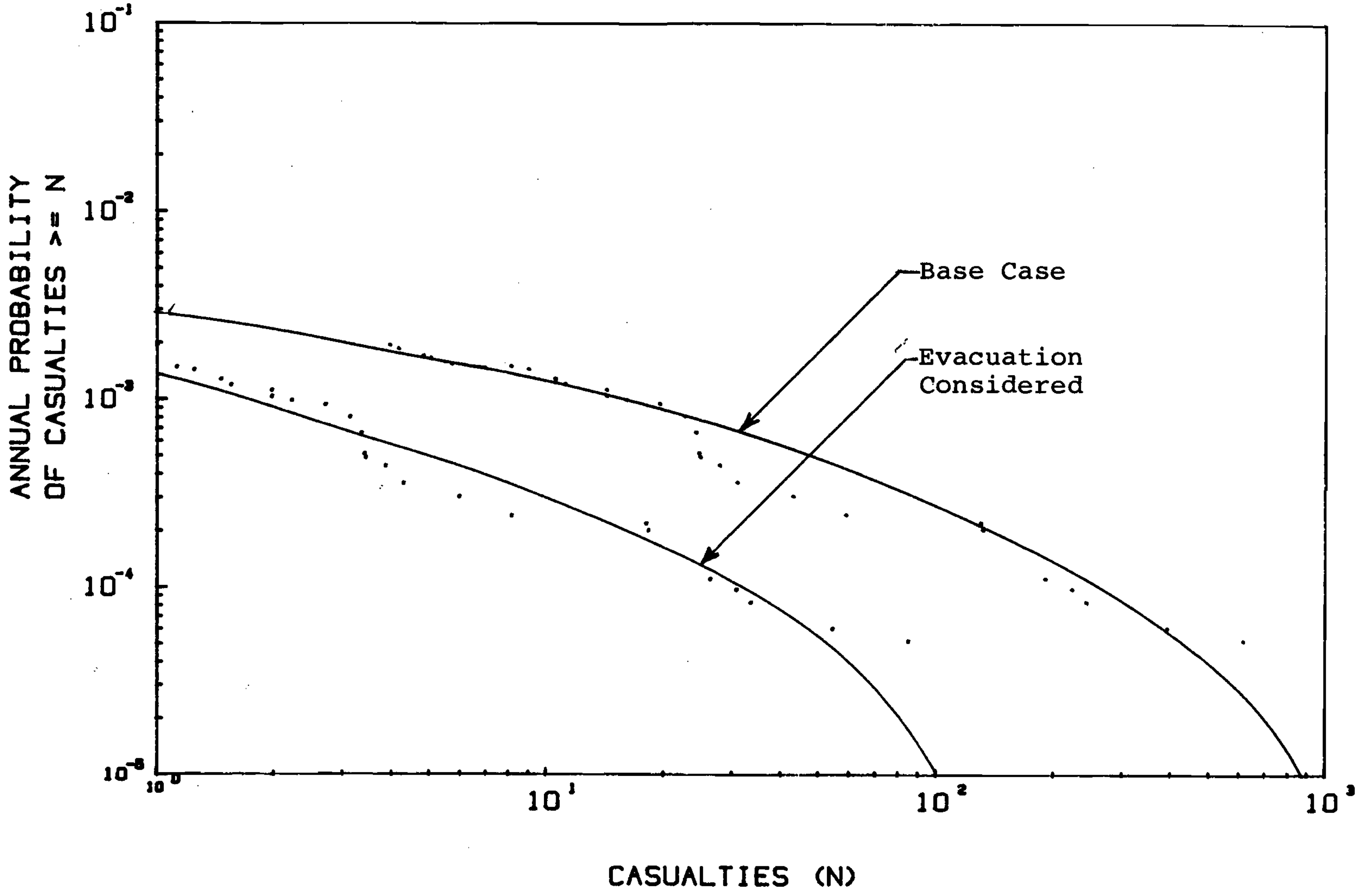


Figure 6.4 Variation in Risks When Emergency Evacuation is Implemented for Chlorine Releases on Route 1.

higher end of the casualty scale; in fact, a reduction of casualties by a factor of 10 is seen. This is because when a large fraction of the population is removed from the hazard area, the effective hazard is reduced substantially.

A comparison of the risk profiles for the case of LPG with and without emergency evacuation is not shown. This is because the nature of the hazard associated with LPG releases is such that before any emergency action can be taken, the hazard event would have occurred, if the damage and puncture of tank car occurs immediately after rail accident. However, if delayed release is a possibility (as from a slightly damaged car) then emergency evacuation certainly provides benefits. The latter type of responses are not considered in our risk assessment model at the present time.

6.4.3 Effect of Accident Rate

The accident rate we used is primarily a function of the track class, even though it is also dependent on the train speed (see Table 4.7). In developing the risk profile for the base case, we utilized the accident rate values consistent with the class of track on each segment of the two routes studied. These accident rate values were obtained from the accident data and the total freight traffic data and were indicated in Table 4.1. It is noticed that, depending on the definition used to "describe" an accident, the computed accident rate values for the routes considered could differ by a factor of 6. We have studied, therefore, the sensitivity of the risk results to changes in the value of the accident rate parameter.

Figure 6.5 shows a comparison between the base case risk profile for chlorine on Route 1, and the risk profile with accident rate 10 times the base case rate, all other parameters being the same. We see that the risk curve in the latter case is shifted up by a factor of 10, along the annual probability scale. This is because, in our model indicated in Chapter 2, the accident rate is multiplied by all other conditional probabilities to obtain the overall probability of casualties. That is, the probability that a specified number of casualties occur in a year is directly proportional to the accident rate. We have, in generating the results presented in Figure 6.5, tacitly assumed that the accident rate is not dependent on the speed. Therefore, even though 10 times base case accident rate is considered, the train speeds on the individual segments of the route were not changed in our calculation.

One important observation that can be made from the results in Figure 6.5 is that as the accident rate increases, the number of casualties for a given annual probability increases, disproportionately to the increase in accident rate, at the larger casualty end of the risk profile. This means that any improvement in operational procedure that contributes to the reduction of the accident rate provides a substantial reduction in the potential for catastrophic accidents (with casualties greater than 100).

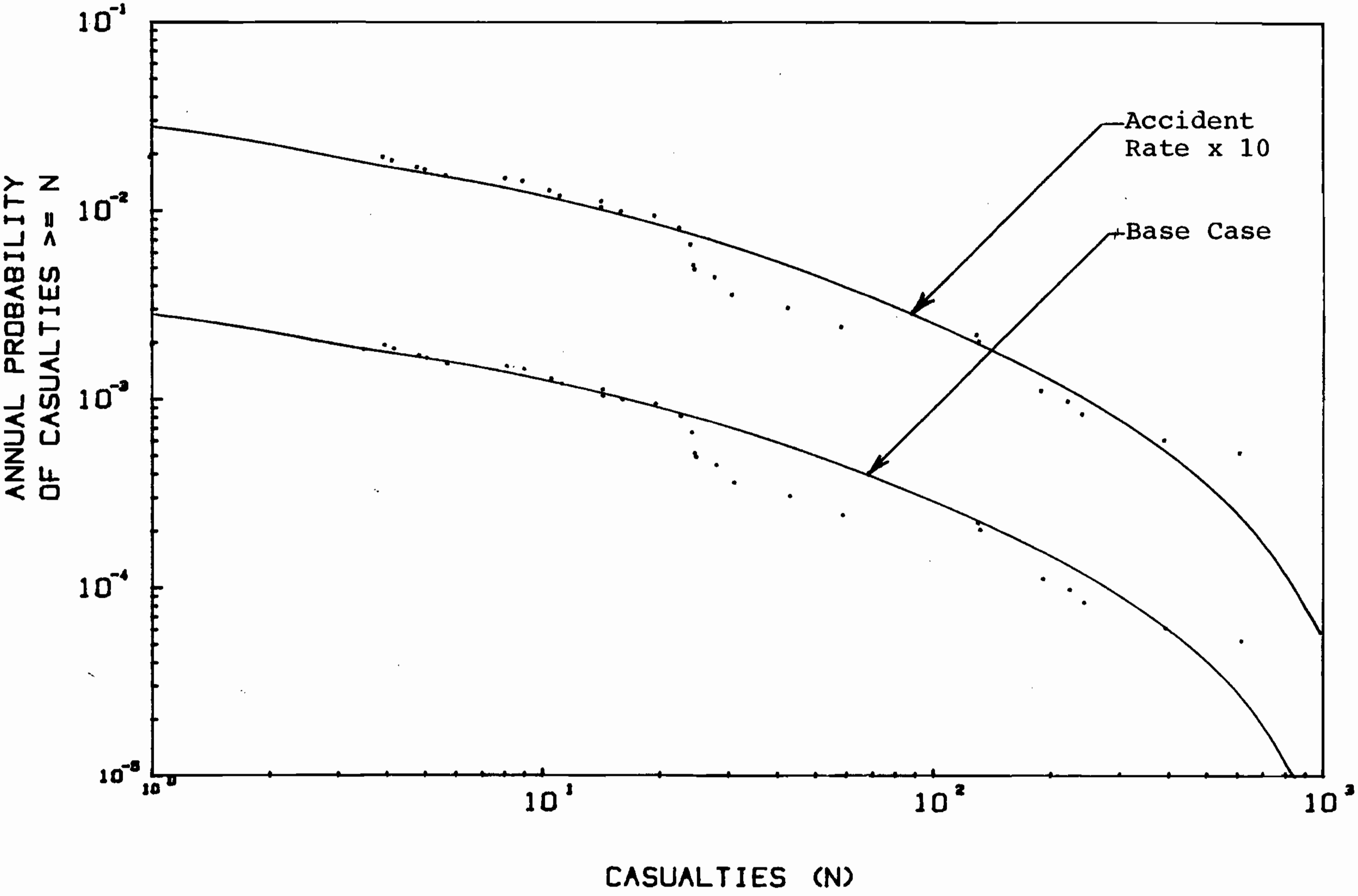


FIGURE 6.5 Sensitivity of Risk Values to Changes in the Accident Rate

6.4.4 Effect of Source of Data

In this study, we have gathered data and correlations that are representative of national average values (for the U.S.) as well as data that are specific to the route segments investigated. It is not always possible, in a risk assessment study, to have all of the data specific to the route(s) of interest. In order to evaluate the possible error that may occur if national average values are used (instead of route specific data), we have developed the risk profiles with both sets of data. Figure 6.6 shows these risk profiles for chlorine transportation on Route 1 (base case) and chlorine transporation on Route 1 using national average values for both accident rates and number of chlorine cars per train. However, in both cases, the same route specific overall freight traffic density values were used.

We notice from the results in Figure 6.6 that had we used nothing but the national average values in all of our calculations, the risk results would not have been very different from those generated with route specific information. This conclusion, of course, is applicable to only this route, simply because the coincidence is fortuitous. That is, the accident rates on the routes studied are very close to those of the national average values (Table 4.10) for the track class of the routes. In addition, the average numbers of chlorine cars per train on Route 1 are comparable to the national average values (see Table 4.11). The results in Figure 6.6 indicate that the base case results are slightly more conservative (i.e., predict higher probabilities of occurrence) compared to the national average case.

6.4.5 Other Parameter Effects

Another operational parameter that has significant effect on the risk profile is the speed of the train. The train speed affects both the number of cars derailing in an accident and the probability of hazmat release from tank cars. In our base case studies, we have used the values of train speeds appropriate to each segment of the route. The values for train speeds were obtained from a detailed analysis of freight train schedules on the routes of interest. These speed values are considerably less than the maximum permissible speeds for the class of track in the segment. The lower speed values for trains carrying hazardous materials are dictated by the strict operational policy of the railroad on the routes studied.

It can be argued that an increase in speed will increase the annual probability value (for exceeding a given casualty level) by the square root of the speed increase factor at low casualty levels and by larger amount at high casualty (greater than 100) level. A similar dependence on speed results when the speed is decreased. Because of the square root dependence, the effect of speed is more prominent as the speed increases above the operating speed than when speed decreases.

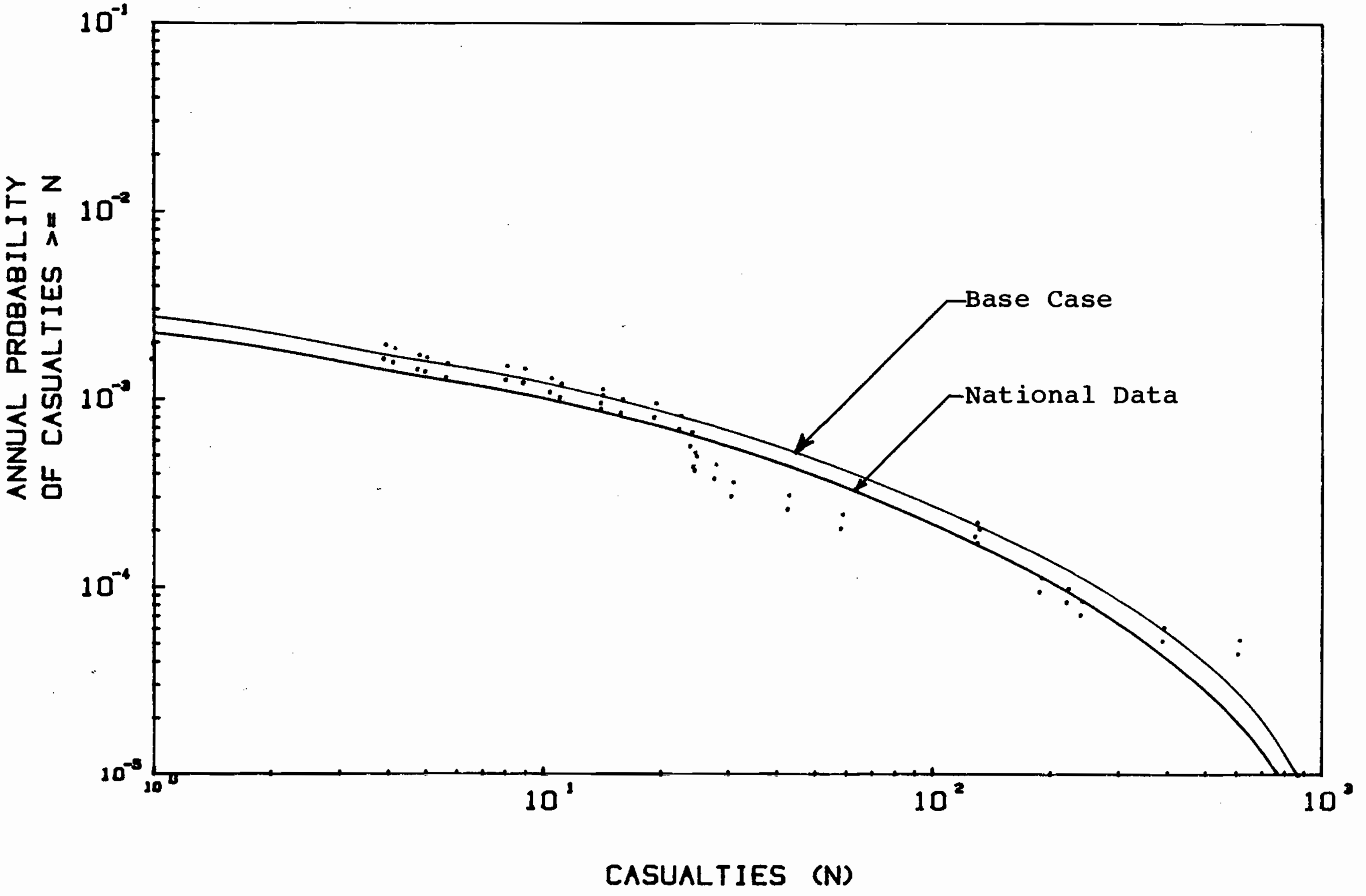


FIGURE 6.6 Comparison of Risk Profiles with National Accident Parameters and Route Specific Data Parameters: Chlorine, Route 1

CHAPTER 7

DISCUSSIONS, CONCLUSIONS, AND RECOMMENDATIONS

7.1 DISCUSSIONS

In this report, a rail transportation risk assessment model was formulated and applied to two specific routes between an origin and destination point, for the shipments of three hazardous chemicals. The model developed is a generic model, and is based on calculating the risks using both operational parameter values and chemical specific models describing the (chemical) behavior in the environment

This risk assessment model utilizes, to a large extent, information and data that are generally available in the public domain on the transportation and railroad accidents involving general freight and hazardous materials. One important exception, however, is the annual volume of hazardous material or specific chemical traffic data; these are not available easily in the public domain. When the risk model is to be applied to evaluate the transportation risks associated with a specific chemical hauled on a given route, one has to use segment specific traffic data. If these are not available and one uses a factored national average value for traffic density, it is difficult to predict a priori the error that may occur in the calculated risk values.

The model indicated in this report is simple in concept, and at the same time is very detailed in considering the various types of conditional probabilities. Because of this, the calculations are involved. One of the key assumptions in the model for the evaluation of annual probability of release is that the entire contents of the tank car are released if the tank car suffers a puncture. This puncture probability is represented by a single value (a binomial probability). In reality, however, a whole spectra of leak sizes and rates of leak of chemicals from tank cars are possible, each leak with its own release probability. The approach of considering each size of leak was not followed in the model because of two reasons. First, the spectrum of sizes of leaks, their probabilities of occurrence, the dependence of these on the specific chemicals, etc., are not easily available. Second, even if these values were available, their detailed consideration in the model would increase the calculation complexity. Third, it was uncertain how much increased accuracy would have resulted from a detailed consideration of various sizes of leaks. Instead, the approach we have used is that the release from tank car can be represented by a single (binomial) probability of release and consider the release of the entire contents of the car. Such an approach is conservative.

We have not considered explicitly in the model the probability of chemical releases from tank cars that are initially undamaged in an accident but which release contents later, due to secondary effects. The principal cause of such secondary releases is a fire in a neighboring tank car or metal failure during salvage operations. We estimate the probabilities of such secondary releases to be a factor of 5 to 10 less than direct accident caused releases. Therefore, the secondary releases were not explicitly considered in the model.

In estimating the casualties, we have assumed that the entire population inside the hazard area will become casualties. Two important features of this conservative calculation approach is to be noted. First, the hazard area calculated may, in certain circumstances, be wholly within the railroad property or the right-of-way. This is especially true in the case of accidents within classification yards which involve the release of flammable gases or flammable liquids. In these situations, the number of casualties will be small and limited to personnel within the yard. The present model would predict a larger number of casualties simply because the "shielding effect" of yard area is not considered. That is, the model is overly conservative. In fact, this effect can account for the predicted large casualty number in the case of LPG (see Figure 6.1B).

The second important aspect of our model in calculating the expected casualties is the non-consideration of several mitigating effects that inherently protect population from hazardous situations. These include such phenomena as (i) the population density near the railroad tracks in suburban and rural areas being considerably smaller than the county average value; (ii) population density varies with time of day and type of area - urban, rural, suburban, etc.; (iii) buildings and structures provide short term protection against direct effects of the hazardous chemicals; (iv) emergency evacuation undertakings following large scale accidents. Most of these mitigating circumstances tend to reduce the hazardous impact of chemical releases. By not considering these in our model, explicitly, we have made the model results on casualties very conservative; i.e., larger than would be expected.

In this report, we have given mathematical models for calculating the hazard areas for the case of toxic vapor dispersion in the atmosphere, and for the various fire scenarios. These represent the state-of-the-art models and consider chemical specific property parameters such as the density of vapor, fire emissive power, etc., and related phenomena such as gravitational dispersion. These models give larger hazard areas and somewhat shorter downwind travel distances, for the case of toxic vapor dispersion and larger hazard areas for fire scenarios than the values presented by Andrews(8). As indicated in an earlier section, these researchers have used the dispersion models which are applicable to only neutral density gases. We do not believe that these (latter) models should be used for evaluating hazard areas.

The hazard area calculated for each release scenario is weighted by the probability of occurrence of that scenario, given that a release has occurred. These weighted areas are summed to obtain a single "expected" area of hazard for one tank car release of the hazmat. The effect of using this approach is that finer details in the risk profile are lost. That is, the profiles presented in this report are less steep than true risk profiles. We may be presenting a higher probability of large casualty accidents (almost by an order of magnitude) and somewhat lower probabilities (by a factor of about 3) for the low casualty events. We feel that this approach is conservative.

Finally, we have not differentiated in our model the type of population in terms of the general public, railroad and other emergency personnel. As discussed in Chapter 1, our main aim in this project has been the development of risk profiles for that segment of population that is exposed to involuntary risks. It has been determined that about a third to half of the fatalities reported from railroad accidents involving hazmat releases affect the railroad emergency response personnel (Raj(13)). This is probably because of the proximity of the railroad personnel, especially the ones on the train, to hazmat releases in an accident. That such a high fraction of total annual fatalities is borne by railroad personnel, in spite of the very low number density of this class of "population" compared to the general population, indicates that the risk to the general population from the hazmat transport on rail is small indeed.

7.2 CONCLUSIONS

Based on the results generated and presented in this report, we make the following conclusions:

1. For the routes studied, both LPG and chlorine transportation present comparable risks. However, a potential exists, with very low annual probability of occurrence, for casualties exceeding 100 in the case of chlorine. The lower traffic volume of chlorine and its higher potential hazard area yield a risk profile which is similar to that of LPG which has higher traffic volume but lower hazard area.

2. The risk to the public from the transport of sulfuric acid on rail is at least an order of magnitude smaller than that from chlorine for comparable volumes hauled on the same route. Both annual probabilities and magnitude of casualties are smaller than those for LPG and chlorine. This is because of the considerably smaller hazard area presented by sulfuric acid spills compared to those of LPG or chlorine.

3. The two routes studied yield very similar risk profiles. The difference in the magnitude of the annual probabilities for the two routes is well within the accuracy of prediction of the probability values.

This is a surprising finding, and indicates that even though two routes may appear significantly different in characteristics (as we presumed during their selection) they may be comparable in overall risks. This is precisely the reason for conducting a detailed risk assessment of each route.

4. The route specific risk results obtained are much smaller than the national risk values predicted for similar chemicals by other researchers. However, when appropriate traffic volumes are taken into account, the results are comparable.

5. The reduction in release probability has a substantial benefit or a moderate benefit, depending on the chemical characteristics.

   For LPG, a tenfold reduction in the release probability results in a tenfold decrease in the annual probability of casualties being larger than 1. For chlorine, however, the same tenfold decrease in the conditional probability of release from a tank car results in a threefold decrease in the annual probability of casualties being larger than 1. For casualties larger than 100, the decrease in the annual probabilities is by about a factor of 5 or 6.

   This indicates that while considerable benefit accrues from improving tank car structure and providing safety devices, the benefit may not be proportional to reduction in release probability over the entire spectrum of events for all materials transported. A case-by-case analysis is necessary to determine the degree of effectiveness.

6. Emergency evacuation and protection provided by buildings and structures reduce the risk markedly, especially for the case of large casulaties. A ten fold reduction in potential casualties is possible. However, the effect of these parameters is not significant when the number of casulaties is small; i.e., when the hazard areas are small.

7.3 RECOMMENDATIONS

Based on the results of the risk analysis study presented in this report we recommend that:

1. The risk analysis model developed in this study be improved by incorporating several additional features which will provide better risk estimates. We recommend that, at the very least, the following features be included in a revised model.

- Evaluation of individual hazard scenario occurrence probability and the area of hazard for the scenario, consequent to a hazmat release. At present only an expected hazard area is used in calculating the overall casualties.

- Effect of emergency response operation. A sub-model should be included to consider the beneficial aspect of emergency response and the resulting reduction in casualtites.

- Effect of time of day variation in population density. This should be included at least for the urban and industrial areas through which the freight traffic may pass through.

2. More detailed data be collected regarding the population type and density near the railroad right-of-way, when a specific route risk analysis is to be performed.

3. The risk model be improved to take into account, explicitly, the risks to railroad employees and emergency response personnel in addition to the risk to the general public.

4. A rational method be developed to consider the tank car material properties in risk assessment. Specifically, this should include mathematical modeling to represent the accident severity in terms of dynamical parameters.

5. Testing procedures currently used for evaluating the tank car material properties be modified to take into account the process of rupture that occurs in a railroad accident that involves a tank car. Also to be considered in the test procedure modifications should be the effects of scale of the accident.

APPENDIX A

DETERMINATION OF THE CONDITIONAL PROBABILITY OF DERAILMENT OF A SPECIFIED NUMBER OF CHEMICAL CARS IN A TRAIN DERAILMENT

Consider the derailment situation depicted schematically in Figure A.1. A total of N_D freight cars derail which includes several of the hazmat cars carrying the Chemical X. There are a total of N_T freight cars in the train and N_X number of hazardous material cars.

In the analysis developed below it is assumed that:

(i) The probability of any car in the train initiating a derailment is the same and is uniformly distributed.

(ii) All of the hazardous material cars carrying a particular Chemical X are randomly distributed individually.

The number of cars that derail in an accident depends on several factors including the train speed, the initiating cause of derailment (track caused or equipment caused), the terrain, track curvature, etc. Derailments initiated at the rear end of the train, in general, involve a limited number of cars simply due to the fact that there are not many cars in the rear of the train. The derailments in the rear could be considered to be of the same length as front derailments, with an imaginary extension of the train beyond its end. This concept, alluded to by Nayak in an unpublished report, is utilized in the derivations below.

This concept assumes that short length derailments are concentrated towards the rear of the train and long derailments are uniformly distributed over the rest of the train. However, if an imaginary extension of the rear of the train is "assumed" then it can be argued that long derailments are uniformly distributed over the entire train length. In other words, each car in the train is as likely to be a derailment "seed" as any other car. This assumption of equal probability of derailment initiation by any car in the train has not been tested, to date, with any data available. However, for rolling equipment caused derailments the assumption may be valid. This concept is used in deriving the conditional probabilities for hazmat cars to derail, given that several cars derail in an accident. The mathematical development is shown below.

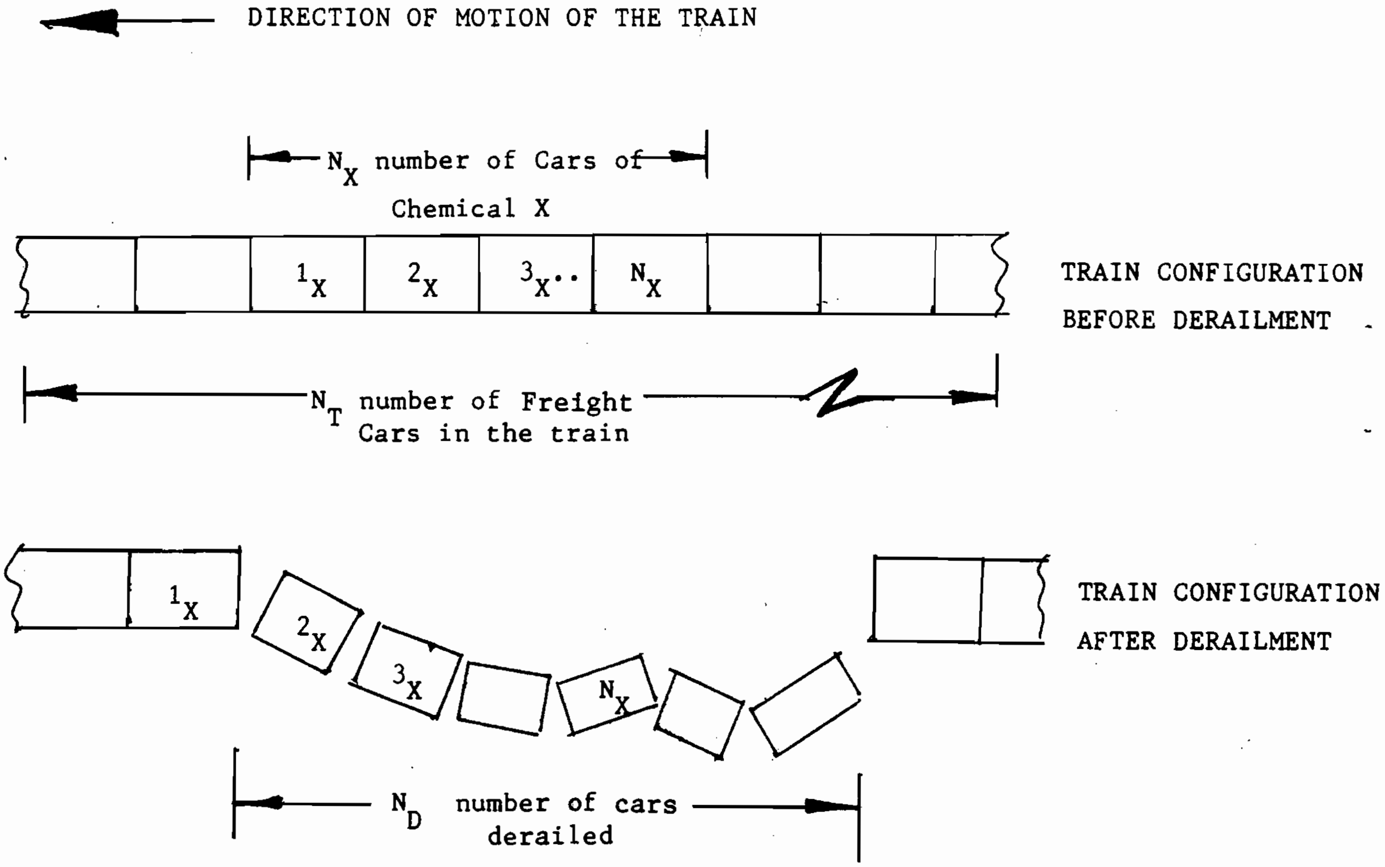


FIGURE A.1: SCHEMATIC REPRESENTATION OF THE DERAILMENT OF CARS INDICATING THE VARIOUS TYPES OF CARS DERAILED

A.1: ALL CHEMICAL-X CARS BLOCKED

The probability that any one car in the train can initiate a derailment = $1/N_T$

The probability that all N_X cars of hazmat X derail (for $N_D > N_X$) = [Probability that derailment initiation occurs in any of the (N_D-N_X) cars in front of the Chemical X car blocks] + [Prob. of initiation in the first X car]

$$= (N_D - N_X)/N_T + 1/N_T \qquad (A.1)$$

Now the probability that exactly J_X cars of Chemical X derail is equal to the probability of occurrence of events in which either the forward J_X cars of the block or the end J_X cars of the Chemical X block derail. Since we have assumed that the derailments are sequential there are only two initiating points in the train which will derail N_D cars, exactly J_X of which are Chemical X cars. Therefore, for the case $N_D > N_X$

$$P(J_X \mid N_D, N_T) = \begin{cases} 2/N_T & \text{for } 1 \leqslant J_X \leqslant N_X \\ (N_D - N_X + 1)/N_T & \text{for } J_X = N_X \end{cases} \qquad (A.2)$$

For the case where the number of cars N_D derailed is less than the number of hazmat X cars (i.e., $N_X > N_D$), we can show that:

$$P(J_X \mid N_D, N_T) = \begin{cases} 2/N_T & \text{for } J_X < N_D \\ (N_X - N_D + 1)/N_T & \text{for } J_X = N_D \\ 0 & \text{for } J_X > N_D \end{cases} \qquad (A.3)$$

A.2 RANDOMLY DISTRIBUTED CHEMICAL-X CARS IN THE TRAIN

It can be easily argued that if the N_X cars of the chemical are randomly distributed in the train the probabilities of J_X cars derailing are smaller than the values given by Equations A.2 & A.3 for values of J_X close to N_X. That is, the above equations give conservative values for the probability of derailment for larger number of X cars derailing.

Given that N_D cars derail among N_T freight cars in the train the probability that any <u>single</u> randomly placed Chemical X car can be found in the derailed set is

$$p = N_D / N_T \tag{A.4}$$

This probability is a binomial probability.

Assuming statistical independence in the physical location of the hazmat cars it can be shown easily that:

$$P(J_X \mid N_D, N_T, N_X, \text{random} \ldots) = \begin{cases} \dfrac{N_X!}{J_X!\,(N_X-J_X)!}\; p^{J_X}\,(1-p)^{N_X-J_X} & \text{for } N_D > N_X \\[2ex] \dfrac{N_D!}{J_X!\,(N_D-J_X)!}\; p^{J_X}\,(1-p)^{N_D-J_X} & \text{for } N_D < N_X \end{cases} \tag{A.5}$$

where the left hand side of the above equation represents the probability of finding exactly J_X cars of X in the derailed set when chemical X cars are randomly distributed.

APPENDIX B

CHLORINE DISPERSION MODELS & CALCULATIONS

B.1 Physical & Thermodynamic Properties

In the calculations below, the following properties of chlorine are used. (All parameters are in SI units unless otherwise specified.)

Parameter	Equation	Value	Units
Vapor Pressure Equation	$p = 10^{\left[9.543-\left(\frac{1086}{T+0.04}\right)\right]}$ T (in degrees K)		N/m^2
Vapor Pressure at 21°C	-	7.07×10^5	N/m^2
		102.5	psia
68°C		2.28×10^6	N/m^2
		331.3	psia
Normal Boiling Point	-	239.1	K
Density of Liquid	$\rho_L = (2173.3 - 2.6\ T)$		kg/m^3
at boiling point	-	1551.7	kg/m^3
at 21°C	-	1409.0	kg/m^3
at 68°C	-	1286.7	kg/m^3
Density of Saturated vapor at 129.1°K	ρ_v	3.686	kg/m^3
Molecular Weight	μ	77	kg/kmole
Lethal Concentration Level (immediately fatal)	C^*	1000	ppm
Fraction of Mass that flashes to vapor when released from			
21°C	f_1	17	%
68°C	f_2	32	%

B.2 Continuous Release Dispersion Model

This model is described in detail in the U.S. Coast Guard publication (AMSHAH, Ref 28). This model is strictly applicable only to the dispersion of neutral buoyancy gases and vapors. However, it can be applied for describing the dispersion of heavy chlorine vapor released continuously from a tank car because (i) the source size is small, and (ii) most of the dispersion to reach 1000 ppm level occurs when the vapor-air mixture has essentially neutral buoyancy.

The peak ground level concentration C_{max} (in density units) at any distance X from the source is given by

$$C_{Max}(X) = \frac{\dot{m}_V}{2\pi \ \sigma_Y(X) \ \sigma_Z(x) * U} \qquad (B.1)$$

Where σ_Y and σ_Z are the crosswind and vertical dispersion coefficients whose values are dependent on the atmospheric stability and the downwind distance. These can be estimated using published information given in AMSHAH (1974). The mass rate of vapor release is $\dot{m}_V$ and U is the mean wind speed. For any specified hazard concentration C^*, the value of X the downwind distance that satisfies the above equation is the downwind hazard distance.

The crosswind concentation C(X,Y), at any given downwind and crosswind locations, can be estimated by the equation

$$C\ (X,Y) = C_{max}\ (X) * \mathrm{Exp}\ [-Y^2/(\ 2*\sigma_Y^2\ )] \qquad (B.2)$$

where Y is the off-axis coordinate distance.

The maximum width crosswind, for a given concentration C^*, occurs at some value of X between 0 and maximum downwind dispersion distance. We define this distance as X_{max} and the maximum semi width is Y_{max}. The hazard area can then be calculated by the approximate formula (assuming that area to be elliptical).

$$A_{haz} = (\pi/2) * Y_{max} * X_{max} \qquad (B.3)$$

Specific Example:

The conditions assumed as

continuous release rate	4 kg/s and 10 kg/s
wind speed	3 m/s
atmospheric stability type	F (very stable)
lethal concentration	1000 ppm (2.95×10^{-3} kg/m^3)

Table B.1 shows the results of applying equations B.1 and B.2 to the above set of conditions

TABLE B.1

HAZARD DISTANCES FOR CONTINUOUS RELEASE OF CHLORINE

Downwind Distance	Dispersion Coefficients		For 3 kg/s Release Rate		For 10 kg/s Release Rate	
X (m)	σ_y (m)	σ_z (m)	Max Conc. at X $=10^{-3}x$ (kg/m^3)	Semi Width to 1000 ppm (m)	Max Conc. at X $=10^{-3}x$ (Kg/m^3)	Semi Width to 1000 ppm (m)
100	3.95	2.28	23.36	8.1	58.89	9.7
150	5.69	3.24	11.53	9.4	28.82	12.1
200	7.37	4.11	7.01	9.7	11.53	13.9
250	9.94	4.91	4.79	8.9	12.00	15.1
800	10.62	5.67	3.53	6.4	8.82	15.7
350	12.10	6.37	2.73	-	6.82	15.8
400	13.75	7.05	-	-	5.47	15.3
450	15.49	7.69	-	-	4.51	14.1
500	16.80	8.30	-	-	3.80	12.0
550	18.32	8.89	-	-	3.26	8.2
600	19.81	9.45	-	-	2.83	-

Hazard area for 4 kg/s release = 5,500 m^2.
Hazard area for 20 kg/s release = 14,890 m^2.

B.3 Heavy Gas Dispersion of Instantaneously Released Vapor Mass

The details of this model are given by Raj in the VKI Symposium Volume (ref 25). Only the resulting equations are presented here.

The instantaneously released heavy vapor cloud starts spreading radially due to its higher density while at the same time it is being dragged downwind by the wind. Also, simultaneously air is entrained into the cloud due to atmospheric turbulence as a result of which the mean cloud concentration decreases. The cloud is assumed to be spreading in a radially symmetric fashion as it moves downwind. During the initial period, there will be a siginificant upwind motion of the cloud boundary even though the cloud center is moving downwind.

The radius of the cloud at long times after release is given by:

$$R^2(t) = 2t\sqrt{\left[2\,g\,(V_i/\pi)\left(\frac{\rho_i}{\rho_a}-1\right)\right]} \qquad \text{(B.4)}$$

where

R = cloud radius at time t
g = acceleration due to gravity
V_i = initial volume of vapor released
ρ_i = initial vapor density at release
ρ_a = ambient air density
t = time after release
π = 3.14159

The time for the cloud average concentration to reach a value χ_e is given by

$$t_e = \left[\frac{9}{8}\,\frac{E_e^2}{\pi^2}\,\frac{V_i}{g\left(\frac{\rho_i}{\rho_a}-1\right)K_V}\right]^{\frac{1}{3}} \qquad \text{(B.5)}$$

where

$$E_e = \frac{\text{volume of cloud}}{\text{initial volume of cloud}} = 1+\left(\frac{1}{\chi_e}-1\right)\frac{\mu_a}{\mu_v}\,\frac{\rho_i}{\rho_a} \qquad \text{(B.6)}$$

t_e = time of dispersion for cloud concentration to reach χ_e

K_V = atmospheric turbulent diffusion coefficient [obtained from graph given in VKI (1983)]

μ_a, μ_v = molecular weights, respectively, of air and vapor

χ_e = mean molar or volumetric concentration for lethality or other casualty.

The downwind hazard distance is obtained from

$$X_e = U * t_e \qquad (B.7)$$

The total hazard area can then be calculated by the (approximate) equation

$$A = [X_e * R_e + (\pi/2) * R_e^2] \qquad (B.8)$$

Specific Example

It was calculated in Chapter 5 that depending on the circumstances of instantaneous leak of chlorine from a tank car, either 17% or 52% of the car contents will flash to vapor (See Table 5.2). **The hazardous distance, and area calculated for these cases, are indicated in Table B.2 below.**

TABLE B.2

HAZARD DISTANCES FOR THE INSTANTANEOUS RELEASE OF CHLORINE VAPORS

	Symbol	Unit	Case 1		Case 2	
Mass of Vapor Released	M_i	kg	13.8×10^3		26×10^3	
Saturated Vapor Density	ρ_i	kg/m^3	3.686		3.686	
Volume of Saturated Vapor	V_i	m^3	3.744×10^3		7.054×10^3	
Ambient Air Temperature (assumed)	T_a	K	294		294	
Ambient Air Density	ρ_a	kg/m^3	1.2		1.2	
Turbulent Diffusion Co-efficient in vertical direction for stable atmosphere	K_V	m^2/s	0.0186		0.0186	
Hazard Concentration	χ_e	ppm	500	1000	500	1000
Ratio of final cloud Volume to Initial Volume (see equation B.6)	E	-	2500	1250	2500	1250
Dispersion Time (equation B.5)	t_e	s	890.5	561	1100	693
Dispersion Distance (equation B.7)	X_e	m	2672	1683	3300	2080
Radius of cloud at t_e	R_e	m	626	497	734	1582
Hazard Area (equation B.8)	A_e	$(km)^2$	2.3	1.2	3.3	1.8

Note:

Case 1 = 17 % vapor flash
Case 2 = 52 % vapor flash

APPENDIX C

LPG HAZARD AREA CALCULATIONS

C.1 Physical & Thermodynamic Properties of LPG

Parameter	Equation	Value	Units
Vapor pressure equation (T in degrees K)	$p = 10\left[8.955-\left(\frac{813.2}{T-25.16}\right)\right]$		N/m^2
Vapor pressure at 21°C		8.51×10^5 123.4	N/m^2 psia
at 68°C		2.4×10^6 348.2	N/m^2 psia
Normal boiling point	T_B	233.0	K
Liquid density	ρ_L		
Density/boiling point		499.2	kg/m^3
Density at 21°C		432.1	kg/m^3
Density of saturated vapor vapor at 233K	ρ_v	2.2	kg/m^3
Molecular weight	μ	44.0	kg/kmole
Flammability limits			
Upper limit	C_{UFL}	8.4	%
Lower limit	C_{LFL}	1.8	%
Liquid regression rate in large fires	y	2×10^{-4}	m/s
Heat of vaporization at saturation at ambient pressure	λ	4.3×10^5	J/kg
Heat of combustion	ΔH_c	5.0×10^7	J/kg
Combustion/Radiative efficiency	η	0.2	
Flame emissive power	E_f	150	kW/m^2

C.2: Hazard Areas

C.2.1: Pool Fire

When all of the contents of an LPG tank car are released rapidly due to tank failure caused by mechanical puncture or impact, a significant fraction of the released mass flashes to vapor and the remaining volume drops to the ground as liquid. The liquid spreads on the ground. If, in addition, the liquid is ignited it forms an expanding pool fire. The principal hazard from this pool fire is due to thermal radiation from the fire.

The maximum size to which a burning pool expands on flat ground has been given in a paper by Raj (ref 17). Also Raj (ref 25) has reviewed the fire thermal radiation models applicable to LPG fires. Using these models, the following calculations are made for pool fire hazard area resulting from one tank car release of LPG:

Mass of LPG released	65×10^3	kg
Volume of liquid spilled	130	m^3

For conservative calculations, it is assumed that all of the mass spreads on the ground as liquid (i.e., flash fraction is ignored). Then,

Maximum radius of spread if there was no fire [using the model given by Raj (ref 17)]	160	m
Maximum time of spread without fire	294	s
Maximum spread radius with fire	50	m
Duration of burn with fire	91	s

Thermal radiation hazard distance can be obtained by applying the inverse square law given by

$$S = \left[\frac{\rho_L V_L \Delta H_C \eta}{4 \pi t_b \dot{q}''_{haz}} \right]^{1/2} \qquad (C.1)$$

where V_L is the spilled volume of liquid, ΔH_C is the heat of combustion, η is the fraction of combustion energy which is radiated, t_b is the duration of burning the pool fire, and $\dot{q}''_{haz}$ is the radiant thermal flux level at which casualty is inflicted.

For the purposes of LPG risk assessment, we assume that radiation hazard level is 20 kW/m^2 which is the level at which serious 2nd degree burns can be inflicted resulting in fatalities. Using this value and equation C.1, we get

Thermal hazard distance for LPG pool fire (from the center of fire) = S = 170 m

Hence, the pool fire hazard area = $\pi S^2 = 9.1 \times 10^{-2}$ $(Km)^2$

C.2.2: Vapor Fire

If the instantaneously released liquid and vapor puff are not ignited immediately, then the vapors produced disperse in the atmosphere as a heavy gas cloud puff. More vapor is generated by the liquid spilled on the ground by boiling on the ground. During dispersion, the vapor cloud is mixed with air and forms a flammable vapor cloud. Because of the presence of a variety of ignition sources in urban areas, and to some extent in rural areas, the probability of ignition of the vapor cloud increases continuously as a function of downwind distance. Geffen, et al (1980) have discussed the nature of this ignition probability variation as a function of downwind distances.

For conservative risk calculation purposes, we assume that:

- Ignition occurs only when the mean vapor concentration of the cloud is equal to one-half of the lower flammability limit.
- Hazard area is equal to the area swept by an ignited vapor cloud during dipersion.
- Dispersion area can be calculated using the heavy gas dispersion model discussed in Appendix B, Section 3.

Mass of saturated LPG vapor released (assuming 35% mass flash to vapor) = M_i = 22.8×10^3 Kg

Volume of saturated vapor released = V_i = 10.7×10^3 m^3

Final concentration for dispersion calculation (one-half of LFL) = C_{haz} = 0.9% by volume

Molecular weight of LPG having (60% propane & 40% butane) = μ = 50 kg/kmole

Assuming that dispersion takes place in very stable weather with 3 m/s wind speed, we can calculate the duration of dispersion, maximum downwind distance, and cloud radius using equations B.5, B.7 and B.4 respectively.

Duration of dispersion = t_e = 225 s

Maximum radius of spread = R_e = 320 m

Maximum downwind distance (to 0.5 C_{LFL} concentration) = X_e = 675 m

Vapor fire hazard area (see equation B.8) = A_{haz} = 0.38 $(km)^2$

C.2.3 Vapor Cloud Detonation

Vapor clouds of propane dispersed in the atmosphere can detonate, even in the unconfined state, when sufficiently energetic ignition occurs. It is less certain, however, whether a deflagration type of burning of an unconfined vapor cloud can transit to detonation. For the purposes of risk calculation however, we assume that it is possible to induce detonation in an unconfined propane-air mixture.

The blast effects of detonation are calculated by using the TNT equivalent approach (see Geffen, et al(9)). We further assume that:

- only the instantaneously released vapor mass partipates in the detonation
- because of inefficiencies in the atmospheric mixing process and uncertainties in the time at which ignition of vapor cloud occurs leading to detonation, only 10% of the released vapor mass will detonate (Burgess, 1970).
- 100% fatality results in an area within which the peak overpressure is above 6.0 x 10^4 Pa (10 psia) and 10% fatality within the 1.7 x 10^4 Pa (2.5 psia) contour.

The TNT equivalent mass of LPG is given by

$$\text{TNT equivalent mass in kg} = 0.1 \frac{M_v \quad \Delta H_C}{5 \times 10^6} \qquad (C.2)$$

Where M_v is the mass of propane vapor released and ΔH_C is the heat of combustion of propane.

The overpressure-distance relationship is given by (Geffen, et al):

$$p = 82.88 \frac{(M_{TNT})^{\frac{1}{3}}}{X^{1.4362}} \qquad (C.3)$$

Where p is in Pascals, X in meters, and M_{TNT} in kg.

Applying the above equations to the case of 1 tank car LPG release we have:

- Mass of vapor released instantaneously = $M_V = 22.8 \times 10^3$ Kg
- Distance to 100% lethality criteria (i.e., $P = 6.9 \times 10^4$ Pa) = $X = 2200$ m
- Hazard area = $A = 3.8\ (Km)^2$

C.2.4: BLEVE & Fire Ball

The exposure of an LPG tank to a fire results in two phenomena occurring. First, the boiloff from the heat input is vented into the atmosphere through the relief valve. This gas outflow is ignited and forms a torch fire. Second, the tank wall not backed by liquid inside overheats and weakens. Failure of the tank wall is sudden, resulting in the rupture of the tank, release of remaining contents instantaneously, followed by the ignition of the contents released. This ignition results in the formation of a fire ball.

The initial radius of this hemispherical ball of fire is given by the equation (Geffen, et al):

$$r = 1.93\ M_V^{1/3} \qquad (C.4)$$

where r is in meters and M_V the mass of propane vapor in the fire ball (in kg). We calculate the size of the fire ball using the above equation and the following assumptions:

Total mass of vapor vented before the BLEVE occurs is small compared to the lading mass.

About 60% of the released mass flashes to vapor (that is, the liquid in the tank just before release is at about 58°C).

Thermal radiation hazard zone extends about 100 m beyond the edge of the fire ball radius on the ground.

Based on these assumptions, we get:

- Mass of LPG vapor participating in the fireball = 39×10^3 kg
  radius of fireball on the ground = 66m
  (Equation C.4)
- Total hazard radius = 100 + 66 =166m
- Hazard area on the ground due to fireball thermal radiation $=8.7\times10^{-2}$ km^2

C.2.5: Rocketing of BLEVEd Tank Car

Rocketing of tank cars that "tear" circumferentially has been observed in some accidents. The distances to which parts of the damaged "tub" are hurled vary, depending on several uncontrollable factors. An empirical correlation has been given by Nayak, et al, for the maximum rocketing distance as a function of tank car capacity. A typical rocketing range is about 300 meters.

In calculating the hazard zone, we assume that the area within this range and width equal to tank diameter will form the fatality zone. Hence,

$$\text{Area of hazard} = 0.3 \times 0.004 = 1.2 \times 10^{-3}\ (\text{km})^2$$

C.2.6: Fragmentation Hazards

Fragmentation debris from tank rupture can be hurled to as far as 610 m (Geffen, et al, 1980). Assuming that the hazard area is formed by the length and width equal to the tank car length, we have

$$\text{Hazard area} = 0.61 \times 0.02 = 1.2 \times 10^{-2}\ (\text{km})^2$$

APPENDIX D

TANK CAR MATERIAL PROPERTIES: CONSIDERATION IN RISK ANALYSIS

D.1 INTRODUCTION

One of the methods by which the potential for releases of hazardous materials from tank cars involved in accidents can be reduced is by constructing the tank cars out of materials that are able to withstand the impact loads better than the presently used materials. However, the question of how much improvement can be achieved by using better materials has to be considered in the overall context of reduction in risks to the public. In this Appendix, we have attempted to discuss the information known about tank car materials, their consideration in risk analysis, and the potential benefits that may accrue from use of different types of specification for the materials.

D.2 MATERIAL PARAMETERS

The tank car material parameters that are most likely to be determining factors for release of hazardous material consequent to a rail accident are:

- tensile strength of tank car material
- elongation of tank material in the welded condition
- fracture toughness of tank car materials
- Nil-Ductility Transition Temperature (NDTT)
- Charpy V-Notch (CVN) Energy Absorption characteristics
- Fracture Appearance Transition Temperature (FATT)

The principal physical event of interest, on which the above properties have influence, is the puncture or failure of tank car metal leading to a release. Our review of reports (see References 29 thru 35) on investigation of material properties of tank cars involved in accidents reveals that while the information presented is elaborate from a material property perspective, the results cannot be directly utilized in a risk assessment. The only way the material property parameters can be connected to risk analysis is through their effect on the probability of release given an accident condition. None of the studies we have reviewed have attempted to get any correlation between material properties and probability of release.

D.3 USING MATERIAL PROPERTY IN RISK ANALYSIS

A railroad accident is a complex phenomenon. The release of hazardous materials from tank cars in an accident depends on the train dynamics, construction features of the tank cars, tank car material properties, and the local topographical features at the accident site. The effect of these parameters cannot be represented easily in a mathematical formula. However, if the severity of the accident can be represented by a suitably defined index, then it may be possible to develop either empirical or semi-empirical correlations relating the probability of release to the accident severity index. We assume that the functional relationship between this accident severity index may be represented by

$$I = f(U, M, \ldots) \qquad \text{(D.1)}$$

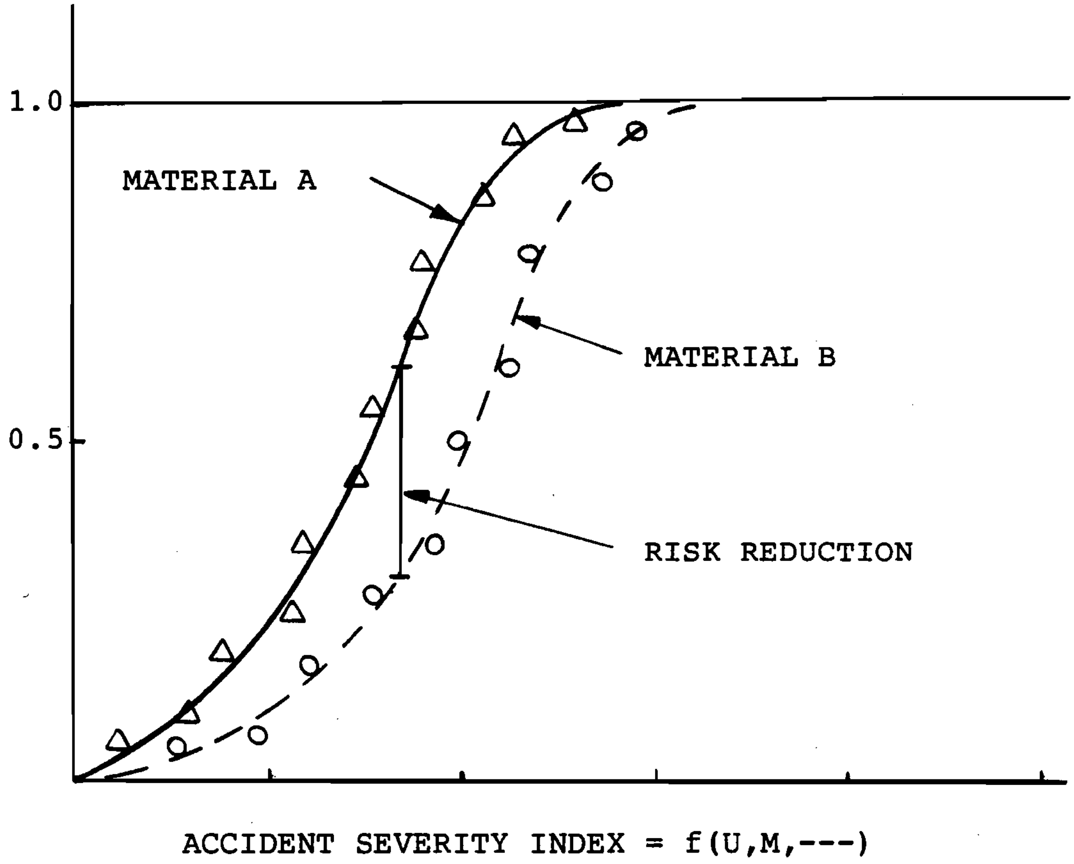
where I is the accident severity index, U the speed of train, M the mass of loaded tank car, etc. We can then represent, perhaps, the relationship between the hazmat release probability (q) and the accident severity by a relationship of the type

$$q_{release} = F(I, \sigma, \ldots\ldots) \qquad \text{(D.2)}$$

where σ is the ultimate strength of the material of the tank car.

Figure D.1 is a schematic illustration of what a relationship between release probability and the accident severity may be. Also illustrated is the possible reduction in release probability value with the provision of improved tank car materials.

Unfortunately, there are no investigations which have attempted to develop detailed functional forms f and F of the above equations. Nayak, et al (reference 5) have given a form of the relationship which relates q with only U (see Equation 4.2). Other investigators (Andrews, reference 8), have provided analytical correlation of the ultimate strength of tank car material and the speed at which failure may result due to impact. Such a correlation is illustrated in Figure D.2. The analytical study assumes a fully loaded chlorine car pressurized to 200 psi. As shown, the materials with higher ultimate strength fail at higher speeds due to impact. When a tank car impacts, head on, a nonyielding target (example - concrete barrier, boulder, etc.), the speed at which failure occurs is 32 mph if the material is made of ASTM A515-70 steel with 68 ksi ultimate strength. The same investigators also pointed out that as the shell thickness of a tank car is increased, the probability of puncture decreases. For example, when shell thickness is increased from 0.5 inch to 1 inch, the probability of puncture reduces from 6.9 x 10^{-4} to 4.9 x 10^{-4} (by a factor of 1.4). Figure D.3 illustrates this dramatic reduction in puncture probability. Obviously, one has to keep in mind the cost implications due to increased thickness of shells before recommending the use of thicker shell walls.



U: Speed of Tank Car

M: Mass of Tank Car

FIGURE D.1 RISK REDUCTION POTENTIAL UTILIZING BETTER MATERIALS

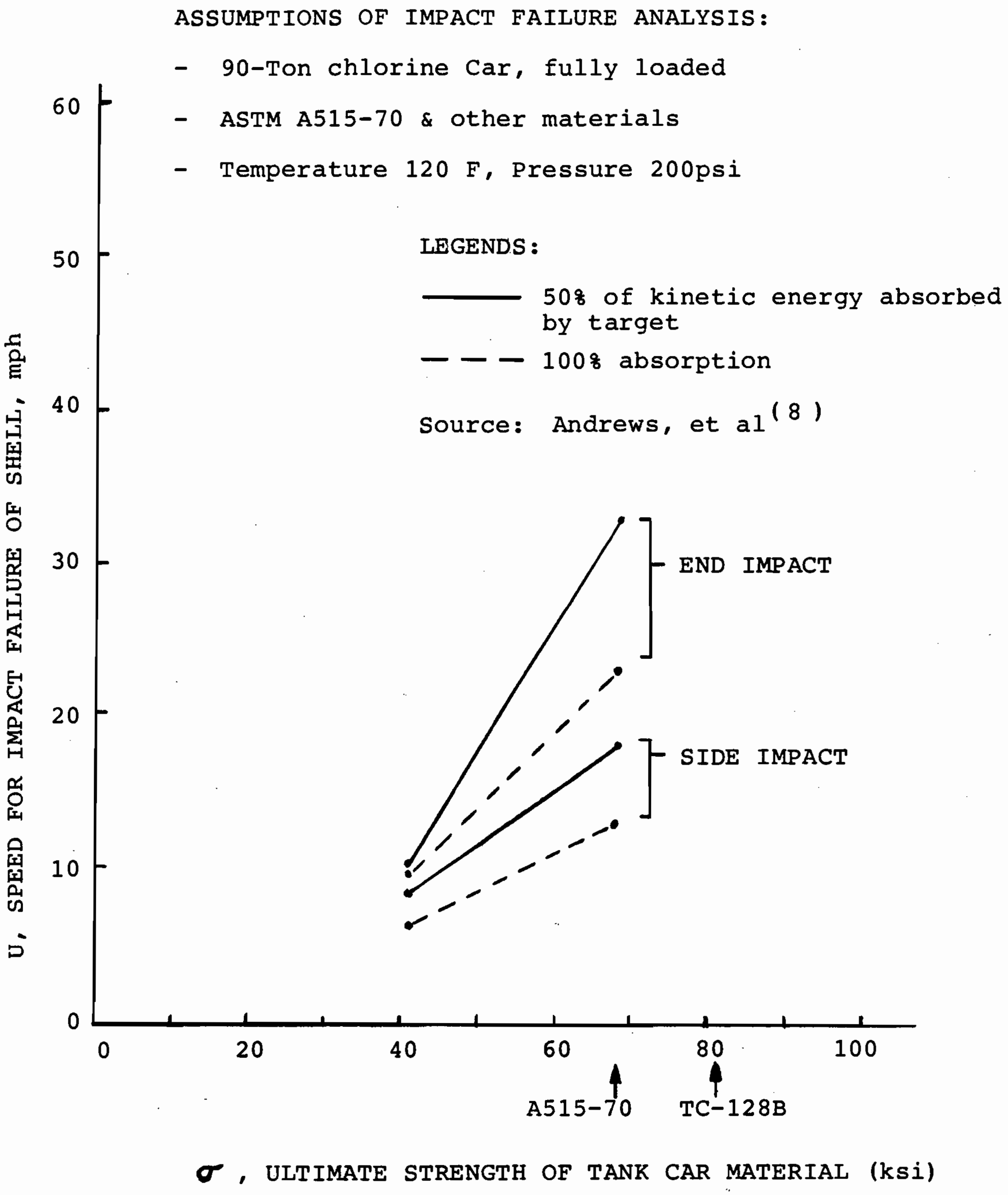
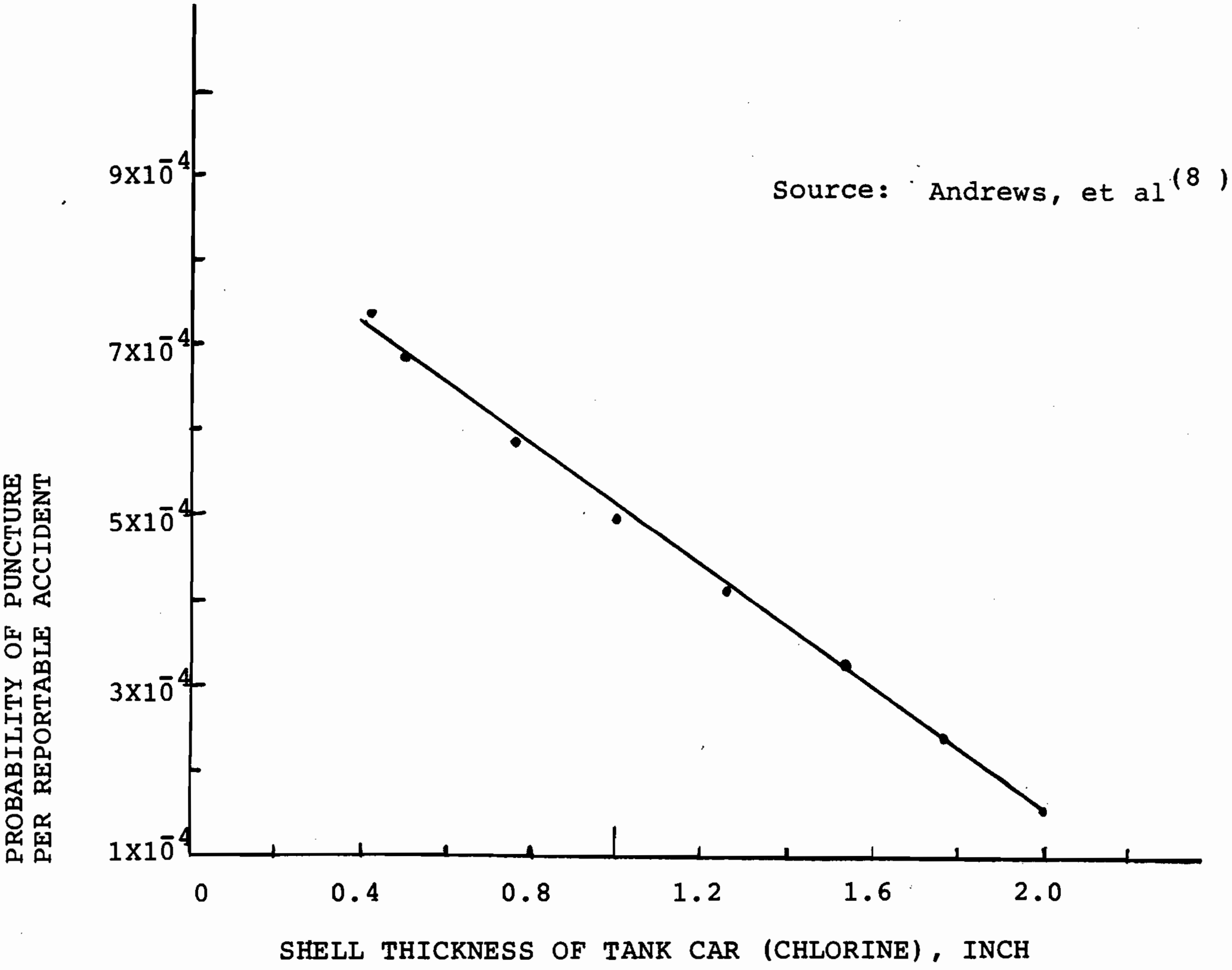


FIGURE D.2 RELATIONSHIP BETWEEN ULTIMATE STRENGTH OF MATERIAL AND THE SPEED AT WHICH FAILURE DUE TO IMPACT MAY OCCUR



Source: Andrews, et al(8)

FIGURE D.3 PROBABILITY OF PUNCTURE vs SHELL THICKNESS

NOMENCLATURE

Symbol	Definition	Reference Equation	Units
A	Hazard area	2.11	$(km)^2$
a	Constant defined in equation 2.15b Also a constant defined in Table 4.12		
b	A constant defined in equation 2.15b		
C	Concentration of vapors at any point downwind of release point	B.2	kg/m**3
C_N	Number of casualties	2.11	
$C_{N,X}$	Number of casualties due to the release of chemical-X		
E_f	Fire emissive power		W/m^2
F	Frequency of occureence of an event	2.1 to 2.5	#/yr
f	Fraction of chemical which flashes to vapor when released from pressure		
G	Gross traffic density on the segment of track		ton/yr
H_C	Heat of combustion of the chemical		J/kg
I_X	Number of chemical-X cars releasing contents in accident		
J_X	Number of chemical-X cars derailing		
L	Length of segment of track or main line		km
M	Mass of chemical released in an accident		kg
N	Number of events, freight cars, etc		
N_D	Number of freight cars derailing		
N_T	Number of freight cars in a train		
N_X	Number of chemical-X cars in a train		
P	Various probabilities (See special section below)		
p	Vapor pressure of the chemical		N/m^2

Symbol	Definition	Reference Equation	Units
Q	Quantitiy of hazmat released from a tank car		m^3
q	probability of chemical-X being released given that a chemical-X car is derailed		
q''_{haz}	Thermal radiation hazard flux level		W/m^2
R	Radius of toxic hazard cloud		m
S	Hazard distance from the release area		m
T	Temperature of chemical before release		K
t	Time		s
U	Train speed before derailment		m/s
V_L	Volume of liquid chemical released		m^3
X	Distance in the downwind direction		m
Y	Distnce in the cross wind direction		m
Z	Distance in the vertical direction		m
	Also the rate of occurrence of accident on the main line	2.2	#/ton Mile

DEFINITION OF VARIOUS PROBABILITY SYMBOLS

$P_R(I_X)$	Annual probability of release of chemical-X from exactly I_X tank cars
$P_R(I_X \mid A)$	Release probability from exactly I_X cars given that an accident has occurred
$P(I_X \mid J_X)$	The probability of exactly I_X cars releasing when there are J_X cars of chemical-X in the derailed set of cars
$P_R(I_X \mid N_X, N_T)$	Conditional probability of release of chemical-X from I_X cars given that a train has N_X cars of chemical-X and N_T total freight cars
$P_R(I_X \mid N_D, N_X, N_T)$	Conditional probability of I_X cars releasing given that in a train with N_X cars of chemical-X N_D freight cars derail

$P(N)$	Annual probability of occurrence of exactly N accidents over a given track segment
$P(N_T)$	Probability that a given train contains exactly N_T number of freight cars
$P(N_X \mid N_T)$	Probability that in a train there are N_X, cars of chemical-X given that the a train has N_T freight cars in total
$P_D(N_D \mid N_T,U,.)$	Conditional probability of N_D freight cars derailing at a train speed of U and other track conditions being given, when the train has N_T cars and it suffers an accident

GREEK SYMBOLS

Symbol	Definition	Reference Equation	Units
μ	Molecular weight of the chemical		kg/kmole
ρ	Population density		$\#/(km)^2$
ρ_a	Density of air		kg/m^3
ρ_v	Density of vapor released		kg/m^3
σ	Standard deviation		m
σ	Also used for material ultimate strength		N/m^2
σ	Also used for atmospheric dispersion coefficient		m

SUBSCRIPTS

A	Accident
C	Collision on Mainline
C,Y	Collision in Yard
D	Derailment
haz	Refers to the hazard condition
i	Initial condition before release
L	Liquid property
M	Mainline
T	Total # of cars in a freight train
X	Pertaining to chemical-X
Y	Yard condition

SUPERSCRIPTS

max	Pertains to the maximum value
"	To be read as per unit area
•	To be interpreted as per unit time

REFERENCES

1. "Railroad Safety Statistics - Accident Locations/Hazardous Material Flow/Accident Rates", Federal Railroad Administration, Office of Safety, U.S. DOT, Washington, D.C., 1981.

2. "Accident/Incident Bulletin", Federal Railroad Administration, Office of Safety, U.S. DOT, Washington, D.C., V 148 (1978) to V 151 (1982).

3. "Transport Statistics in the United States", U.S. DOT, Washington, D.C., 1982.

4. AAR (1983), "Yearbook of Railroad Facts", 1982 Edition, Association of American Railroads, Washington, D.C., 20036.

5. Nayak, P.R., Rosenfield, D.B., and Hagopian, J.H. (November 1983), "Event Probabilities and Impact Zones for Hazardous Materials Accidents on Railroads", Report #DOT/FRA/ORD-83-20, Federal Railroad Administration, Washington, D.C., 20590.

6. "Hazardous Material Statistics", Bureau of Explosives, Association of American Railroads, Washington, D.C., 1984.

7. "Census of the United States, 1980", Bureau of Census, U.S. Department of Commerce, Washington, D.C., 1982.

8. Andrews, W.B. (March 1980), "An Assessment of the Risk of Transporting Liquid Chlorine by Rail", Report #PNL-3376, Pacific Northwest Laboratories, Battelle Memorial Institute to The U.S. Department of Energy under Contract #DE-AC06-76RL01830.

9. Geffen, C.A., et al (1980), "An Assessment of the Risk of Transporting Propane by Truck and Train", Pacific Northwest Laboratory of Battelle, Report #PNL-3308 to U.S. Department of Energy, Washington, D.C.

10. Rowe, W.D., (1977), "An Anatomy of Risk", John Wiley & Sons, New Yourk, N.Y.

11. Glickman, T.S. (March 1982), "Risks of Catastrophic Derailments Involving the Release of Hazardous Materials", TSC Project Memorandum, #PM-223-U-1.1-6, Cambridge, Mass., 02141.

12. Glickman, T.S., and D.B. Rosenfield (1984), "Risks of Catastrophic Derailments Involving the Release of Hazardous Materials", Management Science, V30, N4, April 1984.

13. Raj, P.K. (Nov 1981), " Mitigating Effects of Emergency Evacuation and Other Factors on the Fatality Risks to Public from Hazardous Material Releases in Transportation Accidents", Report to US DOT/TSC by Technology & Management Systems, Inc, Burlington, Mass.

14. Glickman, T.S. (1983), "Rerouting Railroad Shipments of Hazardous Materials to Avoid Populated Areas", Accident Analysis & Prevention, V15, N5, P329-335.

15. Berkowitz, R.L., Shaver, D.K., and Rudd, T.J. (1981), "Special Routing of Spent Fuel Shipment Study", Report to USDOT/FRA, Office of Rail Safety Research, Washington.

16. DOT (June 1981), "Guidelines for Selecting Preferred Highway Routes for Large Quantity Shipments of Radioactive Materials", Report #DOT RSPA/MTB-81/5, Washington, D.C. 20590.

17. Raj, P.K., (Nov 1981), "Models for Cryogenic Liquid Behaviour on Land and Water", J Haz Materials, v5, p 111-130

18. DOT (1984), "Emergency Response Guidebook", U.S. Department of Transportation, Research & Special Program Administration (MTB), Washington, D.C. 20590.

19. Student, P.J. (1981), "Emergency Handling of Hazardous Materials in Surface Transportation", Bureau of Explosives, Association of American Railroads, Washington, D.C.

20. Bennett, G.F., Feates, F.S., and Wilder, I. (Editors), "Hazardous Materials Spills Handbook", McGraw Hill Book Company, New York, 1982.

21. "Liquefied Petroleum Gases: Storage and Handling", NFPA 58, National Fire Protection Association, Inc., Boston, MA 1983.

22. Perry, R.H. and Chiton, C.H. (Editors), "Chemical Engineering Handbook", 5th Edition, McGraw Hill Book Company, New York, 1973.

23. Burgess, D.J., and Zabetakis, M., "Detonation of a Flammable Cloud Following a Propane Pipeline Break", U.S. Bureau of Mines Report of Investigation # 7752, 26p, 1973.

24. Petracek, S.J., Moon, A.E., Kiang, R.L., and Siddignee, M.W. (June 1977), "Railroad Classification Yard Technology: A Survey and Assessment", Report #FRA/ORD-76/304 by Stanford Research Institute to FRA, Washington, D.C.

25. VKI, (1983), "Heavy Gas Dispersal", 1981-82 Lecture Series Publication, von Karman Institute, Brussels, Belgium; see the article "Heavy Gas Dispersion - A State of the Art Review of the Experimental Results and Models ", by P.K. Raj, in this proceedings.

26. Raj, P.K., (July 1982), (Editor)," MIT-GRI LNG Safety and Research Workshop Proceedings; Vol III - LNG Fires-Combustion and Radiation", Report by Technology & Management Systems, Inc, Burlington, MA to Gas Research Institute, Chicago.

27. Munday, G. "Unconfined Vapor Cloud Explosions", The Chemical Engineer, p 178-281, 1976.

28. "Assessment Models in Support of Hazard Assessment Handbook", NTIS # AD-776617, U.S. Coast Guard, Washington, D.C., January 1984.

29. Early, J.G.; Interrante, C.G., National Bureau of Standards, "A Metallurgical Evaluation of Two AAR M-128 Steel Tank Car Head Plates Used in Switchyard Impact Tests", A Report Prepared for the Federal Railroad Administration (DOT), NBSIR 80-2039, Report No. 10, Dec. 1979/Issued May 1980.

30. "Impact Properties of Steels Taken From Four Failed Tank Cars", A Report Prepared for the Federal Railroad Administration (DOT) by National Bureau of Standards (Author: C.G. Interrante), Report No. FRA-OR&D 75-51, June 1976.

31. Interrante, C.G.; Low, S.R.; Early, J.G., (National Bureau of Standards), Dancer, D. (Federal Railroad Administration), Report #11 "Observations of the April 8, 1979 Railroad Accident at Crestview, Florida, A Report Prepared for Federal Railroad Administration (DOT), Report No. NBSIR 84-2858, April 1984.

32. "Railroad Accident Report - Louisville & Nashville Railroad Company Freight Train Derailment and Puncture of Hazardous Materials Tank Cars, Crestview, Florida, April 8, 1979", Report No. NTSB-RAR-79-11.

33. "Analysis of Proceedings of the NTSB Into Derailment and Hazardous Materials", Report No. NTSB-SEE-78-2, April 4-6, 1978.

34. Hicho, G.E.; Brady, C.H., (NBS), "Hazardous Materials Tank Cars - Evaluation of Tank Car Shell Construction Material", A Report to the Federal Railroad Administration (DOT), NBS Report 312.01/14, September, 1970.

35. Interrante, C.G.; Early, J.G.; and Hicho, G.E., "Analysis of Findings of Four Tank Car Accident Reports", A Report for the Federal Railroad Administration (DOT) NBSIR 75-655, January 1975.

36. O' Driscoll, J.J.; Director, Hazardous Materials & Safety; Southern Railway System; Personal Communication to P.K. Raj, April 1985.