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Federal Railroad
Administration

Event Probabilities and Impact Zones for Hazardous Materials Accidents on Railroads

Office of Research and
Development
Washington DC 20590

P. Ranganath Nayak
Donald B. Rosenfield
John H. Hagopian

Arthur D. Little, Inc.
Acorn Park
Cambridge MA 02140

Tai Liu
494-2456

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16. Abstract

Procedures are presented for evaluating the probability and impacts of hazardous material accidents in rail transportation. The significance of track class for accident frequencies and of train speed for accident severity is quantified. Special attention is given to the analysis of track-caused accidents. Quantitative estimates are provided of the amount of hazardous material released per accident, as well as of the area affected by these releases. An error analysis is made of the various probabilities.

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PREFACE

This report presents methods for the quantitative estimation of the risk associated with the transportation of hazardous materials by rail. The work was sponsored by the United States Department of Transportation, Federal Railroad Administration (FRA), Office of Research and Development, Washington, DC, and performed by Arthur D. Little, Inc. under contract DOT-TSC-1607. The project was monitored by the Transportation Systems Center (TSC), Department of Transportation, Cambridge, Massachusetts.

The authors are grateful to Dr. Theodore S. Glickman* of the Transportation Systems Center for his support and guidance in the course of their investigations. We also wish to acknowledge the extensive support provided by Mr. Paul Brenner of Arthur D. Little, Inc., and by our erstwhile colleague, Mrs. Antoinette Musser Bradley.** Finally, we wish to mention the exceptional job done by Mr. Hans Sachdeva in preparing this report for publication.

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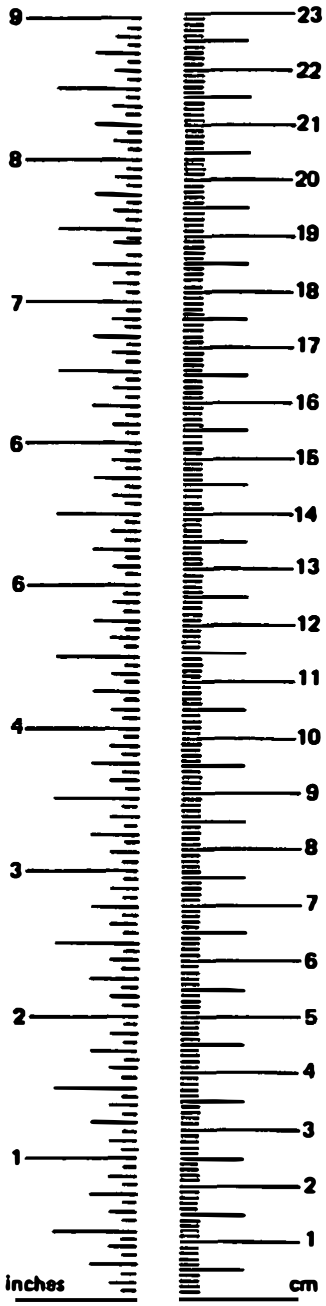
*Now at Virginia Polytechnic Institute and State University.

**Now at Mitre Corporation.

METRIC CONVERSION FACTORS

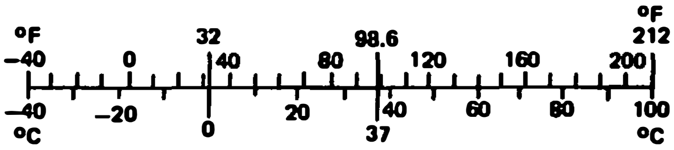
Approximate Conversions to Metric Measures

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



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	35	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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*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.

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

APPENDICES

LIST OF FIGURES

LIST OF TABLES

LIST OF TABLES (continued)

LIST OF TABLES (continued)

LIST OF TABLES (continued)

GLOSSARY OF SYMBOLS

Symbol	Meaning
a_R	Amount of hazardous material released per car (gallons)
A_R	Amount of hazardous material released per accident (gallons)
AC	Accident cause
AT	Accident type
d	Regression constant for m_{N_D} on v
D	Traffic density on a link
e	Regression constant for σ_{N_D} on v
E	Exposure
$\mathcal{E}$	Number of events in collision rate model
E(x)	Expected value of $x = m_x$
f	Regression constant for q on v
F	Frequency
F^*	Statistic for significance testing
g	Regression constant for m_{a_R} on v
G	Gross tons per train
G_H	Group or block size for grouping of cars in trains
h	Regression constant for σ_{a_R} on v
HM	Hazardous material
I	Radiation intensity
J	Time integral of radiation intensity
k	Number of cars suffering a secondary release due to fire from a primary release
K	Constant of proportionality between $\mathcal{E}$ and F for collisions
L	Link length
m_x	Mean (or expected) value of x
N_D	Number of cars derailing in an accident
N_H	Number of hazardous material cars in a train
N_{HD}	Number of hazardous material cars derailing in an accident
N_R	Number of hazardous material cars releasing their contents in an accident

Symbol	Meaning
N_T	Total number of cars in a train
p(x)	Probability distribution of x
P(x)	Probability of x
P(T)	Pressure as a function of time
P_R	Percentage of a resource affected by aftermath of a release
P_A	Probability of an accident
P_{AH}	Probability of an accident to a train carrying hazardous material
P_C	Conditional probability that a particular commodity is released given that one of a group of commodities is released
P_{CD}	Probability that at least one car is derailed or damaged in a collision
P_H	Probability that a train carries hazardous material
P_R	Probability of a release given an accident
q	Probability that a derailed hazardous material car will release its contents
r	Probability of a secondary release, caused by fire from a primary release impinging on other cars
t	Time of exposure
t_a	Time of arrival of blast wave
t_o	Time of passage of blast wave
TT	Track type
TC	Track class
v	Train speed at time of accident (mph)
Var(x)	Variance of x = σ_x^2
x	A random variable
$x \mid y$	x given y
y	A random variable
Z	Accident rate

Symbol	Meaning
α_{INJ}	Area within which injuries occur (km^2)
α_{IRR}	Area within which severe irritation occurs (km^2)
α_L	Area within which lethal effects occur (km^2)
α_{PD}	Area within which property damage occurs (km^2)
β	Parameter for discretizing the continuous gamma distribution
Φ	Constant of proportionality in collision analysis
λ	Parameter of the gamma distribution
η	Parameter of the gamma distribution
π_H	Expected value of the ratio of N_H to N_T
σ_x	Standard deviation of x

1. SUMMARY

This report presents methods for the quantitative estimation of the risk associated with the transportation of hazardous materials by rail.

Accident rates are developed separately for yard and mainline accidents. For each of these, derailments and collisions are treated separately. For derailments, track-caused accidents are also analyzed separately. Furthermore, for mainline accidents, the effect of track class on accident rate is developed. This effect is found to be extremely important, as can be seen from the following tabulation.

Track Class	1	2	3	4	5&6
Mainline derailment rate (accidents per million gross ton-miles)	53.2	17.3	5.59	0.589	0.840

The empirically developed rate for Classes 5 and 6 (which were combined because of a lack of data for Class 6) is considered to be an anomaly, resulting from either a small sample size, or mis-reporting of track class, or errors in the estimation of the number of gross ton-miles for these two classes of track. The true rate for Classes 5 and 6 is almost certainly less than the rate for Class 4.

The severity of an accident, as defined by the number of cars derailing or damaged, is found to be strongly dependent on the speed at which the accident takes place. For derailments, the mean number of derailing cars, m_{N_D}, is found to be:

$$m_{N_D} = 1.7\ v^{0.5}, \qquad (1\text{-}1)$$

where v is the train speed in miles per hour. The variance of the number of cars derailing is found to be:

$$\sigma^2_{N_D} = 2.7 \text{ v.} \tag{1-2}$$

The distribution of train speed varies significantly from one track class to another. The mean speeds for mainline derailments are given in the following tabulation:

Track Class	1	2	3	4	5&6
Average train speed (mph)	8.0	14.9	21.3	29.7	37.6

Thus, the average accident severity increases as track class increases.

A similarly strong dependence on speed is found for the probability of release, q, which is the probability that a derailed hazardous material car will release all or part of its contents. For all accidents, the following expression provides a good approximation to q:

$$q = 0.045 \text{ v}^{0.5}. \tag{1-3}$$

Furthermore, the mean amount of material released from a car that does release also depends on the speed:

$$m_{a_R} = 2000 \text{ v}^{0.5}, \tag{1-4}$$

where m_{a_R} is the mean value of the amount released per car (in gallons).

Thus, speed is seen to have a three-fold effect on the hazardous impact of an accident. As speed increases:

1. The number of cars derailing increases, thus increasing the probability that hazardous material cars present in the train will derail.

2. The probability that a derailed hazardous material car will release its contents increases.

3. The amount released from a releasing car increases.

The report provides rigorous analytical models for analyzing these effects, as well as quantitative results, leading to probability distributions for the total amount released in an accident, A_R. These are presented in Chapter 10.

The final step in the analysis procedure is to estimate the impacts on people and property of the accidental release of hazardous material. These impacts are estimated in terms of the area surrounding the site of the accident within which one or more of the following impacts may be expected:

- fatalities,
- injuries,
- severe irritation, or
- property damage.

The impacts are found to be strongly dependent on the total amount released, A_R, as well as on the type of hazardous material that is released. Estimates of these impacts are presented in Chapter 12.

Among the major contributions of this report are the rigor with which data was analyzed; the innovative models that were developed of the behavior of a train in an accident; the quantitative analysis of the effects of track class and of train speed; the quantitative analysis of the effects of track-caused accidents; and the development of confidence bounds or error estimates for the various probabilities.

2. INTRODUCTION

A. OBJECTIVES

This report presents the results of work performed by Arthur D. Little, Inc., for the Transportation Systems Center (TSC) of the U.S. Department of Transportation (DOT) under Contract Number DOT-TSC-1607. The objective of this work was to develop analytical techniques for assessing the risk involved in the transportation of hazardous materials (HM) on the network of U.S. railroads. Specifically, the contract called for three tasks to be performed:

1. The development of probability distributions for the severity of hazardous-material accidents in rail transportation, aggregated over all possible causes of accidents.

   Due consideration was to be given to the basis for measuring accident rates (e.g., ton-miles, car-miles, or train-miles); the definition of severity; important factors controlling the desired probability distribution; intended use of these distributions by TSC; and also the methods by which traffic flow estimates were to be developed by TSC.

   Specific thought was to be given to the use of statistical techniques and analytical models for enriching what was expected to be a relatively sparse historical record and which would not, therefore, be a firm basis for direct extrapolation into the future.

2. The development of probability distributions similar to those developed in Task 1 with attention, in this case, confined to track-caused accidents.

3. The development of accident impact models which, given that an accident of specified severity had occurred, could be used to estimate the magnitude of the impact on the people and their property in the vicinity of the accident.

> In this task, consideration was to be given to the nature of the hazardous material being released; methods by which traffic flow estimates were to be obtained; and to the need for grouping hazardous materials (when appropriate) to simplify the application of the models.

In planning the study, certain objectives were defined; viz., that the effects on risk of at least the following variables ought to be quantified:

1. The condition of the track over which the hazardous materials are being transported;
2. The speed at which the transport occurs;
3. The nature of the hazardous material being transported;
4. The quantity of hazardous material being transported in a typical train; and
5. The presence of classification yards en route, through which the hazardous materials must pass.

The effect of route-dependent characteristics, such as population density and property density, were to be accounted for separately, by superposing demographic statistics on the Federal Railroad Administration (FRA) Network Model [1].*

With the achievement of these objectives, as reported herein, it is possible to examine several aspects of risk-identification and reduction, of which the following are representative:

1. Identification of high-risk areas in the country;
2. Speed reduction for trains carrying hazardous materials;
3. Improvements in track quality;
4. Re-routing of trains to avoid poor-quality track;
5. Re-routing of trains to avoid areas of dense population;
6. Use of through trains to avoid classification yards; and
7. Changes in train consists, such as the use of unit trains of hazardous materials.

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*See References at the end of this Chapter.

It is also conceptually straightforward, using the methods presented herein, to forecast future risk(s), taking into account possible changes in the flow of hazardous materials, demographic shifts, track deterioration or upgrading, as well as changes such as limits to tank capacity or the installation of head or thermal shields on tank cars.

The capabilities of the analytical models presented herein may be compared with the results of recent parallel work conducted elsewhere. Work sponsored by the Department of Energy (DOE) at Battelle [2,3] has concentrated on the broad issue of the transportation risk arising from the consumption of materials important in energy production. The rail transportation portion of these studies [3] has concentrated heavily on risk-reduction measures associated with tank-car redesign, whereas in the study documented in this report, these possibilities were intentionally ignored.

On the other hand, the Battelle work does not address the analysis of risk-reduction options involving changes in train make-up, speed, track upgrading, or routing, which are the focus of the Arthur D. Little study. It is worth noting that the results of the analysis of risk-reduction redesign obtained by Battelle [3] can be introduced into the Arthur D. Little approach via a change in certain empirical parameters. A further interesting aspect of the Battelle work is the analysis of evacuation subsequent to a release of hazardous material. This is certainly an important factor in risk analysis, and is a useful complement to the work in the present report.

This study also sought to overcome certain deficiencies in other earlier analyses of the transport of hazardous materials by rail, a representative sample of which is cited in the Bibliography in Appendix A. The differences:

1. These studies are often concerned with qualitative methodology rather than with quantitative analysis of risk.

2. The models they use are generally applicable to one specific hazardous material or another.

3. The techniques were not suited to a nationwide analysis of risk, this being an important objective for the Transportation Systems Center, since it was, and is, its intention to use the FRA's Railroad Network Model to conduct a computerized, nationwide risk analysis.

B. CONCEPTUAL BACKGROUND

Any analysis, whether statistical or theoretical, must be based on a conceptual model, which then defines the kinds of questions that are to be asked and the types of analyses to be made. Within any given conceptual analysis, one approach to the analysis varies from another, not in any fundamental sense, but in the extent to which it relies on historical data as opposed to a theoretical model.

The conceptual model underlying the analyses presented in this report is based on certain observations and goals:

1. The harmful exposure of people or property to a hazardous material requires a series of events in an event chain. Each event is probabilistic, in the sense that its occurrence is not certain, given that the prior event in the chain has taken place: one can only assign a probability to its occurrence. This is also true of the first event in the chain, the occurrence of a train accident.

2. Many factors determine the conditional probability of an event, which is the probability that it will occur; given the condition that the prior event in the chain has occurred. These factors must be taken into account.

3. Several aspects of the event chain are common to accidents that do and do not involve hazardous materials. For example, it is likely that on a given class of track and in the absence of any special rules, the speeds at which trains travel on a given segment of track are independent of whether they carry hazardous materials or not. (Despite the recommendation by the Association of American Railroads (AAR) that trains carrying DOT 112 and DOT 114 tank cars be slowed down by 10 miles per hour (mph), the historical record of accidents does not indicate that trains carrying tank cars operate at lower speeds than other trains.)

As another example, the number of cars that derail when a train derails may depend on such factors as the speed of derailment or the number of cars in the train, but the number is not likely to depend on whether or not the cars carry hazardous materials. This observation is particularly important, since it justifies the use of a much larger set of data--all accidents--in modeling those portions of the event chain that are not influenced by the presence of hazardous materials.

4. The model must do more than fit past experience accurately; it must provide a basis for analyzing future conditions that have not occurred in the past, and also for estimating the probability of occurrence of unusually severe incidents. Such catastrophic events may not have occurred in the past, partly because their probability of occurrence is low, and partly because the history of large movements of hazardous materials is a relatively recent one.

C. APPROACH

1. Overview

Figure 2-1 shows the approach to modeling that was used. The events in the chain are most easily described by grouping them into three major categories:

1. The occurrence of a train accident;
2. The occurrence of a hazardous-material release, conditional upon a train accident having occurred; and
3. The impact upon people and property of hazardous materials, conditional upon a release having occurred.

Each of these segments is discussed separately in the following paragraphs.

2. Train Accident Rates and Frequencies

A train accident (or "rail equipment accident/incident") is defined [4] as "any collision, derailment, fire, explosion, act of God, or other event involving operation of railroad on-track equipment (standing or moving), which results in more than $1,750 in damages to railroad on track equipment, signals, track, track structure, and roadbed."

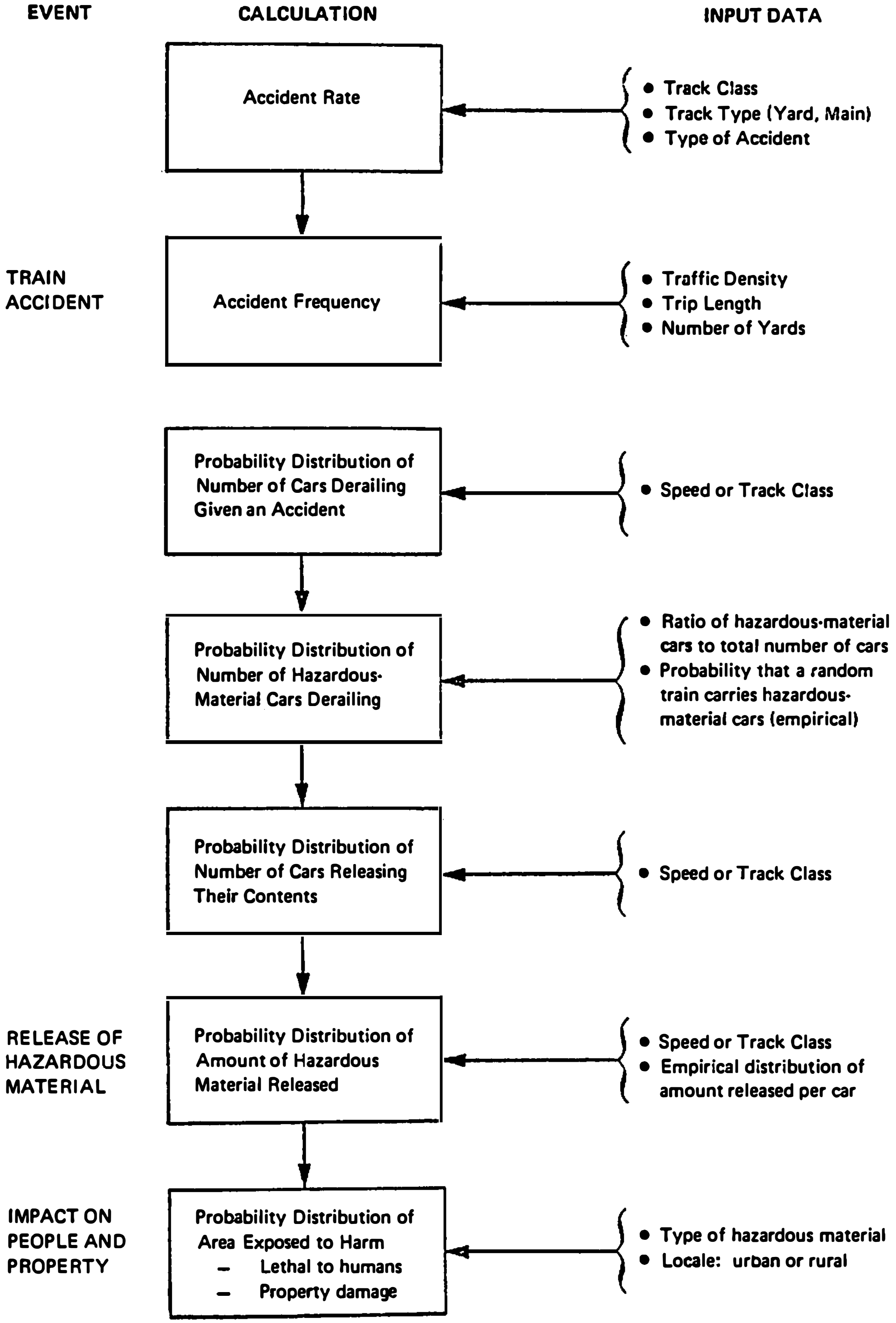


FIGURE 2–1. STRUCTURE OF THE MODEL FOR ANALYZING THE POTENTIAL IMPACTS OF HAZARDOUS MATERIALS TRANSPORTED OVER A RAIL LINK

The threshold of $1,750 has been gradually increased since 1977 to account for the effects of inflation.

The accident frequency for a link in a railroad network is stated in terms of the expected number of accidents per year. This frequency depends on the exposure on that link and on the accident rate. For example, the rate for derailments might be stated in the expected number of accidents per gross ton-mile (GTM); the complementary measure of exposure on a link is then the GTM per year.

The rate of train accidents depends on certain significant factors, each of which is described below.

1. The type of track determines the appropriate measure of exposure and, therefore, the accident rate. There are four generic track types used by the FRA [4] in its accident reporting system; viz., mainline, yard, siding, and industry. This report is confined to an analysis of mainline and yard accidents. The inclusion of siding and industry track accidents would have substantially complicated the models without significantly improving the accuracy of the analysis of risk.

2. For mainline accidents, the class of track [5] is shown to be an important determinant of accident rates. While the true underlying variable is track quality, it is not yet known how quality is to be defined and measured. Track class was therefore used as a surrogate for track quality. In making this approximation, it is important to note that true track quality may vary widely within a given track class. See Chapter 11, Section B.

3. The type of accident obviously affects the accident rate. The measure of exposure for derailments is different from that for collisions, and the rates are therefore different. The FRA [4] classifies accidents into 11 different types, of which only the most important types are included in this report: derailments and collisions of all types. These two accident types account for more than 90 percent of all accidents, and for a similar proportion of the risk from hazardous materials transportation.

4. Accidents can be grouped according to their cause; rates then depend on the cause. For this study, two broad groups of causes were used: "all causes" and "track causes."

The rate of accidents may also depend on other factors, such as train speed and make-up, variations of true track quality within a given track class (such as might reflect variations from one railroad to another), or weather conditions. Although these other factors were examined in detail, it was not found to be feasible to include them in the model either because supporting data were unavailable, or because future users of the model would not have access to information regarding these factors.

Estimates of accident rates were made purely on the basis of historical statistics, with the exception that in the choice of a basis for measuring accident rates (the gross ton-mile was eventually chosen for derailments), analytical reasoning was employed. The basis of this choice of a measure of "exposure," as well as the accident rates determined from historical data, are presented in Chapter 3.

Once the accident rate is known and the exposure on a rail link is specified, the expected frequency of accidents can be determined by multiplying the two together. The frequency can either be stated on a temporal basis (per year) or on a traffic basis (per million gross tons or MGT).

In summary, the first step determines the expected frequency of accidents:

$$m_F = Z(TT, TC, AT, AC) . E \qquad (2-1)$$

where

m_F = mean value of F,

F = frequency of accidents,

Z = accident rate,

TT = type of track,

TC = track class,

AT = accident type,

AC = accident cause, and

E = exposure.

Note that the appropriate measure of the exposure E, and therefore of the accident rate Z, depends on both the "type of track" variable, TT, and the "type of accident variable," AT, as shown at greater length in Chapter 3.

3. Hazardous Materials Release Given an Accident

If an accident occurs and its characteristics (such as track class, track type, etc.) are known, one may derive the probability distribution of the amount of hazardous material released in the accident as follows.

The conditional probability that the train contains hazardous material is first obtained. It is denoted by:

$$P_H(TT, TC, AT, AC).$$

Then the conditional probability distribution for the number of cars derailing is obtained. It is represented by:

$$p(N_D | v),$$

where N_D is the number of cars derailing and v is the speed at which the accident occurs.

Next the probability distribution of the number of hazardous-material cars derailing, N_{HD}, which is conditional on the number of cars derailing, is obtained. It has an additional parameter, π_H, the proportion of hazardous-material cars to all cars. The conditional distribution is denoted by:

$$p(N_{HD} | N_D, \pi_H).$$

Then, the probability distribution of the number of cars releasing their contents, conditional on the number of hazardous-material cars derailing, is obtained:

$$p(N_R | N_{HD}, q).$$

In this expression, q is the release probability, which is a function of the speed at which the accident occurs and is thus written q(v).

The probability distribution of the total amount of hazardous material released, A_R, is then found. It is denoted by:

$p(A_R|N_R, v)$.

4. Impact Given a Hazardous Material Release

Finally, the area within which lethal effects will be felt by human beings, denoted by α_L, is shown as a deterministic function of the amount of hazardous material released, conditional on the type of material that is released:

$\alpha_L(A_R|HM)$,

where HM designates the hazardous material. Similar impact areas exist for injurious or irritating effects on people and for property damage, and are denoted by:

$\alpha_{IN}(A_R|HM)$, $\alpha_{IRR}(A_R|HM)$, and $\alpha_{PD}(A_R|HM)$.

The expected impact area is estimated for several groups of chemicals and for each of the types of impacts listed above. The development of these estimates presented a considerable challenge, since the need for relatively simple results that could be used in a nationwide risk analysis conflicted with the known complexity of the phenomena that can occur after the release of certain hazardous materials. This conflict was resolved by taking the following steps:

- The various hazardous materials were grouped into a relatively small set of categories, based on their physical and chemical properties, including the types of phenomena that have been observed to occur upon their release.

- Two specific chemicals were chosen to represent each category: a "representative" one and a "worst-case" one.

- When necessary, reasonable assumptions were made regarding the probability of occurrence of competing post-release scenarios. Examples of competing scenarios, for a compressed flammable gas, include: a torch fire; a pool fire; a boiling liquid expanding vapor explosion (BLEVE) combined with one of the above two; a vapor cloud fire; a vapor cloud detonation; and a vapor cloud that disperses without igniting.

- Reasonable estimates were made of the input parameters required by many of the impact models for the various scenarios. Examples of these parameters are the stability condition of the atmosphere, the wind velocity, and the density of ignition sources.

The procedures used in applying these four steps are described in subsequent chapters, as are the results. The underlying models are described in Appendix C.

5. Synthesis

All of these probability distributions are synthesized as follows:

1. Given an accident characterized by TT, TC, AT, and AC, the probability that the train carries hazardous material is P_H.

2. Given an accident of a train carrying hazardous material, as well as TT, TC, AT, and AC, the probability distribution for the lethal area is:

$$p(\alpha_L | \mathrm{TT, TC, AT, AC}, N_H > 0, \mathrm{HM}) =$$

$$\int_v p(v | \mathrm{TT, TC, AT, AC}) \sum_{N_D} p(N_D | v) \sum_{N_{HD}} p(N_{HD} | N_D, \pi_H, N_H > 0) \sum_{N_R} p(N_R | N_{HD}, q)$$

$$\times \int_{A_R} p(A_R | N_R, v)\, \alpha_L(A_R | \mathrm{HM})\, dA_R\, dv. \qquad (2\text{-}2)$$

In this expression, N_H is the number of hazardous-material cars in the train, and

$p(v|TT, TC, AT, AC)$

is the conditional probability distribution for the speed at which an accident occurs, given the various accident characteristics of TT, TC, AT, and AC.

An equation similar to (2-2) holds for the areas of injury or property damage α_I and α_{PD}.

Equation (2-2) is the central result of this report; the rest of the report is concerned with either developing approximate versions of it or with estimating the conditional probability distributions that occur within it.

The subsequent analyses in this report first show:

$p(N_D|v)$.

Next, both

$p(N_{HD}|N_D, \pi_H, N_H > 0)$

and

$p(N_{HD}|TT, TC, AT, AC, N_H > 0)$

are shown, the latter being derived by combining the former with the conditional probability distribution for accident speed,

$p(v|TT, TC, AT, AC)$.

Here, in addition to the distribution of accident speeds, the historical dependence of π_H on TT, TC, AT, and AC is taken into account.

Finally, both

$p(N_R|N_{HD}, q)$

and

$p(N_R|TT, TC, AT, AC, N_H > 0)$

are presented, as are:

$p(A_R | N_R, v)$,

and

$p(A_R | TT, TC, AT, AC, N_H > 0)$.

In each case, the second distribution, which is conditioned by the track type, track class, accident type, and accident cause, assumes historical values for important parameters. The other less restrictive versions of the probability distributions allow the user to insert arbitrary values of these parameters.

6. Application

Equation (2-2) was applied in three different ways. One approach was aimed at determining the mean and variance of the probability distribution of A_R, and gaining an approximate idea of the shape of the overall distribution. In this approach, many of the intermediate probability distributions described above are not explicitly derived, nor are they necessary. Only the mean and variance of each distribution are necessary.

The second approach involved the use of actual historical distributions of the amount released per car in combination with the means and variances of the number of cars releasing, to obtain explicit distributions for the total amount released. The advantages of this approach are that the distributions themselves are obtained rather than just their parameters.

The third approach involved the development of a mathematical representation of a train consist, aimed at developing analytical estimates of the number of hazardous-material cars derailing (N_{HD}), given the total number of cars derailing (N_D). The approach then uses historical data to obtain distributions of the number of cars releasing (N_R), given N_{HD} and the amount released (A_R), given N_R. This approach allows one to examine specific policy alternatives not otherwise amenable to analysis. An example of such a policy is a rule specifying a limit to the number of hazardous-material cars that may be carried in a train. The disadvantage of this approach is that the associated computational techniques are complex and ill-suited to the requirements of a nationwide or regional risk analysis. For this reason, this approach was not exercised to any great extent, except to make a brief comparison of its results with those of the other approaches described above.

For the sake of brevity, the analysis approach that estimates means and variances (parameters of probability distributions) is described as being based on "parameter models." The second approach is described as being based on "distribution models." The third approach is described as computer-based since the use of a computer is essential in its application.

D. DATA SOURCES: THEIR USES, AND LIMITATIONS

To develop and calibrate the models described in Section C, several sources of information had to be utilized:

1. The FRA Railroad Accident/Incident Report System (RAIRS);
2. The Materials Transportation Bureau (MTB) incident reports;
3. The National Transportation Safety Board (NTSB) investigations;
4. The Association of American Railroads (AAR) and Railway Progress Institute (RPI) Tank Car Safety Research and Test Project reports;
5. Information contained in state rail plans; and
6. Work on estimating flows of commodities, including hazardous materials, on the links of the FRA Network Model, being done at Princeton University [1].

The uses to which the FRA and MTB data sources were put are summarized in Table 2-1, and shown somewhat more explicitly in Table 2-2. Several problems were encountered in the quantitative analysis of the FRA/RAIRS and MTB data, examples of which are shown in Table 2-3 and Figure 2-2. A considerable amount of effort was expended in overcoming these problems and limitations. However, in the interest of brevity, the techniques used are not described in this report.

With reference to Figure 2-2, it is particularly worth noting that even when FRA and MTB records can be found for the same accident, the estimates of impact are not comparable. The FRA estimates include the number of cars releasing (but not the amount of hazardous material released), as well as the number of people killed or injured or the dollar damage to property due to all causes. The MTB estimates include the amount released, as well as the impacts on people and property--but only if they were caused specifically by the release of hazardous materials, and not by other consequences of the train wreck.

E. REFERENCES

1. "Federal Railroad Administration Network Model," Volume 1 (User's Manual), Report prepared by IBM Federal System Division, May 1975.
2. Andrews, W. B., "An Assessment of the Risk of Transporting Liquid Chlorine by Rail," Report No. PNL-3376, March 1980.
3. Geffen, C. E., "An Assessment of the Risk of Transporting Propane by Truck and Train," Report No. PNL-3308, March 1980.
4. "FRA Guide for Preparing Accident/Incident Reports," Federal Railroad Administration, 1975.
5. Code of Federal Regulations, Title 49, Part 213, "Track Safety Standards," 1977.

TABLE 2-1. USES OF DATA SOURCES

1. Determining 'Exposure' by Track Class:
    - FRA/Network
    - Princeton
    - State Rail Plans
2. Modeling Train Accidents
    - FRA/RAIRS
3. Modeling Hazmat Train Accidents
    - FRA/RAIRS
    - MTB
    - NTSB
    - AAIR/RPI
4. Modeling Impacts
    - MTB
    - Prior Investigations

TABLE 2-2. SOURCES OF INFORMATION FOR VARIOUS INDEPENDENT VARIABLES AND MEASURES OF SEVERITY

INDEPENDENT VARIABLES	DATA SOURCES	
	FRA	MTB
Flows		
Accident Type	✓	
Commodity		✓
Track Class	✓	
Speed	✓	
Track Type	✓	
Cause	✓	

SEVERITY MEASURES	DATA SOURCES	
	FRA	MTB
$ Damages	✓	✓
No. Killed	✓	✓
No. Injured	✓	✓
No. Evacuated	✓	
No. Hazmat Cars Derailing	✓	
No. Hazmat Cars Releasing	✓	✓
Quantity of Hazmat Released		✓

TABLE 2-3. PROBLEMS IN FEDERAL RAILROAD ADMINISTRATION DATA

- Occasionally Missing Information
  - --Speed
  - --Track class
  - --Track density
  - --Track data
    - -No. of cars
    - -No. of cars derailing
    - -1st car position
- Multiple Reports
  - --Up to seven
  - --Difficult to automatically identify joint code date/time searches
  - --Duplication of
    - -Damages
    - -Killed
    - -Injured
    - -Cars on train
    - -Cars derailing
- Hazardous Material Not Identified

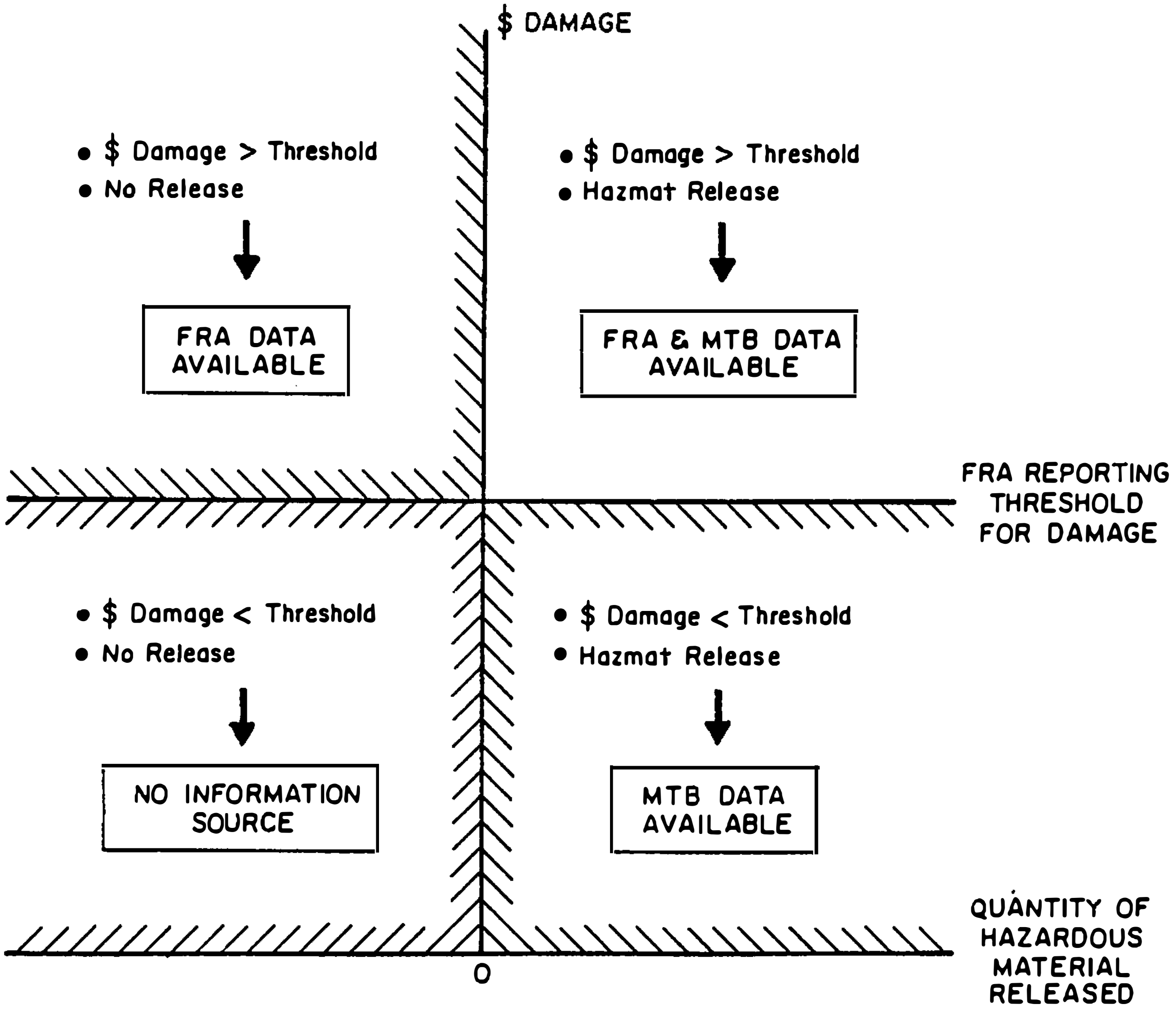


FIGURE 2-2. DATA SOURCES

3. ACCIDENT FREQUENCIES AND RATES

A. INTRODUCTION

This chapter presents historical data on accident rates and frequencies. Analyses that provide a useful perspective of the problem of railroad safety in general and of hazardous-material transport in particular are also presented.

Three major sources of information were used in developing the data presented here. Accident data were obtained largely from the Federal Railroad Administration's (FRA's) Railroad Accident/Incident Reporting System (RAIRS). Data for 1975, 1976, and 1977 are used. Data prior to 1975 contained less information on hazardous-material (HM) accidents; data for 1978 and subsequent years were not available at the start of this work.

Information on the total number of releases of hazardous material, the nature of the material released, and the quantity released per car and per accident were obtained from the Materials Transportation Bureau's (MTB's) data for the years 1971 through 1977. Data on flows, such as car-miles and ton-miles, were estimated by the Transportation Systems Center (TSC) and provided to Arthur D. Little, Inc.

Several other minor sources of information were also used, and these are cited where appropriate.

B. CHOICE OF EXPLANATORY VARIABLES

A "model" for railroad accidents consists of a choice of explanatory variables that are thought to influence or determine the rate at which accidents happen, as well as their severity, and of an explicit relationship between variables to be predicted (such as accident frequencies and severities) and the explanatory variables. The relationship might be obtained purely by curve-fitting of historical data, by theoretical modeling, or by a combination of the two.

As one's knowledge of railroad operations increases, it becomes evident that there are a host of factors that are important in accident analyses. However, the requirements of a large-scale safety study can be such that many of these factors have to be ignored, for one or more of the following reasons:

1. Data regarding the factors are not available;
2. The additional accuracy gained by including a factor does not justify its inclusion; or
3. The factor is important only for a small portion of all accidents.

On the basis of these qualitative criteria, several important choices were made in this study concerning variables to be included in the study of accident rates. These choices are briefly discussed below.

- Accident Location: Accidents are analyzed according to whether they occur on a mainline or in yards. Accidents occuring on sidings or on industry track are not included, as discussed in Chapter II.
- Accident Types: Two key accident groups are collisions (head-on and rear-end only) and derailments.
- Accident Causes: Track-caused accidents are analyzed separately; otherwise, there is no disaggregation of accidents according to their cause.
- Track Conditions: Track classification is accounted for in the analysis of mainline accidents; track quality variations within a track class are not.

C. CHOICE OF MEASURES OF ACCIDENT RATES

In any industrial activity, it is to be expected that the number of accidents that occur in a fixed period of time will increase as the level of activity increases. It is commonplace, therefore, to measure safety not by the number of accidents that occur in a year (i.e., by a frequency), but by an accident rate. An accident rate is simply the number of accidents divided by an appropriate quantitative measure of the level of industrial activity. For many industrial accidents, rates are defined as accidents per man-hour. In another example--passenger transportation--the rate most often used is the number of accidents per passenger-mile. The use of such rates is essential, for the purposes of both comparison and prediction. As an example, no useful comparison can be made on the basis of the following hypothetical statement:

> *Railroad A had 500 accidents in 1978, while Railroad B had 50.*

It is necessary to know how "big" the railroads are. As another example, if a new segment of track is being constructed, it is impossible to predict how many accidents will occur on it, unless past accident rates are estimated and then extrapolated.

In the context of railroad accidents, several measures of industrial activity offer themselves:

1. Carloadings,
2. Train-miles,
3. Car-miles,
4. Ton-miles, and
5. Number of classifications in yards.

The choice must depend on reasonable evidence that accident numbers are, in fact, proportional to the chosen measure. In this sense, carloadings are an inappropriate measure. A car that is loaded and travels 1 mile to its destination certainly has a much lower probability of an accident than another that travels 1000 miles to its destination.

In the following paragraphs, the various alternative measures are discussed, and the most suitable ones chosen for the following groups of accidents:

- Mainline collisions;
- Mainline derailments and all other types of accidents; and
- Yard accidents (derailments and collisions).

1. Mainline Collisions

Approximately 75 head-on collisions occur on mainline track each year. To estimate how much this number might increase if the railroads were to suddenly increase the amount of freight they transport by a large amount, it is necessary to develop a theoretical model of what leads to a head-on collision. The model developed for this investigation is described below.

Consider a single-track route segment that is L miles long, and carries traffic both eastbound and westbound. Trains traveling in opposite directions cross each other by the use of passing sidings. Once in a rare occasion, this does not happen as planned and a head-on collision occurs. It is assumed that each "crossing" of trains is an event that is a potential candidate for a head-on collision. There is a small probability, denoted by K, that any event will lead to a head-on collision. If

$\mathcal{E}$ = number of events (crossings) per year,

K = probability of a collision per event, and

F = number of collisions per year,

then the expected value of n is:

$$\bar{F} = K\mathcal{E}.$$

The value of $\mathcal{E}$ can be approximately determined as follows. Assume that there are N eastbound trains per year traveling at an average speed v mph, and a similar number westbound. The number of events experienced by any eastbound train can be computed as follows. From the moment it starts its trip to the moment it reaches its destination, a certain number of westbound trains will enter the route segment; it must pass every one of them. It must also pass every westbound train that was en route at the moment it started its trip.

Each eastbound train spends (L/v) hours en route. The number of westbound trains originating per hour is $N/8760$, where 8760 is the number of hours in a year. Thus, the number of new westbound trains that enter the segment is:

$(L/v)(N/8760)$ trains.

The average time between westbound trains is $(8760/N)$ hours. Their average spacing or headway is:

$v(8760/N)$ miles.

On the average, therefore, the number of westbound trains that are on the segment at any given moment is:

$(L/v)(N/8760)$ trains.

Thus, the number of encounters per eastbound train is:

$2LN/8760v$.

Since there are N eastbound trains per year, the total number of encounters per year is:

$$E = 2LN^2/8760v, \tag{3-1}$$

and the number of head-on collisions per year will be proportional to this number.

If each train weighs G gross tons, the annual traffic density is:

$D = 2\ NG$ tons per year.

This leads to an expression for N:

$N = D/2G$.

Equation (3-1) may now be rewritten in the form:

$$E = [L/2/8760G^2 v] \times D^2.$$

If one now groups those route segments which have similar values for G and v, then these two factors can be treated as constants within that group, and one has, within a group of track segments:

$$\mathcal{E}_j = C_j D_L^2$$

where 'j' denotes the various groups, and $C_j = 1/(2 \times 8760G^2 v_j)$.

Within a group, there will be several segments with parameters (L_1, D_1) and so on. The total exposure within the group is:

$$\mathcal{E}_j = \sum_i \mathcal{E}_{ji} = C_j \sum_i L_{ji} D_{ji}^2, \qquad (3\text{-}2)$$

where i denotes each individual link.

Within a group, the expected number of accidents per year is:

$$\bar{F}_j = K_j \mathcal{E}_j = K_j C_j \sum_i L_i D_i^2,$$

which may be rewritten in the form:

$$\bar{F}_j = \Phi_j \sum_i L_i D_i^2, \qquad (3\text{-}3)$$

with Φ_j being a group-constant, equal to $K_j C_j$.

The groups used in this report are the track classes. If one obtains historical data for:

- The annual number of mainline head-on collisions within each track class; and
- The values of L_i and D_i for all mainline segments within each track class;

then Equation (3-3) can be solved to obtain the constants Φ_j:

$$\Phi_j = \bar{F}_j / \sum_i L_{ji} D_{ji}^2. \qquad (3\text{-}4)$$

One can now predict the expected number of head-on collisions on any segment, if one has:

- Its track class, j;
- Its length, L; and
- Its traffic density, D.

For then:

$$\overline{F}_{segment} = \phi_j \, L \, D^2. \tag{3-5}$$

Thus, accident frequencies (number of accidents per year) will vary with a measure that can only be written as $(\text{ton})^2$-miles. On segments of the same track class and of equal length, the accident frequency will vary with the square of the traffic density. There is no simpler measure of accident rate that is useful for head-on collisions.

Similar considerations apply to other types of collisions, including:

- Rear end,
- Side,
- Raking, and
- Broken-train,

since they also depend on "encounters" between trains. Each will show an approximate proportionality between the number of accidents per year on a segment and the square of the traffic density on that segment.

It is therefore proposed that all types of mainline collisions be grouped together, sorted according to track class, and analyzed using Equation (3-4). Predictions can then be made using Equation (3-5).

2. Mainline Derailments

There are three possible candidates for exposure measures for mainline derailments: train-miles, car-miles, and ton-miles. Traditionally train-miles is used, but it was eliminated from consideration in this study because of its obvious shortcomings, including the strong likelihood [1] that, per mile of travel, a longer and heavier train has a higher probability of suffering an accident than a shorter one. The reasons are clear:

- Coupler failures become more likely as draft forces increase;
- Equipment defects become more likely as the number of cars in the train increases; and
- Derailments caused by train action or collisions caused by an excessive stopping distance increase in probability as trains become longer and heavier.

A recent study [2] included a thorough evaluation of the two remaining alternatives: car-miles and ton-miles. It was concluded that each had desirable characteristics, and that neither was evidently preferable. Therefore both will be used in this report.

In summary, mainline derailment frequencies for a segment (numbers per year) are expected to vary with the length of the segment, and with either the number of cars (empty and loaded) traversing it per year or the gross tonnage of all traffic traversing it per year.

3. Yard Accidents

The only measure of yard activity that is readily available is the number of cars classified per year. Therefore, this measure is used in this report for yard accidents whether derailments or collisions. For each car traversing a yard, there is a certain probability of an accident. This probability is derived separately for collisions and for derailments.

D. HISTORICAL ACCIDENT STATISTICS

Accident data maintained by the FRA and by the MTB were analyzed to obtain a quantitative understanding of how many accidents occur annually, of what types, on what classes of track, on what types of track, due to what causes, involving what kinds of hazardous materials, and with what consequences. A representative selection of these analyses is presented here.

Accidents classified according to accident type, track class, and track type are enumerated in Tables 3-1 through 3-6, each of which is for one track class. The following important observations may be made from these tabulations:

- Mainline and yard accidents account for 92% of all accidents;
- Derailments account for 73% of all accidents, while collisions of all kinds account for another 20%;
- Accidents on Class 1 track account for 51% of all accidents; of these, almost 70% occur in yards; and
- Some 73% of all collisions occur in yards, in contrast to only 36% of all derailments.

When the data are regrouped according to the choice of accident types and track types made in Section B, one obtains Table 3-7, which summarizes accident data. An important observation here is the sparseness of the accident data for Class 6 track. Statistical tests revealed that accident rates determined from these data would have a large standard error. Moreover, experience has shown that Class 6 track is not, by and large, a major cause of concern for safety. For these reasons, Classes 5 and 6 track are combined in all subsequent analyses.

Next, mainline accidents were grouped according to their causes. The results are presented in Table 3-8. On the basis of the data presented in Table 3-8, it was concluded that track-caused collisions can be ignored; therefore, accident rates are not estimated for them.

TABLE 3-1. ACCIDENTS ON CLASS 1 TRACK (1975-1977)

	Main		Yard		Siding		Industry	
Accident Type	Frac.	No.	Frac.	No.	Frac.	No.	Frac.	No.
Derailment	.892	2489	.618	6558	.779	682	.689	608
Head-on Collision	.013	36	.016	174	.019	17	.022	19
Rear-end Collision	.021	58	.041	432	.062	54	.034	30
Side Collision	.031	87	.242	2568	.071	62	.142	125
Raking Collision	.007	19	.038	408	.018	16	.028	25
Broken Train Collision	.002	6	.005	49	.005	4	.008	7
Railway Highway Crossing	.014	40	.002	18	.002	2	.008	7
Grade Crossing	∿ 0	1	∿ 0	3	-	-	-	-
Obstruction	.003	7	.002	26	.001	1	.013	11
Explosion/Detonation	-	-	.001	7	.001	1	.001	1
Fire/Rupture	.007	18	.015	163	.022	19	.026	23
Other	.010	29	.020	208	.019	17	.031	27
TOTAL	1.00	2790	1.00	10614	.999	875	1.002	883

Source: FRA RAIRS

TABLE 3-2. ACCIDENTS ON CLASS 2 TRACK (1975-1977)

	Main		Yard		Siding		Industry	
Accident Type	Frac.	No.	Frac.	No.	Frac.	No.	Frac.	No.
Derailment	.878	3252	.607	928	.754	156	.748	86
Head-on Collision	.013	47	.012	19	.010	2	.043	5
Rear-end Collision	.020	73	.060	91	.073	15	.052	6
Side Collision	.016	58	.226	346	.073	15	.087	10
Raking Collision	.007	25	.043	66	.029	6	.026	3
Broken Train Collision	.006	22	.005	8	.010	2	-	-
Railway Highway Crossing	.037	138	.001	1	-	-	-	-
Grade Crossing	.001	2	.001	1	.001	1	-	-
Obstruction	.003	11	.001	1	-	-	-	-
Explosion/Detonation	.001	2	.001	1	-	-	-	-
Fire/Rupture	.008	29	.009	13	.015	3	.009	1
Other	.012	44	.035	54	.034	7	.035	4
TOTAL	1.002	3703	1.001	1529	.999	207	1.00	115

Source: FRA RAIRS

TABLE 3-3. ACCIDENTS ON CLASS 3 TRACK (1975-1977)

	Main		Yard		Siding		Industry	
Accident Type	Frac.	No.	Frac.	No.	Frac.	No.	Frac.	No.
Derailment	.811	4038	.633	176	.731	76	.846	11
Head-on Collision	.013	67	.022	6	.019	2	-	-
Rear-end Collision	.030	147	.083	23	.067	7	-	-
Side Collision	.014	69	.191	53	.106	11	-	-
Raking Collision	.009	44	.029	8	.039	4	-	-
Broken Train Collision	.008	42	.014	4	.029	3	.154	2
Railway Highway Crossing	.057	284	.004	1	-	-	-	-
Grade Crossing	∿ 0	1	-	-	-	-	-	-
Obstruction	.006	28	.007	2	-	-	-	-
Explosion/Detonation	.002	8	-	-	-	-	-	-
Fire/Rupture	.020	98	.011	3	.010	1	-	-
Other	.030	151	.007	2	-	-	-	-
TOTAL	1.00	4977	1.001	278	1.001	104	1.00	13

Source: FRA RAIRS

TABLE 3-4. ACCIDENTS ON CLASS 4 TRACK (1975-1977)

	Main		Yard		Siding		Industry	
Accident Type	Frac.	No.	Frac.	No.	Frac.	No.	Frac.	No.
Derailment	.693	2015	.649	96	.800	39	.667	10
Head-on Collision	.021	60	-	-	-	-	-	-
Rear-end Collision	.036	104	.020	3	-	-	.133	2
Side Collision	.022	64	.270	40	.143	7	.067	1
Raking Collision	.019	55	.020	3	.020	1	-	-
Broken Train Collision	.017	48	.014	2	-	-	-	-
Railway Highway Crossing	.091	264	-	-	-	-	.067	1
Grade Crossing	.001	4	-	-	-	-	-	-
Obstruction	.006	16	-	-	-	-	-	-
Explosion/Detonation	∿ 0	1	-	-	-	-	-	-
Fire/Rupture	.045	132	.014	2	.020	1	.067	1
Other	.050	144	.014	2	.020	1	-	-
TOTAL	1.001	2907	1.001	148	1.003	49	1.001	15

Source: FRA RAIRS

TABLE 3-5. ACCIDENTS ON CLASS 5 TRACK (1975-1977)

	Main		Yard		Siding		Industry	
Accident Type	Frac.	No.	Frac.	No.	Frac.	No.	Frac.	No.
Derailment	.718	442	.784	40	.750	12	1.00	3
Head-on Collision	.020	12	-	-	-	-	-	-
Rear-end Collision	.070	43	-	-	.125	2	-	-
Side Collision	.016	10	.137	7	-	-	-	-
Raking Collision	.034	21	.078	4	-	-	-	-
Broken Train Collision	.016	10	-	-	.125	2	-	-
Railway Highway Crossing	.057	35	-	-	-	-	-	-
Grade Crossing	-	-	-	-	-	-	-	-
Obstruction	.007	4	-	-	-	-	-	-
Explosion/Detonation	-	-	-	-	-	-	-	-
Fire/Rupture	.042	26	-	-	-	-	-	-
Other	.021	13	-	-	-	-	-	-
TOTAL	1.001	616	.999	51	1.00	16	1.00	3

Source: FRA RAIRS

TABLE 3-6. ACCIDENTS ON CLASS 6 TRACK (1975-1977)

	Main		Yard		Siding		Industry	
Accident Type	Frac.	No.	Frac.	No.	Frac.	No.	Frac.	No.
Derailment	.744	29	.800	8	-	-	-	-
Head-on Collision	.026	1	-	-	-	-	-	-
Rear-end Collision	-	-	-	-	-	-	-	-
Side Collision	.026	1	.200	2	-	-	-	-
Raking Collision	.026	1	-	-	-	-	-	-
Broken Train Collision	-	-	-	-	-	-	-	-
Railway Highway Crossing	.051	2	-	-	-	-	-	-
Grade Crossing	-	-	-	-	-	-	-	-
Obstruction	.026	1	-	-	-	-	-	-
Explosion/Detonation	-	-	-	-	-	-	-	-
Fire/Rupture	.026	1	-	-	-	-	-	-
Other	.007	3	-	-	-	-	-	-
TOTAL	1.002	39	1.00	10	-	-	-	-

Source: FRA RAIRS

TABLE 3-7. SUMMARY OF ACCIDENT DATA (1975-1977)

Track Class	TRACK TYPE			
	MAINLINE		YARD	
	Collisions	Derailments	Collisions	Derailments
1	206	2,489	3,631	6,558
2	225	3,252	530	928
3	369	4,038	94	176
4	331	2,015	48	96
5	96	442	11	40
6	3	29	2	8
Unknown	45	37	999	1,489
TOTAL	1,275	12,302	5,315	9,295

Source: FRA/RAIRS

TABLE 3-8. MAINLINE ACCIDENT CAUSES (1975-1977)

Track Class	ACCIDENT TYPE			
	DERAILMENTS		COLLISIONS	
	Track-Caused	Other Causes	Track Caused	Other Causes
1	1,548	941	6	200
2	1,628	1,624	7	218
3	1,507	2,531	11	358
4	639	1,376	11	320
5 and 6	45	426	3	96
Unknown	-	37	-	45
TOTALS	5,367	6,935	38	1,237

Source: FRA/RAIRS

Investigations were made of the frequency with which hazardous-material releases occur in rail transportation; these data are shown in Table 3-9, as a function of the amount of property damage caused by the hazardous material. Two facts are evident from this tabulation:

1. A large majority of hazardous-material releases are not of major consequence; in fact, 76% cause property damage of less than $100 per incident; and
2. Among the more severe incidents, the vast majority (31 out of 38, or 82%) are caused by just three chemical groups: flammable gases, flammable liquids, and corrosives.

These conclusions are bolstered by the data shown in Figure 3-1, for the number of injuries attributable to each chemical group over the years from 1971 through 1977.

E. HISTORICAL DATA ON EXPOSURE

1. Mainline Operations

The data shown in Table 3-10 were provided by the Transportation Systems Center. The data are based on estimated flows on the FRA Network Model, developed by using a routing algorithm and data from the FRA 1% waybill sample for 1976, along with statistical techniques for scaling up the waybill sample.

It is useful to know how to relate train-miles, car-miles, and ton-miles with one another. First however, it is necessary to know the relationship between:

- Empty and loaded car-miles; and
- Revenue and gross ton-miles.

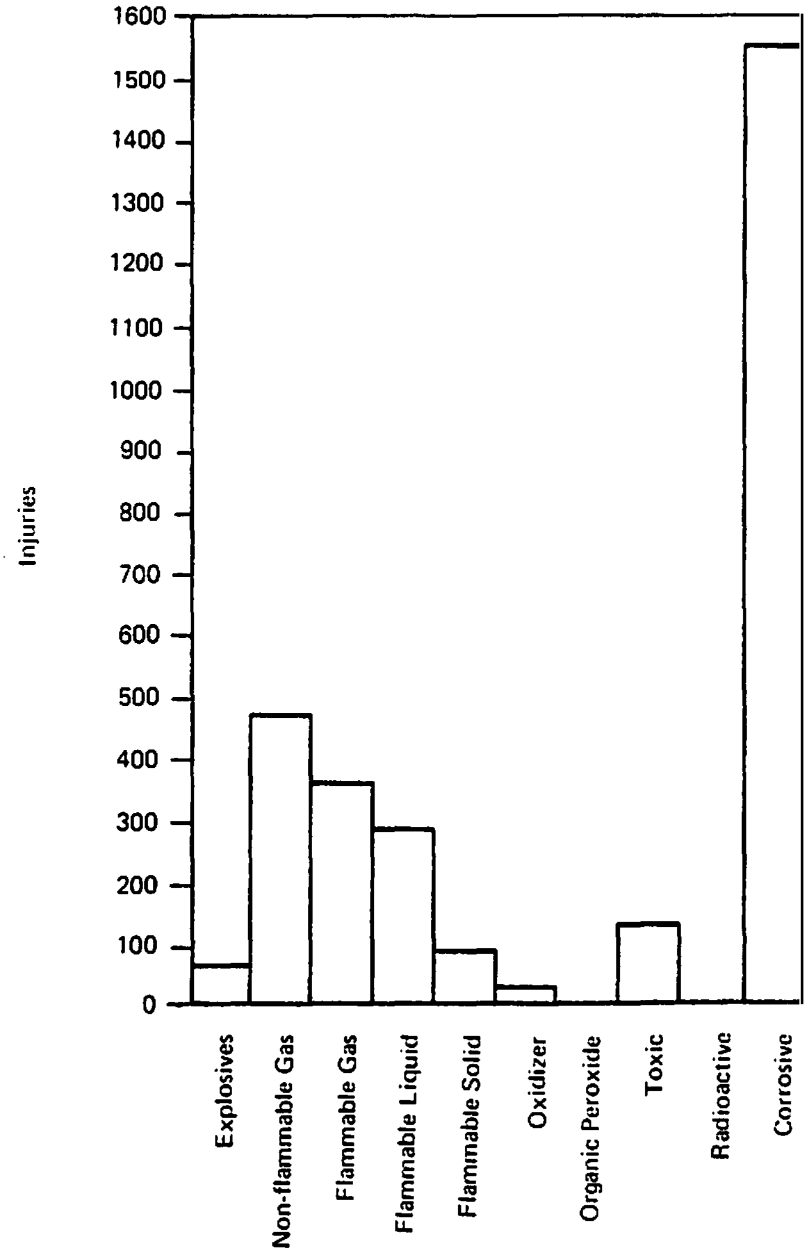
In 1976, 55.5% of all car-miles were generated by cars carrying cargo; the remaining car-miles were generated by empty cars being returned to a point where they could pick up another load [3]. Car-mile data

TABLE 3-9. COMPARISON OF DOLLAR DAMAGE* RANGES FOR HAZARDOUS-MATERIAL COMMODITY GROUPS

	No. Releasing (1971-1977)	Fraction with dollar damage of 0	0-1	1-10	10-30	50-100	100-500	500-500,000	1,000 2,000	Greater than 2,000
Explosives	42	0.29	0.36	0.05	0.10	0.14	0.05	0.02	0.02	0.02
Non-flammable Gas	378	0.50	0.43	0.05	0.02					
Flammable Gas	562	0.45	0.42	0.04	0.04	0.02	0.02	∿0	∿0	∿0
Flammable Liquid	1043	0.31	0.54	0.09	0.06	0.01	0.01			
Flammable Solid	86	0.33	0.54	0.11	0.02	∿0				
Oxidizer	325	0.10	0.80	0.08	0.03					
Organic Peroxide	1	1.00								
Toxic	190	0.21	0.63	0.10	0.05	0.01	0.01			
Radioactive	6		0.50	0.33	0.17					
Corrosive	1749	0.41	0.51	0.06	0.02	∿0	∿0			
TOTAL	4382									

*Includes damage due to the hazardous material only.

Source: MTB.



Source: MTB

FIGURE 3–1. INJURIES BY COMMODITY GROUP BASED ON RELEASES, 1971–1977

TABLE 3-10. MAINLINE EXPOSURE DATA

Measure of Exposure	Class of Track					
	1	2	3	4	5 & 6	ALL
Loaded Car-Miles (10^6)	145.1	585.3	2,237	10,650	1,745	15,360
Total Car-Miles (10^6)	261.2	1,055	4,031	19,180	3,144	27,680
(a)Total Car^2-Miles (10^{12})	147	388	1,050	8,390	2,180	12,100
Revenue Ton-Miles (10^9)	7.56	30.5	117	555	90.9	800
Revenue Ton^2-Miles (10^{15})	123	324	878	7,010	1,820	10,100
Gross Ton-Miles (10^9)	15.6	62.8	241	1,140	187	1,650
Gross Ton^2-Miles (10^{15})	520	1,370	3,710	29,700	7,700	42,700

Source: TSC and Arthur D. Little, Inc., estimates.

Assumptions:
- 52.1 Revenue Ton-Miles per Loaded Car-Mile
- 0.555 Loaded Car-Miles per Total Car-Mile
- 30 Tons Tare Weight per Car

(a) Computed as follows: for a segment, multiply length (miles) by the square of the number of cars traversing the segment; take the sum overall segments in a given track class.

developed from an analysis of the 1% FRA waybill sample include only loaded car-miles, since waybills are not required for empty cars. These data must be multiplied by the factor (1/0.555) to obtain total car-miles.

Similarly, ton-miles obtained from the waybill sample are revenue ton-miles; i.e., the tonnage of the freight multiplied by the distance it travels. What is required, however, is an estimate of gross ton-miles. To obtain this value, one assumes the average tare (empty) weight of freight cars to be 30 tons. This weight is transported by every car for every mile it travels, whether loaded or empty. Therefore, the "dead" ton-miles are:

(loaded car-miles) x (30/0.555).

When this number is added to the revenue ton-miles, one obtains an estimate of gross ton-miles.

To obtain the gross-ton^2-miles estimates, one has to square the ratio of gross ton-miles to revenue ton-miles and multiply it by the net ton^2-miles.

If one wishes to perform a risk analysis of either a specific train or a "typical" train, one has to know how may cars are in it (N_T), or what its gross tonnage is (G). Then, per train-mile, one has N_T car-miles and G gross ton-miles. For the typical U.S. train, $N_T = 67$ cars [3], and G is estimated to be about 4500 tons. However, N_T can vary from a theoretical lower limit of 1 to a practical upper limit of about 200. Gross tonnages may vary from a low of a few 100 tons to a maximum of perhaps 15,000 tons.

Some of the exposure data shown in Table 3-10 may be compared with data published by the AAR [3] and the Interstate Commerce Commission [4]. For example, the total car-miles shown in Table 3-10 for all track classes is 27.7×10^9. For 1976, the comparable AAR number is 28.5×10^9. The revenue ton-miles shown in Table 3-10 add up to 801×10^9. The comparable AAR number is 791×10^9; the ICC figure (for Class I and Class II railroads) is 800×10^9. The agreement between the various sources is satisfactory. Neither the AAR nor the ICC cites gross ton-mile figures. In addition, the ton^2-mile measure is apparently being used for the first time. Estimates do not appear in any source outside of this report. Despite the good agreement on the totals, the exposure data by track class may contain inaccuracies due to an assumption; viz., that the ratio of revenue ton-miles to loaded car-miles as well as the ratio of loaded car-miles to total car-miles, is independent of track class. Since data on the variation of these parameters with track class are not available, the track class exposure data in Table 3-10 represent the best estimates possible at present.

2. Yard Operations

A recent FRA study [5] provides estimates of the number of cars classified each year in yards of all types. Although it is clear that yard classification risk will vary, depending on whether one is examining flat or hump yards, this variable was excluded since information concerning it is not available on the FRA Network Model, which is to be the basis for future risk analyses. The total number of cars classified per year in all classification yards in the U.S. is approximately 3.9×10^8.

F. HISTORICAL ACCIDENT RATES

Data on historical accident frequencies (numbers per year) are presented in Section D. The appropriate measures of exposure for defining accident rates are presented in Section C. Historical data on exposure are presented in Section E. This section combines information from all three of these sections to develop estimates of historical accident rates.

1. Mainline Derailments

When the numbers in Table 3-8 are combined with the numbers in Table 3-10, one obtains the mainline derailment rates shown in Table 3-11. (Note that Table 3-8 contains three years' data, whereas

TABLE 3-11. HISTORICAL MAINLINE DERAILMENT RATES

Class of Track	1	2	3	4	5 and 6	ALL*
Derailment Rate--All Causes (Accidents per 10^9 Gross Ton-Miles)	53.2	17.3	5.59	0.589	0.840	2.49
Derailment Rate of Track-Caused Accidents (Accidents per 10^9 Gross Ton-Miles)	33.1	8.64	2.08	0.187	0.080	1.08

Source: Arthur D. Little, Inc.

*Includes accidents with unknown Track Class.

Table 3-10 contains estimates of only one year's exposure. For the two to be on the same basis, the numbers in Table 3-8 must be divided by 3.)

The quirk that is observed in Table 3-11 in the rate for Class 5 & 6 track (which is higher than that for Class 4 track) is probably anomalous, although no specific source of error has been found so far. The possible errors arising from any anomalies are not large, however, since Classes 5 and 6 track account for only 8% of all gross ton-miles, as can be seen from Table 3-10, and for only 4% of all accidents, as can be seen from Table 3-8.

2. Mainline Collisions

As for mainline derailments, the data in Tables 3-8 and 3-10 can be appropriately combined to obtain rates for mainline collisions. These are shown in Table 3-12. Rates are not estimated separately for track-caused collisions since they are low, as can be seen from Table 3-8.

3. Yard Accidents

Yard accident frequencies (three years' data) are provided in Table 3-7. In Section E, it was estimated that approximately 3.9×10^8 cars are classified each year. One can thus obtain the following estimates of yard accident rates:

Yard collisions : 4.5 per million classifications; and

Yard derailments : 7.9 per million classifications.

G. TRAIN ACCIDENT FREQUENCIES AND PROBABILITIES

It is important to make a distinction between the accident rates estimated in Section F and accident frequencies and probabilities. Suppose one is analyzing a situation in which the exposure per year (gross ton-miles per year, for example) is E, and the accident rate is Z (accidents per gross ton-mile, for example). Then the expected frequency of accidents annually is:

TABLE 3-12. HISTORICAL MAINLINE COLLISION RATES

Class of Track	1	2	3	4	5 and 6	ALL*
Collision Rates--All Causes [Accidents per 10^{17} (Gross Ton)^2-Miles]	13.2	5.47	3.32	0.372	0.429	0.990

Source: Arthur D. Little, Inc., estimates.

*Includes accidents with unknown Track Class.

$$m_F = E\ Z. \tag{3-6}$$

If it is assumed that accidents occur as a Poisson process, then the probability that there will be precisely F accidents in a year is:

$$p(F) = \frac{(m_F)^F}{F!} e^{-m_F}. \tag{3-7}$$

The probability that there will be at least one accident is "the probability of an accident," P_A:

$$P_A = p(F \geq 1) = 1 - p(0) = 1 - e^{-m_F}. \tag{3-8}$$

When m is small, $P_A \approx m_F$ and $P_A \simeq P(1)$; then m_F is large, P_A approaches unity.

The same argument can be extended to examine the frequency of accidents to trains carrying hazardous materials. Let P_H represent the probability that a train involved in an accident is carrying hazardous materials. Then the expected frequency of accidents to hazardous-material trains is:

$$m_H = P_H\, m_F = P_H\, E\ Z. \tag{3-9}$$

Furthermore, the probability that at least one hazardous-material train will suffer at least one accident is:

$$P_{AH} = 1 - e^{-m_H} = 1 - e^{-m_A P_H} \tag{3-10}$$

If $m_F\, P_H$ is small, then $P_{AH} \simeq m_F\, P_H$.

The expected frequency of accidents can be shown as a function of the probability of an accident:

$$m_F = \ell n\left(\frac{1}{1 - P_A}\right). \tag{3-11}$$

Thus, the frequency of hazardous-material accidents is:

$$m_H = m_F P_H = P_H \ln(\frac{1}{1 - P_A}). \quad (3\text{-}12)$$

One pertinent observation that may be made is that when the expected frequency (number of accidents in a year) is small, then the probability of an accident (per year) is numerically equal to the frequency. When the expected frequency increases, however, the probability tends asymptotically to a value of unity. This difference is relevant to analyses of risk in situations where multiple accidents are expected to occur.

H. REFERENCES

1. Leilich, R. H., "Study of the Economics of Short Trains," Prepared by Peat, Marwick, Mitchell and Co., NTIS Report No. PB-235-411, June 1974.

2. Nayak, P. R. and Palmer, D. W., "Issues and Dimensions of Freight Car Size: A Compendium," Report No. FRA-ORD-79/56, March 1980.

3. Association of American Railroads, "Yearbook of Railroad Facts," 1977 Edition.

4. "Transport Statistics in the United States, Year Ended December 31, 1976" (Part I: Railroads, Their Lessors and Proprietary Companies), Interstate Commerce Commission.

5. Petracek, S. J., et al, "Railroad Classification Yard Technology," Report No. FRA/ORD-76/304, January 1977.

4. NUMBER OF CARS DERAILING

A. INTRODUCTION

One of the inputs required by the model presented in Chapter 2 is the probability distribution of the number of cars that derail or are damaged in a typical accident. It is assumed not only that this number is a random variable, but also that the number is strongly dependent on train speed and not on train length. The latter assumption is more or less justified for trains that are more than 25 cars long, as may be seen from the data in Appendix B.

The following paragraphs provide historical data on the number of cars derailed or damaged, along with best-fit estimates of the mean and variance of this random variable, as functions of speed.

B. YARD AND MAINLINE DERAILMENTS--ALL CAUSES

Federal Railroad Administration (FRA) accident data were analyzed to obtain the values of means and standard deviations for N_D (the number of cars that derail in an accident) displayed in Table 4-1.

Upon examining the data, three issues of concern become apparent. The first is the dip in average derailment sizes in the 55- to 60- mph range. From a statistical viewpoint, the t-statistic based on the difference in average derailment size between 56- to 60- mph derailments and 31- to 55- mph derailments (for yard and mainline combined) is:

$$\frac{8.40 - 11.8}{\frac{10.0}{\sqrt{130}} + \frac{11.13}{\sqrt{2105}}} = -2.8.$$

On the basis of these two numbers alone, the drop is significant at the 1 percent level, but the drop could be statistical. On examining the data, the difference appears to be due mainly to the low

TABLE 4-1. MEANS AND STANDARD VARIATIONS OF THE NUMBER OF CARS DERAILING (DERAILMENTS DUE TO ALL CAUSES)

Speed	MAINLINE			YARD		
	Data Points	m_{N_D}	σ_{N_D}	Data Points	m_{N_D}	σ_{N_D}
0-5	1643	4.80	4.30	7263	4.21	3.78
5-10	3177	5.51	4.72	1765	4.75	3.04
11-15	1193	5.69	5.04	187	4.83	3.61
16-20	1398	6.35	5.48	40	5.22	3.65
21-25	1546	7.74	6.94	12	7.58	3.99
26-30	1056	9.65	8.54	8	7.13	7.43
31-35	522	11.30	9.86	6	12.17	10.98
36-40	662	11.36	11.07	5	6.0	2.74
41-45	343	11.05	11.16	5	5.0	4.06
46-50	387	11.04	12.45	1	27.0	0.0
51-55	169	10.93	12.17	-	-	-
56-60	128	8.13	10.09	2	2.5	2.12
61-65	37	14.49	15.68	-	-	-
66-70	38	12.42	12.37	-	-	-
71-75	1	4.0	-	-	-	-
76-80	-	-	-	1	4.0	0.0
>80	1	2.0	-	-	-	-

incidence of derailments of more than 30 cars for 55- to 60-mph derailments (5 out of 128 compared with the 49 out of 557 incidents for derailments in the 45- to 55-mph range). The significance of this difference is about 7 percent. One might have expected 11 derailments with fewer than 30 cars derailing in the 55- to-60-mph range, and this might have increased the mean value to 10 or 11. Consequently, a statistical explanation is not completely unreasonable.

The second issue is the possible existence of bias in the estimation of speeds. Figure 4-1 presents a comparison of statistics for those derailments* in which the speed was recorded and those for which the speed was estimated. None of the differences is extremely significant, the maximum t-value being 2.12. However, the aggregated difference over all speed classes, which is equal to the sum of t-values divided by the square root of the number of speed classes, is 3.05. Although this does not alter the estimated curve a great deal, it should be noted that there is an effect that may be caused by biasing toward lower values in the estimation of speeds.

This difference may also explain the dip in derailment lengths in the 55- to-60-mph range. (Many of the large derailment accidents may have been recorded at different speeds.) Because recorded speed data are limited and the magnitudes of differences in Figure 4-1 are not large, both recorded and estimated speeds were used in subsequent analyses.

The final issue is the comparison of means and variances for yard and mainline derailment in each speed range. The statistical tests of significance are presented in Table 4-2. As shown in this table, there are statistical differences, especially at low speed values, for which there are a great deal of data. However, the development of separate best-fit curves for yard and mainline accidents is unnecessary

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*For some derailments, the appropriate data field was blank, and it was not known whether the speed was recorded or estimated. These are omitted.

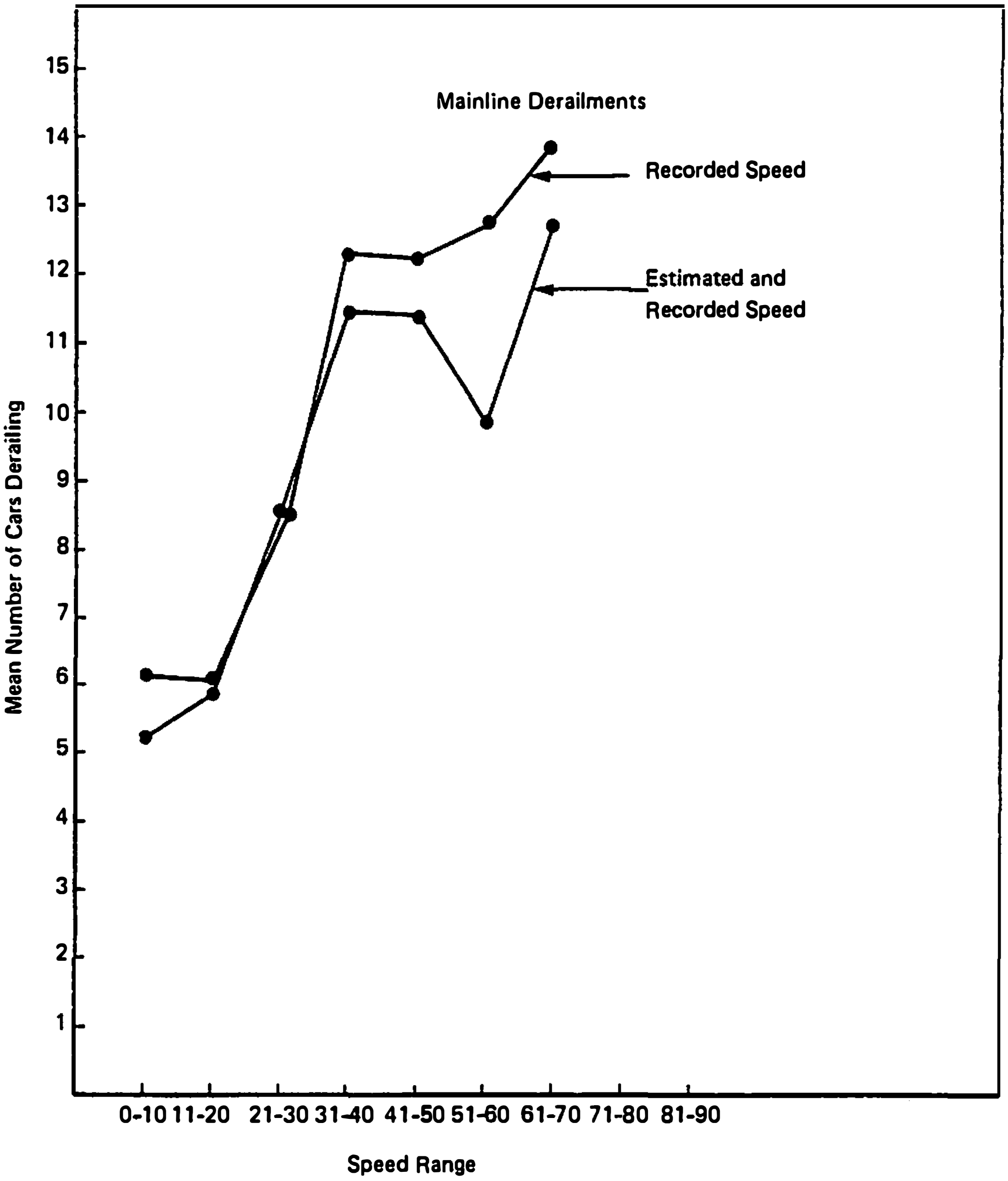

FIGURE 4–1. NUMBER OF CARS DERAILING: COMPARISON OF RECORDED AND ESTIMATED SPEED

TABLE 4-2. SIGNIFICANCE TESTS FOR DIFFERENCES IN THE MEANS AND VARIANCES OF NUMBER OF CARS DERAILING AT VARIOUS SPEEDS FOR MAINLINE AND YARDS

Speed	t-value for Difference in Means	Significance	F*-value for Two Variances	Significance
0-5	3.92	10^{-4}	1.29	Zero
6-10	4.86	10^{-7}	2.4	Zero
11-15	2.09	4%	1.95	Zero
16-20	1.56	12%	2.25	∿0.4%
21-25	.12	Not significant	3.0	∿4%
26-30	.87	Not significant	1.32	Not significant
31-35	.18	Not significant	.8	Not significant
36-40	3.23	∿1.5%	16.3	∿2%
41-45	2.5	∿5%	7.5	∿15%
45-50	1.28	∿20%	-	-
56-60	.7	Not significant	-	-

because the differences are not large in magnitude, even though they are statistically significant: speed explains most of the variance in the number of cars derailing. For this reason, curves were fitted to the combined data.

The mean value of N_D is denoted by $m_{N_D}(v)$ and its variance by $\sigma^2_{N_D}(v)$. A comprehensive regression analysis was made to determine a simple curve that best fit the data.

Both weighted regression and unweighted regressions were used to determine the best fit. Table 4-3 displays the results of the analysis.

The statistic F^* is given by:

$$F^* = \sum_1^n W_i \, [f(v) - \hat{f}(v)]^2 \tag{4-1}$$

where

$\hat{f}(v)$ = empirical function,

$f(v)$ = estimated function,

$$W_i = \begin{cases} 1 & \text{for unweighted scheme,} \\ nN_i / \sum_1^n N_i & \text{for weighted scheme, which allows for a direct comparison of the schemes.} \end{cases}$$

Based on Table 4-3, the following functional forms are utilized:

$$\left.\begin{aligned} m_{N_D} &= 1.7v^{0.5}, \\ \sigma^2_{N_D} &= 2.7v. \end{aligned}\right\} \begin{array}{l} \text{Mainline and Yard Derailments} \\ \text{(All Causes)} \end{array} \tag{4-2}$$

The raw data as well as these regressions are shown in Figure 4-2.

For m_{N_D}, the best one-parameter fit is nearly optimal for the unweighted fit and moderate for the weighted fit (although the percentage of the variance explained in the latter case is still 78% and the percentage of the total sum of squares explained is 97.3%). The

TABLE 4-3. MEANS AND STANDARD DEVIATIONS OF THE NUMBER OF CARS DERAILING (DERAILMENTS DUE TO ALL CAUSES)

Functional Form	m_{N_D}						$\sigma^2_{N_D}$					
	Unweighted Fit			Weighted Fit			Unweighted Fit			Weighted Fit		
	c	d	F*	c	d	F*	c	d	F*	c	d	F*
$c + dv$	4.836	.1241	33.98	3.8786	.1654	6.396	5.395	2.869	11598	1.1204	2.608	1748
$c + dv^{0.5}$	1.674	1.341	28.76	1.776	1.323	6.739	70.39	29.56	13309	-28.15	19.63	3630
$c + dv^2$	6.696	.00152	50.43	4.974	.00306	19.072	33.71	.0376	15196	16.641	.0535	1918
$c + d \log v$	- .464	2.937	32.27	1.563	2.127	12.83	-105	61.15	19722	-27.419	29.688	6427
dv	-	.2271	113.81	-	.315	113	-	2.754	11697	-	2.651	1757
$dv^{0.5}$	-	1.6074	32.83	-	1.7678	15.78	-	18.394	20505	-	12.5795	5902
dv^2	-	.0378	326.33	Not attempted			-	.04899	22191	Not attempted		
cv^d	3.12	.322	30.7	2.65	.360	7.98	1.472	1.162	11833	6.11	.673	3200
ce^{dv}	6.0	.0115	40.8	4.481	.02	12.03	23.7	.0325	16921	Not attempted		

* The total variation (around the means) to which F can be compared is:

	Unweighted	Weighted
a(v)	121	70
b(v)	58416	17631

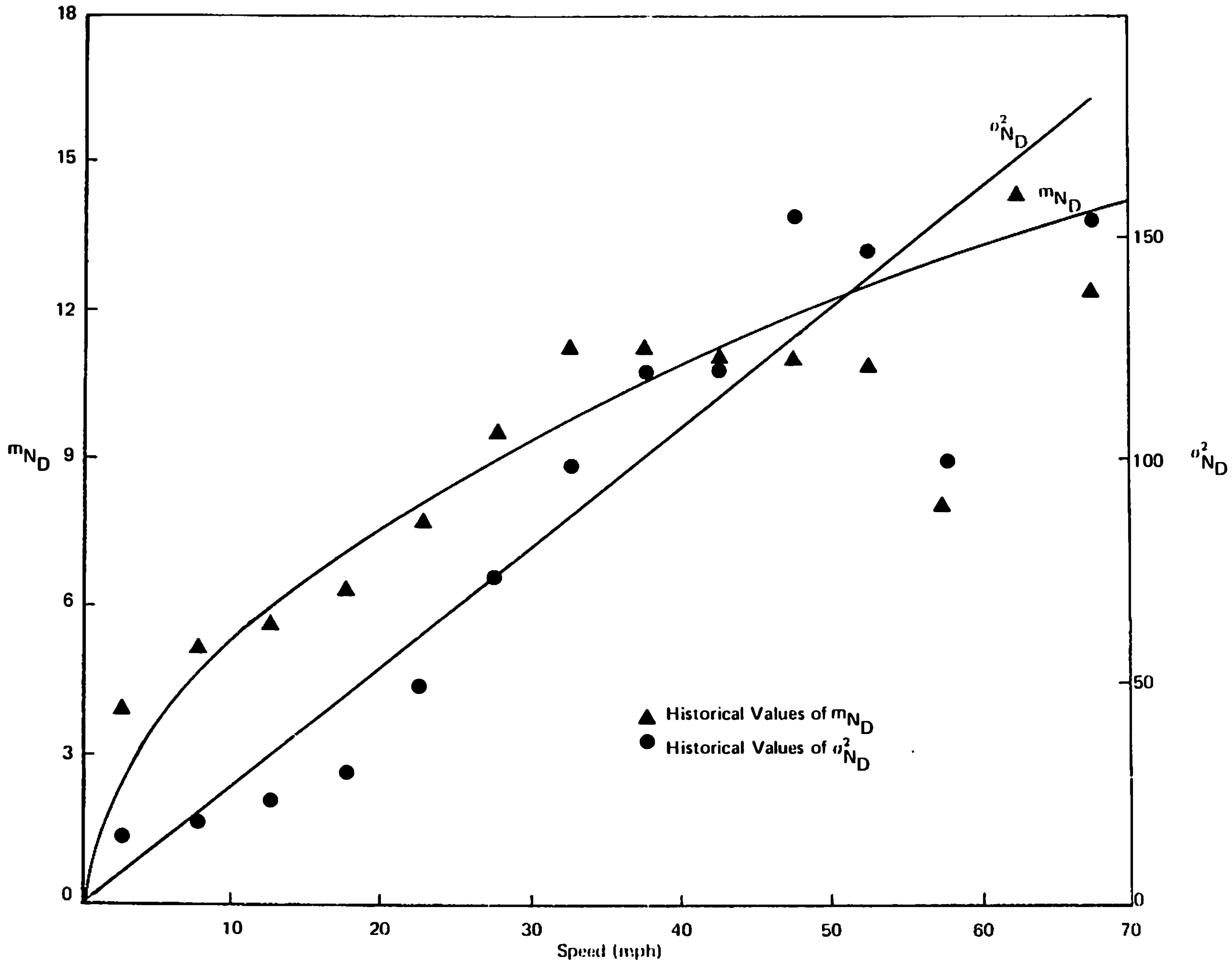

FIGURE 4–2. HISTORICAL VALUES FOR m_{N_D} AND $\sigma^2_{N_D}$ AND ESTIMATED FUNCTIONS

one-parameter shape is far easier to use in further analyses, however, and was chosen for this reason. For the case of b(v), the one-parameter fit is nearly optimal.

C. YARD AND MAINLINE DERAILMENTS DUE TO TRACK CAUSES

Track-caused derailments are longer than the set of all derailments. The data are presented in Table 4-4. The general functional forms are assumed to be the same, but with a different parameter value for a(v) only. The functional equations estimated to give the best fit are:

$$m_{N_D} = 2.1v^{0.5}, \quad \text{.... Track-caused Yard and Mainline Derailments} \qquad (4\text{-}3)$$

$$\sigma^2_{N_D} = 2.7v$$

D. COLLISIONS

The major differences between collisions and derailments are in the functions of m_{N_D} and σ_{N_D}. Table 4-5 presents the aggregated statistics for the number of cars derailed (or damaged) in those collisions for which at least one derailing car was reported. Based on these statistics, the following functional forms were determined to be the most appropriate for collisions.

$$m_{N_D} = 1.25v^{0.5}, \quad \text{.... Yard and Mainline Collisions}$$

$$\sigma^2_{N_D} = 2.3v \qquad (4\text{-}4)$$

E. COLLISIONS WITHOUT DAMAGED CARS

A relatively large number of collisions in which no cars are described as either derailing or being damaged have been recorded by the FRA. It is important, in the context of the model of Chapter 2, to determine what proportion of collisions fall into this category, and eliminate them from further consideration.

TABLE 4-4. MEANS AND STANDARD DEVIATIONS OF THE NUMBER OF CARS DERAILING (TRACK-CAUSED DERAILMENTS)

Speed (mph)	Mainline			Yard		
	Data Points	m_{N_D}	σ_{N_D}	Data Points	m_{N_D}	σ_{N_D}
0-10	2875	5.624	4.737	5322	4.447	3.244
11-20	1153	6.867	5.131	100	4.960	3.124
21-30	1162	10.219	7.626	8	7.5	5.1
31-40	368	15.554	11.074	2	5.0	-
41-50	128	17.867	12.704	4	9.75	10.305
51-60	43	16.674	11.767	-	-	-
61-70	6	15.333	12.867	-	-	-
71-80	-	-	-	1	4	-

In the following, it is assumed that P_{CD} is the fraction of collisions in which at least one car is damaged or derailed. The specific number of interest is contained in Table 4-5: $P_{CD} = 0.54$. We thus have the following result for yard and mainline collisions:

P_{CD} = 0.54 (fraction of collisions in which at least one car is derailed or damaged),

$1 - P_{CD}$ = 0.46 (fraction of collisions in which no cars are derailed or damaged).

TABLE 4-5. STATISTICS FOR THE NUMBER OF CARS DERAILED OR DAMAGED IN COLLISIONS

Speed (mph)	Number of Points	m_{N_D}	σ_{N_D}	P_{CD}
0-5	3223	2.1	2.0	.56
6-10	383	2.7	2.3	.53
11-15	100	3.7	3.8	.46
16-20	53	4.7	8.0	.52
21-25	39	5.3	6.5	.57
26-30	32	6.8	6.3	.47
31-35	13	9.4	9.0	.35
36-40	26	8.0	9.0	.43
41-45	14	7.1	5.3	.47
46-50	11	15.1	14.3	.48
51-55	4	*	*	*
56-60	7	*	*	*
61-65	1	*	*	*
66-70	1	*	*	*
71-75	1	*	*	*
76-80	1	*	*	*
>80	1	*	*	*
Overall	3910	2.5	3.0	.54

*Insufficient data.

5. PRESENCE OF HAZARDOUS-MATERIAL CARS IN TRAINS

A. INTRODUCTION

An input needed for the model presented in Chapter 2 is the probability that a train suffering an accident carries hazardous-material cars. This probability, denoted by P_H, may be assigned a value of unity if one is examining the risk associated with trains known to be carrying hazardous materials. On the other hand, if one is analyzing more aggregated risks, historically based estimates of P_H are useful. These estimates are presented in this chapter.

The value of P_H for a given large collection of traffic is determined by another characteristic parameter, the ratio of hazardous-material cars to all cars. This parameter is denoted by π_H. Its historically observed values are presented. The relationship between P_H and π_H is explored, and formulas are presented for estimating P_H values from given values of π_H.

B. RATE OF OCCURRENCE OF HAZARDOUS-MATERIAL CARS

The proportion of hazardous-material cars to all cars in a typical train is denoted by π_H. Thus, if:

N_H = hazardous-material cars per train, and

N_T = total number of cars per train,

then

$$\pi_H = N_H/N_T. \tag{5-1}$$

One estimate of π_H can be obtained by dividing the loaded car-mile estimates for hazardous materials with those for all commodities (data provided by TSC):

$$\pi_H = \frac{4.4 \times 10^8}{1.5 \times 10^{10}} = 0.029.$$

An alternative estimate of π_H can be obtained by assuming that a hazardous-material car has the same probability of being involved in an accident (i.e., being derailed or damaged) as any other car. Then:

$$\pi_H = N_{HD}/N_D , \tag{5-2}$$

where

N_{HD} = number of hazardous-material cars derailed or damaged, and

N_D = total number of cars derailed or damaged.

Data regarding the value of π_H estimated in this fashion for derailments are shown in Table 5-1.

For collisions, the historical values of π_H were found to be as follows:

π_H = 0.020 for all mainline collisions; and

= 0.025 for all yard collisions.

C. PROBABILITY THAT A RANDOM TRAIN CONTAINS HAZARDOUS-MATERIAL CARS

Given an aggregation of traffic in which a fraction π_H of all cars consists of hazardous-material cars, there will be a fraction P_H of all trains that contains one or more hazardous-material cars. There is no direct observation available of this parameter. However, it may be approximated as follows:

$$P_H \cong \frac{\text{No. of Accidents to Trains Carrying Hazardous-Material Cars}}{\text{Total No. of Accidents}} \tag{5-3}$$

When one attempts to estimate P_H in this manner for the various combinations of track type, accident type, track class, and accident cause, the data are found to be sparse, and the estimates are subject to large errors. A way to circumvent this difficulty is to estimate the relationship between P_H and train speed, aggregating over all other

TABLE 5-1. FRACTION OF DERAILING CARS THAT CONTAIN HAZARDOUS MATERIAL

Location	N_{HD}	N_D	$\pi_H = N_{HD}/N_D$
Main	1635	89066	.018
Yard	706	41578	.017
Siding	117	5287	.022
Industry	84	3545	.024
Other	12	615	.020
TOTAL	2554	140091	.018
Main--Class 1	190	13883	.0137
Main--Class 2	400	21396	.0187
Main--Class 3	670	31873	.0210
Main--Class 4	280	16560	.0169
Main--Classes 5 & 6	54	3754	0.0144

factors. An approximate value of P_H is then obtained for each subset of accidents by estimating the average train speed for that subset and obtaining the corresponding value of P_H.

The historical relationship between P_H and train speed is shown in Table 5-2. The derived values of P_H for various accident subsets are shown in Table 5-3.

D. EXTRAPOLATION OF π_H and P_H VALUES

The values of P_H are based on an underlying grand average value of π_H, which can be seen from Table 5-1 to be 0.018. If this value were to change--due to a change in the level of hazardous material being transported--both the π_H values in Table 5-1 and the P_H values in Table 5-3 would change as well.

A reasonable assumption for the π_H values for the accident subsets is that they would all change in the same proportion as the grand average π_H. Thus, if the π_H value for all traffic doubled from 0.018 to 0.036, one might expect π_H for mainline Class 1 accidents to double from 0.0137 to 0.0274.

The change in P_H values is somewhat more complex. Consider a train with N_T cars. Assume that hazardous-material cars occur in groups or blocks, the size of the block being G_H. The train has (N_T/G_H) blocks, each of which might be a hazardous-material block with probability π_H.

The probability that none of the blocks is a hazardous-material block is also the probability that the train carries no hazardous-material cars, and is given by:

$$1 - P_H = (1 - \pi_H)^{N_T/G_H} = \exp\left\{\frac{N_T}{G_H} \ln (1 - \pi_H)\right\} \qquad (5\text{-}4)$$

$$\simeq \exp\left\{- \frac{\pi_H N_T}{G_H}\right\} \text{ for } \pi_H << 1.0.$$

TABLE 5-2. RELATIONSHIP BETWEEN P_H AND TRAIN SPEED

Speed (mph)	P_H
0-5	.058
6-10	.066
11-15	.076
16-20	.103
21-25	.108
26-30	.135
> 31*	.150
Average	.08

*Aggregated because of limited data.

TABLE 5-3. ESTIMATED PROBABILITY THAT A TRAIN IN AN ACCIDENT IS CARRYING HAZARDOUS MATERIALS

Accident Group	Probability P_H
Yard derailments	.057
Mainline derailments	.097
Mainline Class 1 derailments	.052
Mainline Class 2 derailments	.091
Mainline Class 3 derailments	.123
Mainline Class 4 derailments	.114
Mainline Classes 5 and 6 derailments	.128
Track-caused yard derailments	.063
Track-caused mainline derailments	.086
Yard collisions, $N_D > 0$	.081
Mainline collisions, $N_D > 0$	.090
Mainline Class 1 collisions, $N_D > 0$	.071
Mainline Class 2 collisions, $N_D > 0$	.082
Mainline Class 3 collisions, $N_D > 0$	.095
Mainline Class 4 collisions, $N_D > 0$	.101
Mainline Classes 5 and 6 collisions, $N_D > 0$	.110

Thus:

$$P_H = 1 - \exp\left\{-\frac{\pi_H N_T}{G_H}\right\} . \tag{5-5}$$

Designate by P_H' and π_H' the values corresponding to a hypothetical scenario, and by P_H the value corresponding to $\pi_H = 0.018$. When Equation (5-5) is applied to these two pairs of values, the result can be combined to yield the following extrapolating equation for P_H:

$$P_H' = 1 - (1 - P_H)^{\pi_H'/0.018} . \tag{5-6}$$

6. NUMBER OF HAZARDOUS-MATERIAL CARS DERAILING

A. INTRODUCTION

When an accident to a train occurs, a certain number (N_{HD}) of hazardous-material (HM) cars derail. This number is a random variable, strongly influenced by the total number of cars derailing, N_D, and the proportion of hazardous-materials car to all cars, π_H. This chapter presents an approach to estimating the probability distribution of N_{HD}. The approach is to estimate the mean and variance of N_{HD}, and then to fit a gamma distribution to these parameters. The continuous gamma distribution is then made discrete to obtain the distribution of N_{HD}. Formulas are presented for the mean and variance of N_{HD}. The gamma-fitting procedure is then described.

This method is intended for use in situations in which the exact number of hazardous-material cars in a train is not specified. When the number is specified, a more complex model is necessary. This model is presented in Appendix B. The objectives of this work did not call for its numerical application.

B. GENERAL STATISTICAL FORMULAS

Much of the analytical development presented in the following pages uses the two following expressions [1]:

$$E(Y) = E(E(Y|X)) \qquad (6\text{-}1)$$

and

$$Var(Y) = E(Var(Y|X)) + Var(E(Y|X)) \qquad (6\text{-}2)$$

where

E() denotes mean or expected value,

Var() denotes variance, and

$Y|X$ denotes "y given X."

Both Y and X are random variables.

C. MEAN AND VARIANCE OF NUMBER OF HAZARDOUS-MATERIAL CARS DERAILING

Let N_D denote the total number of cars derailing or damaged in an accident, with N_{HD} denoting the number of those that carry hazardous materials.

To compute the expectation and variance of N_{HD} given N_D, we assume that cars are in blocks of length G_H, a random variable. If the overall rate of occurrence of hazardous-material cars is π_H, then the expectation of N_{HD} given N_D and G_H is:

$$E\left[N_{HD} | N_D, G_H\right] = \pi_H N_D \; . \tag{6-3}$$

The number of blocks derailing is (N_D/G_H). For any of these blocks, there is a probability π_H that it is a hazardous-material block with G_H hazardous-material cars, and a probability $(1 - \pi_H)$ that it is not a hazardous-material block. The number of hazardous-material blocks can be taken to be a random variable with a binomial distribution with probability parameter π_H. The variance of the number of hazardous material blocks, given (N_D/G_H) total blocks derailing is therefore [2]:

$$\left[\frac{N_D}{G_H}\right] \pi_H \; (1 - \pi_H).$$

Since each block contains G_H cars, the variance of the number of hazardous-material cars derailing is:

$$\mathrm{Var}(N_{HD} | N_D, G_H = (N_D/G_H) G_H^2 \pi_H (1 - \pi_H). \tag{6-4}$$

Equation (6-2) is next applied to Equation (6-4) to remove the conditional dependence on G_H. The result is:

$$\mathrm{Var}(N_{HD} | N_D) = \pi_H (1 - \pi_H) N_D m_{G_H}, \tag{6-5}$$

where

$$m_{G_H} = E(G_H).$$

When Equation (6-2) is applied once more to Equation (6-5), one obtains the unconditional variance for N_{HD}:

$$\mathrm{Var}(N_{HD}) = \pi_H (1 - \pi_H) m_{G_H} E(N_D) + \pi_H \mathrm{Var}(N_D). \tag{6-6}$$

Similarly, the unconstrained mean value of N_{HD} is obtained by combining Equations (6-1) and (6-3):

$$E(N_{HD}) = \pi_H E(N_D). \tag{6-7}$$

In Chapter 4, it was determined that the following general expressions hold:

$$E(N_D | v) \equiv m_{N_D} = d\, v^{0.5} \tag{6-8}$$

and

$$\mathrm{Var}(N_D | v) \equiv \sigma_{N_D}^2 = ev, \tag{6-9}$$

where v is the speed. The values of d and e are shown in Table 6-1.

TABLE 6-1. VALUES OF REGRESSION CONSTANTS FOR MEAN AND VARIANCE OF N_D

Accident Category	Constant d	 e
Mainline and Yard Derailments (All Causes)	1.7	2.7
Mainline and Yard Derailments (Track-caused)	2.1	2.7
Mainline and Yard Collisions (Given at least one derailing car)	1.25	2.3

Note: $E(N_D) \equiv m_{N_D} = dv^{0.5}$

$\mathrm{Var}(N_D) \equiv \sigma^2_{N_D} = ev$

The unconditional means and variances for N_D can be obtained by applying Equations (6-1) and (6-2) to (6-8) and (6-9):

$$E(N_D) = d\, E(v^{0.5}), \tag{6-10}$$

and

$$Var(N_D) = e\, E(v) + d\, Var(v^{0.5}). \tag{6-11}$$

The mean and variance of $v^{0.5}$ and the mean of v is to be taken over the accident subset that is of interest.

When Equations (6-10) and (6-11) are made conditional on the variables TT, TC, AT and AC, and are then introduced into Equations (6-6) and (6-7), the final, desired expressions are obtained:

$$E(N_{HD}|TT, TC, AT, AC) = \pi_H d\, E(v^{0.5}|TT, TC, AT, AC). \tag{6-12}$$

and

$$\begin{aligned} &Var(N_{HD}|TT, TC, AT, AC) \\ &= \pi_H(1 - \pi_H)\, m_{G_H}\, d\, E(v^{0.5}|TT, TC, AT, AC) \\ &+ \pi_H \left\{(e + d)\, E(v|TT, TC, AT, AC) - d \left[E(v^{0.5}\, TT, TC, AT, AC\right]^2\right\} \end{aligned} \tag{6-13}$$

In Equation (6-13), the following result has been used:

$$\begin{aligned} Var(v^{0.5}|TT, TC, AT, AC) &= E(v|TT, TC, AT, AC) \\ &- \left[E(v^{0.5}|TT, TC, AT, AC\right]^2 \end{aligned}$$

Historical data are not available for the parameter m_{G_H}. A value of $m_{G_H} = 4$ was chosen on the basis that this provided the best fit between historical values of the mean and variance of the number of hazardous-material cars releasing their contents, which are analyzed in Chapter 8.

Values of the conditional means of $v^{0.5}$ and v are given in Table 6-2. These are obtained from FRA accident data. Note that for collisions, the mean values are only for those accidents in which at least one car was reported as being damaged or injured. Thus, when the values from Table 6-2 are used in Equations (6-12) and (6-13) for collisions, the resulting distribution of N_{HD} is conditional on a collision having occurred which $N_D \geq 1.0$. For a random collision, it was noted in Chapter 4 that the probability that $N_D \geq 1$ is $P_{CD} = 0.54$.

D. FITTING A DISTRIBUTION TO THE MEANS AND VARIANCE

Historical data on the number of hazardous-material cars derailing in accidents are shown in Table 6-3. Several one- and two-parameter distributions were fitted to these data, and the gamma distribution was found to approximate the data most accurately, using the Kolmogrov-Smirnov test. The gamma distribution was, therefore, chosen as the generic form for curve-fitting purposes.

When a distribution is developed using the means and variances given in Equations (6-12) and (6-13), it is found that large inaccuracies can occur in the tail of the distribution, essentially because of the large probability that $N_{HD} = 0$. This large probability exists because of the large probability $(1 - P_H)$ that a train in an accident contains no hazardous-material cars. A procedure was therefore developed which yields a gamma distribution conditional on hazardous-material cars being present in the train.

The conditional means and variances for N_{HD} are:

$$E(N_{HD} | N_H \geq 1) = E(N_{HD})/P_H, \qquad (6\text{-}14)$$

TABLE 6-2. MEAN VALUES OF v AND $v^{0.5}$

Accident Group	Mean value of $v^{0.5}$	Mean value of v
Yard derailments	1.89	3.96
Mainline derailments	4.03	18.9
Mainline Class 1 derailments	2.67	7.95
Mainline Class 2 derailments	3.68	14.9
Mainline Class 3 derailments	4.38	21.3
Mainline Class 4 derailments	5.17	29.7
Mainline Class 5 and 6 derailments	5.81	37.6
Track-caused yard derailments	2.28	5.86
Track-caused mainline derailments	3.53	14.6
Yard collisions ($N_D > 0$)	1.74	3.29
Mainline collisions ($N_D > 0$)	3.06	12.6
Mainline Class 1 collisions ($N_D > 0$)	2.15	5.57
Mainline Class 2 collisions ($N_D > 0$)	2.73	9.09
Mainline Class 3 collisions ($N_D > 0$)	3.26	13.6
Mainline Class 4 collisions ($N_D > 0$)	3.51	16.5
Mainline Class 5 & 6 collisions ($N_D > 0$)	4.18	23.5

TABLE 6-3. NUMBER OF HAZARDOUS-MATERIAL CARS DERAILING OR DAMAGED PER ACCIDENT

No. of Cars Derailing	No. of Accidents
0	32,083
1	708
2	236
3	145
4	83
5	40
6	27
7	17
8	7
9	6
10	4
11-15	14
16-20	6
20	1

and

$$\mathrm{Var}(N_{HD}|N_H \geq 1) = \frac{\mathrm{Var}(N_{HD})}{P_H} + \frac{\left[E(N_{HD})\right]^2}{P_H}\left(1 - \frac{1}{P_H}\right), \qquad (6\text{-}15)$$

where N_H is the number of hazardous-material cars in the train.

Once these conditional parameters are derived, by using Equations (6-12) and (6-13), the parameters of the gamma distribution may be obtained.

The gamma distribution is:

$$p(x) = \frac{\lambda^{\eta}}{\Gamma(\eta)} (x)^{\eta-1} \exp(-\lambda x), \qquad (6\text{-}16)$$

where x denotes N_{HD}, given that $N_H \geq 1$.

The parameters λ and η can be obtained from the following expressions:

$$\eta = \frac{\left[E(N_{HD}|N_H \geq 1)\right]^2}{\mathrm{Var}(N_{HD}|N_H \geq 1)}, \quad \lambda = \frac{E(N_{HD}|N_H \geq 1)}{\mathrm{Var}(N_{HD}|N_H \geq 1)}. \qquad (6\text{-}17)$$

One now has an estimate of the complete probability distribution of the number of hazardous material cars derailing, conditional on there being an accident to a train carrying hazardous-material cars. However, this is a continuous distribution, whereas the variable N_{HD} is discrete--it can only take integer values. To overcome this problem, one may determine the probability that N_R = J (some integer) by integrating the area under the probability distribution from J - β to J + 1 - β, where β is a fraction smaller than one.

Then:

$P(N_R = 0|\text{Accident and } N_H > 0)$ = area from 0 to $(1 - \beta)$

$P(N_R = 1|\text{Accident and } N_H > 0)$ = area from $(1 - \beta)$ to $(2 - \beta)$.

and so on.

The value of β was obtained by matching $P(N_{HD} = 0)$ to the historical data. On this basis, β was found to have a value of 0.65.

E. REFERENCES

1. Parzen, E., "Stochastic Processes, Holden-Day, Inc.," 1962.

2. Drake, A. W., "Fundamentals of Applied Probability Theory," McGraw-Hill Book Company, 1967.

7. RELEASE PROBABILITY

A. INTRODUCTION

A factor of considerable interest in any risk analysis model is the probability that a derailed or damaged hazardous-material car will release all or part of its contents. If:

N_{HD} = number of hazardous-material cars derailing or damaged, and

N_R = number of hazardous-material cars releasing all or part of their contents,

then the release probability is defined to be:

$$q = E\left(\frac{N_R}{N_{HD}}\right) \tag{7-1}$$

It is reasonable to assume that the release probability depends on speed; it is therefore written q(v). Historical estimates of its value are presented in the following sections.

B. DERAILMENTS

From the FRA accident data base, empirical distributions of q(v) for derailments on mainline and yard track were tabulated (Tables 7-1 through 7-3). An initial investigation was made to see whether a common q(v) function would be appropriate to all track types. Chi-squared tests (and test on the differences in proportions where appropriate) were performed on the number of cars releasing and not releasing for mainline, yard, and other types of track. The only significant differences are indicated below:

1. On comparing mainline and yards in the 16- to 20-mph range, 57 out of 219 mainline cars released, while 0 out of 12 yard cars released. The test statistic for the proportion difference is:

TABLE 7-1. RELEASE PROBABILITY: DERAILMENTS (1975-1977)

v (mph)	Number of HM Cars Releasing	Number of HM Cars Derailing	q(v)
0-5	53	746	.07
6-10	58	495	.12
11-15	9	147	.06
16-20	61	241	.25
21-25	36	221	.16
26-30	51	176	.29
31-35	32	122	.26
36-40	48	179	.27
41-45	25	76	.33
46-50	31	81	.38
51-55	14	33	.42
56-60	7	14	.5
61-65	-	-	-
66-70	1	23	.04

TABLE 7-2. RELEASE PROBABILITY: MAINLINE DERAILMENTS (1975-1977)

v (mph)	Number of HM Cars Releasing	Number of HM Cars Derailing	q(v)
0-5	11	117	.09
6-10	34	283	.12
11-15	7	112	.06
16-20	57	219	.26
21-25	36	215	.17
26-30	51	176	.29
31-35	31	121	.26
36-40	47	172	.27
41-45	25	74	.34
46-50	31	80	.39
51-55	14	33	.42
56-60	4	10	.40
61-65	-	-	-
66-70	1	23	.04
71-75	-	-	-
76-80	-	-	-
> 80	-	-	-

TABLE 7-3. RELEASE PROBABILITY: YARD DERAILMENTS (1975-1977)

v (mph)	Number of HM Cars Releasing	Number of HM Cars Derailing	q(v)
0-5	26	502	.05
6-10	18	173	.10
11-15	2	17	.12
16-20	-	12	0
21-25	-	1	0
26-30	-	-	-
31-35	1	1	Small sample
36-40	-	-	-
41-45	-	-	-
46-50	-	-	-
51-55	-	-	-
56-60	-	-	-
61-65	-	-	-
66-70	-	-	-
71-75	-	-	-
76-80	-	-	-
> 80	-	-	-

$$\frac{\frac{57}{219} - \frac{0}{12}}{\sqrt{\frac{\hat{p}(1-\hat{p})}{219} + \frac{\hat{p}(1-\hat{p})}{12}}} = 2.04$$

where

$$\hat{p} = \frac{57 + 0}{219 + 12} = 0.25,$$

which is significant at 4 percent.

2. In the 0- to 5-mph range, derailments on "other" types of track show a higher release probability (although mainline and yards are not significantly different), as shown in Table 7-4.

Apart from these speed ranges, there are no significant differences, and thus the overall distribution of Table 7-1 was used.

Several functions were tested as models for q(v). (For simplicity, only one- and two-parameter functions were tested.) The data show a sharp decline in release frequency for the highest speed class, although this is based on only 23 derailments out of a total of 2554 derailments. Therefore, the effect of this apparent outlier point should be mitigated by applying a weighted regression, where the weights are the number of derailments.

The following one-parameter function was within 2.22% of the minimum error and was chosen to simplify the modeling. This function is:

$$q(v) = 0.045\, v^{0.5}\,. \tag{7-2}$$

The total weighted sum-of-squares around the mean was 0.1390, which yields a percentage variation explained of 74%. A graph of q(v) and the empirical values are presented in Figure 7-1.

TABLE 7-4. RELEASE PROBABILITY COMPARISON IN THE 0 TO 5 MPH RANGE FOR VARIOUS TRACK TYPES

Location	Cars Releasing	Cars Not Releasing	Total Cars	q(v)
Mainline	26	476	502	0.052
Yard	11	106	117	0.094
Others	16	111	127	0.126
TOTAL	53	693	746	0.071

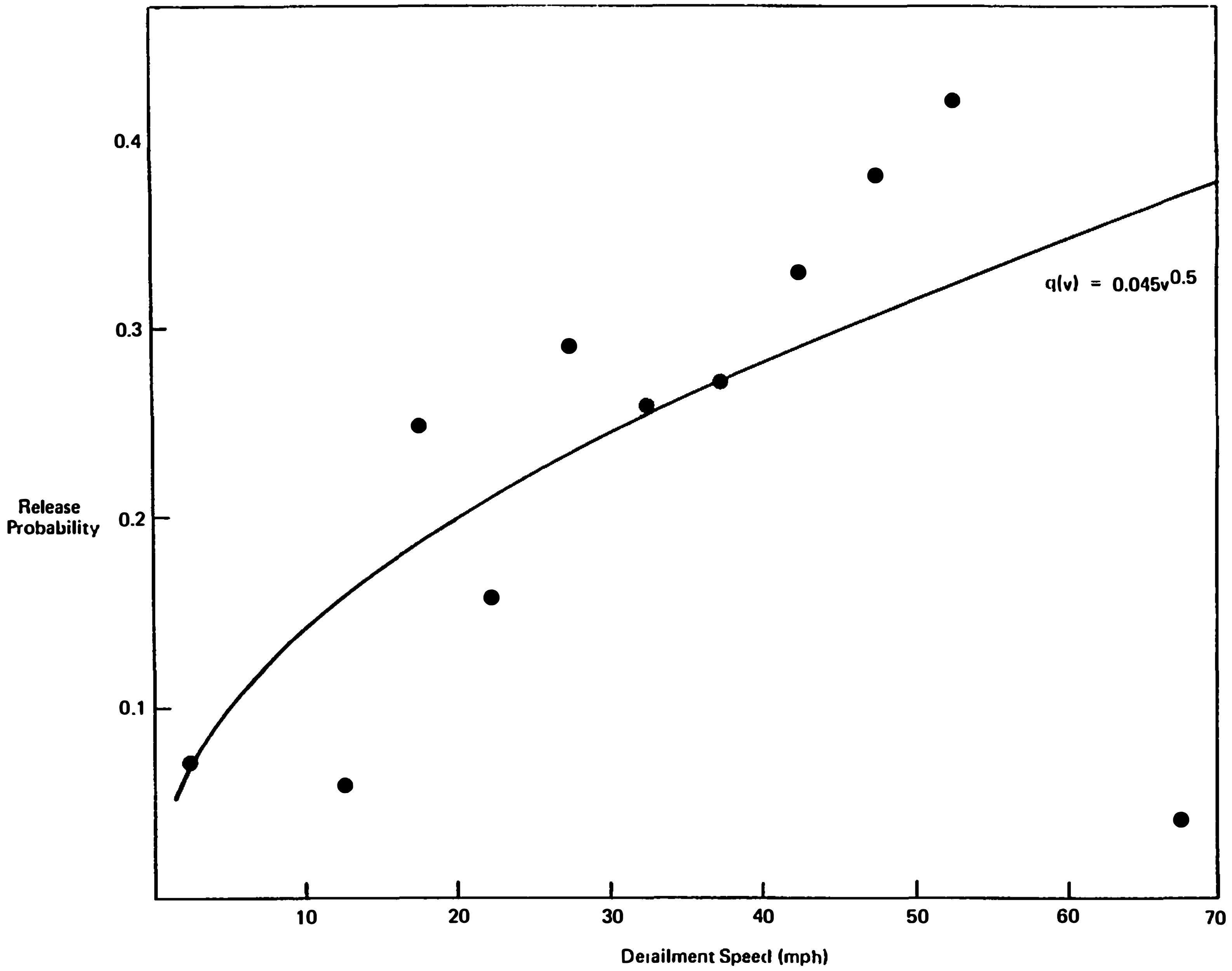

FIGURE 7–1. RELEASE PROBABILITY $q(v)$, SHOWING RAW DATA AND ANALYTICAL REPRESENTATION

C. COLLISIONS

Estimation of q(v) for collisions was hampered by the limited amount of data for hazardous materials releases in collisions. Table 7-5 presents the data for the 1975-1977 period. Although the overall ratio of the number of cars releasing to the number derailed or damaged (i.e., the release probability) of 0.129 is somewhat less than the comparable value for derailments, it is believed that this is partly due to the lower velocities that are generally observed in collisions and partly because of the practice of locating hazardous-material cars away from the ends of trains. Utilizing the functional form of q(v) for derailments, one would expect 15 cars to release out of 205 in the 0- to5-mph range and 4 out of 33 in the 6- to 10-mph range . Historical data are in reasonable agreement with these expectations (considering the sparseness of the data) and, thus, the identical form of q(v) is recommended for collisions as for derailments.

TABLE 7-5. RELEASE PROBABILITIES FOR COLLISIONS (1975-1977)

v (mph)	Number of HM Cars Releasing	Number of HM Cars Derailing	q(v)
0-5	19	205	.093
6-10	1	33	.030
11-15	3	7	.078
16-20	0	1	.000
21-25	1	4	.250
26-30	4	4	1.000
31-35	1	3	.333
36-40	3	5	.600
41-45	0	1	.000
46-50	3	7	.428
71-75	0	1	.000
Overall	35	271	.129

8. NUMBER OF HAZARDOUS-MATERIAL CARS RELEASING THEIR CONTENTS

A. INTRODUCTION

The distribution of the number of hazardous-material cars releasing their contents is analyzed in this chapter. This distribution depends on the distribution of the number of hazardous-material cars derailing, N_{HD}, and on the release probability, q. The issue of how much of hazardous material is released is dealt with in the Chapters 9 and 10.

B. NUMBER OF HAZARDOUS-MATERIAL CARS RELEASING

If a hazardous-material car derails, the probability that it will release its contents is termed the "release probability" and is denoted by q(v), or q. Once such a release occurs, there is a probability 'r' that the initial or primary release will cause a secondary release due to fire from 'k' additional cars, and (1 - r) that no secondary release occurs. Thus, for one derailing hazardous-material car, one has:

$$\text{Prob (1 car releases)} = q(v)\ (1 - r),$$

and

$$\text{Prob (1 + k cars release)} = q(v)\ r.$$

Thus, given one derailing hazardous-material car, the expected number of releasing cars is:

$$\begin{aligned} E(N_R \mid N_{HD} = 1) &= 0 \cdot (1 - q) + 1 \cdot q \cdot (1 - r) + (1 + k) \cdot q \cdot r \\ &= q(1 + kr). \end{aligned} \tag{8-1}$$

The variance can be derived in a similar way:

$$\text{Var}(N_R \mid N_{HD} = 1) = q(1 + 2kr + k^2 r) - q^2\ (1 + 2kr)^2. \tag{8-2}$$

On the assumption that secondary releases are infrequent, it is not unreasonable to assume that the secondary releases caused by each primary release are independent. Then, given N_{HD} hazardous-material cars derailing, the mean and variance for the number of cars releasing are:

$$E(N_R|N_{HD}) = N_{HD} \; E(N_R|N_{HD} = 1),$$

and

$$\mathrm{Var}(N_R|N_{HD}) = N_{HD} \; \mathrm{Var}(N_R|N_{HD} = 1).$$

When Equations (8-1) and (8-2) are introduced into these expressions, one obtains:

$$E(N_R|N_{HD}) = N_{HD} \, q(v) \; (1 + kr), \tag{8-3}$$

and

$$\mathrm{Var}(N_R|N_{HD}) = N_{HD} \left\{ q \; (1 + 2 \, kr + k^2 r) - q^2 \; (1 + kr^2) \right\}. \tag{8-4}$$

Repeated application of Equations (6-1) and (6-2) leads to:

$$E(N_R|TT, \; TC, \; AT, \; AC) = \pi_H (1 + kr) \; E(q \; m_{N_D} | TT, \; TC, \; AT, \; AC) \tag{8-5}$$

and

$$\begin{aligned} \mathrm{Var}(N_R|TT, \; TC, \; AT, \; AC) = {} & \pi_H (1 + 2kr + k^2 r) \; E(q \; m_{N_D} | TT, \; TC, \; AT, \; AC) \\ & + \pi_H \left\{ (1 - \pi_H) \; m_{G_H} - 1 \right\} (1 + kr)^2 \; E(q^2 \; m_{N_D} | TT, \; TC, \; AT, \; AC) \\ & + \pi_H^2 \; (1 + kr)^2 \left\{ E(q^2 \; \sigma_{N_D} \; TT, \; TC, \; AT, \; AC) + \right. \\ & \left. + \mathrm{Var}(q \;_{N_D} | TT, \; TC, \; AT, \; AC) \right\}. \end{aligned} \tag{8-6}$$

The conditional distributions of the number of hazardous-material cars derailing, derived in Chapter 6, have been used here.

Finally, the velocity-dependent expressions derived in Chapter 4 for m_{N_D} and $\sigma^2_{N_D}$ and in Chapter 7 for q are introduced into Equations (8-5) and (8-6) to yield:

$$E(N_R|TT, TC, AT, AC) = \pi_H(1 + kr)\ df\ E(v|TT, TC, AT, AC), \tag{8-7}$$

and

$$\begin{aligned} Var(N_R|TT, TC, AT, AC) &= \pi_H(1 + 2kr + k^2r)\ df\ E(v|TT, TC, AT, AC) \\ &+ \pi_H \left\{(1 - \pi_H)\ m_{G_H} - 1\right\} (1 + kr)^2\ df^2\ E(v^{1.5}|TT, TC, AT, AC) \\ &+ \pi_H^2\ (1 + kr)^2 \left\{(e + d^2)\ f^2\ E(v^2|TT, TC, AT, AC)\right. \\ &\left.- d^2f^2\ [E(v|TT, TC, AT, AC)]^2\right\}. \end{aligned} \tag{8-8}$$

The procedure described in Chapter 6 for fitting the gamma distribution and making it discrete can be applied to Equations (8-7) and (8-8), if a discrete probability distribution for N_R is desired.

The necessary conditional means of the velocity are shown in Table 8-1. As in Chapter 6, the data for collisions are conditional on at least one car derailing or being damaged in the collision. The values of the parameters d, e and f are summarized in Table 8-2.

C. VALUES FOR r, m_{G_H} AND k

Data on 'r' are hard to come by. Some information is available in an Association of American Railroads/Railway Progress Institute (AAR/RPI) Tank Car Safety Research and Test Project Report [1]:

Number of accidents with a release : 434

Number of accidents with a secondary release : 43

TABLE 8-1. MEAN VALUES OF $v^{0.5}$, v, $v^{1.5}$ AND v^2

Accident Group	Mean Value of			
	$v^{0.5}$	v	$v^{1.5}$	v^2
Yard derailments	1.89	3.96	9.53	27.3
Mainline derailments	4.03	18.9	98.5	554
Mainline Class 1 derailments	2.67	7.95	26.5	98.6
Mainline Class 2 derailments	3.68	14.9	64.1	290
Mainline Class 3 derailments	4.38	21.3	111	604
Mainline Class 4 derailments	5.17	29.7	182	1150
Mainline Classes 5 and 6 derailments	5.81	37.6	257	1814
Track-caused yard derailments	2.28	5.86	12.7	32.9
Track-caused mainline derailments	3.53	14.6	68.0	347
Yard collisions $(N_D > 0)$	1.74	3.29	7.23	20.6
Mainline collisions $(N_D > 0)$	3.06	12.6	63.6	362
Mainline Class 1 collisions $(N_D > 0)$	2.15	5.57	17.5	64.6
Mainline Class 2 collisions $(N_D > 0)$	2.73	9.09	35.3	152
Mainline Class 3 collisions $(N_D > 0)$	3.26	13.6	66.8	358
Mainline Class 4 collisions $(N_D > 0)$	3.51	16.5	91.9	555
Mainline Classes 5 & 6 collisions $(N_D > 0)$	4.18	23.5	152	1043

TABLE 8-2. VALUES OF REGRESSION CONSTANTS

Accident Category	Constants		
	d	e	f
Mainline and yard derailments (All causes)	1.7	2.7	0.045
Mainline and yard derailments (Track-caused)	2.1	2.7	0.045
Mainline and yard collisions (Given at least one derailing car)	1.25	2.3	0.045

Note:

$$E(N_D) \equiv m_{N_D} = dv^{0.5}$$

$$Var(N_D) \equiv \sigma^2_{N_D} = ev$$

$$q = fv^{0.5}$$

Thus:

$$r = 43/434 = 0.1 .$$

This estimate must be treated with caution. It is likely to be high because the AAR/RPI project concentrated on severe hazardous-material accidents, which generally have a higher value of r.

Historical data are not available for the parameters m_{G_H} and k. They were assigned values of $m_{G_H} = 4$ and $k = 2$ on the basis that these resulted in the best fit between the predicted and historical values of the mean and variance of N_R, for mainline derailments. With a value of $r = 0.1$, and for $m_{G_H} = 4$, $k = 2$, predicted values are:

$$m_{N_R} = 0.0312$$

$$\sigma^2_{N_R} = 0.0745$$

Predicted values for mainline derailments

The historical values are:

$$m_{N_R} \cong 0.028$$

$$\sigma^2_{N_R} = 0.072$$

Historical values for mainline derailments

It may be seen that the historical and predicted values of m_{N_R} and $\sigma^2_{N_R}$ are fairly close.

D. QUANTITATIVE RESULTS FOR MEANS AND VARIANCES

The velocity moments given in Table 8-1 were introduced into Equations (8-7) and (8-8), along with the parameter values shown in Table 8-2. Using $r = 0.1$, $k = 2$ and $m_{G_H} = 4$, the estimates of the mean and variance of N_R shown in Table 8-3 were obtained.

TABLE 8-3. PREDICTED MEAN AND VARIANCE FOR THE NUMBER OF CARS RELEASING THEIR CONTENTS

Accident Group	m_{N_R}	$\sigma^2_{N_R}$
Yard derailments	.0062	.01172
Mainline derailments	.0312	.0745
Mainline derailments, Class 1	.0100	.0205
Mainline derailments, Class 2	.0255	.0567
Mainline derailments, Class 3	.0413	.0984
Mainline derailments, Class 4	.0461	.1170
Mainline derailments, Classes 5 & 6	.0621	.1660
Track-caused yard derailments	.0102	.0192
Track-caused mainline derailments	.0297	.0680
Yard collisions, $N_D > 0$	.0056	.0104
Mainline collisions, $N_D > 0$	.0170	.0403
Mainline Class 1 collisions, $N_D > 0$	.0075	.0152
Mainline Class 2 collisions, $N_D > 0$	.0122	.0265
Mainline Class 3 collisions, $N_D > 0$	.0184	.0431
Mainline Class 4 collisions, $N_D > 0$	.0223	.0550
Mainline Classes 5 & 6 collisions, $N_D > 0$	.0317	.0836

It is important to note the following conditions on these means and variances:

- They are not conditional on the train carrying at least one hazardous-material car. Thus, means and variances conditional on having $N_H \geq 1$ must be developed for the gamma-fitting process before distributions of N_R are developed. The process is described in Chapter 6; and

- For collisions, the values are conditional on at least one car having been derailed or damaged in the accident.

E. REFERENCE

1. Railway Progress Institute/Association of American Railroads Tank Car Safety Research and Test Project, "Final Phase 01 Report on Accident Review," Review No. RA-01-4-16, June 1972.

9. AMOUNT OF HAZARDOUS MATERIAL RELEASED: MEAN AND VARIANCE

A. INTRODUCTION

The quantity of hazardous material released in an accident, denoted by A_R, is analyzed in this chapter. Its distribution is determined by the distributions of the number of cars releasing (N_R) and of the amount released per car, a_R. Historical data for the distribution of a_R are presented. These data are then used, along with distribution of N_R (obtained in Chapter 8) to obtain analytical results for the means and variance of A_R.

An alternative, more complex procedure is used in Chapter 10 to obtain numerical results for the distribution of A_R. While these numerical results are more accurate, the analytical results presented in the following paragraphs are more generally useful and flexible, and provide more insight.

B. QUANTITY RELEASED PER CAR

When a hazardous-material car releases its contents; it does not necessarily release all of them. In many instances, minor releases occur due to damage to fittings, but nevertheless these releases have to be reported to the FRA and the MTB. To determine how much material is released per car, MTB data were analyzed. Since it might be expected that the quantity released per car is a function of speed, the mean and variance of a_R were plotted as functions of speed, as shown in Figure 9-1. Because of the sparseness of the data, it was not possible to develop separate plots for releases conditional on track class, track type, and so forth. Both the mean and variance appear to increase with an increase in velocity. Unfortunately, there is also a great deal of random fluctuation in the data, primarily because the sample size is small. Statistical tests were performed to compare these statistics for

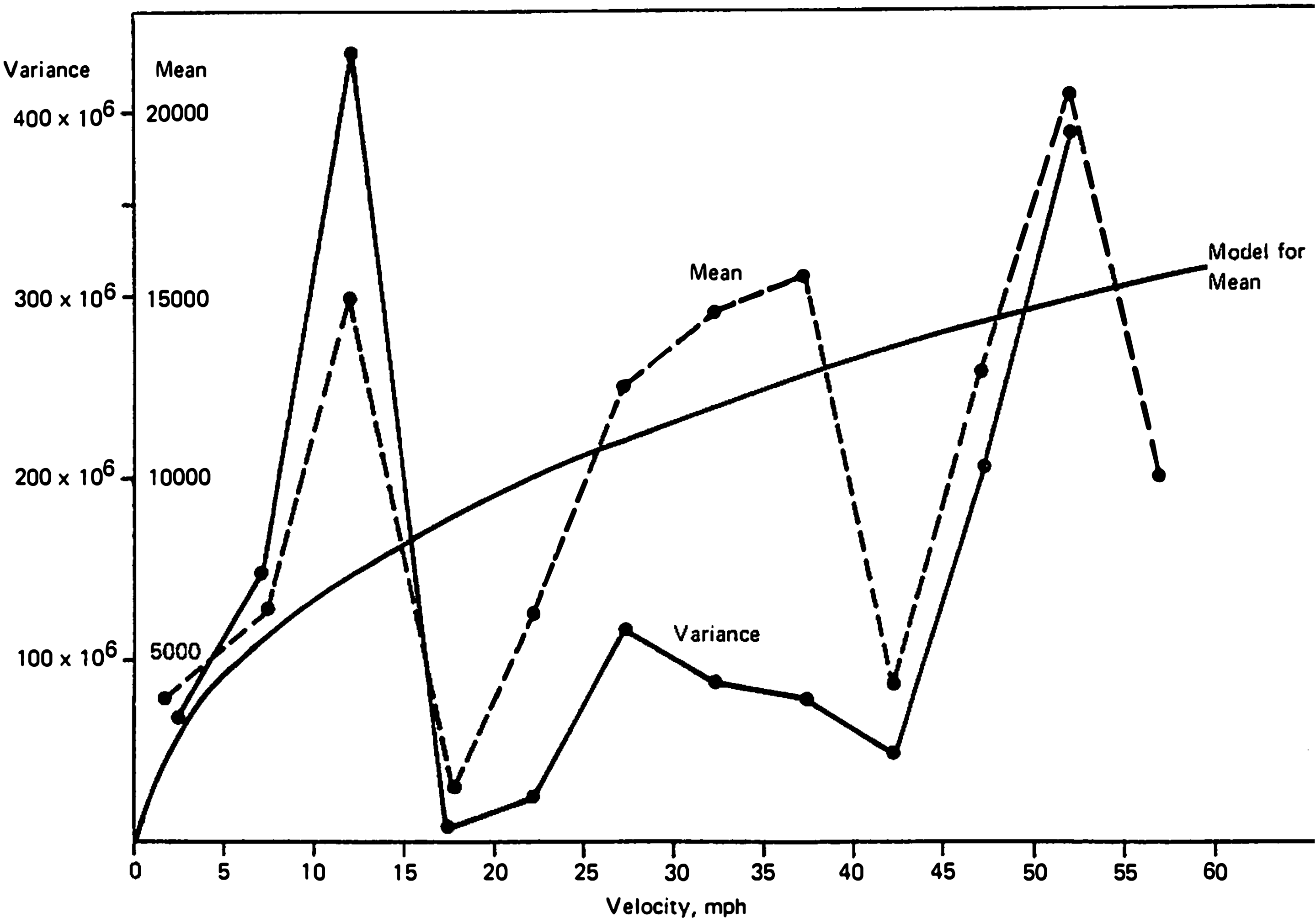

FIGURE 9–1. MEAN AND VARIANCE OF AMOUNT RELEASED PER CAR

releases in accidents occurring at less than and greater than 5 and 10 miles per hour (mph). Table 9-1 presents the mean and variances for these classifications and Table 9-2 presents the results of the statistical tests.

For modeling purposes, a constant value of variance with respect to velocity was assumed. This value is equal to 1.31×10^8 gal^2. The assumption of a constant rather than a slight trend does not affect any of the results in a significant manner. Furthermore, the significance test does not strongly indicate that there is variation with respect to speed. For the means there does appear to be a trend with respect to speed.

The relationships used are:

$$m_{a_R} = 2 \times 10^3 \, v^{0.5} \text{ gallons,} \qquad (9\text{-}1)$$

$$\sigma^2_{a_R} = 1.3 \times 10^8 \, (\text{gallons})^2. \qquad (9\text{-}2)$$

It should be noted that the model assumes that the amounts released from each releasing car are independent and identically distributed. It is difficult to support this assumption, because of the limited amount of data, but this is reasonable from a physical point of view. There were only a limited number of accidents (25) for which releases were recorded and in which there was more than one car releasing. (This was due to the limited amount of Materials Transportation Bureau (MTB) data, which are presented in Figure 9-2.) Although the mean and variance of the amount released per car in these multi-car releases show slight increases over the mean and variance of amount released in one-car accidents, tests show no significant differences. If there is a difference, the statistics do not show it, because of the limited amount of data. It was assumed, therefore, that the amounts released per car are independent, identically distributed random variables.

TABLE 9-1. MEANS AND VARIANCES OF THE AMOUNT RELEASED PER CAR (a_R) FOR SELECTED VELOCITY CATEGORIES, IN GALLONS

Velocity Category	Mean	Variance (millions)
0-5	3767	72
0-10	5175	107
> 5	11044	133
>10	11664	140

TABLE 9-2. TESTS OF SIGNIFICANCE FOR VARIATIONS IN THE MEAN AND VARIANCE OF THE AMOUNT RELEASED PER CAR

Comparison	t-Value	F^*-Value	Significance
Means: 0-5 vs > 5	3.79	-	Very significant
Means: 0-10 vs > 10	3.57	-	Very significant
Variances: 0-5 vs > 5	-	1.85	∿ 1%
Variances: 0-10 vs > 10	-	1.31	Not significant

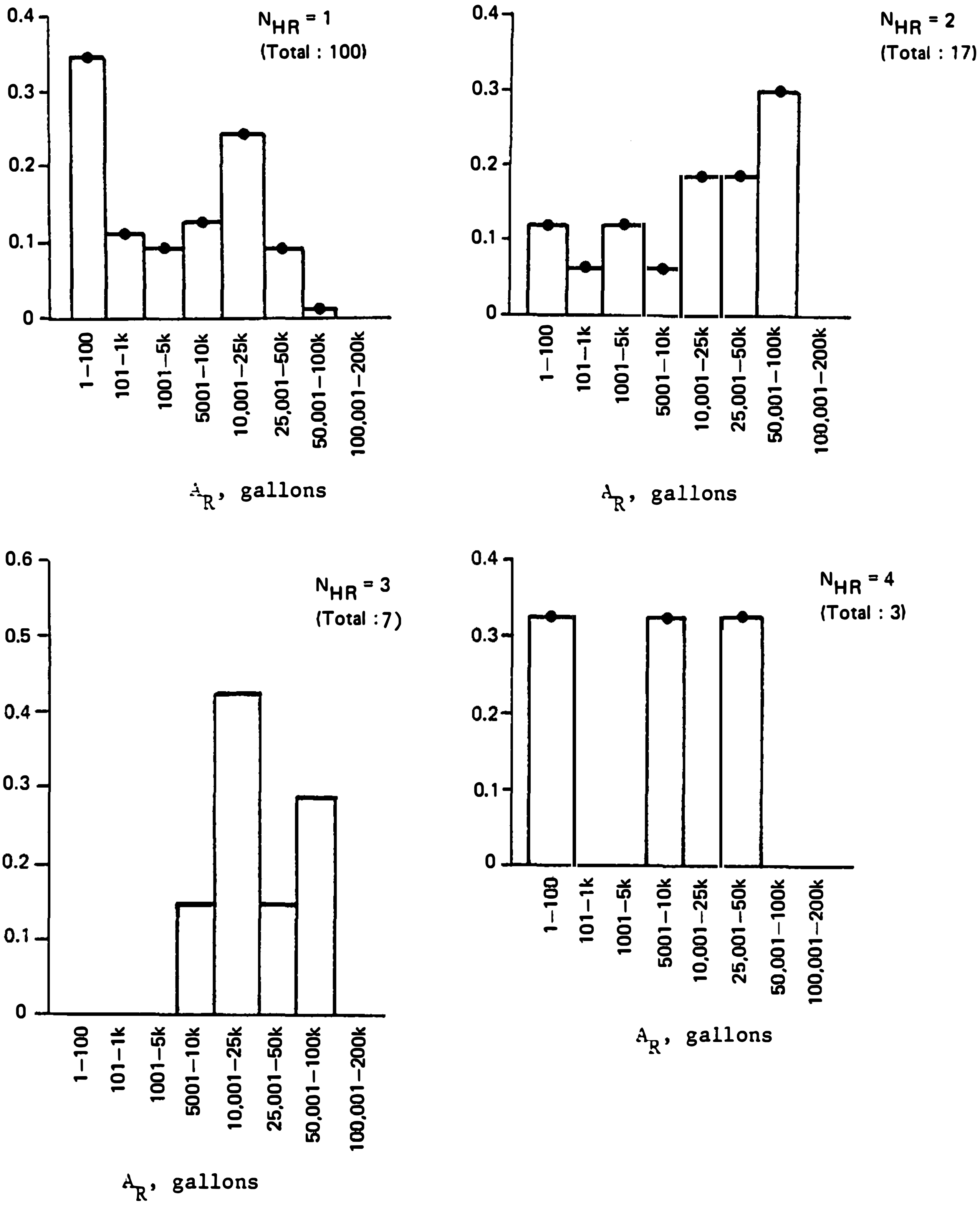

FIGURE 9–2. DISTRIBUTION OF AMOUNT RELEASED AS A FUNCTION OF THE NUMBER OF CARS RELEASING.

(Not shown are one accident with N_{HR} = 5 and A_R = 100–200K gallons, and another with N_{HR} = 6 and A_R = 50–100K gallons.)

C. AMOUNT RELEASED PER ACCIDENT

The amount released from N_R cars has a mean and variance given by:

$$E(A_R|N_R) = N_R\, m_{a_R}, \tag{9-3}$$

and

$$Var(A_R|N_R) = N_R\, \sigma^2_{a_R} \tag{9-4}$$

The means and variances of A_R conditional on an accident having occurred in a given group (defined by TT, TC, AT, and AC) can be obtained by combining Equations (8-5) and (8-6) for the mean and variance of N_R with Equations (9-3) and (9-4), using the process defined by Equations (6-1) and (6-2).

The resulting expressions are:

$$E(A_R|TT, TC, AT, AC) = \pi_H(1 + kr)\, E(m_{N_D}\, a_R q|TT, TC, AT, AC) \tag{9-5}$$

and

$$\begin{aligned}
Var(A_R|TT, TC, AT, AC) &= \pi_H(1 + kr)\sigma^2_{a_R}\, E(m_{N_D} q|TT, TC, AT, AC) \\
&+ \pi_H(1 + 2kr + k^2r)\, E(m_{N_D}\, m^2_{a_R} q|TT, TC, AT, AC) \\
&- \pi_H(1 + kr)^2 \left[1 - m_{G_H}(1 - \pi_H)\right]\, E(m_{N_D}\, m^2_{a_R} q^2|TT, TC, AT, AC) \\
&+ \pi^2_H(1 + kr)^2 \left\{E(\pi_{N_D}\, m^2_{a_R} q^2|TT, TC, AT, AC)\right. \\
&\left. + Var(m_{N_D}\, m_{a_R}\, q|TT, TC, AT, AC)\right\}.
\end{aligned} \tag{9-6}$$

When the following general forms are introduced into Equations (9-5) and (9-6):

$$m_{N_D} = d\ v^{0.5}$$

$$\sigma_{N_D} = ev$$

$$q = f\ v^{0.5}$$

$$m_{a_R} = g\ v^{0.5}$$

$$\sigma_{a_R} = h\ ,$$

One obtains the following expressions:

$$E(A_R|TT,\ TC,\ AT,\ AC) = \pi_H(1 + kr)\ dfg\ E(v^{1.5}|TT,\ TC,\ AT,\ AC) \qquad (9\text{-}7)$$

and

$$\begin{aligned} Var(N_R|TT,\ TC,\ AT,\ AC) &= \pi_H(1 + kr)\ dfh\ E(v|TT,\ TC,\ AT,\ AC) \\ &+ \pi_H(1 + 2kr + k^2r)\ dfg^2\ E(v^2|TT,\ TC,\ AT,\ AC) \\ &- \pi_H(1 + kr)^2 \left[1 - m_{G_H}[1 - \pi_H]\right]\ df^2g^2\ E(v^{2.5}|TT,\ TC,\ AT,\ AC) \\ &+ \pi_H^2(1 + kr)^2 \left\{ fg(efg + d)\ E(v^3|TT,\ TC,\ AT,\ AC) \right. \\ &\qquad \left. - dfg\ [\ E(v^{1.5}|TT,\ TC,\ AT,\ AC)]^2 \right\}\ . \qquad (9\text{-}8) \end{aligned}$$

Values for d, e, f, g and h are shown in Table 9-3. Values for the conditional moments of velocity are presented in Table 9-4.

TABLE 9-3. VALUES OF VARIOUS REGRESSION CONSTANTS

Accident Category	Constant				
	d	e	f	g	h
Mainline and Yard Derailments (All causes)	1.7	2.7	0.045	2×10^3	1.3×10^8
Mainline and Yard Derailments (Track-caused)	2.1	2.7	0.045	2×10^3	1.3×10^8
Main and Yard Collisions	1.25	2.3	0.045	2×10^3	1.3×10^8

Note:

$m_{N_D} = dv^{0.5}$

$\sigma^2_{N_D} = ev$

$q = fv^{0.5}$

$m_{a_R} = gv^{0.5}$

$\sigma^2_{a_R} = h$

TABLE 9-4. MOMENTS OF THE DISTRIBUTION OF ACCIDENT SPEEDS

Accident Group	Expected value of					
	$v^{0.5}$	v	$v^{1.5}$	v^2	$v^{2.5}$	v^3
Yard derailments	1.89	3.96	9.53	27.3	95.5	414
Mainline derailments	4.03	18.9	98.5	554	3300	20500
Mainline Class 1 derailments	2.67	7.95	26.5	98.6	412	1920
Mainline Class 2 derailments	3.68	14.9	64.1	290	1360	6560
Mainline Class 3 derailments	4.38	21.3	111	604	3420	19900
Mainline Class 4 derailments	5.17	29.7	182	1150	7480	49700
Mainline Class 5 and 6 derailments	5.81	37.6	257	1814	13044	95950
Track-caused yard derailments	2.28	5.86	12.7	32.9	99.1	380
Track-caused mainline derailments	3.53	14.6	68.0	347	1890	10700
Yard collisions, $N_D > 0$	1.74	3.29	7.23	20.6	83.6	480
Mainline collisions, $N_D > 0$	3.06	12.6	63.6	362	2220	14200
Mainline Class 1 collisions, $N_D > 0$	2.15	5.57	17.5	64.6	269	1220
Mainline Class 2 collisions, $N_D > 0$	2.73	9.09	35.3	152	702	3400
Mainline Class 3 collisions, $N_D > 0$	3.26	13.6	66.8	358	2030	11900
Mainline Class 4 collisions, $N_D > 0$	3.51	16.5	91.9	555	3510	22900
Mainline Class 5 and 6 collisions, $N_D > 0$	4.18	23.5	152	1043	7425	53750

D. QUANTITATIVE RESULTS FOR MEANS AND VARIANCES

Equations (9-7) and (9-8) may be used to obtain numerical expressions for the mean and variance of A_R. This was done, using the contents of Tables 9-3 and 9-4 and also the parameter values $r = 0.1$, $k = 2$, and $m_{G_H} = 4$. The results are shown in Table 9-5.

E. THE GAMMA-FITTING PROCEDURE

To fit an accurate gamma distribution to the distribution of A_R, it is necessary to recognize the significant probability mass at $A_R = 0$. This mass arises partly from the large probability $(1 - P_H)$ that the train does not carry hazardous materials, but also from the probability that no hazardous-material cars derail, and that even if they do derail, they do not release their contents. It is preferable to obtain means and variances for A_R that are conditional upon a release occurring (i.e., $A_R > 0$) before fitting the gamma distribution.

1. Probability of Release

The probability that a release occurs, given an accident, is denoted by P_R:

$$P_R = P(A_R > 0|\text{Accident}). \tag{9-9}$$

The probability of a release can be derived as follows:

If N_D cars derail, (N_D/G_H) blocks derail. If a block derails, the probability that at least one car in the block releases is:

$$\begin{aligned} 1 - P(\text{none releases}) &= 1 - P(\text{given car does not release})^{G_H} \\ &= 1 - (1 - q)^{G_H}. \end{aligned} \tag{9-10}$$

Thus, the probability that a hazardous-material car releases, given that a block derails is:

TABLE 9-5. MEAN AND VARIANCE OF THE AMOUNT RELEASED PER ACCIDENT

Accident Group	m_{A_R}	$\sigma^2_{A_R}$
Yard derailments	30.33	1.18
Mainline derailments	331.87	13.73
Mainline derailments, Class 1	67.84	2.45
Mainline derailments, Class 2	224.50	8.09
Mainline derailments, Class 3	437.70	17.46
Mainline derailments, Class 4	575.20	25.43
Mainline derailments, Class 5 and 6	866.00	42.40
Track-caused yard derailments	49.80	1.86
Track-caused mainline derailments	283.20	5.75
Yard collisions, $N_D > 0$	24.88	1.05
Mainline collisions, $N_D > 0$	171.60	7.18
Mainline Class 1 collisions, $N_D > 0$	47.20	1.74
Mainline Class 2 collisions, $N_D > 0$	95.40	3.46
Mainline Class 3 collisions, $N_D > 0$	180.40	7.16
Mainline Class 4 collisions, $N_D > 0$	248.00	10.63
Mainline Classes 5 and 6 collisions, $N_D > 0$	410.40	19.47

P(given block is hazmat) P(one releases|hazmat block)

$$= \pi_H \left[1 - (1 - q)^{G_H} \right] . \tag{9-11}$$

Thus, the probability that no hazardous-material car releases is:

$$= \quad \text{P(no cars release|block derails)}^{N_D/G_H}$$

$$= \quad 1 - \pi_H + \pi_H \, (1 - q)^{G_H} \quad {}^{N_D/G_H} \tag{9-12}$$

For a given value of N_D, one can develop a binominal expansion as follows:

$$\text{P(release)} \;=\; 1 - \text{P(no release)}$$

$$\approx \frac{N_D}{G_H} \;\; \pi_H \left[1 - (1 - q)^{G_H} \right]$$

$$\approx \quad 1/2 \left[\pi_H \;\; - (1 - q)^{G_H} \right]^2 \left[\frac{N_D}{G_H} \right] \left[\frac{N_D}{G_H} - 1 \right]$$

$$= \left[\frac{N_D}{G_H} \right] \pi_H \, \bar{q} \; - \; \frac{1}{2} \; (\pi_H \, \bar{q})^2 \; \left[\left(\frac{N_D}{G_H} \right)^2 - \left(\frac{N_D}{G_H} \right) \right] + \; \ldots . \tag{9-13}$$

where

$$\bar{q} \;=\; 1 - \left[1 - q(v) \right]^{G_H} . \tag{9-14}$$

In the expansion, the first term dominates the expression, and thus, the first term alone is an excellent approximation. In addition, at a given velocity, by taking the expected value of N_D, one has:

$$P(A_R > 0|\text{Accident}) = \frac{m_{N_D}}{G_H} = \pi_H \bar{q} \,. \qquad (9\text{-}15)$$

If a distribution of speeds is being used, then the expected value of Equation (9-15) must be computed. Now:

$$\bar{q} = 1 - (1 - q)^{G_H}$$

$$= 1 - (1 - 0.045\ v^{0.5})^{G_H} \qquad \text{(From Chapter 7)}$$

$$\simeq 0.045\ G_H\ v^{0.5} - (1/2)\ G_H(G_H - 1)\ (0.045)^2\ v.$$

Consequently, as a first approximation, $\bar{q}$ varies as the square root of v. As m_{N_D} is also proportional to the square root of v (Chapter 4), the right hand side of Equation (9-15) varies approximately as v. Thus, if v is taken from a distribution, the velocity that should be used in Equation (9-15) is E(v).

2. <u>Modified Mean and Variance for A_R</u>

The procedure for obtaining a mean and variance for A_R given that $A_R > 0$ parallels the procedure described in Chapter 6. The resulting expressions are:

$$E(A_R|TT,\ TC,\ AT,\ AC;\ A_R > 0)$$

$$= m_{A_R}/P_R \qquad (9\text{-}16)$$

and

$$\mathrm{Var}(A_R \mid TT,\ TC,\ AT,\ AC;\ A_R > 0)$$

$$= \frac{\sigma^2_{A_R}}{P_R} + \left(\frac{m_{A_R}}{P_R}\right)(1 - \frac{1}{P_R}) \qquad (9\text{-}17)$$

where

$$m_{A_R} = E(A_R \mid TT,\ TC,\ AT,\ AC)$$

is given by Equation (9-7) and in Table 9-5, and

$$\sigma^2_{A_R} = \mathrm{Var}(A_R \mid TT,\ TC,\ AT,\ AC)$$

is given by Equation (9-8) and in Table 9-5. Estimated values of P_R are given in Table 9-6.

Once the conditional mean and variance are obtained, the remainder of the procedure for obtaining a gamma distribution is identical to that presented in Section 6D. However, the distribution of A_R does not need to be made discrete (while those of N_{HD} or N_R do), since A_R is a continuous variable.

TABLE 9-6. ESTIMATED PROBABILITY THAT A HAZARDOUS MATERIAL IS RELEASED, GIVEN AN ACCIDENT

Accident Group	P_R
Yard derailments	0.0043
Mainline derailments	0.0197
Mainline Class 1 derailments	0.0067
Mainline Class 2 derailments	0.0167
Mainline Class 3 derailments	0.0260
Mainline Class 4 derailments	0.0281
Mainline Class 5 and 6 derailments	0.0368
Track-caused yard derailments	0.0071
Track-caused mainline derailments	0.0192
Yard collisions, $N_D > 0$	0.0039
Mainline collisions, $N_D > 0$	0.0134
Mainline Class 1 collisions, $N_D > 0$	0.0063
Mainline Class 2 collisions, $N_D > 0$	0.0101
Mainline Class 3 collisions, $N_D > 0$	0.0146
Mainline Class 4 collisions, $N_D > 0$	0.0172
Mainline Class 5 and 6 collisions, $N_D > 0$	0.0237

10. AMOUNT OF HAZARDOUS-MATERIAL RELEASED PER ACCIDENT: DISTRIBUTION

A. INTRODUCTION

This chapter provides quantitative results for the distribution of the amount of hazardous material released per accident, A_R, for particular grouping of accidents. These results are not based on the gamma-fitting procedure discussed in Chapter 9. While that procedure provides greater flexibility for general application, it was decided that, for predetermined accident groups, greater accuracy could be obtained by using the procedure described below.

B. THE PROCEDURE

Instead of computing the mean and variance of A_R, one can compute the actual distribution of A_R by starting with the estimated discrete distribution of the number of cars releasing, $P(N_R | TT, TC, AT, AC)$.

Then:

$$P(A_R | TT, TC, AT, AC) = \sum_{M=o}^{\infty} P(N_R = M | TT, TC, AT, AC) \, (a_R^*)^M$$

where $(a_R^*)^M$ denotes the M-th convolution of the distribution of the random variable a_R with itself. The distribution of a_R (which is the amount released per car) is available from historical data; certain parameters of this distribution are shown in Figure 9-1.

C. RESULTS

The distribution of the A_R obtained by applying the method described above are presented in Figures 10-1, 10-2, 10-3 and 10-4. The following conditions apply to these distributions:

- All are conditional on an accident occurring to a train carrying hazardous-material cars (i.e., $N_H > 0$);

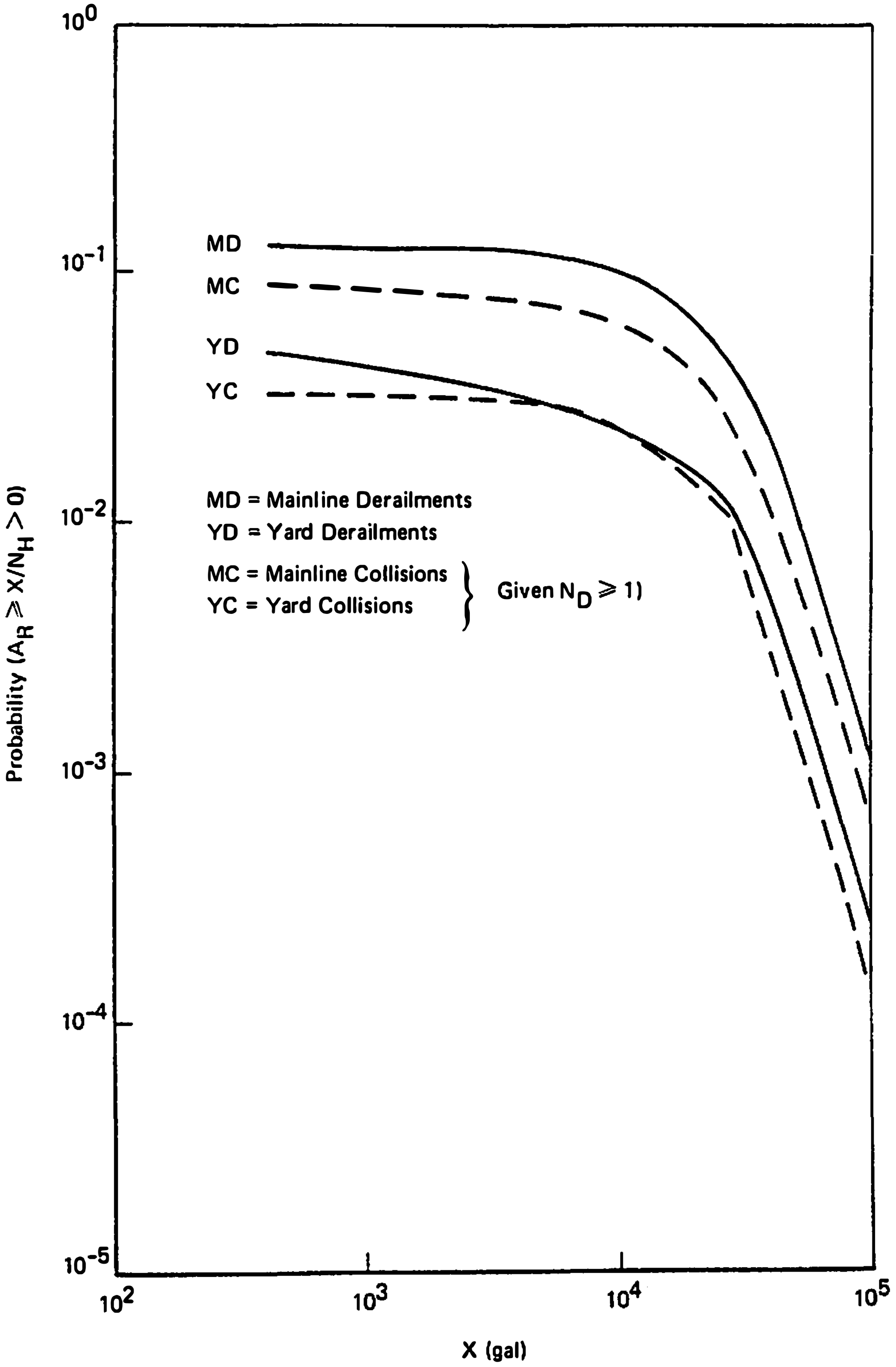

FIGURE 10–1. CUMULATIVE DISTRIBUTIONS OF AMOUNT RELEASED, A_R, GIVEN THAT $N_H > 0$. (ALL MAINLINE AND YARD COLLISIONS AND DERAILMENTS).

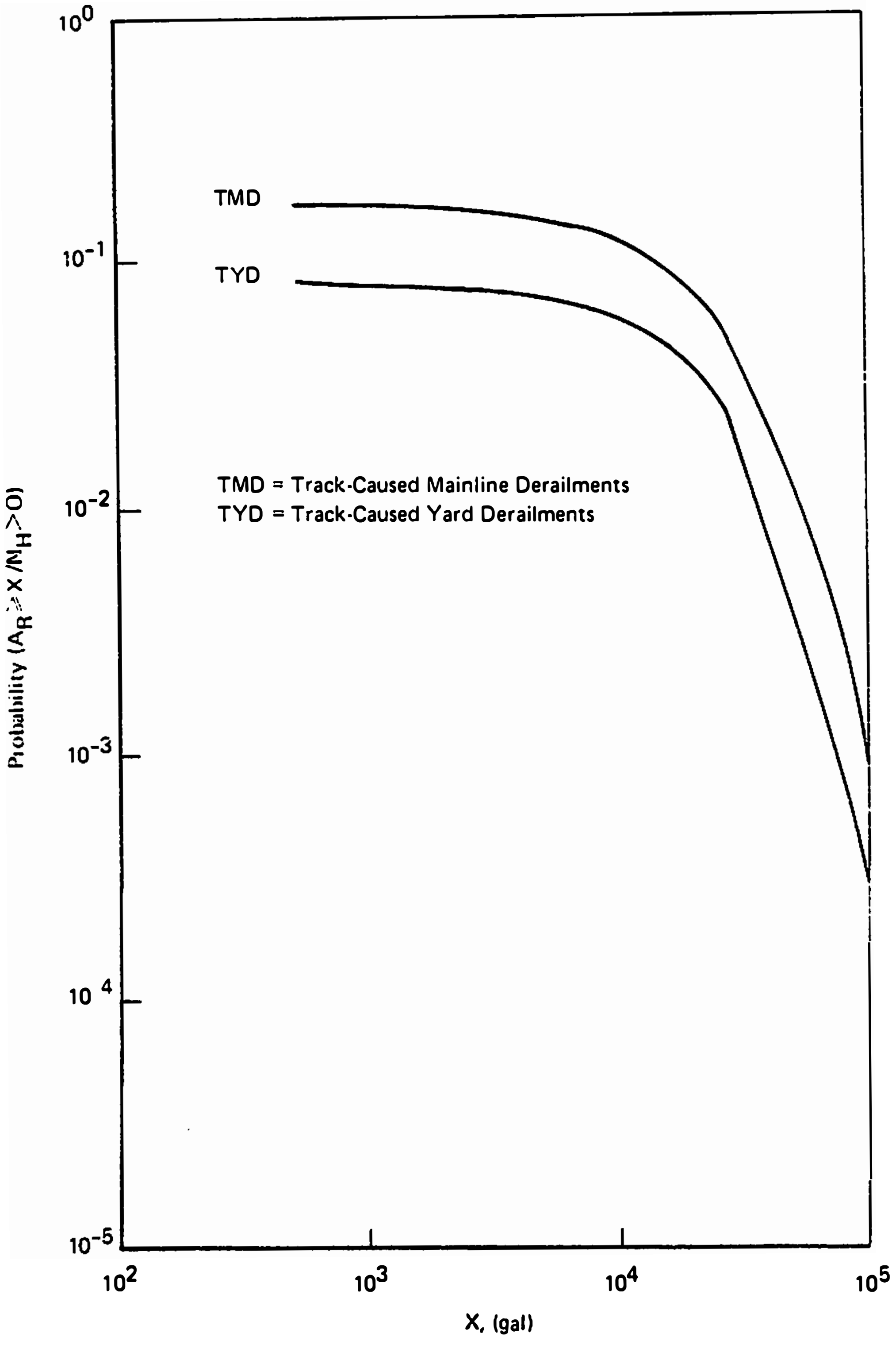

FIGURE 10–2. CUMULATIVE DISTRIBUTIONS OF AMOUNT RELEASED, A_R, GIVEN THAT $N_H > 0$. (ALL TRACK-CAUSED MAINLINE AND YARD DERAILMENTS).

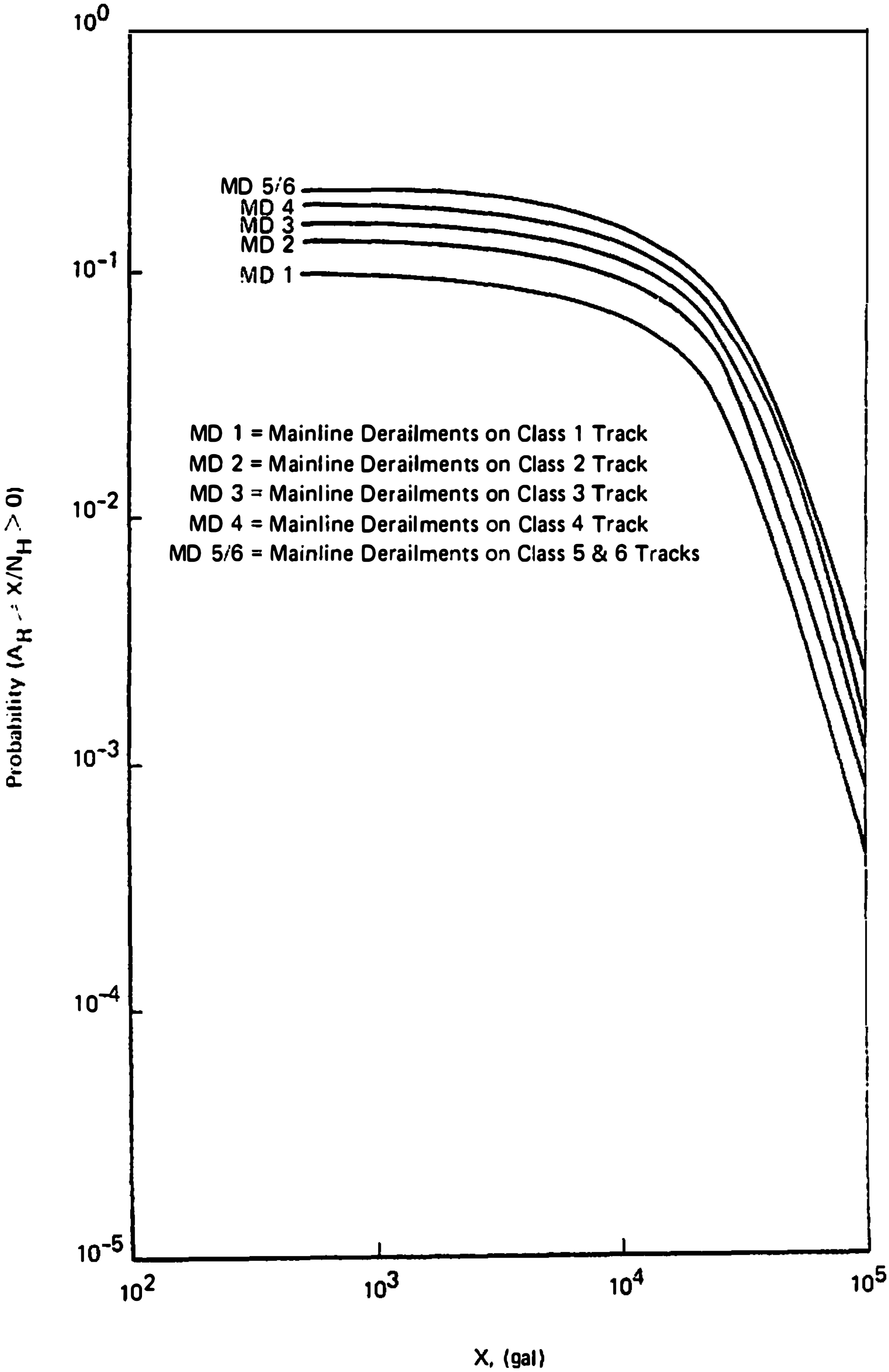

FIGURE 10–3. EFFECT OF TRACK CLASS ON THE CONDITIONAL DISTRIBUTION OF AMOUNT RELEASED FOR MAINLINE DERAILMENTS

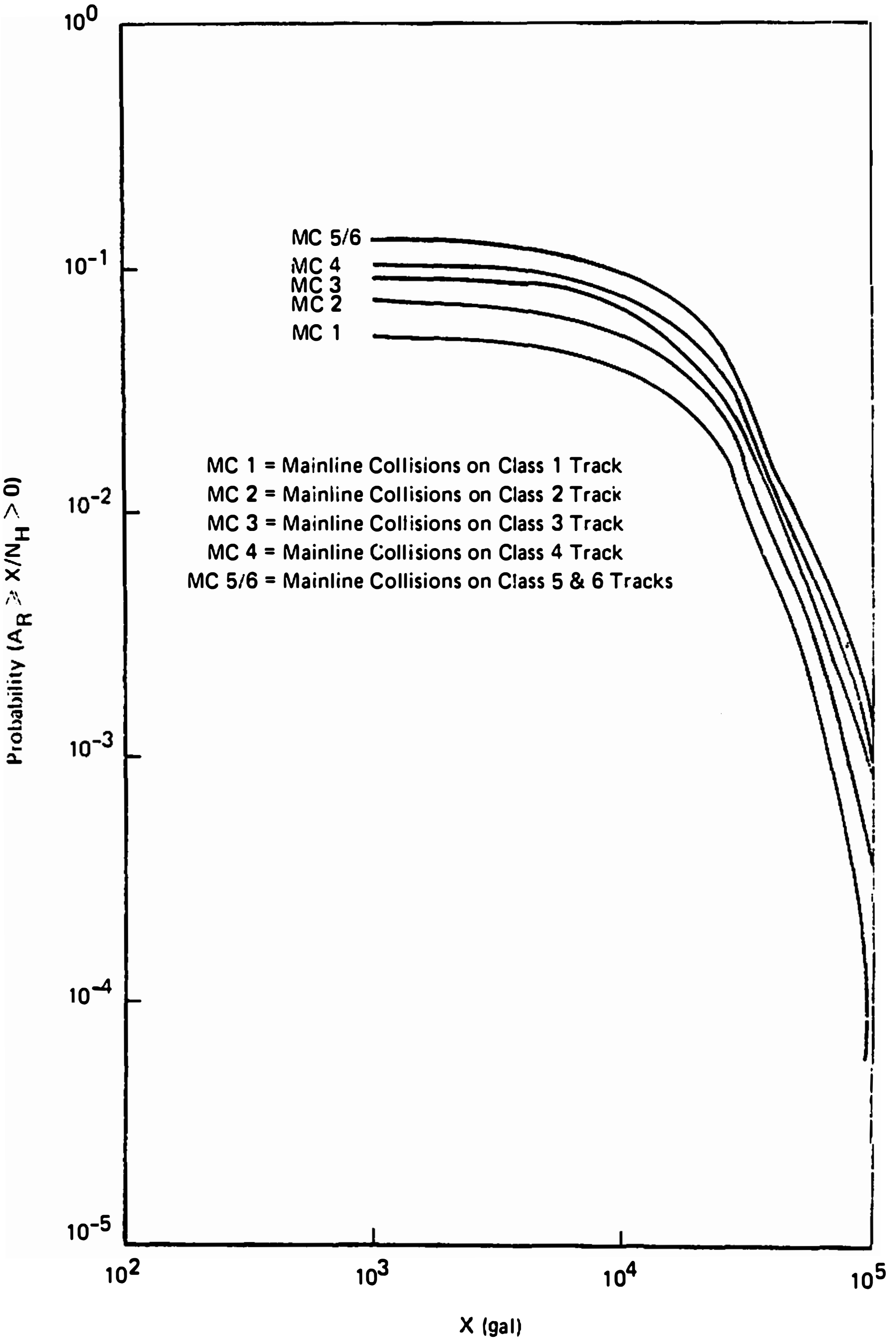

FIGURE 10–4. EFFECTS OF TRACK CLASS ON THE CONDITIONAL DISTRIBUTION OF AMOUNT RELEASED FOR MAINLINE COLLISIONS

- The distributions for collisions are additionally conditional on at least one car derailing or being damaged; and
- The distributions are not conditional on having $A_R > 0$. This condition is not necessary, since the distributions are fully computed, rather than being estimated from their means and variances.

To facilitate the analysis of small releases, Table 10-1 presents the value of $P(A_R = 0 | \text{Accident and } N_H > 0)$. These are the values to which the curves in Figures 10-1 through 10-4 tend as x tends to zero.

D. ACCURACY CHECK

Data on the amount released per accident were obtained from the Materials Transportation Bureau (MTB) data base, and are compared with the estimates resulting from the "simple" (parameter estimation and gamma-fitting) model of Chapter 9 and the "complex" (parameter estimation, gamma-fitting, and convolution) model of Chapter 10 and shown in Table 10-2. Significant differences exist: the historical data show that the probability that the amount released is less than 1000 gallons is 0.37, while the models provide estimates of 0.22 and 0.27. There is reason to believe that the differences may result from biases in the data, resulting principally from missing data regarding the amount released in some large accidents. An alternative test was constructed by using historical data for the distributions of both the number of cars releasing and the amount released per car in a convolution procedure, to estimate a synthetic distribution for the amount released per accident. This distribution is shown in the last column in Table 10-2. It may be seen that, in comparison with this historically based computation, the complex model provides excellent results, while the simple model is reasonably accurate.

E. APPLICATION OF PROCEDURE

The following is a step-by-step summary of how to obtain a distribution of the amount released.

TABLE 10-1. PROBABILITY THAT $A_R = 0$ GIVEN AN ACCIDENT WITH $N_H > 0$

Accident Group	$P(A_R = 0 \mid \text{Accident} \;\&\; N_H > 0$
Yard derailments	0.924
Mainline derailments	0.796
Mainline Class 1 derailments	0.970
Mainline Class 2 derailments	0.816
Mainline Class 3 derailments	0.787
Mainline Class 4 derailments	0.752
Mainline Class 5 & 6 derailments	0.711
Track-caused yard derailments	0.886
Track-caused mainline derailments	0.776
Yard collisions ($N_D > 0$)	0.952
Mainline collisions ($N_D > 0$)	0.880
Mainline Class 1 collisions ($N_D > 0$)	0.928
Mainline Class 2 collisions ($N_D > 0$)	0.901
Mainline Class 3 collisions ($N_D > 0$)	0.876
Mainline Class 4 collisions ($N_D > 0$)	0.863
Mainline Class 5 & 6 collisions ($N_D > 0$)	0.826

TABLE 10-2. COMPARISONS OF TABULATED RELEASE DISTRIBUTIONS GIVEN $A_R > 0$ FOR DERAILMENTS

X (Gallons)	$P_r (A_R \leq X \mid A_R > 0)$			
	Empirical[1] Observations	Simple[2] Model	Complex[3] Model	Historically[4] Based Computation
1,000	.37	.22	.27	.29
5,000	.49	.43	.36	.39
10,000	.61	.59	.47	.50
25,000	.83	.83	.74	.78
50,000	.92	.95	.95	.965
100,000	.99	.996	.996	.994

[1] 130 MTB accidents.

[2] Model described in Chapter 9.

[3] Model described in this chapter, Section B.

[4] Uses convolution procedure, incorporating historical distributions for number of cars releasing as well as the amount released per car.

1. Choose the track type, TT (yard, main); Track Class, TC (1 through 5 & 6; for main track only); Accident Type, AT (derailments and collisions); and accident cause, AC (all causes and track causes);

2. Determine the accident rate from the data in Chapter 3;

3. Determine the expected accident frequency by combining accident rates with estimates of exposure;

4. For an accident, determine the probability P_H that the train carries hazardous materials, and for collisions, that at least one car is derailed or damaged, P_{CD}. Values for P_{CD} are presented in Chapter 4 and for P_H in Chapter 5;

5. Given an accident, the probability that $A_R = 0$ is given by:

   $$(1 - P_R)$$

   where P_R is the probability of a release, given in Table 9-6;

6. Given an accident, the distribution of A_R is obtained by multiplying the curves in Figures 10-1 through 10-4 by P_H for derailments and by P_H P_{CD} for collisions; and

7. Given N accidents within a group, the probability distribution for A_R is obtained by taking the N-th convolution of the distribution obtained in step 6, above.

11. ERROR ANALYSIS OF THE RISK ESTIMATES

A. INTRODUCTION

An invariable concern in performing a risk analysis is the accuracy of the risk estimates that are developed. This concern expresses itself in two different ways:

1) If the predicted risk is low in some absolute sense, how likely is it that the risk is understated, and by how much? The desire here is to make sure that one is not being lulled into a false sense of security.

2) Conversely, there is an equal desire not to be alarmist: to make sure, when high levels of risk are predicted, that one is not grossly overestimating them.

In the literature on risk analysis, this concern is typically addressed by developing "confidence bounds" on estimates of risk. This term is a misnomer, because the bounds are not statistically valid ones, with an associated confidence level. The bounds are usually developed by a series of qualitative, intuitive arguments, which have a ring of plausibility to them, but which are not capable of proof. Despite this shortcoming, they are valuable because they provide a measure of insight into the accuracy--or lack thereof--of the estimates of risk.

In the present project, an attempt was made to develop rigorous confidence bounds, with some measure of success. Qualitative and quantitative reasoning had to be combined to develop useful estimates of error. The overall process is described here, along with recommended bounds for the probability distribution of the amount released, A_R. This description is preceded by a discussion of various sources of error in the risk estimation procedures developed in this report.

B. SOURCES OF ERROR

1. Inadequate Historical Experience

The risk estimates are based, to a large extent, on historical data regarding releases of hazardous materials. To the extent that these data are sparse, the possibility exists that they represent a biased sample, and that future experience may be different. There is no rigorous way to quantify this error, except through analytical modeling which, of course, begs the whole issue of the accuracy of analytical models.

2. Systematic Errors in Historical Data

Systematic errors may exist in historical accident data. Possible examples include misreporting of accident cause and train speed, and the absence of data on the amount of hazardous materials released in some large accidents. To the extent that these errors can be measured, they can be corrected for, and have been in this report. If only qualitative information regarding the extent of these errors exists, the appropriate course is to perform an analysis of the sensitivity of the risk estimates to data errors.

3. Errors in Quantitative Modeling

Several models have been developed in the preceding chapters, for estimating the distributions of such random variables as train speed, total number of cars derailing, probability that a train carries hazardous materials, number of hazardous-material cars derailing, release probability, and amount released per car. Many of these models are based on historical data and involve a curve-fitting procedure which smoothes out fluctuations in the data. This smoothing procedure may be regarded as a logical method of correcting sampling errors in the data. On the other hand, differences between the fitted curve and the data may equally well be regarded as modeling errors.

4. Errors in Model Structure

It is conceivable that some significant independent variable that alters risks has not been included in the analytical models. To the extent that the value of this variable in a future application of the models is different from its implicit value in the historical data on which the models are based, errors will occur in predicting risk. An example of such a hidden variable is a true measure of track quality. This report has used a surrogate for this variable; viz., track class. It is known that the quality of track (and, conceivably, the derailment rate) may vary widely within a given track class. The models developed in this report are based on a nationwide averaging within each class of track. When applying these models, if the segments of track within a track class are sufficiently short, they may differ significantly in quality from the nationwide class average, and thus lead to errors in the risk estimates.

Since errors of this type are forced by the lack of historical data on pertinent variables, there is no routine procedure for estimating their magnitude. In some instances, imaginative procedures can be developed, but they would involve substantial effort and have not, therefore, been pursued in this project. As an example, the nation's track within a given track class could be segmented into several major groups--based on the owning railroad, for example. Accident rates can then be derived for each group, and statistical tests made to determine the significance of the differences, if any.

C. REVIEW OF RISK-ESTIMATION PROCEDURE

For convenience, the overall structure of the risk-estimation procedure is reviewed here. In the context of this discussion, "risk" is synonymous with "the probability distribution of the amount released."

The first step is to determine the probability of a train accident, P_A, or the expected frequency of train accidents, m_F. The key historical variable is the accident rate, discussed in Section 3-G.

The second step is to determine the probability P_H that the train carries hazardous materials, $P_H = P(N_H > 0)$, where N_H is the number of hazardous-material cars.

The third step is to determine the probability $P(A_R > 0 \mid \text{Accident and } N_H > 0)$ that the amount released is greater than zero, given that a train carrying hazardous materials has been involved in an accident.

The fourth step is to determine the probability distribution $P(A_R \mid A_R > 0)$ for the amount released, given that it is greater than zero. (The combined results of the second, third and fourth steps are presented in the tabulations in Chapter 10.)

The fifth and final step is to appropriately combine the four steps to develop an unconditional probability distribution for the amount released. In this context, it is important to note that, in many situations, this distribution will have a significant mass, or probability, at $A_R = 0$; i.e., the probability that no release occurs at all may be close to unity. The cumulative probability that a spill occurs will be small, and will be significantly altered by the probability that no spill occurs. It is therefore possibly more important to estimate the errors in the probability that $A_R = 0$ than in the distribution of A_R, given that it is greater than zero.

D. QUANTITATIVE ERROR ESTIMATES

1. Train Accident Rates

Train derailment rates are estimated in Chapter 3, Section F, to have the following values per gross ton-mile:

Class of Track	1	2	3	4	5&6
Rate* per Billion GTM	53.2	17.3	5.59	0.589	0.840

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*All causes.

There is no analytically correct and practicable procedure for estimating bounds on these rates. An intuitively acceptable procedure has been devised and is recommended for use. For Class 3 track, as an example, the upper bound on the rate is taken to be the geometric mean of the rates for Classes 2 and 3; the lower bound is the geometric mean of the rates for Classes 3 and 4. For Class 1, the upper bound is taken to be:

$$\text{Rate}_1 \times \left(\frac{\text{Rate}_1}{\text{Lower Bound}_1} \right) = \text{Rate}_1 \times \left(\frac{\text{Rate}_1}{\sqrt{\text{Rate}_1 \ \text{Rate}_2}} \right)$$

$$= (\text{Rate}_1)^{3/2} \div \sqrt{\text{Rate}_2} \ .$$

Similarly, the lower bound for Class 4 is to be:

$$(\text{Rate}_4)^{3/2} \div \sqrt{\text{Rate}_3} \ .$$

Based on this procedure, the tabulation shown in Table 11-1 is arrived at.

Because of the anomalous behavior of Classes 5 and 6, this procedure cannot be applied to them. Because of their relatively small level of exposure, it was not considered important to develop bounds for their rates.

It is also recommended that the same procedure be applied to track-caused derailments and to collisions. The results are as shown in Tables 11-2 and 11-3.

For yard accident rates, it is recommended that the bounds be derived by examining the bounding factors for Class 1 mainline accidents; the ratio of the upper bound to the best estimate and of the best estimate to the lower bound is 1.96 for derailments and 1.55 for collisions. If the same factors are used for yard accidents, the values shown in Table 11-4 are obtained.

TABLE 11-1. UPPER AND LOWER BOUNDS FOR ACCIDENT RATES FOR VARIOUS CLASSES OF TRACK: ALL MAINLINE DERAILMENTS

Class of Track	1	2	3	4
Lower-bound Rate*	30.3	9.83	1.82	0.191
Best Estimate Rate*	53.2	17.3	5.59	0.589
Upper-bound Rate*	94.5	30.3	9.83	1.82

*Per billion GTM.

TABLE 11-2. UPPER AND LOWER BOUND ESTIMATES FOR ACCIDENT RATES FOR VARIOUS CLASSES OF TRACK: TRACK-CAUSED MAINLINE DERAILMENTS

Class of Track	1	2	3	4
Lower-bound Rate*	16.9	4.24	0.624	0.056
Best Estimate Rate*	33.1	8.64	2.08	0.187
Upper-bound Rate*	64.8	16.9	4.24	0.624

*Per billion GTM.

TABLE 11-3. UPPER AND LOWER BOUND ESTIMATES FOR ACCIDENTS FOR VARIOUS CLASSES OF TRACK: MAINLINE COLLISIONS

Class of Track	1	2	3	4
Upper-bound Rate*	8.50	4.26	1.11	0.125
Best Estimate Rate*	13.2	5.47	3.32	0.372
Lower-bound Rate*	20.5	8.50	4.26	1.11

*Per 10^{17} $(\text{gross-ton})^2$ miles.

TABLE 11-4. UPPER AND LOWER BOUND ESTIMATES FOR ACCIDENT RATES IN YARDS: DERAILMENTS AND COLLISIONS DUE TO ALL CAUSES

	Yard Derailments	Yard Collisions
Upper-bound Rate*	15.5	7.0
Best Estimate Rate*	7.9	4.5
Lower-bound Rate*	4.0	2.9

*Accidents per 10^6 cars.

2. Probability That Hazardous Materials are Present

Given a train accident, the probability that hazardous materials are present on the train is P_H. Historical estimate of P_H are given in Table 5-3; a model for estimating P_H in new situations is presented in Chapter 5, Section D. A parameter in that model is π_H, the proportion of hazardous-material cars to all cars. In the following the sensitivity of P_H to variations in π_H is examined, for the class of mainline derailments.

For mainline derailments, historical data indicate that:

π_H = 0.018 (Table 5-1) and P_H = 0.097 (Table 5-3).

Table 5-1 also indicates that within mainline track, π_H varies from a low of 0.014 for Class 5 track to a high of 0.021 for Class 3 track. Using these as likely bounds on the value of π_H for all mainline derailments, the formula in Chapter 5, Section D indicates that P_H would vary from 0.076 to 0.119. This analysis suggests that the following would be reasonable bounds for P_H for mainline derailments:

Uper bound = 0.097 x 1.2 = 0.116

Lower bound = 0.097 ÷ 1.2 = 0.081.

The factor of 1.2 is used to obtain symmetric bounds that closely approximate the observed bounds of 0.076 and 0.119, respectively.

It is also recommended that the same ratio of 1.2 be applied to obtain bounds on P_H for other accident scenarios.

3. Probability of a Release

The probability of a release, given a train accident, is:

$$P(A_R > 0)|\text{Accident}) = P_H \times P(A_R > 0|\text{Accident } \& \ N_H > 0),$$

the second term on the right being the conditional probability of a release, given that an accident occurs to a train carrying hazardous materials. Bounds on the factor P_H have already been discussed. The conditional probability in the above expression depends principally on two factors: the release probability q(v) and the number of hazardous-material cars derailing, given a train accident. Uncertainties in the latter factor have been dealt with in the analytical model, which is represented by both its mean and variance. The release probability, on the other hand, is presented only by its expectation. Reference to Figure 7-1 indicates that the regression actually used can vary significantly from the observed values. Typical errors are on the order of ± 30%. If the estimates of q(v) are increased and decreased by these amounts for mainline derailments, one finds that $P(A_R > 0 \mid \text{Accident and } N_H > 0)$ varies in direct proportion, ranging from a low of 0.143 to a high of 0.265, with a best estimate of 0.204. (See Table 10-1. For mainline derailments, the probability that $A_R = 0$ is 0.796. The complement of this, 0.204, is the probability that $A_R > 0$.) It is recommended that factors of 0.7 and 1.3 be applied to obtain lower and upper bounds on $P(A_R > 0 \mid \text{Accident and } N_H > 0)$, for all accident scenarios.

4. Distribution of Amount Released, Given a Release

The final step is to estimate errors in the conditional probability distribution:

$$P(A_R \mid A_R > 0).$$

For example, this cumulative distribution for mainline derailments may be derived as follows from Figure 10-1:

$$P(A_R \leq x \; A_R > 0) = \frac{P(A_R \leq x \; N_H > 0) - P(A_R = 0 \mid N_H > 0}{1 - P(A_R = 0 \mid N_H > 0)}$$

$$= \frac{P(A_R \leq x \mid N_H > 0) - 0.796}{0.204}$$

Thus,

$$P(A_R \leq 1000 | A_R > 0) = \frac{0.054}{0.204} = 0.265.$$

A rigorous lower bound was developed for the cumulative distribution $P(A_R | A_R > 0)$ for all mainline derailments. Two methods of estimating the upper bound were used, one based on estimating sampling error in the observed releases for which the MTB data base provided data, and the second based on applying the Chebyshev inequality to the observed distribution of the amount released, given a release. This inequality states that:

$$P(A_R \geq x | A_R > 0) \leq \frac{E(A_R | A_R > 0)}{x}$$

The two bounds were developed for several values of $A_R = x$, and that one was used which was closer to the estimated distributions based on Figures 10-1 through 10-4. This is a 95 percent confidence level lower bound. The ratio of the lower bound to the best estimate was then determined, and applied in an inverse fashion to determine an upper bound. The results are as shown in Table 11-5.

As can be seen, the bounds are fairly tight, except at low values of x, where the importance of confidence bounds is diminished in any case.

It is recommended that, for ease of application, a ratio of 1.1 (or its inverse) be applied in all instances to obtain lower and upper bounds on the cumulative probability distribution $P(A_R \leq x | A_R > 0)$. When this results in an upper bound on the probability larger than unity, the upper bound should be set equal to 1.

TABLE 11-5. UPPER AND LOWER BOUND ESTIMATES FOR THE CUMULATIVE DISTRIBUTION OF THE AMOUNT RELEASED PER ACCIDENT: ALL MAINLINE DERAILMENTS

Amount Released, x	$P(A_R \leq x \mid A_R > 0)$ Lower Bound	Best Estimate	Upper Bound	Ratio
1,000	0.21	0.27	0.35	1.33
5,000	0.34	0.35	0.36	1.03
10,000	0.43	0.47	0.51	1.09
25,000	0.73	0.74	0.75	1.01
50,000	0.83	0.95	1.00	1.14
100,000	0.94	0.995	1.00	1.06
200,000	0.97	0.9999	1.00	1.03

12. AREA AFFECTED BY A RELEASE

A. INTRODUCTION

The objective of this chapter is to develop an easily applied methodology for the probabilistic estimation of the impact of hazardous-material releases upon the public and its personal property, given the amount released in an accident, A_R. The techniques used for estimating the probability of a hazardous-material accident and the distribution of the amount released, given such an accident, are discussed in preceding chapters. A guideline observed in developing the methodology was that it should be sufficiently general to permit impact assessment for most categories of hazardous materials with minimal input from the user as to the specific characteristics of the transport route and its environs.

The development of a satisfactory methodology required consideration of three constraints:

1. The requirement that the method allow rapid risk assessments of the transport of hazardous materials within entire regions of the United States, the implication being that one could not assume the ready availability of detailed data for every segment of any particular route in order to perform a risk assessment.

2. The method had to address the risks due to broad categories of hazardous materials, allowing the use of consolidated commodity flow data. Thus, the impact assessment method would have to incorporate the average characteristics of those hazardous materials that comprise each of the several broad categories.

3. Since the specific environmental, topographical, and demographic characteristics of each route segment would not be available for use, and since hazardous materials were to be addressed in terms of broad categories, impact models for these categories should encompass only those major phenomena that characterize each category, i.e., they cannot and should not attempt to model the unique features or hazards associated with specific materials within any given category. (This constraint logically follows from the first two.)

The outline of this chapter provides a convenient format for description of the approach that was developed. The sections of interest in sequence are entitled:

- Selection of Hazardous-Material Categories,
- Identification of Feasible Scenarios and Necessary Models,
- Damage Criteria,
- Selection of Representative Chemicals: Approaches to Impact Assessment,
- Impact Assessment Methods, and
- Summary of Impact Assessment Results

Although there are 35 categories of hazardous materials designated by four-digit Standard Transportation Commodity Codes (STCC), the actual number of categories requiring detailed consideration is far fewer. In the next section, the rationale for consolidating or deleting categories down to a total number of 12 is examined. Shipments of explosives and radioactive materials were not included in the evaluation.

Section B considers the three basic physical states of hazardous materials (compressed gases, liquids, and solids) and outlines their basic characteristics in terms of possible events upon their release.

Section C identifies the generic assessment models needed to assess the <u>hazards</u> for any given release. Details of the models themselves are presented in Appendix C, while Appendix D describes how each is to be applied.

Hazard-assessment models generally provide an estimate of the magnitude of a harmful physical parameter, such as the overpressure from an explosion, as a function of spatial coordinates and elapsed time. Section D--Damage Criteria--reviews the literature with the purpose of relating levels of such physical parameters to expected effects on human beings and on property. Ultimately, this allows estimation of the distance from the release site within which people may expire, suffer injury, or within which buildings may be damaged. Thus, an impact assessment can be defined as the coupling of a hazard-assessment methodology with a methodology relating levels of damage to physical parameters.

Section E presents the methodology for choosing specific hazardous materials to represent each of the 12 categories. In addition, it describes how the results of impact assessments for these materials were consolidated to provide estimates of the "average" and "worst case" impacts associated with each category.

Most hazardous materials can cause more than one basic effect upon release. A liquefied compressed gas, for example, may vent as a gas and/or as a liquid. The gas may ignite to form a flame jet, travel downwind and ignite to produce a flash fire or detonation, or harm exposed people due to inhalation. The liquid may flash or form a pool, ignite to produce a pool fire, and so on. Section F--Impact Assessment Methods--which covers conditional scenario probabilities, attempts to estimate the relative probability of each major scenario feasible for each of the 12 categories of hazardous materials chosen previously.

Section G--Summary of Impact Assessment Results--provides the actual results of assessment model application to each of the representative hazardous materials. For each feasible chain of events, it summarizes affected areas and associated conditional probabilities of occurrence as a function of the amount released, A_R.

Conservative assumptions have been made in a number of the impact-assessment models. Thus, we expect that the methodology as presented will give an overestimate of the absolute value of the impact. However, the models are valid for making comparisons between risk-control alternatives, this being the major objective behind the development of the assessment models.

B. SELECTION OF HAZARDOUS-MATERIAL CATEGORIES

1. Background

Commodity flow data for hazardous materials are recorded in accordance with the Standard Transportation Commodity Code (STCC) classification scheme. At the four-digit level, these codes designate 35 individual categories, many of which are quite similar to others in chemical and physical attributes.

An analysis of the behavior of hazardous materials upon their release and of the various mechanisms by which the public or its property can be adversely affected reveals that there are far fewer such mechanisms than there are STCC categories. Indeed, one can only envision the following actions of hazardous materials involved in a typical railroad accident:

- The hazardous material remains in the container;
- Gas vents from the tank;
- Liquid vents from the tank;
- Spilled liquid has a low vapor pressure--it does not evaporate;
- Spilled liquid rapidly vaporizes (due to boiling);
- Spilled liquid slowly volatilizes; and
- The solid spills and remains upon the ground.

Depending upon whether the hazardous material is ignited or not, the only significant damage mechanisms are the following:

- Fires or burns due to thermal radiation exposure after gas, vapor, liquid, or solid ignition;
- Injury or damage due to the effects of an explosion;
- Injury due to toxic vapor or gas inhalation;
- Injury or damage due to direct contact with the hazardous material;

- Injury or damage due to contact with, or inhalation of, radioactive materials; and

- Injury due to rocketing of car fragments.

The difference between the number of four-digit STCC categories and the number of post-release phenomena suggests that an attempt to consolidate the 35 STCC categories into a more managable and pertinent set is warranted. This is accomplished below through a systematic evaluation of each category, elimination of those that are not desired or cannot be addressed by the current study, and consolidation of those which are differentiated by attributes not pertinent to the task of impact assessment.

2. Class A, B, and C Explosives

Comprehensive commodity flow data for explosives are generally unavailable to the Department of Transportation, since most such materials are shipped under the direction of the Department of Defense. Consequently, the hazardous materials comprising the three STCC categories for explosives are not addressed in this study.

3. Compressed Gases

The category of non-flammable compressed gases includes a wide variety of compressed gases, either liquefied or non-liquefied, that do not meet the flammability criteria set forth in 49CFR 173.300(b). Within this group are those materials which may be oxidizing, cryogenic, poisonous or corrosive, or possess combinations of these attributes, as well as those that may be simple asphyxiants. Similarly, the major category of flammable compressed gases includes substances that are pyrophoric (which is rare), oxidizing, poisonous, corrosive, or even detonable under the proper conditions, as well again as those which are simple asphyxiants if not ignited.

Because of the rather unique properties and hazards of the materials in these categories, it is prudent to retain the individual classifications, "Non-flammable Compressed Gas" and "Flammable Compressed Gas," in subsequent analyses.

4. Flammable Liquids

The five STCC categories encompassing flammable liquids include all materials that are liquids at ambient pressures and temperatures and which have flash points below 100°F (37.8°C). Members of subgroups may also be pyrophoric, thermally unstable, poisonous, polymerizable, or corrosive.

All of these materials have the basic attributes of being relatively volatile liquids with a high fire hazard and the potential for toxic vapor exposure or injury by direct contact. Consequently, the five individual categories can reasonably be consolidated into the single category of "Flammable Liquids."

5. Combustible Liquids

Three STCC categories exist for liquids with flash points at or above 100°F (37.8°C) and below 200°F (93.3°C). With generally lower vapor pressures, the hazardous materials covered are not so hazardous as flammable liquids. Nevertheless, under appropriate conditions, those with flash points near the lower end of the given range can produce the major impact scenarios associated with flammable liquids. It is feasible to consider all such materials under the single category of "Combustible Liquids."

6. Flammable Solids

According to 49 CFR 173.150, a "flammable solid is any solid material, other than one classed as an explosive, which, under conditions normally incident to transportation, is liable to cause fires through friction, retained heat from manufacturing or processing, or which can be ignited readily, and, when ignited, burns so vigorously and persistently as to create a serious transportation hazard. Included in this class are spontaneously combustible and water-reactive materials." Such substances are covered by two STCC categories including such diverse materials as oily rags, fish scraps, phosphorus, and metallic sodium.

The first four-digit STCC category (49 16) for these hazardous materials includes mainly specific chemical or metallic materials (such as phosphorus, metallic sodium, powdered magnesium, and the like) which have an unusual hazard potential. Thus, it is recommended that this category be retained as a separate entity. The second category consisting mainly of ordinary combustibles such as rubber scrap, oily rags, fish scrap, and ground charcoal, must therefore also be kept separate. To differentiate between them, the first will be referred to as "Flammable Solids--Special Hazard" and the second as "Flammable Solids--Ordinary Hazard."

7. Oxidizing Materials

An oxidizer is a substance that readily yields oxygen to stimulate the combustion of organic matter. The single STCC number for this category covers liquids, such as fuming nitric acid as well as numerous solids. Since a single STCC number is provided and solids are not classified separately from liquids, the single category of "Oxidizing Materials" is appropriate for further analyses.

8. Organic Peroxides

With certain qualifications, an organic peroxide is generally a derivative of hydrogen peroxide in which one or more of the hydrogen atoms has been replaced by organic radicals. Relatively few in number, the substances covered by this category include both solids and liquids and can be addressed as a single category.

9. Poison Class A and Poison Class B

Class A poisons are gases or liquids of such a nature that a very small amount of the gas or vapor of the liquid when mixed with air becomes dangerous to life. Class B poisons are liquids or solids, other than Class A poisons or irritating materials, which are known to be so toxic to man as to create a hazard to health during transportation; or which, in the absence of adequate data on human toxicity, are presumed to be toxic to man because they fall within any one of the three specified toxicity categories when tested on laboratory animals. The various substances designated as Class A or B poisons may also be flammable, oxidizing, or corrosive.

Since "Class A" refers to gases and liquids, and since these physical states, on average, disperse more widely than the states associated with Class B poisons, it is necessary to retain each class as a separate entity. These will be referred to by the terms "Poison Class A" and "Poison Class B."

10. Irritating Materials and Etiologic Agents

An irritating material is a liquid or solid substance, not including any Class A poisonous material, that, upon contact with fire or when exposed to air, gives off dangerous or intensely irritating fumes. An etiologic agent is a viable micro-organism, or its toxin, which causes or may cause human disease. Since there is a single category for these materials, and they have some unique properties, the category is retained with the designation "Irritating Materials."

11. Radioactive Materials

Because of the special nature of radioactive materials and the considerable complexity and difficulty in assessing the impact of releases to the environment, it was decided that these hazardous materials would not be addressed in this study.

12. Corrosive Materials

A corrosive material is a liquid or solid that causes visible destruction or irreversible alterations in human skin tissue at the site of contact, or, in the case of leakage from its packaging, a liquid that exhibits a severe corrosion rate on steel. Within the seven four-digit STCC categories devoted to this category are included substances which are additionally poisonous, or in the unique case of bromine, also oxidizing.

The nature of the seven STCC categories does not allow or warrant their differentiation in subsequent aspects of this analysis. Consequently, all seven categories can be consolidated into the single category of "Corrosive Materials."

13. Other Restricted Articles: Groups A, B, and C

These three STCC categories--Groups A, B, and C--are a "catchall," for materials that do not meet any definition of a hazardous material *per se*, but which nevertheless have certain undesirable properties. Since the materials cannot be considered significantly hazardous and may have vastly dissimilar properties, they are not included in the subsequent analysis.

14. Summary

Table 12-1 presents a summary of the categories remaining after consolidation or deletion of the 35 individual classifications originally considered. In addition, it notes the four-digit STCC numbers covered by each category.

Table 12-2 is a compilation of data from the Material Transportation Bureau from 1971 through 1977. These data indicate that the 12 categories in Table 12-1 cover 100% of all deaths due to hazardous-material release, 98% of all injuries, and 99% of all releases. It is apparent that the deletion of certain STCC categories does not significantly alter the coverage of the types of impact of greatest concern.

C. IDENTIFICATION OF FEASIBLE SCENARIOS AND NECESSARY MODELS

1. Background

The task of impact modeling requires the identification of analytical techniques for estimating the area that will be affected by a hazardous-material release. This effort, in turn, requires identification of those phenomena which are capable of causing death, injury, or property damage upon release of the hazardous material.

TABLE 12-1. SUMMARY OF SELECTED HAZARDOUS-MATERIAL CATEGORIES

Category	STCC Numbers
1. Non-flammable compressed gases	4904
2. Flammable compressed gases	4905
3. Flammable liquids	4906, 4907, 4908, 4909, 4910
4. Combustible liquids	4912, 4913, 4915
5. Flammable solids: special hazard	4916
6. Flammable solid: ordinary hazard	4917
7. Oxidizing materials	4918
8. Organic peroxides	4919
9. Poison Class A	4920
10. Poison Class B	4921, 4923
11. Irritating materials	4925
12. Corrosives	4930 through 4936

Note: STCC numbers deleted from consideration include: 4901-4903 for explosives, 4926-4929 for radioactive substances, and 4940, 4943 and 4946 for "other restricted articles."

TABLE 12-2. RELATIVE COMPARISON OF HAZARDOUS-MATERIAL GROUPS BY SEVERITY MEASURE*

Commodity	Number Killed	Number Injured	Number of Releases
Explosives	0	60	42
Non-flammable compressed gas	2	450	378
Flammable compressed gas	14	345	562
Flammable liquid	1	275	1043
Flammable solid	2	85	86
Oxidizer	0	30	325
Organic peroxide	0	5	1
Toxic	0	125	190
Radioactive	0	0	6
Corrosive	0	1555	1749
Miscellaneous	0	0	6
Total	18	2930	4388

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*Based on data from Materials Transportation Bureau for 1971-1977.

2. Release Scenarios

It is best to discuss release phenomena in the context of the physical and chemical properties of substances. Therefore, the basic categories of gases, liquids, and solids are investigated in the following subsections to identify phenomena of interest for subsequent modeling efforts.

a. Compressed or Liquefied Gases

Figure 12-1 shows an event tree for the events that are most likely to occur when a tank car of compressed or liquefied gas is involved in a railroad accident. Starting from the accident itself at the top of the diagram, rectangles identify the discrete series of events that may follow.

For massive releases of gas or flashed vapors, it is evident that a vapor dispersion model is necessary; one preferably designed for instantaneous releases to the atmosphere. It is also clear that:

- The model must allow estimation of the size of the hazard zone in the event that the cloud ignites to cause a flash fire or a free-air detonation;
- Some method is needed to estimate the probability of cloud ignition as a function of time; and
- An approach is desirable for estimating the amount of vented liquid that immediately flashes to vapor.

Immediate ignition of venting gas requires a flame-jet model, whereas ignition of spilled liquid necessitates a model for pool fires. Slow evaporation of a liquid after supercooling and pooling suggest the need for a technique for estimating the rate of an evaporation, as well as a continuous-source vapor-dispersion model. Finally, the possibility that the tank car may experience a boiling liquid expanding vapor explosion (BLEVE), or otherwise explode, requires yet another method for hazard-zone estimation.

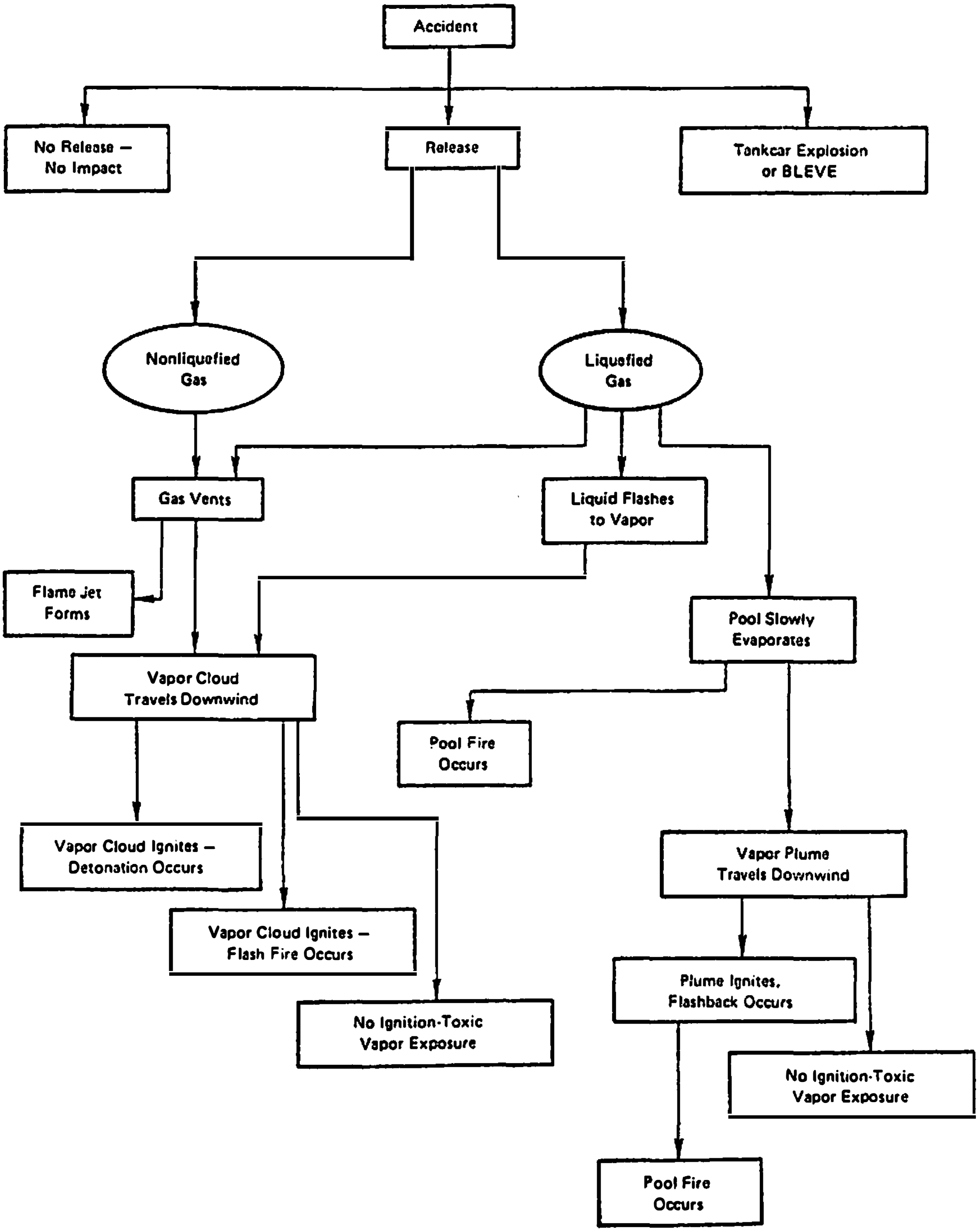

FIGURE 12–1. EVENT TREE FOR COMPRESSED GASES

Scenarios not addressed by the event tree include spills of soluble liquids into water and the subsequent use of that water for public consumption or crop irrigation. In addition, no consideration is given to any harmful effects of such spills upon aquatic wildlife.

b. Liquids

If liquid spills into water are ignored, scenarios of interest will be those shown in the event tree of Figure 12-2. These scenarios are a subset of those presented for compressed gases, and any models provided for liquefied gases should be adaptable to these liquids of lower volatility.

c. Solids

Formulation of an event tree for releases of solids is not necessary because these rarely cause major injury or damage. Two models suffice: one for the burning of ordinary combustibles, and another for the burning of substances with special hazards.

d. Summary

Based upon the results of the previous analysis, it is possible to develop a model "flowsheet" that designates the required models and shows how the output of some models satisfies the input requirements of others. Figure 12-3 presents such a flowsheet; the capital letters A through M are used to indicate individual models.

3. Details of Models

Appendix C provides details of each of the hazard models utilized in the study. Appendix D describes how the models were applied for the purposes of impact assessment.

D. DAMAGE CRITERIA

1. Background

Hazard-assessment models permit users to estimate the concentration levels of toxic and physical agents at specified locations and times

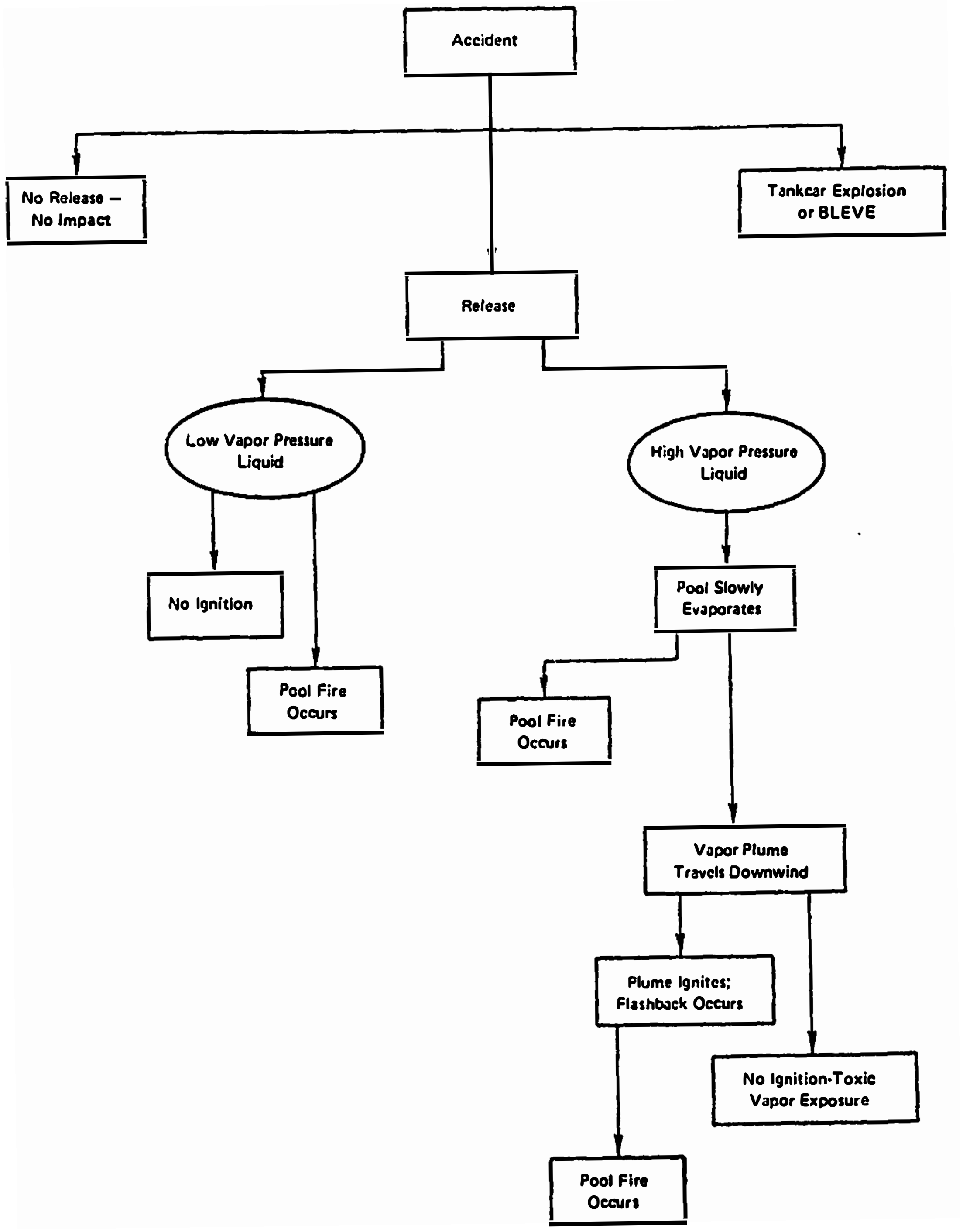

FIGURE 12–2. EVENT TREE FOR LIQUIDS

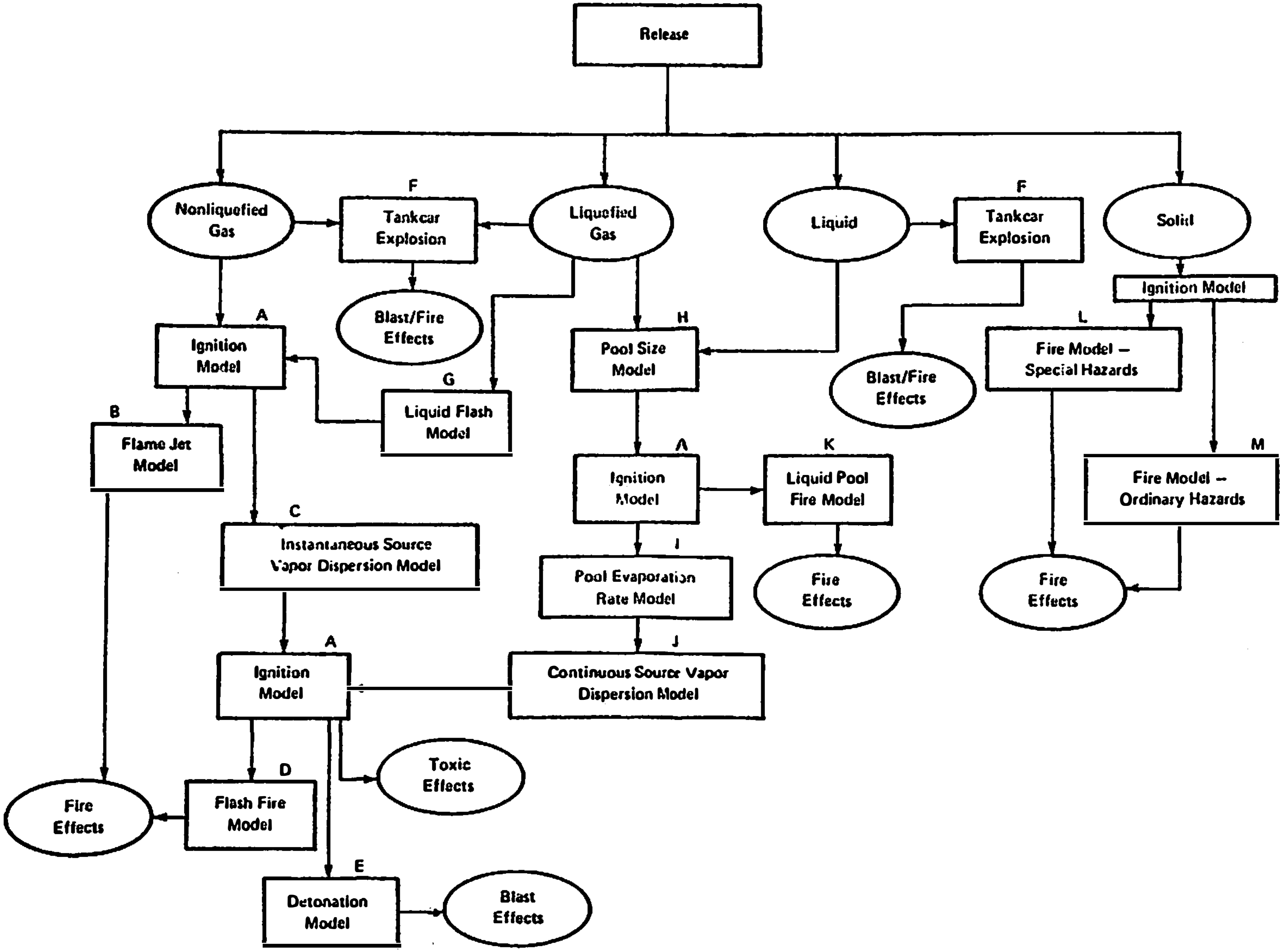

FIGURE 12–3. MODEL UTILIZATION FLOWSHEET

after a spill. For overall risk-assessment purposes, however, their results must be translated into estimates of the harm to members of the public and their property.

2. Explosion Effects

Appendix D of Ref. [1] notes the necessity of relying upon the results of studies conducted for and by the Military in assessing damage caused by explosions. Although such studies have concentrated upon investigations of condensed-phase and nuclear explosions, as opposed to the diffuse explosions more typically expected from the release of hazardous materials, results stated in terms of basic blast wave parameters (overpressure, for example) can be considered sufficiently accurate for universal application.

In documentation cited above [1], prepared for the U.S. Coast Guard during its vulnerability modeling program, the available damage-assessment techniques are reviewed and expressions directly applicable to the current study are derived. These are presented in the following subsections along with discussions as to how they should be utilized.

a. Classification of Effects on Humans

Numerous documents and studies have classified damage to people caused by explosions into three categories:

1. Primary Damage--Direct blast effects caused by the interaction between the blast wave and personnel only, with no other intervening factors;
2. Secondary Damage--Injury due to missiles and fragments; and
3. Tertiary Damage--Injury due to translation (violent movement due to the blast wave) and subsequent collision with an obstacle.

b. Primary Damage

Reference [1] utilizes data from Ref. [2] to relate the peak overpressure from an explosion to lung hemorrhage, the primary cause of death from direct blast effects. Using the free-field (side-on) overpressure at infinitely large durations in assessing levels of lethality (current practice), one can develop an expression in the form:

$$p_r = -77.1 + 6.91 \text{ Log}_e (P_p), \tag{12-1}$$

where P_p is the peak overpressure at any location in units of N/m^2, and p_r is a measure of the percent of the vulnerable resource affected in the form of a normally distributed random variable with a mean value of 5 and a variance of 1. Given a value for p_r, a user would enter Table 12-3 to read the percentage of exposed people expected to be killed. For example, an overpressure of 150,000 N/m^2 inserted in the equation gives a p_r value of 5.26. Entering Table 12-3 with this value then suggests that approximately 60% of humans (and probably other animals) would die from exposure to the stated overpressure.

The main non-lethal injury expected from direct blast effects is eardrum rupture. Again, with data from Ref. [2], Ref. [1] derives the equation:

$$p_r = -15.6 + 1.93 \text{ Log}_e (P_p). \tag{12-2}$$

For the same overpressure of 150,000 N/m^2, p_r now has a value of 7.4, and thus approximately 99.2% of the exposed population could be expected to be affected.

c. Secondary Damage

The task of developing similar expressions for secondary damage due to explosions (injury due to missiles, fragments, and environmental debris set in motion by the event) is considerably more complex. It is difficult to assess the size distribution and detailed motion of thousands of individual missiles, or estimate the probability of impact with exposed humans. As an approximation, Ref. [1] presents the expression:

$$p_r = -27.1 + 4.26 \text{ Log}_e J, \tag{12-3}$$

TABLE 12-3. RELATIONSHIP BETWEEN PERCENTAGES AND p_r's

%	0	1	2	3	4	5	6	7	8	9
0	—	2.67	2.95	3.12	3.25	3.36	3.45	3.52	3.59	3.66
10	3.72	3.77	3.82	3.87	3.92	3.96	4.01	4.05	4.08	4.12
20	4.16	4.19	4.23	4.26	4.29	4.33	4.36	4.39	4.42	4.45
30	4.48	4.50	4.53	4.56	4.59	4.61	4.64	4.67	4.69	4.72
40	4.75	4.77	4.80	4.82	4.85	4.87	4.90	4.92	4.95	4.97
50	5.00	5.03	5.05	5.08	5.10	5.13	5.15	5.18	5.20	5.23
60	5.25	5.28	5.31	5.33	5.36	5.39	5.41	5.44	5.47	5.50
70	5.52	5.55	5.58	5.61	5.64	5.67	5.71	5.74	5.77	5.81
80	5.84	5.88	5.92	5.95	5.99	6.04	6.08	6.13	6.18	6.23
90	6.28	6.34	6.41	6.48	6.55	6.64	6.75	6.88	7.05	7.33
—	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
99	7.33	7.37	7.41	7.46	7.51	7.58	7.65	7.75	7.88	8.09

The p_r values are the three-digit numbers in the table. Percents are read along the top and side margin of the table. The vertical column of percents gives the decade; the horizontal column gives the unit. The table entry appearing in the row of the decade value and the column of the unit value is the p_r value corresponding to that percent. The last two rows in the table provide a finer reading for very high percent--from 99.0 to 99.9. The second to last row is the tenths of percent to be added to 99%. The last row consists of the corresponding p_r values.

where J is the dynamic overpressure impulse defined by the integral of the overpressure as a function of time for the duration of the positive phase of the blast wave (in units of N-s/m^2). In mathematical terms:

$$J = \int_{t_a}^{t_o} P(T)\, dT, \qquad (12\text{-}4)$$

where $P(T)$ = overpressure as a function of time at a given location,

t_a = arrival time of the blast wave, and

t_o = time at which positive phase of the blast wave ends.

Derivation of this expression for P_r assumes that all exposed persons outside of buildings in the region traversed by the blast wave would suffer injury from missiles. This assumption leads to overestimates of the expected injury rate. In the absence of a more rigorous approach to the problem, however, it must be utilized until better criteria become available.

d. Tertiary Damage

Reference [1] deals with deaths and injuries due to forcible movement of exposed people and subsequent impact with the ground, a wall, or other object due to the blast wave. Assuming an average sized person and an impact distance of 10 feet, one can derive the following expression:

$$p_r = -46.1 + 4.82 \text{ Log}_e J, \qquad (12\text{-}5)$$

where J is the impulse level in N-s/m^2 and p_r leads to the percentage of exposed population killed. For injury, mostly broken bones, the expression presented is:

$$p_r = -39.1 + 4.45 \text{ Log}_e J. \qquad (12\text{-}6)$$

Evaluation of these expressions indicates that damage due to impulse is completely overshadowed by damage due to overpressure at any point, and it is reasonable to ignore the former.

e. Explosion Damage to Structure

Using data from Ref. [2] for frame structures exposed to the blast wave caused by 500 tons of TNT (based on Ref. [1]), one can derive the following two expressions:

- <u>For glass breakage only</u>:

$$p_r = -18.1 + 2.79 \, \text{Log}_e \, (P_p); \text{ and} \qquad (12\text{-}7)$$

- <u>For structural damage</u>:

$$p_r = -23.8 + 2.92 \, \text{Log}_e \, (P_p); \qquad (12\text{-}8)$$

where P_p again is the peak overpressure at a given location in units of N/m^2.

Reference [2] reports that threshold glass breakage (1%) occurs at a peak overpressure of 1,700 N/m^2. By assuming that 90% of all glass will break at the overpressure level (6,200 N/m^2) associated with threshold structural damage (1%), Ref. [1] obtains the two data points needed to derive the p_r expression. The approach appears to be conservative, but logically correct in a qualitative sense. It ultimately provides the percentage of buildings that will experience glass breakage as a function of overpressure.

The approach for estimating the percentage of buildings that will suffer structural damage is not so logically correct, however. Reference [2] provides data relating the extent of damage to a given frame building as a function of overpressure. These data are:

Damage Level	Peak Overpressure (N/m^2)
Threshold structure damage (1%)	6,200
Structural damage (50%)	20,700
Total damage (99%)	34,500

It appears that Ref. [1] incorrectly assumes that 1% of buildings will experience damage at 6,200 N/m^2, 50% will suffer damage at 20,700 N/m^2 and so on, where in truth the 20,700 N/m^2 overpressure is intended to suggest that 50% of a given building is destroyed. This interpretation is confirmed by data in Ref. [3], indicating that an overpressure of 20,700 N/m^2 is sufficient to <u>shatter</u> non-reinforced concrete or cinder block walls, and that entire walls of standard type homes can be blown in at the lower overpressure of 13,800 N/m^2.

To resolve this inconsistency in Ref. [1], it is concluded that the second p_r expression presented above can only be utilized to assess the level of damage to a structure exposed to a given overpressure. Furthermore, it is concluded that shielding effects in densely populated areas, at some later time, should be given credit, so that the second or third line of structures around a blast site are not assumed to suffer the same damage levels as structures in the first line or ring about the site.

f. Additional Considerations

Reference [1] has not attempted to estimate the number of deaths and serious injuries to persons inside buildings that suffer substantial damage. Obviously, if a building suffers total destruction because of a blast, people inside that structure will be hurt.

As a first attempt at deriving p_r expressions for these cases, it is suggested that 50% of people in a building that suffers <u>total</u> damage will die and that 90% will be injured significantly. If the structure is 50% damaged, it is suggested that 25% of the inhabitants will die and that 12.5% will be injured. These estimates allow this factor to be addressed quantitatively. Thus;

- for deaths due to building damage:

$$p_r = -8.7 + 1.31 \, \text{Log}_e (P_p); \text{ and} \tag{12-9}$$

- for injuries due to building damage:

$$p_r = -43.51 + 4.77 \text{ Log}_e (P_p). \tag{12-10}$$

3. Fire Effects

An assessment of the impact caused by a vapor-cloud flash fire or a burning pool requires consideration of thermal radiation levels as well as the duration of exposure. Using data from Ref. [4], one can use Ref. [1] to derive the following expression for death from burns:

$$p_r = -14.9 + 2.56 \text{ Log}_e (tI^{4/3} \times 10^{-4}), \tag{12-11}$$

where t is the duration of exposure in seconds and I is the thermal radiation flux in joules/m^2-s.

For non-lethal burns, it is desired to obtain an expression describing the threshold for first-degree burns. Reference [1] finds that the equation described by:

$$tI^{1.15} = 550{,}000 \tag{12-12}$$

fits the data well. If exposures in any region exceed this level, non-lethal burns can be expected for exposed personnel.

Where property is of concern, levels at which exposed wood ignites spontaneously have to be evaluated. Reference [1] develops the necessary criteria through manipulation of an analysis presented in Ref. [5]. For ignition of wood from pool fires, the radiation intensity (I_s) must exceed the level:

$$I_s = 2.54 \times 10^4 \text{ joules/m}^2\text{-s}, \tag{12-13}$$

and the duration of the fire must exceed the time given by:

$$t = (61{,}000/I_r - I_s)^{1.25} . \tag{12-14}$$

4. Toxic Effects

As a practical matter, the release of toxic substance to the environment cannot generally be expected to affect large exposed populations adversely, unless the substance disperses rapidly and in such a manner as to afford no chance of escape to affected people. Thus, an assessment of potentially widespread and significant toxic effects can be limited to a consideration of harmful acute exposures deriving from vapor inhalation. Chronic (i.e., long-term) exposures to harmful vapor concentrations can be excluded on the basis that the public will voluntarily and promptly evacuate potentially harmful areas, or will be forced to do so by public health officials.

Similarly, the likelihood of ingestion and or skin or eye contact with hazardous substances in the solid or liquid state can be considered a rare event except under extraordinary circumstances. Although a few foolhardy members of the public may wander through a spill site, and a few careless or uninformed members of emergency response forces may be affected, their numbers will generally be few and not of consequence to the final result of an overall, comparative risk assessment.

An assessment of the effects of a toxic vapor cloud necessitates the classification of exposure consequence into three categories:

- Lethal injury,
- Sublethal injury, and
- Severe irritation.

Lethal injuries (or fatalities) will occur at vapor concentrations sufficiently high to cause death immediately, or within a time span less than that necessary for escape to less affected regions. To simplify the selection of lethal exposure levels for representative hazardous substances, it is not unreasonable to assume that the maximum available time for escape from a hazardous condition is one-half hour. The lethal concentrations associated with this time duration then provide the desired criterion for estimating the area in which the exposed population may expire. The selection of such a simple criterion obviates the need for complex dose-response relationships, while providing a conservative approach to satisfying the needs of impact analysis.

During the joint National Institute of Occupational Safety and Health/ Occupational Safety and Health Administration (NIOSH/OSHA) Standards Completion Program, considerable effort was devoted to the definition of concentrations that are "immediately dangerous to life or death." The resulting Immediately Dangerous to Life and Health (IDLH) levels for OSHA-regulated substances [6] were chosen to represent the maximum concentrations from which a person could escape within 30 minutes without any escape-impairing symptoms or any irreversible health effects. These concentrations, therefore, provide convenient and generally realistic values for use in defining the borderline between concentrations that are harmful and those that are severely irritating.

Members of the public experiencing moderate to severe irritation are likely to be concerned that their exposures have caused them more serious harm. In consequence, they may seek medical treatment and add to the burden of emergency medical teams. It is worthwhile, therefore, to develop a conservative definition of concentration levels that are capable of causing significant irritation.

Table 12-4 lists representative chemicals* that can cause vapor exposures over widespread areas. For each of these chemicals, the table provides estimates of each of the three concentration levels described above, based upon a review of the pertinent literature.

5. Application of Damage Criteria

The vapor concentrations presented above are well suited to the estimation of affected downwind areas. The other damage criteria, however, are in the form of equations relating a physical parameter to the fraction of exposed resources that are expected to be harmed. They are better suited, therefore, to more rigorous risk assessments, which are beyond the objectives of this study.

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*These hazardous materials were selected through a process described in Section F.

TABLE 12-4. TOXIC VAPOR DAMAGE CRITERIA FOR THIRTY MINUTE EXPOSURE

Chemical	Lethal (ppm)**	Sublethal (ppm)	Irritating (ppm)
Ammonia	2500	500	140
Aniline	500	100	0
Boron Trichloride	3000	100	75
Bromine	400	10	2
Chlorine	50	25	7
Dimethylamine	4000	2000	300
Gasoline	8000	2000	1000
Hydrochloric acid	4350	100	50
Hydrogen chloride	3500	100	75
Hydrogen sulfide	600	300	240
Methyl alcohol	70000	25000	0
Methyl bromide	2600	2000	1500
Nitrobenzene	1000	200	0
Nitrogen tetroxide	800	50	20
Phosgene	15	2	1
Sulfuric acid	75	20	2
Toluene	10000	2000	1500
Xylene	15000	10000	4000
Butadiene Ethylene Hydrogen LPG Monochlorodifluoromethane	600000	450000	300000

*The vast majority of these criteria evolved from a rapid review of limited available data from experiments with animals and the application of a considerable degree of judgment. It is entirely possible and likely that one or more values are substantially incorrect.

**ppm = parts per million.

To simplify applications of these latter criteria, it was decided to utilize the equations to define the physical parameter values associated with a 40% probability of damage. Furthermore, it was assumed that the deaths, injuries, and property losses expected from a particular release scenario could be derived by totaling only those losses occurring within the 40% damage isopleth, this being accomplished by further assuming that all resources within the hazard area have the potential to be adversely affected. In this approach, overestimation of damages within the 40% isopleth will hopefully be counterbalanced by the assumption that no damages occur outside.

Table 12-5 summarizes the damage criteria for explosions and fires using this strategy and others noted on the table for special cases.

E. SELECTION OF REPRESENTATIVE CHEMICALS: APPROACHES TO IMPACT ASSESSMENT

1. Background

It is the objective of this portion of the analysis to review historical hazardous-material spill statistics to identify those substances that have been most commonly spilled. The short list of substances developed for each category is subsequently utilized to develop impact assessments for both "average" and "worst case" spill scenarios. The approach for this effort is also described in the following paragraphs, while the results are presented in Section G.

2. Data Sources Utilized

Ideally, the data base for spills would only include those incidents involving railroad cars. Unfortunately, however, the task of sorting and analyzing existing data bases to obtain such data would have required a massive and costly effort that was not considered as being justified by the objectives of this study. Thus, the analysis of spill data considered all spills reported to the Department of Transportation (DOT) as being transportation-related.

TABLE 12-5. SUMMARY OF PHYSICAL AGENT DAMAGE AND APPLICATION CRITERIA

Basic Event	Damage Receptors	Effect	Cause	Damaging Factor	Damage Criteria	Criteria Bases	Application
Explosion	Humans	Lethal Injury	Lung Hemorrhage	Peak Overpressure	139,407 N/m^2	40% Lethality	Outdoor Population
	Humans	Non-lethal Injury	Eardrum Rupture	Peak Overpressure	37,951 N/m^2	40% Injury	Outdoor Population
	Humans	Non-lethal Injury	Missiles	Dynamic Overpressure Impulse	1,766 $N\text{-}s/m^2$	40% Injury	Outdoor Population
	Humans	Lethal Injury	Building Collapse	Peak Overpressure	28,773 N/m^2	40% Lethality	Indoor Population
	Humans	Non-lethal Injury	Building Collapse	Peak Overpressure	24,770 N/m^2	40% Injury	Indoor Population
	Buildings	Glass Breakage	Shock Wave	Peak Overpressure	3,605 N/m^2	40% Available Glass Breakage	Structures
	Buildings	Structural Damage	Shock Wave	Peak Overpressure	17,631 N/m^2	40% Structural Damage	Structures
Fire (any type)	Humans	Lethal Injury	Burns	Thermal Radiation	$tI^{1.33} = 2.16\times10^7$ J/m^2	40% Lethality	Outdoor Population
	Humans	Non-lethal Injury	Burns	Thermal Radiation	$tI^{1.15} = 5.5\times10^5$ J/m^2	Lower Limit	Outdoor Population
Pool Fire	Buildings	Fire Damage	Ignition	Thermal Radiation	$I_r > 2.54\times10^4$ $J/m^2\text{-}s$ and $\left[t \geq \frac{61000}{I_r - I_s}\right]^{1.25}$	Lower Limit	Structures

Notes: t = effective duration of fire exposure (seconds)
I_r = effective radiation intensity at receptor ($J/m^2\text{-}s$)
I_s = 2.54×10^4 $J/m^2\text{-}s$

In 1977, the DOT Office of Hazardous Materials (OHM) made available a detailed analysis of the 12,063 hazardous-material incident reports received during calendar year 1976. Encompassing all modes of transportation, but primarily consisting of reports from highway and railroad carriers, the detailed data sheets listed all substances spilled in that year, identified the commodity category of each, and provided the exact number of spills involving each substance. It was decided to utilize the results of this effort to identify the hazardous materials to be used in developing the "average" and "worst case" impact-assessment scenarios. Necessary assumptions are:

- That the mix of commodities that are transported by railroads and that are involved in accidents does not vary substantially from the distribution suggested by the OHM data; and
- That the results of the impact assessment would not be significantly distorted by the inclusion of a few "erroneous" substances in the list (vis-a-vis shipment by railroad), if some judgment is applied to adjust results.

3. Approach

The analysis for non-flammable compressed gases presented below demonstrates the overall approach taken to developing a short list of substances that presents the bulk of the risk associated with spills of this type of substance. For this particular category, the effort ultimately led to a list of six specific substances (one is actually representative of the broader class of simple asphyxiants) that have been most often spilled in the past. Each substance is assigned a conditional probability of release, given that an accident has occurred and that a substance in this commodity category has been released.

A subsequent portion of the overall impact-assessment analysis evaluates the areas associated with the major adverse effects of each substance as a function of the amount released. Analogous areas for each substance (e.g., the areas in which humans will expire due to toxic vapor exposure) are then utilized, in combination with conditional probabilities, to develop "composite" results that are representative of the effects of the average or typical spill involving this category of materials. A simple inspection of overall results then permits selection of those results associated with feasible "worst case" events. With these two sets of data, the analyst can consider what is most likely to occur during a typical incident, and also define the upper limits of expected adverse impacts.

4. Analysis for Non-flammable Compressed Gases

The major impact of a non-flammable compressed gas (NFCG) release is exposure of the public to airborne contaminants. Table 12-6 presents a summary of the NFCG releases that occurred during 1976 and lists the concentrations in air that are immediately dangerous to life and health (i.e., IDLH values extracted from OSHA documents cited previously or estimated by Arthur D. Little). Where the word "asphyxiant" appears in this list, it implies that the gas or vapor is not truly toxic, but can nevertheless cause harm through depletion of oxygen in the atmosphere. All such designations were made by Arthur D. Little, based upon a review of toxicological data. Substances with IDLH's of 50,000 ppm can also be considered simple asphyxiants for the purposes of this analysis, although it must be realized that some of the substances with this IDLH do have additional toxicological effects.

Table 12-7 separately combines all simple asphyxiants and all commodities with not otherwise specified (NOS) designations, and, in its second column, presents the fraction of all spills associated with each specific commodity or type of commodity. These results are essentially the conditional probabilities of release. They are not useful as yet, however, because the category of NOS materials is comprised of materials with undefinable properties. Thus, it is assumed that the NOS materials are distributed in terms of adverse impact in a fashion similar to the better identified commodities, and "adjusted" conditional probabilities of release are computed with simple ratios. These are presented in the third column of the table.

TABLE 12-6. NON-FLAMMABLE COMPRESSED GAS SPILL DATA (1976)

Commodity	Number of Releases	IDLH (ppm)
Anhydrous ammonia	80	500
Argon	1	Asphyxiant
Boron trifluoride	2	100
Chlorine	11	25
Compressed gas (NOS)	40	?
Carbon dioxide	9	50,000
Dichlorodifluoromethane	3	50,000
Dispersant gas (NOS)	1	?
Fert. ammoniating sol.	2	?
Fire extinguishers	6	50,000 (est.)
Helium	1	Asphyxiant
Hydrogen Chloride	5	100
Monochlorodifluoromethane	1	50,000 (est.)
Nitrogen fertilizer soluble	3	?
Nitrogen	3	Asphyxiant
Oxygen	6	-

TABLE 12-7. DATA ANALYSIS RESULTS FOR NON-FLAMMABLE COMPRESSED GASES

Commodity	P	P(adjusted)
Anhydrous ammonia	0.461	0.656
Asphyxiants	0.138	0.197
Chlorine	0.063	0.090
NOS compounds	0.264	-
Hydrogen chloride	0.029	0.041
Boron trichloride	0.011	0.016
Oxygen	0.034	-
	1.000	1.000

Note: Monochlorodifluoromethane is chosen as representative of the class of simple asphyxiants. Boron trichloride replaces boron trifluoride because of lack of data on the latter compound. Oxygen is deleted from consideration because of its unusual properties and potential effects.

Similar evaluations were performed for each of the other 11 commodity categories, using appropriate measures of hazard potential. The results of these are presented below, together with a brief discussion of the specific approach used.

5. Flammable Compressed Gases

The OHM data base shows 14 substances or types of materials to be responsible for the 262 releases of flammable compressed gases recorded in 1976. Four of these materials account for a total of only eight spills and can reasonably be excluded from further consideration. Three other substances are of the same chemical family and can be represented by anhydrous dimethylamine. Once NOS materials are deleted, the adjusted conditional probabilities are determined to be those presented below:

Commodity	P_C(adjusted)
Liquefied Petroleum Gas	0.827
Hydrogen	0.054
Butadiene	0.049
Ethylene	0.023
Hydrogen sulfide	0.023
Dimethylamine	0.024
	1.000

6. Flammable Liquids

Flammable liquids accounted for almost 51% of the releases reported to the OHM during 1976. Because of the wide variety of compounds encompassed by this category, and the fact that most commodities are grouped under vague headings, such as "cement liquid NOS" (accounted for 288 releases), it is necessary to apply a considerable amount of judgment in the selection of materials that are representative.

The most spills (42.07%) involved a single category for paints, enamels, lacquers, and stains. The solvents used in these formulations include a wide range of hydrocarbons, alcohols, esters, ketones, and glycol esters. Notably, the highly toxic solvents such as benzene, tetrachloroethane, and carbon tetrachloride have been largely eliminated in recent years, so the primary hazard from spills is that from fires. To "model" this group of substances, the solvent toluene is chosen as representative. It displays a moderate to high flammability hazard as well as a moderate level of toxicity.

NOS materials accounted for 32.77% of releases. These are considered as materials of undefinable characteristics, so they are excluded from the final selection. Similarly, another 4.51% of spills are excluded since they involve a relatively few spills, each of a large number of compounds.

Gasoline, kerosene, various naphthas, and other hazardous materials derived from petroleum account for 17.18% or so of releases. To cover the category fully, it is assumed that 8.6% of spills involve gasoline, and the remainder involve xylene. Thus, both highly flammable and moderately flammable liquids are included.

Alcohols of various types account for 3.4% of spills. Methyl alcohol is conservatively chosen as being representative due to its toxicity and widespread use.

Consolidation of these data leads to the following relationship:

Commodity	P_C(adjusted)
Toluene	0.673
Gasoline	0.136
Xylene	0.136
Methyl alcohol	0.055
	1.000

7. Combustible Liquids

Fully 69.2% of combustible liquid spills involve NOS materials or one or two spills each for a variety of specific substances. The rest involve various fuel oils, kerosene, and other basic petroleum products. Since these liquids are of relatively low volatility and, therefore, present negligible vapor-dispersion hazards, fuel oil No. 2 is selected as representative of the entire group.

8. Flammable Solids (Special Hazard)

The 12,063 hazardous-material incident reports contain approximately 50 involving flammable solids with unusual properties. Among those in which the hazardous material is specifically identified, about one-half involves phosphorus and its compounds and the other half involves sodium and its compounds. Consequently, phosphorus (11 spills) and sodium hydrosulfite (9 spills) are chosen as representative, and each is assigned a conditional probability of 0.5.

9. Flammable Solids (Ordinary Hazards)

No more than 19 of the 12,063 spills involve the rather ordinary combustible materials designated as flammable solids. Because of the common nature of their hazards, and the low incidence of spills, this category is excluded from further consideration.

10. Oxidizing Materials

The 112 releases recorded for oxidizing materials involve 36 individual commodities or type identifiers. On a gross basis, these can be segregated into the following groups:

Commodity	No. Spills	P_C
Ammonium nitrate and compounds	38	0.3393
Others with 1 or 2 spills	23	0.2054
Oxidizing material-NOS	17	0.1518
Sodium compounds	14	0.1250
Calcium hypochlorite mix	11	0.0982
Nitro carbo nitrate	5	0.0446
Permanganate potash	4	0.0357
	112	1.0000

After specific hazardous materials are selected as representative of subgroups, and the NOS, poorly defined, or low-frequency-of-spillage substances are deleted, the final list becomes:

Commodity	P_C (adjusted)
Ammonium nitrate	0.6032
Sodium chlorate	0.2222
Calcium hypochlorite	0.1746
	1.0000

11. Organic Peroxides

Organic peroxides account for 26 of the reported spills, with 19 of them listed for unspecified hazardous materials and the rest for two specific compounds. To represent the entire group, a single specific compound is selected; viz., tert-butyl hydroperoxide. It is an oxidizer, flammable, and may explode in fires.

12. Poison Class A

Of the 12,063 spills reported in 1976, only 8 involved Class A poisons. Phosgene accounted for four incidents, while four other compounds each accounted for a single event. Phosgene and nitrogen tetroxide are chosen as representative of the group, each with a conditional probability assignment of 0.5.

13. Poison Class B

Class B poisons were involved in 554 releases during 1976, as follows:

Commodity	No. Spills	P_C
NOS materials	340	0.6136
Organic phosphates	59	0.1065
Carbolic acid	22	0.0397
Dinitrophenol solution	18	0.0325
Cyanide compounds	17	0.0307
Mercury compounds	16	0.0289
Parathion	15	0.0271
Methyl parathion	10	0.0181
Aniline	10	0.0181
All others	47	0.0848
	445	1.0000

By definition, all these hazardous materials are usually solids or liquids. In the case of solids, it is difficult to envision a scenario in which there would be widespread injury to the public. In the case of liquids, however, one must be concerned with evolution of toxic vapor, as well as the possibility of pool fires when the hazardous material is also a flammable liquid.

To account for these factors, data were reviewed to determine the split between spills of liquids and those of the solids. This indicated that about 85% involved liquids, while the remainder involved solids. Then, specific compounds were chosen to reflect the wide range of properties of these hazardous materials. This resulted in the list:

Commodity	P_C(adjusted)
Methyl bromide[*]	0.01
Xylene[§]	0.20
Aniline[†]	0.20
Nitrobenzene[†]	0.20
Others[Φ]	0.39

14. Irritating Materials

Spills of irritants and etiologic agents are rare. Nine were reported for all modes of transportation in 1976, and even then, at least one of these (the single spill listed for an etiologic agent) was incorrectly placed in this category. Since it is highly unlikely for significant injuries to take place when irritants are spilled, this category is excluded from further consideration.

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[*] Actually a liquefied gas of high toxicity.

[§] A representative hydrocarbon in which many toxic solids are dissolved.

[†] A combustible liquid with toxic vapors.

[Φ] A solid or liquid with little or no capability to disperse and/or otherwise cause harmful effects. Examples include dry solids that are non-flammable as well as water solutions of pesticides.

15. Corrosive Materials

Of all hazardous material spills from all modes in 1976, about 34% involved corrosive materials. For railroads alone, they accounted for about 40% of all reported releases over a multi-year period. In terms of deaths and injuries (using results from a complete multi-year analysis of Federal Railroad Administration (FRA) accident records), they did not cause any deaths, but did cause 1,555 (53%) of the 2,930 injuries that were reported.

The most common injury is a skin burn caused by physical contact with a corrosive substance. Also of concern are situations in which fumes from a spilled substance injure people downwind from the spill. The following results of the analysis for corrosive materials pay special attention to substances which are particularly troublesome in this regard:

Commodity	P_C(adjusted)
Phosphoric acid	0.39
Sodium hydroxide (caustic soda)	0.35
Sulfuric acid, fuming	0.15
Hydrochloric acid	0.10
Bromine	0.01

F. IMPACT-ASSESSMENT METHODS

For each chemical group, various possible post-release scenarios were identified, as discussed in Section C. For each scenario, a quantitative impact model was developed. These models are described in Appendix C. Input data required by each model include, among others:

- The volume of hazardous material that is released (a random variable estimate of whose probability distribution is presented in Chapter 10);
- Densities of ignition sources (discussed in Appendix D); and
- Atmospheric stability conditions (also discussed in Appendix D).

For each category of chemicals, a conditional scenario probability has to be assigned. In other words, given a release of material in some category, if there are four mutually exclusive post-release scenarios, what is the probability of occurrence of each one? Informed estimates of these probabilities were made and are presented in the following subsections. For most categories of materials, an examination of the results presented in Section G shows that the overall impact estimates are not sensitive to the particular choice of scenario probabilities. The one exception is "flammable compressed gases." For this category, improved probability estimates should be made as additional information is generated over time.

1. Scenario Probabilities

Scenario	Scenario Probability
• Non-flammable Compressed Gases	
Liquid releasing with flashing	1.0
• Flammable Compressed Gases	
Flame jet	0.30
Pool fire	0.28
BLEVE (fireball only)	0.20
Vapor cloud dispersion	0.01
Vapor cloud detonation	0.01
BLEVE and rocketing	0.20
• Flammable Liquids	
Pool fire	0.9
No ignition	0.1
• Combustible Liquids	
Pool fire	0.5
No ignition	0.5
• Flammable Solids	
Ignition	0.1
No ignition	0.9
• Oxidizing Materials	
Detonation	0.05
No impact	0.95

- Organic Peroxides

Detonation	0.05
No impact	0.95

- Class A Poisons

Liquid release with flashing	1.0

- Class B Poisons

Pool fire	0.5
No ignition	0.5

- Corrosives

Vaporization	1.0

G. SUMMARY OF IMPACT-ASSESSMENT RESULTS

1. Background

This section presents the results of the overall impact-assessment analysis. These results evolved from application of the models described in Appendix C in a manner detailed in Appendix D.

2. Non-flammable Compressed Gases

Table 12-8 summarizes results for the category of non-flammable compressed gases. The scenario of primary interest is the release of liquid from a ruptured tank car. As it vents from the tank, some part of the liquid will flash-vaporize to form a toxic vapor cloud. The remainder, which is assumed to have cooled down to its boiling point at ambient pressure, will form a pool that boils and vaporizes continuously.

The appropriate assessment models were used to address separately the initial release of vapor and the subsequent evolution from the pool. Results were compared and impact zones chosen from the set of answers associated with the greatest impact. For selected average environmental conditions, the weighted-average areas of potential impact for lethality, sublethal injury, and significant irritation are presented in the first row of the table as a function of the volume of material actually escaping from the tank. The second row similarly presents

TABLE 12-8. IMPACT ASSESSMENT RESULTS FOR NON-FLAMMABLE COMPRESSED GASES

Scenario	Probability	Amount (gallon)	Lethal Zone, α_L (sq. km.*)	Injury Zone, α_{INJ} (sq. km.)	Irritation Zone, α_{IRR} (sq. km.)
Liquid release with flashing -Average case	1.0	1-100	8.4×10^{-3}	1.3×10^{-2}	2.9×10^{-2}
		101-1,000	4.8×10^{-2}	8.0×10^{-2}	7.3×10^{-2}
		1,001-5,000	0.17	0.29	0.65
		5,001-10,000	0.34	0.58	1.3
		10,001-25,000	0.66	1.1	2.8
		25,001-50,000	1.2	2.1	6.7
		50,001-100,000	2.0	3.7	15.4
Liquid release with flashing -Worst case	1.0	1-100	0.13	9.50×10^{-2}	0.40
		101-1,000	0.88	0.67	3.00
		1,001-5,000	3.6	2.9	18.2
		5,001-10,000	7.9	6.8	88.3
		10,001-25,000	16.9	28.2	>100 **
		25,001-50,000	46.3	>100**	>100 **
		50,001-100,000	>100**	>100**	>100 **

*sq. km = square kilometer

**Answers of this magnitude are likely to be considered in error for two reasons: (1) because downwind maximum hazard extents are greater than 100 km. Values for the dispersion coefficients σ_x and σ_y were crudely extrapolated from data for distances less than 100 km. They may be wrong for greater distances; (2) because the "worst case" weather conditions assumed are unlikely to persist for the length of time required for dispersion to these distances. As a consequence, the user should not accept these predictions as being completely valid.

results from the most severe accident that could feasibly be envisioned. In this particular case, the material is liquefied chlorine, and it is presumed to have been released during an inversion of the atmosphere, a condition which supports the propagation of a toxic cloud over large distances.

Each of the three zones should be considered as unique regions with no overlap. For example, given the release of 75,000 gallons under typical circumstances, it should be understood that the area of potential lethality is 2.0 sq. km; that the area of sublethal injury covers a different area of 3.7 sq. km; and that the area in which humans may be distressed, but not truly injured, is yet a different 15.4 sq. km.

3. Flammable Compressed Gases

The most difficult category to consider is that of flammable compressed gases. Depending upon the circumstances surrounding the accident, one can variously expect:

- Formation of a flame jet due to ignited venting gas (literally a huge blowtorch);
- A pool fire;
- A BLEVE resulting in a fireball and a rocketing section of the tank; and/or
- A vapor cloud that disperses and results in a vapor flash fire when ignited; a vapor cloud detonation; and/or toxic vapor inhalation impact.

Table 12-9 provides estimates of the average impact for flame jets, pool fires, and the fireball portion of the BLEVE as a function of the amount spilled. The column entitled "Probability" contains estimates of the probability that any scenario will occur, assuming that some release of hazardous materials occurs. The first and second columns for impacts provide the areas in which wooden structures may be ignited. Areas designated by 0.0 in this and following tables should be interpreted as indicating that the impact zone is smaller than can be reasonably estimated (usually less than 30 sq. m.).

TABLE 12-9. IMPACT ASSESSMENT RESULTS FOR FLAMMABLE COMPRESSED GASES

Scenario	Probability	Amount (gal.)	Lethal Zone, α_L (sq. km.)	Injury Zone, α_{INJ} (sq. km.)	Building Damage Zone, α_{PD} (sq. km.)
1. Flame jet	0.3	Any	1.9×10^{-4}	5.9×10^{-3}	1.9×10^{-4}
2. Pool fire	0.28	1-100	0.0	3.2×10^{-4}	0.0
		101-1,000	2.0×10^{-4}	3.0×10^{-3}	2.0×10^{-4}
		1,001-5,000	1.3×10^{-3}	1.1×10^{-2}	1.3×10^{-3}
		5,001-10,000	3.0×10^{-3}	2.5×10^{-2}	2.9×10^{-3}
		10,001-25,000	6.6×10^{-3}	5.1×10^{-2}	6.6×10^{-3}
		25,001-50,000	1.3×10^{-2}	0.10	1.3×10^{-2}
		50,001-100,000	2.6×10^{-2}	0.18	2.4×10^{-2}
3. BLEVE (Fireball only)	0.2	1-100	0.0	5.0×10^{-4}	0.0
		101-1,000	1.2×10^{-4}	5.2×10^{-3}	1.2×10^{-4}
		1,001-5,000	5.0×10^{-4}	2.2×10^{-2}	5.0×10^{-4}
		5,001-10,000	9.4×10^{-4}	5.1×10^{-2}	9.4×10^{-4}
		10,001-25,000	1.7×10^{-3}	0.10	1.7×10^{-3}
		25,001-50,000	2.8×10^{-3}	0.20	2.8×10^{-3}
		50,001-100,000	4.4×10^{-3}	0.36	4.4×10^{-3}

Table 12-10 presents estimates (average case) for vapor cloud dispersion and vapor cloud detonation. For the first of these scenarios, three columns are for lethal zones in urban, suburban, and rural settings, respectively. The answers differ because of variations in ignition source densities. Similarly, three columns provide estimates for areas in which buildings may ignite due to their presence within a burning vapor cloud.

The latter scenario is addressed in the second half of the table. In order, the impacts covered are:

- Lethal injury to outdoor populations due to lung hemorrhage;
- Sublethal injury to outdoor populations due to eardrum rupture or missile impact;
- Lethal injury to indoor populations due to building damage or collapse;
- Sublethal injury to indoor populations due to building damage or collapse;
- Substantial building damage; and
- Glass breakage.

Table 12-11 presents estimates for impacts due to tank car rocketing. Additionally, it presents composite averages for the three settings considered. These are weighted averages using the probabilities in the "Probability" column.

Finally, the last table of this set, Table 12-12, presents the worst case scenarios visualized; viz., a release of hydrogen sulfide during an inversion, and a remote accident setting in which the cloud is not ignited while in a flammable condition.

4. Flammable Liquids

The set of scenarios for flammable liquid releases is rather limited in scope. Simply stated, either the spilled liquid is ignited to form a pool fire, or it slowly evaporates to provide a toxic vapor plume problem. Results of the analysis are self-explanatory and presented in Table 12-13.

TABLE 12-10. IMPACT ASSESSMENT RESULTS FOR FLAMMABLE COMPRESSED GASES (continued)

Scenario	Probability	Amount (gal.)	Urban Lethal Zone, α_L (sq. km.)	Urban Bldg. Fire Zone, α_{PD} (sq. km.)	Suburban Lethal Zone, α_L (sq. km.)	Suburban Bldg. Fire Zone, α_{PD} (sq. km.)	Rural Lethal Zone, α_L (sq. km.)	Rural Bldg. Fire Zone, α_{PD} (sq. km.)
4. Vapor Cloud dispersion (with and without ignition)	0.01	1-100	4.4×10^{-4}	0.0	6.5×10^{-4}	0.0	6.5×10^{-4}	0.0
		101-1,000	6.1×10^{-4}	6.1×10^{-4}	8.1×10^{-4}	8.1×10^{-4}	2.4×10^{-3}	0.0
		1,001-5,000	1.1×10^{-3}	1.1×10^{-3}	1.4×10^{-3}	1.4×10^{-3}	2.5×10^{-3}	2.5×10^{-3}
		5,001-10,000	1.2×10^{-3}	1.2×10^{-3}	2.0×10^{-3}	2.0×10^{-3}	4.7×10^{-3}	4.7×10^{-3}
		10,001-25,000	1.7×10^{-3}	1.7×10^{-3}	2.2×10^{-3}	2.2×10^{-3}	5.6×10^{-3}	5.6×10^{-3}
		25,001-50,000	2.1×10^{-3}	2.1×10^{-3}	2.9×10^{-3}	2.9×10^{-3}	7.5×10^{-3}	7.5×10^{-3}
		50,001-100,000	2.3×10^{-3}	2.3×10^{-3}	3.5×10^{-3}	3.5×10^{-3}	8.8×10^{-3}	8.8×10^{-3}
		Amount (gal.)	Outdoor Lethal (sq. km.)	Outdoor Injury (sq. km.)	Indoor Lethal (sq. km.)	Indoor Injury (sq. km.)	Building Destruction (sq. km.)	Glass Breakage (sq. km.)
5. Vapor Cloud detonation	0.01	1-100	4.4×10^{-4}	9.6×10^{-4}	1.9×10^{-3}	4.5×10^{-4}	3.8×10^{-3}	3.3×10^{-2}
		101-1,000	2.2×10^{-3}	4.9×10^{-3}	9.4×10^{-3}	2.6×10^{-3}	1.9×10^{-2}	0.16
		1,001-5,000	6.8×10^{-3}	1.5×10^{-2}	2.9×10^{-2}	7.0×10^{-3}	5.8×10^{-2}	0.51
		5,001-10,000	1.3×10^{-2}	2.8×10^{-2}	5.4×10^{-2}	1.2×10^{-2}	0.11	0.94
		10,001-25,000	2.2×10^{-2}	5.0×10^{-2}	9.4×10^{-2}	2.6×10^{-2}	0.19	1.7
		25,001-50,000	3.6×10^{-2}	8.4×10^{-2}	0.16	3.0×10^{-2}	0.31	2.3
		50,001-100,000	5.8×10^{-2}	0.13	0.20	0.11	0.50	4.4

TABLE 12-11. IMPACT ASSESSMENT RESULTS FOR FLAMMABLE COMPRESSED GASES (continued)

Scenario	Probability	Amount (gal.)	Lethal Zone, α_L (sq. km.)	Injury Zone, α_{INJ} (sq. km.)	Building Damage Zone, α_{PD} (sq. km.)
6. BLEVE and tank car rocketing	0.2	Any	6.10^{-4}	3×10^{-3}	3×10^{-3}
Composite average for urban setting		1-100	1.9×10^{-4}	1.9×10^{-4}	6.9×10^{-4}
		101-1,000	2.9×10^{-4}	1.9×10^{-4}	1.7×10^{-3}
		1,001-5,000	7.2×10^{-4}	7.5×10^{-3}	1.7×10^{-3}
		5,001-10,000	1.3×10^{-3}	1.7×10^{-2}	2.8×10^{-3}
		10,001-25,000	2.6×10^{-3}	3.4×10^{-2}	4.8×10^{-3}
		25,001-50,000	4.8×10^{-3}	6.8×10^{-2}	8.0×10^{-3}
		50,001-100,000	8.9×10^{-3}	1.2×10^{-1}	1.3×10^{-2}
Composite average for suburban setting		1-100	2.1×10^{-4}	Same as for urban	Approximately same as for urban
		101-1,000	3.6×10^{-4}		
		1,001-5,000	9.4×10^{-4}		
		5,001-10,000	1.8×10^{-3}		
		10,000-25,000	3.4×10^{-3}		
		25,001-50,000	6.0×10^{-3}		
		50,001-100,000	1.0×10^{-2}		
Composite average for rural setting		1-100	2.3×10^{-4}	Same as for urban	Approximately same as for urban
		101-1,000	4.7×10^{-4}		
		1,001-5,000	1.2×10^{-3}		
		5,001-10,000	2.3×10^{-3}		
		10,001-25,000	4.3×10^{-3}		
		25,001-50,000	7.5×10^{-3}		
		50,001-100,000	1.3×10^{-2}		

TABLE 12-12. IMPACT ASSESSMENT RESULTS FOR FLAMMABLE COMPRESSED GASES (continued)

Scenario	Probability	Amount (gal.)	Lethal Zone, α_L (sq. km.)	Injury Zone, α_{INJ} (sq. km.)	Irritation Zone, α_{IRR} (sq. km.)
Worst case-H_2S vapor cloud that does not become ignited	1.0	1-100	3.3×10^{-2}	2.2×10^{-2}	1.0×10^{-2}
		101-1,000	0.20	0.15	6.7×10^{-2}
		1,001-5,000	0.78	0.60	0.27
		5,001-10,000	1.7	1.3	0.60
		10,001-25,000	3.3	2.7	1.3
		25,001-50,000	6.5	5.5	2.6
		50,001-100,000	11.9	10.3	5.0

TABLE 12-13. IMPACT ASSESSMENT RESULTS FOR FLAMMABLE LIQUIDS

Scenario	Probability	Amount (gal.)	Lethal Zone, a_L (sq. km.)	Injury Zone, a_{INJ} (sq. km.)	Irritation Zone, a_{IRR} (sq. km.)	Building Damage Zone, a_{PD} (sq. km.)
1. Pool fire	0.9	1-100	0.0	4.0×10^{-5}	0.0	0.0
		101--1,000	1.2×10^{-4}	7.7×10^{-4}	0.0	1.2×10^{-4}
		1,001-5,000	4.9×10^{-4}	3.4×10^{-3}	0.0	4.9×10^{-4}
		5,001-10,000	1.1×10^{-3}	7.0×10^{-3}	0.0	1.1×10^{-3}
		10,001-25,000	2.5×10^{-3}	1.5×10^{-2}	0.0	2.5×10^{-3}
		25,001-50,000	5.1×10^{-3}	3.0×10^{-2}	0.0	5.1×10^{-3}
		50,001-100,000	1.0×10^{-2}	5.2×10^{-2}	0.0	1.0×10^{-2}
2. No ignition-Vapor evolution	0.1	1-100	0.0	0.0	0.0	0.0
		101-1,000	0.0	5.1×10^{-5}	9.3×10^{-5}	0.0
		1,001-5,000	0.0	3.0×10^{-4}	5.1×10^{-4}	0.0
		5,001-10,000	0.0	4.0×10^{-4}	1.8×10^{-3}	0.0
		10,001-25,000	0.0	2.2×10^{-3}	3.5×10^{-3}	0.0
		25,001-50,000	0.0	5.5×10^{-3}	8.5×10^{-3}	0.0
		50,001-100,000	0.0	1.3×10^{-2}	1.9×10^{-2}	0.0
Composite average	1.0	1-100	0.0	3.6×10^{-5}	0.0	0.0
		101-1,000	1.1×10^{-4}	7.0×10^{-4}	9.3×10^{-6}	1.1×10^{-4}
		1,001-5,000	4.4×10^{-4}	3.1×10^{-3}	5.1×10^{-5}	4.5×10^{-4}
		5,001-10,000	1.0×10^{-3}	6.3×10^{-3}	1.8×10^{-4}	1.0×10^{-3}
		10,001-25,000	2.3×10^{-3}	1.4×10^{-2}	3.5×10^{-4}	2.3×10^{-3}
		25,001-50,000	4.5×10^{-3}	2.8×10^{-2}	8.5×10^{-4}	4.5×10^{-3}
		50,001-100,000	9.0×10^{-3}	4.8×10^{-2}	1.9×10^{-3}	9.0×10^{-3}
Worst case-pool fire with xylene	1.0	1-100		5.5×10^{-4}	0.0	0.0
		101-1,000	3.7×10^{-4}	4.2×10^{-3}	0.0	3.7×10^{-4}
		1,001-5,000	2.2×10^{-3}	1.7×10^{-2}	0.0	2.2×10^{-3}
		5,001-10,000	4.7×10^{-3}	3.7×10^{-2}	0.0	4.7×10^{-3}
		10,001-25,000	1.1×10^{-2}	7.3×10^{-2}	0.0	1.0×10^{-2}
		25,001-50,000	2.3×10^{-2}	0.14	0.0	2.1×10^{-2}
		50,001-100,000	4.2×10^{-2}	0.26	0.0	4.0×10^{-2}

5. Other Hazardous Materials

Tables 12-14 through 12-20 inclusive present results for all other hazardous-material categories considered in the impact-assessment analysis. As above, results are self-explanatory.

H. REFERENCES

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5. Lawson, D. I. and Simms, D. L., "The Ignition of Wood by Radiation," Brit. J. Appl. Phys., 3, 1952, pp. 288-292.

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TABLE 12-14. IMPACT ASSESSMENT RESULTS FOR COMBUSTIBLE LIQUIDS

Scenario	Probability	Amount (gal.)	Lethal Zone, α_L (sq. km.)	Injury Zone, α_{INJ} (sq. km.)	Building Damage Zone, α_{PD} (sq. km.)
1. Pool fire (also worst case)	0.5	1-100 101-1,000 1,001-5,000 5,001-10,000 10,001-25,000 25,001-50,000 50,001-100,000	0.0 1.2×10^{-4} 6.2×10^{-4} 1.7×10^{-3} 4.0×10^{-3} 8.2×10^{-3} 1.6×10^{-2}	1.5×10^{-4} 2.0×10^{-3} 7.4×10^{-3} 1.8×10^{-2} 3.5×10^{-2} 6.7×10^{-2} 0.12	0.0 1.2×10^{-4} 6.2×10^{-4} 1.7×10^{-3} 4.0×10^{-3} 8.2×10^{-3} 1.6×10^{-2}
2. No ignition	0.5	Any	0.0	0.0	0.0
Composite average	1.0	1-100 101-1,000 1,001-5,000 5,001-10,000 10,001-25,000 25,001-50,000 50,001-100,000	0.0 6.0×10^{-5} 3.1×10^{-4} 8.5×10^{-4} 2.0×10^{-3} 4.1×10^{-3} 8.0×10^{-3}	7.5×16^{-5} 6.0×10^{-5} 3.7×10^{-3} 9.0×10^{-3} 1.8×10^{-3} 3.4×10^{-2} 6.0×10^{-2}	0.0 6.0×10^{-5} 3.1×10^{-4} 8.5×10^{-4} 2.0×10^{-3} 4.1×10^{-3} 8.0×10^{-2}
Worst case	1.0	See Scenario #1 above			

TABLE 12-15. IMPACT ASSESSMENT FOR FLAMMABLE SOLIDS (SPECIAL HAZARD)

Scenario	Probability	Amount (lb.)	Lethal Zone, α_L (sq. km.)	Injury Zone, α_{INJ} (sq. km.)	Building Damage Zone, α_{PD} (sq. km.)
1. Burning railroad car	0.1	Any	1.2×10^{-4}	2.3×10^{-3}	1.2×10^{-4}
2. No ignition	0.9	Any	0.0	0.0	0.0
Composite average	1.0	Any	1.2×10^{-5}	2.3×10^{-4}	1.2×10^{-5}
Worst case	1.0	See Scenario #1 above	1.2×10^{-3}	2.3×10^{-3}	1.2×10^{-4}

TABLE 12-16. IMPACT ASSESSMENT RESULTS FOR OXIDIZING MATERIALS

Scenario	Probability	Amount* (gal. + 10^{-1})	Outdoor Lethal, a_L (sq. km.)	Outdoor Injury, a_{INJ} (sq. km.)	Indoor Lethal, a_L (sq. km.)	Indoor Injury, a_{INJ} (sq. km.)	Building Destruction, a_{PI} (sq. km.)	Glass Breakage, a_{PI} (sq. km.)
1. Detonation (requires heat or shock to occur)	0.1	1-100 101-1,000 1,001-5,000 5,001-10,000 10,001-25,000 25,001-50,000 50,001-100,000	8.7×10^{-4} 4.3×10^{-3} 1.3×10^{-2} 2.5×10^{-2} 4.3×10^{-2} 7.2×10^{-2} 0.11	1.9×10^{-3} 9.7×10^{-3} 3.1×10^{-2} 5.5×10^{-2} 9.7×10^{-2} 0.17 0.48	3.7×10^{-3} 1.9×10^{-2} 5.7×10^{-2} 0.11 0.19 0.31 0.49	9.0×10^{-4} 4.0×10^{-3} 1.4×10^{-2} 2.0×10^{-2} 4.0×10^{-2} 7.0×10^{-2} 0.11	7.5×10^{-3} 3.7×10^{-2} 0.12 0.21 0.37 0.62 0.98	6.6×10^{-2} 0.32 1.0 1.9 3.2 5.4 8.6
2. No Detonation	0.9	Any	0.0	0.0	0.0	0.0	0.0	0.0
Composite Average	1.0	1-100 101-1,000 1,001-5,000 5,001-10,000 10,001-25,000 25,001-50,000 50,001-100,000	8.7×10^{-5} 4.3×10^{-4} 1.3×10^{-3} 2.5×10^{-3} 4.3×10^{-3} 7.2×10^{-3} 1.1×10^{-2}	1.9×10^{-4} 9.7×10^{-4} 3.1×10^{-3} 5.5×10^{-3} 9.7×10^{-3} 1.7×10^{-2} 4.8×10^{-2}	3.7×10^{-4} 1.9×10^{-3} 5.7×10^{-3} 1.1×10^{-2} 1.9×10^{-2} 3.1×10^{-2} 4.9×10^{-2}	9.0×10^{-5} 4.0×10^{-4} 1.4×10^{-3} 2.0×10^{-3} 4.0×10^{-3} 7.0×10^{-3} 1.1×10^{-2}	7.5×10^{-4} 3.7×10^{-3} 1.2×10^{-2} 2.1×10^{-2} 3.7×10^{-2} 6.2×10^{-2} 9.8×10^{-2}	6.6×10^{-3} 3.2×10^{-2} 1.0×10^{-1} 1.9×10^{-1} 3.2×10^{-1} 5.4×10^{-1} 8.6×10^{-1}
Worst Case	See Scenario #1 above.							

*This analysis was originally based on amounts specified in pounds. To facilitate use, the amounts were converted to gallons using an approximate conversion factor.

TABLE 12-17. IMPACT ASSESSMENT RESULTS FOR ORGANIC PEROXIDES

Scenario	Probability	Amount (gal.)	Outdoor Lethal, a_L (sq. km.)	Outdoor Injury, a_{INJ} (sq. km.)	Indoor Lethal, a_L (sq. km.)	Indoor Injury, a_{INJ} (sq. km.)	Building Destruction, a_{PD} (sq. km.)	Glass Breakage, a_{PD} (sq. km.)
1. Detonation (requires heat or shock to occur)	0.1	1-100 101-1,000 1,001-5,000 5,001-10,000 10,001-25,000 25,001-50,000 50,001-100,000	6.8×10^{-4} 3.3×10^{-3} 1.0×10^{-2} 1.9×10^{-2} 3.4×10^{-2} 5.6×10^{-2} 8.8×10^{-2}	1.5×10^{-3} 7.7×10^{-3} 2.4×10^{-2} 4.3×10^{-2} 7.6×10^{-2} 0.12 0.27	2.9×10^{-3} 1.4×10^{-2} 4.4×10^{-2} 8.2×10^{-2} 0.14 0.24 0.38	7.0×10^{-4} 4.0×10^{-3} 1.1×10^{-2} 1.8×10^{-2} 4.0×10^{-2} 6.0×10^{-2} 9.0×10^{-2}	5.8×10^{-3} 2.9×10^{-2} 8.9×10^{-2} 0.16 0.29 0.48 0.76	5.1×10^{-2} 0.25 0.78 1.4 2.5 4.2 6.6
2. No Detonation	0.9	Any	0.0	0.0	0.0	0.0	0.0	0.0
Composite Average	1.0	1-100 101-1,000 1,001-5,000 5,001-10,000 10,001-25,000 25,001-50,000 50,001-100,000	6.8×10^{-5} 3.3×10^{-4} 1.0×10^{-3} 1.9×10^{-3} 3.4×10^{-3} 5.6×10^{-3} 8.8×10^{-3}	1.5×10^{-4} 7.7×10^{-4} 2.4×10^{-3} 4.3×10^{-3} 7.6×10^{-3} 1.2×10^{-2} 2.7×10^{-2}	2.9×10^{-5} 1.4×10^{-3} 4.4×10^{-3} 8.2×10^{-3} 1.4×10^{-2} 2.4×10^{-2} 3.8×10^{-2}	7.0×10^{-5} 4.0×10^{-4} 1.1×10^{-3} 1.8×10^{-3} 4.0×10^{-3} 6.0×10^{-3} 9.0×10^{-3}	5.8×10^{-4} 2.9×10^{-3} 8.9×10^{-3} 1.6×10^{-2} 2.9×10^{-2} 4.8×10^{-2} 7.6×10^{-2}	5.1×10^{-3} 2.5×10^{-2} 7.8×10^{-2} 1.4×10^{-1} 2.5×10^{-1} 4.2×10^{-1} 6.6×10^{-1}
Worst Case	See Scenario #1 above.							

TABLE 12-18. IMPACT ASSESSMENT RESULTS FOR CLASS A POISON

Scenario	Probability	Amount (gal.)	Lethal Zone, α_L (sq. km.)	Injury Zone, α_{INJ} (sq. km.)	Irritation Zone, α_{IRR} (sq. km.)
Liquid release with flashing-Composite average	1.0	1-100	5.7×10^{-3}	5.4×10^{-2}	7.6×10^{-2}
		101-1,000	7.1×10^{-2}	0.78	1.2
		1,001-5,000	0.47	5.8	9.6
		5,001-10,000	1.3	18.1	30.8
		10,001-25,000	3.7	53.2	94.4
		25,001-50,000	9.3	>100*	>100*
		50,001-100,000	22.4	>100*	>100*
Liquid release with flashing-Worst case (phosgene)	1.0	1-100	4.23×10^{-2}	0.49	0.83
		101-1,000	0.71	12.1	25.9
		1,001-5,000	6.6	>100*	>100*
		5,001-10,000	24.8	>100*	>100*
		10,001-25,000	92.4	>100*	>100*
		25,001-50,000	>100*	>100*	>100*
		50,001-100,000	>100*	>100*	>100*

*Answers of this magnitude are likely to be considerably in error for two reasons: (1) because downwind maximum hazard extents are greater than 100 km. Values for the dispersion coefficients σ_x and σ_y were crudely extrapolated from data for distances less than 100 km. They may be wrong for greater distances; (2) because the "worst case" weather conditions assumed are unlikely to persist for the length of time required for dispersion to these distances. As a consequence, the user should not accept these predictions as being completely valid.

TABLE 12-19. IMPACT ASSESSMENT RESULTS FOR CLASS B POISON

Scenario	Probability	Amount (gal.)	Lethal Zone, u_L (sq. km.)	Injury Zone, u_{INJ} (sq. km.)	Irritation Zone, u_{IRR} (sq. km.)	Building Damage Zone, u_{PD} (sq. km.)
1. Pool fire (3 of 4 hazardous materials considered were flammable)	0.5	1-100	0.0	2.0×10^{-4}	0.0	0.0
		101-1,000	1.7×10^{-4}	1.7×10^{-3}	0.0	1.7×10^{-4}
		1,001-5,000	8.9×10^{-4}	7.5×10^{-3}	0.0	8.9×10^{-4}
		5,001-10,000	2.1×10^{-3}	1.6×10^{-2}	0.0	2.1×10^{-3}
		10,001-25,000	4.9×10^{-3}	3.3×10^{-2}	0.0	4.7×10^{-3}
		25,001-50,000	1.0×10^{-2}	6.2×10^{-2}	0.0	1.0×10^{-2}
		50,001-100,000	1.9×10^{-2}	0.11	0.0	1.9×10^{-2}
2. No Ignition - Vapor evolution	0.5	1-100	4.7×10^{-5}	2.9×10^{-4}	0.0	0.0
		101-1,000	4.1×10^{-4}	3.3×10^{-3}	0.0	0.0
		1,001-5,000	2.2×10^{-3}	2.0×10^{-2}	0.0	0.0
		5,001-10,000	5.8×10^{-3}	5.4×10^{-2}	0.0	0.0
		10,001 25,000	1.5×10^{-2}	0.14	0.0	0.0
		25,001 50,000	3.4×10^{-2}	0.34	0.0	0.0
		50,001-100,000	7.6×10^{-2}	0.77	0.0	0.0
Composite Average	1.0	1-100	2.4×10^{-5}	2.5×10^{-4}	0.0	8.5×10^{-5}
		101-1,000	2.9×10^{-4}	2.5×10^{-3}	0.0	4.5×10^{-4}
		1,001-5,000	1.5×10^{-3}	1.4×10^{-2}	0.0	1.1×10^{-3}
		5,001-10,000	4.0×10^{-3}	3.5×10^{-2}	0.0	2.4×10^{-3}
		10,001-25,000	1.0×10^{-2}	8.7×10^{-2}	0.0	5.0×10^{-3}
		25,001-50,000	2.2×10^{-2}	2.0×10^{-1}	0.0	1.0×10^{-2}
		50,001-100,000	4.8×10^{-2}	4.4×10^{-1}	0.0	
Worst Case - Aniline release with no ignition	1.0	1-100	6.7×10^{-4}	3.7×10^{-3}	0.0	0.0
		101-1,000	7.5×10^{-3}	5.0×10^{-2}	0.0	0.0
		1,001-5,000	4.8×10^{-2}	0.38	0.0	0.0
		5,001-10,000	0.14	1.2	0.0	0.0
		10,001-25,000	0.40	3.8	0.0	0.0
		25,001-50,000	1.1	11.3	0.0	0.0
		50,001-100,000	2.7	32.3	0.0	0.0

TABLE 12-20. IMPACT ASSESSMENT RESULTS FOR CORROSIVES

Scenario	Probability	Amount (gal.)	Lethal Zone, α_L (sq. km.)	Injury Zone, α_{INJ} (sq. km.)	Irritation Zone, α_{IRR} (sq. km.)
Liquid release with vapor evolution - Composite average	1.0	1-100	0.0	3.9×10^{-4}	1.5×10^{-3}
		101-1,000	6.1×10^{-5}	4.8×10^{-3}	2.2×10^{-2}
		1,001-5,000	3.7×10^{-4}	3.1×10^{-2}	0.16
		6,001-10,000	1.0×10^{-3}	8.83×10^{-2}	0.50
		10,001-25,000	2.7×10^{-3}	0.24	1.5
		25,001-50,000	6.5×10^{-3}	0.61	4.0
		50,001-100,000	1.5×10^{-2}	1.4	10.2
Liquid release with vapor evolution - Worst case (bromine)	1.0	1-100	2.1×10^{-4}	2.0×10^{-2}	0.11
		101-1,000	2.3×10^{-3}	0.25	1.6
		1,001-5,000	1.3×10^{-2}	1.7	12.0
		5,001-10,000	3.6×10^{-2}	5.0	37.8
		10,001-25,000	9.3×10^{-2}	13.9	>100*
		25,001-50,000	0.22	36.1	>100*
		50,001-100,000	0.49	87.0	>100*

*Answers of this magnitude are likely to be considerably in error for two reasons: (1) because downwind maximum hazard extents are greater than 100 km. Values for the dispersion coefficients σ_x and σ_y were crudely extrapolated from data for distances less than 100 km. They may be wrong for greater distances; (2) because the "worst case" weather conditions assumed are unlikely to persist for the length of time required for dispersion to these distances. As a consequence, the user should not accept these predictions as being completely valid.

APPENDIX A

ANNOTATED BIBLIOGRAPHY

As part of this project, Arthur D. Little, Inc., assembled a Project Resource Library. This library contains documents and data tapes that are required for the project, as well as documents that describe research and information related to this project.

In reviewing the documentation for the Project Resource Library, an annotated bibliography was completed and is provided on the following pages. The bibliography has been arranged into five general categories. They are:

1. Risk and Safety,
2. Hazards and Hazardous Materials: Transportation, Consequences, Safety Analysis,
3. Rail, Railroad, Railcar: Mechanical Tests and Analysis,
4. Association of American Railroads/Railway Progress Institute (AAR/RPI) Track Car Safety Research and Test Project.
5. Miscellaneous.

1. Risk and Safety

Arthur D. Little, Inc., "Estimation of the Frequency and Cost Associated with the Cleanup of Hazardous Materials Spills," for Environmental Protection Agency, Contract Number 68-01-3857, Draft Final Report, September 1978.

> This report estimates the cost to the Federal Government for efforts to contain, clean up and dispose of contaminated materials; restore the environment; and monitor spills of hazardous materials. It considers releases of solids, liquids, and gases to all media.

Stoehr, L. A., et al., "Spill Risk Analysis Program: Methodology Development and Demonstration--Final Report Volume I," Operations Research, Inc., for Department of Transportation (DOT), Report Number CG-D-21-77, Final Report, April 1977.

> The report describes methods for assessing the effectiveness of merchant marine safety regulations. Analytic modeling involves physical parameters; vessel size, speed, maneuverability; and human responses. Logical modeling of casualties addresses the effects of changes in regulations.

White, W. D. and Stoehr, L. A., "Spill Risk Analysis Program: Methodology Development and Demonstration--Final Report, Volume II," Operations Research, Inc., for Department of Transportation, Report Number CG-D-22-77, Final Report, April 1977.

> (See previous entry.)

Simmons, J. A., "Risk Assessment of Storage and Transport of Liquefied Natural Gas and LP Gas," Science Applications, Inc. for Environmental Protection Agency (EPA), Contract Number EPA-68-01-2695, November 1974.

> Described is a method for assessing the societal risk of transporting liquefied natural gas (LNG) or liquefied petroleum gas (LPG) by truck and ship. Data on past experience and projected handling of the liquefied gases are used with flammable plume analyses to estimate the risk of fatalities from liquefield gas shipments. Comparison with fires and explosions from all causes shows a relatively low frequency of LPG-LNG accidents.

Philipson, L. L., "Risk Analysis in Hazardous Materials Transportation: A Mechanism for Interfacing the Risk Analysis Model with the Hazardous Materials Incident Reporting System," University of Southern California for Office of Hazardous Materials, Report Number TES-20-74-6, Final Report September 1974.

> This report describes the risk analysis system of the Office of Hazardous Materials; discusses the system's advantages and shortcomings, and recommends improvements. The present system makes risk analysis, predicts expected shipping losses, and provides comparative risk evaluations, based primarily on the data of the Hazardous Materials Incident Reporting System.

Philipson, L. L., "Investigation of the Feasibility of the Delphi Technique for Estimating Risk Analysis Parameters," University of Southern California, Research Center, for Office of Hazardous Materials, Report Number TES-20-74-4, Final Report, April 1974.

> The report examines the potential for augmenting the data base for a hazardous transportation model through an organized survey of experts. The Delphi experiment which was conducted is described and a Bayes procedure for combining statistical data with the Delphi results is also defined.

Jones, G. P., Barrow, R. W., Struckenbruck, L. C., Holt, E. L., and Keller, R. P., "Risk Analysis in Hazardous Material Transportation, Volume I," University of Southern California, for the Office of Hazardous Materials, Report Number TES-20-73-4-1, Final Report, March 1973.

> A risk analysis model is developed and demonstrated through twenty examples to show its flexibility in accepting data, and the types of results. A demonstration was performed to show the practicality of evaluating special permit petitions.

Jones, G. P., et al., "Risk Analysis in Hazardous Materials Transportation, Volume II, Bibliography," University of Southern California, for Office of Hazardous Materials, Report Number TES-20-73-5-2, March 1973.

> Section 1 of the bibliography contains abstracts. Section 2 contains a concise bibliographic listing.

National Transportation Safety Board, Special Study, "Risk Concepts in Dangerous Goods Transportation Regulation," Report Number NTSB-STS-71-1, January 1971.

> The study examines the salient approaches underlying the development of existing regulations, the difficulties created by regulations, and the needs which must be met by new approaches. The NTSB concludes that a risk-based framework for future regulation is necessary, desirable, and feasible.

Simmons, J.A., et al., "Risk Assessment of Large Spills of Toxic Materials," from Proceedings of the 1974 National Conference of Control of Hazardous Materials Spills, San Francisco, California, August 1974.

Simmons, J. A., et al., "Risk of Catastrophic Spills of Toxic Chemicals," California University, Los Angeles, for Energy Research and Development Administration, Contract Number E(04-3)-34, May 1974.

Berger, R. W., "Use of Risk Analysis for Decision-Making," in Computer Decisions, March 1972.

National Research Council, Committee on Hazardous Materials, "Proceedings: Conference on Hazard Evaluation and Risk Analysis," for United States Coast Guard (USCG), 1971.

Daenzer, B. J., "Fact-finding Techniques in Risk Analysis," American Management Association, New York, 1970.

Garrick, B. J., Baldonado, O. C., and Gekler, W.C., "Estimating the Risk Involved in Transport of Hazardous Materials," Minutes of the Explosives Safety Saminar, Memphis, TN., August 25-27, 1970, Armed Services Explosive Safety Board, Washington, D.C., 1970.

Transportation Systems Safety Research Group, University of Illinois, "Development of Risk Methodology for Transportation Systems Safety," Report of Tasks 1, 2, and 3 to Department of Transportation, Washington, D.C.

2. Hazards and Hazardous Materials: Transportation, Consequences, Safety Analysis

Buckley, J. L., et al., "Hazardous Materials Spills: A Documentation and Analysis of Historical Data," Factory Mutual Research Corp., Norwood, Mass., for EPA-Office of R&D, Report No. EPA-600/2-78-066, April 1978.

> The objective of this study was to provide guidance for the choice of research priorities for spill prevention through documentation and analysis of historical incidents involving hazardous-material spills. Data were analyzed for the period January 1, 1971 through June 30, 1973. To allow comparison of spills of different materials, a hazard potential scheme was developed. Incorporating toxicity and quantity spilled, incidents were ranked on a hazard potential scale ranging from one to ten. The scheme developed is specific to the needs of this study rather than being a general mechanism for comparing spills. Primary and secondary causes of hazardous material spills in various operational areas (in Transit, Loading-Unloading Areas, in Plant Storage, in Plant Processing) were identified. The data were treated to find the frequency and distribution of hazardous-material spills by cause, operational area, and hazard potential.

"Hazardous Materials Transportation--Part 1: General Studies (A Bibliography with Abstracts)," Period Covered: 1964-1977, National Technical Information Service (NTIS), Report No. PS-77/0405, June 1977.

> The transportation of explosives, rocket propellants, chemical warfare agents, industrial chemicals, liquefied natural gas, chlorine, and other hazardous materials is covered. All means of transportation are described. Accidents, economics, and statistics are also included in these reports. Radioactive wastes and materials are excluded. (This updated bibliography contains 243 abstracts, 53 of which are new entries to the previous edition.)

"Hazardous Materials Transportation--Part 2: Radioactive Materials and Wastes (A Bibliography with Abstracts)," Period Covered: 1964-1977, NTIS Report No. PS-77/0406, June 1977.

> The bibliography presents studies on the hazards, risks, and uncertainty of transporting radioactive wastes and materials. The design of shipping containers and special labels for identification purposes for transporting fuels and wastes are also cited. Studies are included on legislation dealing with the safety and health of the population and the environmental problems associated with transporting radioactive materials. (This updated bibliography contains 130 abstracts, 24 of which are new entries to the previous edition.)

Henderson, N. C., et al., "Survey Study of Techniques to Prevent or Reduce Discharges of Hazardous Chemicals," Battelle Columbus Labs., Ohio, Final Report, NTIS Report No. AD-A020 173/1st, August 1975.

A program was conducted for the Office of Research and Development, U.S. Coast Guard, to investigate both off-the-shelf and conceptual techniques for preventing or reducing the discharge of hazardous chemicals from an endangered marine vessel, or to stop or reduce the discharge from an actual leak. First, approximately 50 methods and/or types of equipment were identified. Next, the compatibility of each of the concepts and equipment with the Chemical Response Information System (CHRIS) list of hazardous chemicals was determined on a relative basis. The concepts were then evaluated on the basis of their relative chemical compatibility in combination with overall usefulness and the various types of on-site operations to which they applied.

Allan, D. S., and Harris, G. H., "Chemical Response Information System for Multimodal Accidents (CHRISMA)--A Reevaluation of CHRIS for All Modes of Transportation," Arthur D. Little, Inc., Cambridge, Mass., Final Report, NTIS Report No. AD-A016 296/6 ST, April 1975.

This report examines the need for improved technical and other information for meeting emergencies connected with the transportation of hazardous materials, particularly actual or potential chemical discharges, regardless of mode. The Chemical Hazards Response Information System (CHRIS), under development by the United States Coast Guard to furnish in-depth guidance during emergencies involving waterborne transport, was seen as a likely prototype for other modes as well. It is concluded that the expanded system would indeed be beneficial in reducing losses to life, property, and the environment.

Jaquette, D. L., "Possibilities and Probabilities in Assessment of the Hazards of the Importation of Liquefied Natural Gas," Rand Corp., Santa Monica, California, NTIS Report No. AD-A019 353/2ST, April 1975.

There are at least four main research areas that must be addressed in developing estimates of the risk to population and property from the importation of large quantities of LNG. The report examines the available research approaches directed toward one of these, the assessment of the possible release scenarios and, in particular, their associated probabilities. The character and need for more research are discussed.

Atallah, S., et al., "Supplement--Task III: Summary of LNG Safety Research," Arthur D. Little, Inc., Cambridge, Mass., for DOT/Office of the Secretary of Transportation (OST)-Office of Pipeline Safety, Report No. PB273378, December 1974.

> Results from major published research programs related to assessment and alleviation of potential LNG hazards are described. Topics covered include: vaporization and dispersion from LNG spills, boiling heat transfer rates for LNG on water, superheat "explosions," tank stratification and rollover, thermal radiation from LNG pool fires, detonation conditions, pool spread and thermal radiation from ignited LNG releases on water, deflagration of natural gas-air vapor clouds, and LNG fire control and suppression research. In addition to descriptive material, an extensive bibliography is included and future research needs are suggested.

Fridinger, C. E., et. al., "Development of Performance-oriented Specifications for Drums and Pails for Packaging of Hazardous Materials for Transportation," Naval Surface Weapons Center, Silver Springs, MD, for DOT, Office of Hazardous Material, Final Report No. PB 240 647, December 1974.

> Hazard classifications, performance requirements and tests, and a container rating system were developed. The rationale behind the development is presented in the report. Test plans for qualification and periodic testing and detailed test procedures were prepared. Tests included were leak, distortion, pressure-proof, repetitive shock (vibration), west strength-stacking, drop, puncture, and temperature cycle. A representative sample of drums and pails now regulated by DOT was subjected to the test program. Details of the test results are included in the report.

Lind, C. D., "Explosion Hazards Associated with Spills of Large Quantities of Hazardous Materials"--Phase I: Naval Weapons Center, China Lake, California, for USCG, Washington, D.C., Final Report, NTIS Report No. AD/A-001 242/75L, October 1974.

> The report documents the results of Phase I of a program whose object is to quantify the explosion hazards associated with spills of large quantities of hazardous material such as liquefied natural gas (LNG), liquefied petroleum gas (LPG), or ethylene. The principal results are:(1) a phenomenological description of a spill, (2) an examination of the detonation properties of methane, (3) a qualitative theory of non-ideal explosions, and (4) a plan for Phase II of the study.

Vassalo, F. A., et al., "Review of Proposed Specifications Relating to the Shipment of Ethylene in Tank Cars at Cryogenic Temperatures," Calspan Corp., Buffalo, N.Y., for DOT/Federal Railroad Administration (FRA), Office of R&D, Final Report No. FRA-OR4D 25-41, September 1974.

This report reviews proposed specifications and shipper regulations for 113 series tank cars for transporting liquid ethylene at cryogenic temperatures. The study was limited in scope and was to be directed primarily at the holding time requirements necessary for safe shipment of the commodity. Apparent deficiencies are noted in the proposed in-transit pressure rise specification; a candidate modification is described.

Arthur D. Little, Inc., "A Modal Economic and Safety Analysis of the Transportation of Hazardous Substances in Bulk," for U.S. Department of Commerce, Maritime Administration, Report No. C-76446, May 1974.

The objective of the study was to analyze quantitatively the economics and safety of transporting selected bulk hazardous substances, other than oil, by inland waterway and overland (rail, truck, and possibly pipeline) modes, so that the costs and risks associated with the different modes could be compared. There were three major components to this process: (1) choosing the substances, origin-designation combinations, and shipment characteristics to be studied; (2) determining all costs involved in transporting each substance between the designated points by barge and relevant overland modes; and (3) determining the frequency and quantity of spills likely with each mode and the resultant risk to people, property, and the environment.

Lyman, W., et al, "Survey Study to Select a Limited Number of Hazardous Materials to Define Amelioration Requirements--Vols. I and II," Arthur D. Little, Inc., Cambridge, Mass., for USCG Office of R&D, Washington, D.C., Final Report, NTIS Report No. AD/A-004 311/75T, March 1974.

The work entailed the categorization of hazardous chemicals according to physical and chemical characteristics that were perceived to be amenable and important to the development of amelioration techniques. A total of 400 hazardous chemicals deemed to encompass most of the more critical chemicals in terms of quantity shipped and the severity of the hazards presented were associated with each of approximately 30 amelioration categories. A representative chemical was then selected for each category with the intent that it would provide the basis for searching for, evaluating, and developing amelioration methods from each category. The representative chemicals were chosen by assessing the chemical and physical behavior of the chemicals, their risk indices, and other practical considerations.

Lippian, J. M., "The Transportation of Hazardous Materials: Transport of Benzene by Tank Car," Intern Training Center, U.S. Army Materiel Command, Texarkana, Texas, Master's Thesis, NTIS Report No. AD771105, May 1973.

> Specific recommendations on the identification and labeling of the hazards associated with benzene are discussed and a risk rating model is suggested for general use in the transportation of hazardous materials. Through use of a gross hazard analysis and a fault tree analysis, the basic parameters involved in the transport of benzene are determined.

Lasseigne, A. H., "Hazard Classification of Explosives, Flammable and Oxidizing Materials for Transportation--Evaluation of Test Methods," G.E. Apollo and Ground Systems, Bay St. Louis, Miss., for DOT/Office of Hazardous Materials (OHM), Final Report, NTIS Report No. PB225 422, May 1973.

> The work described herein correlates proposed explosives testing with proposed testing for the classification of other related types of hazardous materials--inorganic oxidizers, organic peroxides, and flammable solids. The work also provides information relative to additional hazard classification testing, further refinements in hazard classification test methodology, and expanded hazard classification test criteria.

"U.S.C.G. Oil Pollution Investigation and Control School: On-Scene Coordinators Manual," C.G. Reserve Training Center, Yorktown, Va., NTIS Report No. AD-758-511, November 1972.

> The report is a handbook for a Federal On-scene Coordinator for use in combating oil and hazardous-material spills. It includes the National, Regional, and Local Contingency Plans, guidelines for the coordinator, and a case study of an oil spill involving the USNS Towle in New York harbor.

"U.S.C.G Oil Pollution Investigation and Control School: Investigator's Manual," C.G. Reserve Training Center, Yorktown, Va., NTIS Report No. AD-758,510, November 1972.

> The report is a handbook for water pollution investigators. It includes applicable laws, the Miranda case, criminal investigative procedures, report writing guidelines, sample reports, photographic techniques, evidence gathering, and an outline of tanker/terminal oil transfer operations.

Rath, G. J., et al., "A Study of Hazardous Materials Information Needs and Identification Systems for Transportation Purposes," Northwestern University Design and Development Center, Evanston, Ill., for DOT/OHM, Final Report No. TSA-20-72-4, May 1972.

> Information needs and methods to transmit that information are analyzed to determine the basic requirements of a hazard-identification system for packages containing, and vehicles carrying, hazardous materials. Persons who come in contact with hazardous-material shipments are identified and a typology developed. Information needs (type, amount, and timing) are listed by category, and sixteen existing labeling systems are evaluated according to these and human factors criteria.

Environmental Protection Agency, Washington, D.C., "Control of Hazardous Material Spills," Presented at the Proceedings of the National Conference on Control of Hazardous Material Spills, Houston, Texas, NTIS Report No. PB-228 736/5, March 1972.

> Contents include: The protection of the environment from hazardous-material spills; prevention of hazardous material spills in heavy process industries; contingency planning for response to hazardous-material spills; the containment of hazardous material spills; the detection and identification of hazardous-material spills; treatment systems for waters contaminated by hazardous materials; the effects of hazardous-material spills on the environment; ecology restoration of waterways following hazardous-material spills.

Ostrem, F. E., and Libovicz, B., "A Survey of Environmental Conditions Incident to the Transportation of Materials," General American Transportation Corporation, Niles, Ill., for DOT/OHM, Final Report No. 1512-1, October 1971.

> A survey was conducted to compile, analyze and summarize environmental data defining the transportation environment. The current availability of information describing the conditions of vibration, shock, impact, heat, cold, compression, puncture, abrasion, humidity and temperature is assessed and significant data presented. Summaries of the data are given to show the extremes of the environmental conditions for each element of the transportation cycle (in-transit, storage and handling) where possible.

Bullerdick, W. A., et al., "A Study to Reduce the Hazards of Tank Car Transportation," Cornell Aeronautical Lab. Inc., Buffalo, N.Y., for DOT/FRA, Final Report No. FRA-RT-71-74, November 1970.

> Principal objectives were to (1) define thermal inputs and associated vapor generation rates for hazardous materials transported in tank cars when subjected to fire exposure; (2) develop performance specifications and conceptual design and application requirements for safety devices preventing catastrophic car failures; and (3) formulate a research program for the design and test verification of recommended safety devices. Prime effort was directed toward the prevention of catastrophic rupture of large-capacity, pressure-type cars. A number of shortcomings with existing safety-relief specifications were indicated. A staged safety relief system was recommended for cars with liquefied compressed gas ladings.

Dawson, G. W., et al., "Control of Spillage of Hazardous Polluting Substances," Battelle Memorial Institute, Richland, Washington, NTIS Report No. PB-197 596, November 1970.

> An evaluation of the water quality aspects germane to the spillage of hazardous polluting substances is developed. Emphasis is placed on definition and classification of chemical materials; the nature of the source of spillage and past experience; analysis of the relative threat to water quality offered by such substances; a review of presently available detection, control, and removal technology, and their relationship to water quality standards; and the relevant administrative, enforcement, and cost-recovery aspects. Over 250 chemicals and compounds, generally those in large-scale production and utilization, are priority-ranked in order of relative threat to water quality.

"Control of Hazardous Polluting Substances," U.S.C.G, Washington, D.C., Final Report, NTIS Report No. PB-199 193, October 1970.

> This study deals with only the water pollution aspect. Focus was placed on accidental spills and effluent discharges in excess of those authorized. The study supports a report on the need for legislation to impose liability and financial responsibility requirements for the cost of removal of hazardous substances discharged from vessels and onshore and offshore facilities. In addition, the study includes an extensive bibliography.

Booz-Allen and Hamilton, Inc., Washington, D.C., "An Appraisal of the Problem of the Handling, Transportation, and Disposal of Toxic and Other Hazardous Materials," for DOT, Final Report, NTIS Report No. PB-236 599/7ST, January 1970.

> The report presents detailed narrative, tables, and graphs as follows: Hazardous-material classification; types and quantities of hazardous materials; accidents involving hazardous materials; transportation environment; disposal of hazardous materials; and references and contacts. Hazardous materials discussed are flammable materials, compressed gases, corrosive materials, explosives, oxidizers, pistons including chemical warfare agents and pesticides, infectious agents, radioactive materials, and molten materials.

National Academy of Sciences, Washington, D.C., "A Study of Transportation of Hazardous Materials," Study Group at Warrentown, Va., NTIS Report No. AD-692 182, May 1969.

> This report constitutes the findings of a study undertaken May 7-9, 1969, for the specific purposes of appraising existing knowledge, procedures, and practices of all transportation modes; exploring improved or revised concepts for approach to regulations, based on scientific knowledge and engineering methods; and suited to the practices and materials of an increasingly technological culture; identifying existing and new resources and facilities needed to support more technology-oriented approaches to public safety regulation; and recommending immediate and longer term actions for improving the present regulatory system for hazardous materials transportation.

National Highway Traffic Safety Administration/Materials Transportation Bureau (NHTSA/MTB), "Emergency Action Guide for Selected Hazardous Materials," DOT, 1978.

Raj, P. K., "Calculation of Thermal Radiation Hazards from LNG Fires--A Review of the State-of-the-Art," Paper presented at the AGA Transmission Conference, St. Louis, Mo., May 1977.

DOT, "First (through Seventh) Annual Report of the Secretary of Transportation on Hazardous Materials Control," Washington, D.C., 1970-1976.

Arthur D. Little, Inc., Cambridge, "Response by Regulated Industry in Terms of the Degree of Prevention and Associated Cost Relative to the Hazardous Substance Portion of Section 311 of the FWCPA Amendments of 1972," for EPA, Final Report, December 1976.

U.S.C.G., "A Manual for Safe Handling of Flammable and Combustible Liquids and Other Hazardous Products," DOT, Report No. CG-174, September 1976.

Robertson, F. A., "Fire Standards and Safety," Symposium conducted at the National Bureau of Standards, Gaithersburg, MD., ASTM Special Technical Publication 614, April 1976.

Porter, C. H., "State Program Implementation Guide: Hazardous Waste Transportation Control," EPA, Washington, D.C., Report No. EPA/530/SW-512, March 1976.

EPA, Washington, D.C., "Development Document for Hazardous Substance Regulations," Draft Report, January 1976.

Wiggins, J. H., "Discussion that Accompanies the Briefing on Technology Assessment of the Fire Hazard in the Occupant Compartments of Various Transportation Modes," Redondo Beach, California, April 1975.

Kalelkar, A. S., et al., "Decision Analysis in Hazardous Material Transportation,"Proceedings of the National Conference on Control of Hazardous Materials Spills, San Francisco, California, August 1974.

Angell, G. R., and Kalelkar, A. S., "The Cost and Relative Spill Hazards Related with the Modal Transport of Hazardous Materials," Proceedings of the National Conference on Control of Hazardous Materials Spills, San Francisco, California, August 1974.

American Insurance Association, Engineering and Safety Service, N.Y., "Special Loss Control Bulletin and Chemical Hazards Committee," Bulletin No. 14, October 1973.

Back, A. A., et al., "Reclassification of Materials Listed on Transportation Health Hazards Supplement," Aerospace Medical Lab, Wright-Patterson AFB, Ohio, Final Report, September 1973.

Arthur D. Little, Inc., Cambridge, Ma., "Radiation from LNG Fires," Reference No. 73854, August 1973.

Maejawa, M., "Experiments on Fire Hazards of Liquefied Flammable Gases," Japan Society of Safety Engineering, May 1973.

Streblow, R. A., et al., "On the Measurement of Energy Release Rates in Vapor Cloud Explosions," University of Illinois, Aeronautical Engineering Department, 1972.

University of Engineers, Inc., "LNG Vapor Dispersion and Fire Tests," A joint effort sponsored by the Philadelphia Gas Works, Walter R. Kidde Co., American Gas Association, Oklahoma, December 1971.

Fine, W. T., "Mathematical Evaluation for Controlling Hazards," Journal of Safety Research, Vol. 3, No. 4, pp. 157-166, December 1971.

Atallah, S., and Allan, D. S., "Safe Separation Distances from Liquid Fuel Fires," Fire Technology, Vol. 7, No. 1, pp. 47-56, 1971.

Arthur D. Little, Inc., Cambridge, Ma., "A Report on LNG Safety Research--Vol. II," prepared for American Gas Association, Project 742-1, 1971.

Association of American Railroads, "Report of the Chief Inspector of the Bureau for the Safe Transportation of Explosives and Other Dangerous Articles," Report Nos. 55 through 61, 1961 through 1968.

Fizer, J. C., "Transporting Hazardous Materials by Rail," Classic System Huntington, W. Va. (article).

American Gas Association, "Consequences of LNG Spills on Land," LNG Safety Program, Phase II.

U.S.C.G., "Hazardous Chemical Data," Report No. CG-446-2, Vol. I-IV.

3. Rail, Railroad, Railcar: Mechanical Tests and Analyses

James, R. K., Chairman, "Special Safety Inquiry: Improved Safety Standards for Insulated Pressure Tank Cars," Hearing convened by FRA, Transcript of Proceedings published by Acme Reporting Co., Washington, D.C., April 1978.

> The subject of the hearings is the need to improve present safety standards for the design and construction of new and existing DOT Specification 105-insulated pressure tank cars.

James, R. K., Chairman, "Special Safety Inquiry: Retrofitting Timetable for 112/114 Uninsulated Pressure Tank Cars," Hearing convened by FRA, Transcript of Proceedings published by ACME Reporting Co., Washington, D.C., April 1978.

> The purpose of the hearing is to obtain information on whether it is possible to speed up the schedule for installation of special safety devices on uninsulated pressure tank cars.

Peters, D., and Yin, S. K., "Non-Destructive Impact between Railroad Cars: Experimental and Analytical Study," School of Engineering and Applied Science - Washington Univ., St. Louis, Mo., for DOT/FRA - Office of R&D, Rept. No. FRA-ORD-76/247, January 1977.

> A computer simulation of the dynamics of rail car impacts is compared with experimental data obtained from full-scale switchyard impacts. The compared cases involve impacts between a standing light hopper car and a moving, fully loaded tank car at speeds ranging from 2 mph to 8 mph. The monitored dynamic responses include vertical car motions, draft gear travel, longitudinal coupler forces, car body accelerations, and vertical bolster loads.

Johnson, M. R., "Development of Performance Specifications for LPG Tank Cars", IIT Research Inst., Chicago, Ill., for DOT/FRA, Cont. No. P.O. 74282, Final Report, January 1977.

> The Material Transportation Bureau has proposed requirements that 112A and 114A tank cars be equipped with a thermal protection system, a tank head puncture resistance system, a safety relief valve, and a coupler restraint system. The specific requirements for each of these systems are defined by performance standards. Over the last several

years results have been obtained from a number of research programs which have been conducted to study various aspects of the tank car safety problem. The relationships of these results to the performance standards which have now been proposed for the tank car safety systems are described.

"Final Standards, Classification, and Designation of Lines of Class I Railroads in the United States", Vols. I and II, Dept. of Transportation, January 1977.

This report follows a thorough public review of the Preliminary Standards Classification and Designation of Lines of Class I Railroads in the United States published by the Department on August 3, 1976, pursuant to Section 503 of the Railroad Revitalization and Regulatory Reform Act of 1976 (P.L. 94-210) (the Act). The review process was conducted by the Rail Services Planning Office of the Interstate Commerce Commission which culminated in their publication of an Evaluation Report of the Secretary of Transportation's Preliminary Classification and Designation of Rail Lines. This Evaluation Report, along with the public testimony elicited at the hearings, was considered by the Department in preparation of this Final Report. Volume I of the Final Report establishes five standards for the classification of the Class I rail system: (1) density, (2) service to major markets, (3) appropriate levels of capacity, (4) national defense, and (5) line potentially subject to abandonment under statutory and ICC procedures. Final Volume II contains designations of all Class I Railroad lines in the United States based upon the standards developed in Final Volume I. Each Class I Railroad line segment in the national rail network was subjected to individual analysis, using the most current information available. Designation and identification of individual line segments in the U.S. railroad network structure are presented using a computerized network information system. Statistical summaries of route mileage by line designation are presented. Cross-reference information is presented. Also, an enlarged fold-out national network map displaying the line designations by category is provided.

Johnson, M. R., "Evaluation of Prototype Head Shield for Hazardous Material Tank Car," IIT Research Institute, Chicago, Ill., for DOT/FRA-Office of R&D, Final Rept. No. FRA/ORD 75/96, December 1976.

The structural integrity of a prototype tank car head shield for hazardous material railroad tank cars was evaluated under conditions of freight car coupling at moderate to high speeds. Test data were obtained when the car was impacted into standing cars over a 3-to 9 mph speed range. The tests produced no visible damage to the shield or the structure connecting it to the tank car, but they demonstrated the presence of severe vibrations resulting from the car impact. The likelihood of fatigue damage was indicated in the connecting structural members where the weight of the shield was supported.

Hahn, E. E., "Increased Rail Transit Vehicle Crashworthiness in Head-On Collisions," IIT Research Institute, Chicago, Ill., for DOT/TSC, Contract No. DOT-TSC-1052, August 1976.

<u>ABSTRACT</u>. A computer code for modeling the collision of two consists of urban railcars was developed. This code was used to establish the critical parameters which govern whether the cars will crush, displace vertically and override, or crush with subsequent override. The draft gear shear pin failure load, spring constant and travel as well as the anticlimber horizontal force characteristics were found to be important parameters. A complex and a simplified model of two impacting consists were modeled and run on the computer. It was concluded that accurate results could be obtained from a simplified model. Acceleration pulse shapes were obtained, suitable for use in determining the nature and severity of passenger injury in a head-on collision.

Tong, P., "Mechanics of Train Collision", DOT/TSC, Cambridge, Mass., for DOT/FRA - Office of R&D, Final Rept. No. FRA-OR&D-76-246, April 1976.

A simple and a more detailed mathematical model for the simulation of train collisions is presented. The study presents considerable insight as to the causes and consequences of train motions in impact. Comparison of model predictions with two full scale train-to-train impact tests shows good correlation. Methods for controlling train motion and kinetic energy dissipation for the minimization of train collision-induced damage are suggested.

Peters, D. A., et al., "Tank Car Head Puncture Mechanisms School of Engineering and Applied Science - Washington Univ., St. Louis, Mo., for DOT/FRA, Rept. No. FRA-ORD-76/269, Final Report, June 1976.

> This report is concerned with the description and analysis of head puncture mechanisms. Three classification yard accidents and one main line accident were studied in detail, train-to-train collision tests were analyzed and the results of impact experiments were evaluated. The main conclusion of the report is that head puncture in classification yards is invariably due to overspeed impact.

Lee, E. H., and Mallett, R. L., "Structural Analysis and Design for Energy Absorption in Impact," Division of Applied Mechanics - Stanford Univ., Stanford, Calif., for DOT Office of University Research (OST), Final Rept. No. DOT-TST-76-44, December 1975.

> A general assessment of the nature of the dynamic problem of analyzing the collision of a vehicle is given. Elastic-plastic theory is used. Theorems are given which provide approximations to the maximum plastic deformation and the duration of plastic flow without determining the whole solution. Application of these to simple models is presented. The ability of porous metal to absorb energy of deformation is also analyzed by solving the microscopic problem of collapse of the cavities. Tests of the behavior of porous metal in impact are presented and related to quasistatic measurements of its deformation properties.

Kennedy, R. G., and Lloyd, F. H., "A Methodology for Evaluating the Economic Impacts of Applying Railroad Safety Standards Vols. I and II, CONSAD Research Corp., Pittsburgh, Pa., for DOT/FRA, Final Rept. No. RP-41, October 1974.

> This report presents an evaluation of safety standards proposed by the Federal Railroad Administration and allows for detailed analysis of individual equipment, track, and human factors standards. Discussions are given of other aspects of the methodology such as the proper analysis time span, the effects of inflation and interest rates, quantification problems and the role of sensitivity analysis. Special attention is given

to accidents and accident prediction and also to data availability and data acquisition. An example is given of the use of the methodology using the safety standards addressed to plain bearings on freight cars. Volume 2 of this report is the manual whose step-by-step procedures are intended for the implementation of economic impact analysis. In developing this manual, high priority was placed on presenting workable procedures that can be used immediately for economic impact evaluation. Special attention is given to accidents and accident prediction, discounting, quantification problems and the role of sensitivity analysis. A completely worked example is presented in the appendix.

Association of American Railroads (AAR) Advisory Committee, "Car and Locomotive Cyclopedia," (a third edition) Simons-Boardman Publishing Corporation, N.Y., 1974.

Definitions and illustrations of railroad cars and locomotives and their components built for domestic and export service, including shop practices and electrical fundamentals.

Adams, D. E., et al., "Rail Hazardous Material Tank Car Design Study," Calspan, Buffalo, N. Y., for DOT/FRA, Contract No. DOT-FR-20069, Prelim. Report, Calspan Rept. No. ZL-5226-D-4, April 1975.

This report provides the basis for defining practical and economical safety improvements and identifies the safety research gaps which must be closed before a prototype tank car can be designed to optimal safety/economic considerations. Six areas were given particular consideration because of their greater potential for success for 112A/114A series tank cars. These were: (1) operational changes, (2) head shields, (3) modified couplers, (4) thermal insulation, (5) tank material changes, and (6) safety relief system modifications. Head shields and modified couplers were found likely to be "cost-beneficial." Other tank car research is reviewed and an improved thermal model for calculating the effects on a tank car exposed to fire is presented. Substantial improvements in car safety appear to be feasible without resort to the use of exotic materials or fabrication techniques which could not be accommodated by existing tank car manufacturing facilities.

Wilkinson, M. T., et al., "A Structural Study of Rail Tank Cars," Louisiana Tech University, Ruston, La., for DOT/FRA, Contract No. DOT-FR-30056, June 1975.

> A review and evaluation of the present specifications under which tank cars are designed is made from a structural viewpoint. Deficiencies in these specifications are reported and specific modifications are recommended. The results of a finite element model and an experimental model of a quarter-scale DOT 112A340W car are reported. These results demonstrate that stresses calculated by simple beam models of tank cars are non-conservative. Finite element analyses are also included on full-scale DOT 111 and DOT 112 cars. These studies show that these cars fail to satisfy the present design requirements in the AAR specifications.

Hohenemser, K. H., et al., "Computer Simulation of Tank Car Head Puncture Mechanisms Classification Yard Accidents," School of Engineering and Applied Science - Washington Univ., St. Louis, Mo., for DOT/FRA Office of R&D, Prelim. Rept. No. FRA-OR&D-75-23, February 1975.

> Development of means for identifying possible puncture mechanisms and quantifying the coupler forces involved is the subject of this report. A mathematical model, capable of simulating train action in the vertical plane, has been developed and used for simulation of three classification yard accidents. A detailed description of the model and the results of simulation are presented. The conclusions of this report must be considered tentative until the results of verification studies become available.

Adams, D. E., "Cost/Benefit Analysis of Thermal Shield Coatings Applied to 112A/114A Series Tank Cars," Calspan Corp., Buffalo, N. Y., for DOT/FRA - Office of R&D, Final Report, Rept. No. FRA-OR&D 75-39, December 1974.

> This report updates the analysis done by AAR/RPI on accident losses. Historical data for insulated 105A tank cars were compared with uninsulated 112A/114A tank cars. Results indicate that the "efficiency" (i.e., expected effectiveness) of the

thermal shield appears to be nearly 100 percent--at least in the critical hours. Computer calculations of the temperatures and pressures produced in tank cars have indicated that significant reductions in tank rupture are expected for even thin insulations if the insulation remains attached to the tank during the fire.

Townsend, W., et al., "Comparison of Thermally Coated and Uninsulated Rail Tank Cars Filled with LPG Subjected to a Fire Environment," Ballistic Research Labs. - U.S. Army, Aberdeen Proving Ground, MD , for DOT/FRA - Office of R&D, Final Rept. No. FRA-OR&D 75-32, December 1974.

Two fire tests were conducted on 128-kiloliter, high-pressure rail tank cars filled with liquified petroleum gas. Both tank cars were exposed to an intense hydrocarbon fire after being outfitted with appropriate instrumentation. The instrumentation was monitored and its output recorded throughout the fire tests. To test the feasibility of insulating railroad tank cars to protect them from fire exposure, one of the cars was coated with a 0.318 centimeter (cm) thermal shield. A comparison of data conclusively shows that a thermal shield significantly alters the thermal response of a rail tank car in a fire environment.

Anderson, C., et al., "The Effects of a Fire Environment on a Rail Tank Car Filled with LPG," Ballistic Research Laboratories - U.S. Army, Aberdeen Proving Ground, MD., for DOT/FRA - Office of R&D, Final Rept. No. FRA-OR&D 75-31, September 1974.

A 127 kiloliter (33,600 gallon) railroad tank car was instrumented and filled with liquefied petroleum gas. A large JP-4 fuel pool fire then engulfed the tank car, and measurements of temperature, pressure, etc., were recorded as a function of time. After 24.5 minutes, the car failed catastrophically via stress-rupture. Mass flow rates and a discharge coefficient have been obtained for the relief valve. An analytical expression has been derived and then used to obtain the heat flux to the wetted surface of the tank car.

Anderson, C., and Norris, E. G., "Fragmentation and Metallurgical Analysis of Tank Car RAX 201", Ballistic Research Labs - U.S. Army, Aberdeen Proving Ground, MD., DOT/FRA - Office of R&D, Final Rept. No. FRA-OR&D 75-30, April 1974.

On 28 July 1973, the Ballistic Research Laboratories performed a full-scale fire test on a 33,000-gallon, DOT 112A340W non-insulated, pressure, rail tank car for the Federal Railroad Administration and Association of American Railroads. The car was filled with liquefied petroleum gas (LPG). After 24.5 minutes of exposure to the fire, the tank car ruptured. This report concerns the mapping of the fragments and metallurgical analysis of the ruptured car, along with an investigation of the cause and initial location of failure.

Adams, D. E., et al., "Cost/Benefit Analysis of Head Shields for 112A/114A Series Tank Cars," Calspan Corp., Buffalo, N.Y., for DOT/FRA - Office of R&D, Final Rept. No. FRA-OR&D 75-34, March 1974.

This analysis was based on a redistribution of accident dollar losses using data from AAR/RPI. Historical data are too limited to provide the correct distribution of losses between head and shell punctures. Supporting evidence is presented indicating that dollar losses are strongly related to puncture distribution for a more extensive set of data including all classes of tank cars. It was concluded that head shields on new and existing 112A/114A pressure-type tank cars would be cost beneficial.

Anderson, C., et al., "Railroad Tank Car Fire Test: Test No. 7," Ballistic Research Laboratories - U. S. Army, Aberdeen Proving Ground, MD., for DOT/FRA - Office of R&D, Final Rept. No. FRA-OR&D 75-37, December 1973.

A fire test was conducted on a one-fifth scale model pressurized railroad tank car on 7 February 1973. The tank car model had a thermal insulation of 4 inches (10.16 cm) of polyurethane encased in a 0.125-inch (0.318-cm) steel jacket. The model was loaded with propane and then engulfed in a JP-4 jet fuel fire.

Anderson, C., et al., "Railroad Tank Car Fire Test: Test No. 6," Ballistic Research Labs - U.S. Army, Aberdeen Proving Ground, MD., for DOT/FRA - Office of R&D, Final Rept. No. FRA-OR&D 75-36, August 1973.

The Department of Transportation is conducting an extensive research program designed to develop methods to minimize personal injury and damage to property caused by fire from ruptured railroad tank cars filled with hazardous materials. The Ballistic Research Laboratories were requested by the Department of Transportation to conduct a series of field tests with scaled model and standard-size railroad tank cars. The test described in this report is one of the scaled model series which had no thermal protective coating, and where the relief valve was turned ninety degrees from the vertical.

Levine, D., and Dancer, D. M., "Fire Protection of Railroad Tank Cars Carrying Hazardous Materials - Analytical Calculations and Laboratory Screening of Thermal Insulation Candidates," Naval Ordnance Lab., White Oak, MD., for DOT/FRA, NTIS Rept. No. AD-747 974, July 1972.

This report describes a laboratory screening program to select two thermal insulation candidates for use in future fire tests of fifth-scale and full-scale LPG tank cars. Also included are analytical calculations to predict pressures and liquid levels in LPG tank cars being heated by fires. (Author)

Everett, J. E., and Phillips, E. A., "Hazardous Materials Tank Cars - Tank Head Protective 'Shield' or 'Bumper' Design," AAR, Chicago, Ill., for DOT/FRA, NTIS Rept. No. PB-202 624-1, January 1972.

The objective of the study was to design a railroad tank car head protective device which will reduce the frequency of head punctures in accidents. Accident data were reviewed in detail for the past six years to correlate head damage frequency and severity with various types of cars, to determine distribution patterns of damage over head surfaces, and to assess the costs to the railroad shipping industry of head punctures. Full-scale head impact tests, previously run, were also reviewed. From these two reviews, design criteria were established and used to design a large number of schemes which were then subjected to a comprehensive cost/benefit analysis. (Author)

AAR Research and Test Department, "Coupler Steel Study," Chicago, Ill., AAR Rept. No. R-107, December 1970.

This report presents the results of a preliminary study of the properties of "C" and "E" steels in "F" couplers selected at random from stocks about to be utilized by railroads. Class "E" couplers were also investigated. The data in this report do not constitute a random sample of the properties of steel in couplers, but they do indicate the characteristics of the several couplers that were studied.

"The Dynamics and Economics of Railway Track Systems," an International Forum published by Railway Systems and Management Assoc., Chicago, Ill., February 1970.

Presents ten papers: "Railroad Track Structures - Current Progress and Future Plans"; "Track and Truck"; "Track for Today's and Tomorrow's Vehicles"; "Moura Railway - Queens/and Government Railways"; Transport Work on the Swedish Railways"; "German Federal Railways"; "British Railways"; "Unconventional Railway Track Support Systems"; "The Influence of Track Dynamics on the Design of Advanced Track Structures"; "Service Testing Concrete Ties in the Search for Optimum Track".

Additional References

Materials Transportation Bureau, "Specification of Pressure Tank Car Tanks", DOT, Washington, D.C., Federal Register (49 Parts 173, 179) Docket No. HM-144, November 1976.

AAR Operations and Maintenance Department - Mechanical Division, "Specifications for Tank Cars, Standard", Washington, D.C., July 1976.

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4. AAR/RPI--Tank Car Safety Research and Test Project Reports

Skogsberg, A. M., and Phillips, E. A., "Phase 11 Report on Inspection of Insulation Jacket Type Thermal Shields on Tank Cars in Accelerated Life Tests," RPI-AAR Tank Car Safety Research and Test Project, Phase 1i, Report No. RA-11-9-39, January 1978.

> Four 112A tank cars were retrofitted with one inch mineral fiber insulation and a steel jacket and subjected to accelerated life testing. Inspections at the end of the tests revealed nothing to indicate that this type of insulation could not maintain its integrity for the life of a tank car.

Porter, R. W., "Evaluation of RPI-AAR and BRL Torch Fire Tests of Tank Car Insulation," RBI-AAR Tank Car Safety Research and Test Project, Phase 11, Report No. RA-11-8-36, September 1976.

> This report compares the torch fire test apparatus developed by RPI-AAR with that of the Ballistic Research Laboratory through tests on laboratory scale and full-size tank car wall structures. The report concludes that while the two apparatus do not yield entirely consistent results, the economy and repeatability of tests with the RPI-AAR equipment indicate that they should be adopted for thermal shield qualifying tests.

Phillips, E. A., Chairman, "Communication Session of Petition of RPI Committee on Tank Cars," presented at Palmer House, Chicago, April 1976.

> These are the minutes of a symposium which reviewed the work of RPI-AAR Tank Car Safety Project and the DOT activities in that field. Also presented is a petition to the DOT concerning proposed rulemaking.

Railway Progress Institute (RPI), Committee on Tank Cars, "Petition before the Materials Transportation Bureau, U.S. Department of Transportation," March 15, 1976.

> While the petition contains references to several proposed rulings and to research done by various agencies, the main thrust of the petition is to permit conversion of existing 112A and 114A tank cars to an improved insulated design, and to approve the installation of head shields.

RPI/AAR Railroad Tank Car Safety Research and Test Project, "Technical Progress Report No. 31, Interim Report," February 1976.

Progress in the various tasks of the RPI-AAR effort is briefly discussed. Of particular interest are remarks made in response to FRA and NTSB recommendations. Also included is a tabulation of accidents and 1% waybill data for hazardous materials.

Phillips, E. A., and Skogsberg, A. M., "Phase 11 Report on Specifications for Thermal Shield Systems on DOT 112A (114A) Tank Cars," RPI-AAR Tank Car Safety Research Project, Report No. RA-11-7-34, January 1976.

Over 100 laboratory tests and several full-scale tests were conducted to measure the effectiveness of various tank car insulating materials. The report concludes that the laboratory apparatus should be used in developing acceptance criteria for thermal shielding.

Phillips, E. A., "Phase 05 Report on Head Shield Fatigue Tests," RPI-AAR Tank Car Safety Research and Test Project, Phase 05, Report No. RA-05-3-35, November 1975.

The RPI-AAR Tank Car Safety Project conducted a series of tests to one-half-inch thick head shields for railroad tank cars. From the data obtained, in-service life predictions were made for each of four attachment schemes. This report describes the study and recommends proposed specifications for head shield attachment designs.

RPI/AAR Railroad Tank Car Safety Research and Test Project, "Track-Train Dynamics Report--Volume II--Harmonic Roll Series," Report No. R-173, February 1975.

A documentation of the American Steel Foundries'work in developing characteristics of the 70-ton truck components, physical restraints, mechanical properties, etc.

RPI/AAR Railroad Tank Car Safety Research and Test Project, "Track-Train Dynamics Report--Volume III--Harmonic Roll Series," Report No. R-174,

A document dealing with work done by the Track-Train-Dynamics Program to develop comprehensive vehicle models to predict dynamic behavior and perform parametric studies. Also included in this document is work done by A. Stucki Company to evaluate the effect of eccentric loading on the roll tendencies of various vehicles.

RPI/AAR Railroad Tank Car Safety Research and Test Project, "Track-Train Dynamics Report: Engineman's Sensitivity Studies," Transportation Systems Center, Cambridge, Mass., Report No. R-188.

The report documents experimental studies of the response of enginemen to various physical stimuli.

RPI/AAR Railroad Tank Car Safety Research and Test Project, "Track-Train Dynamics Report: Track-Train Dynamics Guidelines," Report No. 185.

This book contains guidelines for optimum handling, train makeup, track considerations, etc. The results are based on a parametric study using validated analytical models.

RPI/AAR Railroad Tank Car Safety Research and Test Project, "Track-Train Dynamics Report: Summary of Phase I Activities," Report No. 180.

This is a general overview of the work done in both the experimental and analytical areas designed to achieve Phase I objectives. Details of individual activities are contained in specific books or manuals dealing with that subject.

RPI/AAR Railroad Tank Car Safety Research and Test Project, "Track-Train Dynamics Report: Accident Investigation," Report No. 175.

Recommended procedures for determining the cause of dynamically related derailments and other accidents.

Pellini, W. S., Eiber, R. J., and Olson, L. I., "Phase 03 Report on Fracture Properties of Tank Car Steels--Characterization and Analysis," RPI-AAR Tank Car Safety Research and Test Project, Phase 03, Report No. RA-03-4-32, August 1975.

Statistical examination of fracture properties of tank car steels indicates that brittle fracture is not a significant problem. A clear relationship has been demonstrated between ASTM Ferrite grain size and dynamic tear test rational criteria.

RPI/AAR Railroad Tank Car Safety Research and Test Project, "Track-Train Dynamics Report--Volume I--Harmonic Roll Series," Report No. R-172, November 1974.

A comprehensive review of the problem, relationship of track and car design to the problem, recommended guidelines, based on best of the present knowledge, etc.).

Mate, D. P., and Phillips, E. A., "Phase 10 Report on Development of Shelf Couplers," RPI-AAR Railroad Tank Car Safety Research and Test Project, Report No. RA-10-5-30, September 1974.

> Contained in this report is preliminary design and test data compiled by a coupler foundry, outlining the strength and fabrication complexities of shelf couplers. Photographs and test descriptions are included. The report concludes that shelf couplers would prevent most overriding and telescoping of train cars under conditions approximated by the tests if those couplers are properly mated.

Reedy, G. E., "Phase 05 Report on June 9, 1974 Accident Involving Head Shields," RPI-AAR Railroad Tank Car Safety Research and Test Project, Report No. RA-05-2-29, August 1974.

> An accident involving one car equipped with a head shield is examined. In that accident, the head shield performed well; puncture was avoided. Furthermore, the shield attachment appears adequate. One additional conclusion is that F couplers are essentially ineffective in preventing head damage.

Krauskopf, W. B., "Final Report on Phase 09 Extension Study of Tank Car Bottom Fittings," RPI-AAR Railroad Tank Car Safety Research and Test Project, Report No. RA-09-2-27, May 1974.

> Accident investigation has shown that the bottom fittings are the most vulnerable components of tank cars. This report contains a cost benefit analysis and a number of recommendations for improving the resistance of bottom fittings to damage and leakage.

RPI/AAR Railroad Tank Car Safety Research and Test Project, "Phase 10 Report on February 9, 1974 Accident Involving Type E Top and Bottom Shelf Couplers," Report No. RA-10-4-28, April 1974.

> This is a report of an accident involving a tank car which was equipped with Type E shelf couplers. During the derailment, the couplers remained intact and prevented puncture of the tank car head. The report includes photographs of the couplers.

Phillips, E. A., "Phase 10 Report on July 1, 1973 Accident Involving Type E Top and Bottom Shelf Couplers," RPI-AAR Railroad Tank Car Safety Research and Test Project, Report No. RA-10-3-25, December 1973.

The role of shelf couplers in an accident involving the derailment and puncturing of loaded tank cars is examined. The report concludes that the shelf couplers performed better than standard couplers would be expected to do, although one accident is not statistically significant.

RPI/AAR Railroad Tank Car Safety Research and Test Project, "Track-Train Dynamics Report--Track-Train Dynamics "Bibliography", Report No. R.191, March 1973.

A three-volume publication outlining in abstract form the contents of over 600 articles relating to Track Train Dynamics (TTD), including an extensive thesaurus and key word index.

Reedy, C. E., and Phillips, E. A., "Final Phase 09 Report on Tanks, Fittings, and Attachments in the Mechanical Environment of Accidents," RPI-AAR Railroad Tank Car Safety Research and Test Project, Report No. 09-1-24, February 1973.

In this report, the failures of various parts of tank cars are examined and recommendations for improved designs are promoted. Stresses on stub sills and other body parts are calculated. Accidents involving tank car spills are listed and failed components identified.

Eilber, R. J., Maxey, W. A., and Duffy, A. R., "Phase 12 Report on Analysis of Fracture Behavior of Tank Cars in Accidents," RPI-AAR Railroad Tank Car Research and Test Project, Report No. RA-12-2-20, September 1972.

A summary of tank cars which have been involved in accidents is presented and categorized by the cause of crack initiation. In addition, each category is subdivided into five types of fracture behavior. The nature and origin of tank cracks are discussed in the context of proposed car modifications.

Westin, R. A., "Phase 02 on Dollar Loss Due to Exposure of Loaded Tank Cars to Fires--1975 through 1970," RPI-AAR Railroad Tank Car Safety Research Project, Report No. RA-02-1-10, August 1972.

The purpose of the study is to estimate the maximum probable savings which might be realized by preventing fire damage to loaded tank cars. Data on 3840 damaged cars are used as a base. The benefits are estimated by assuming the installation of various protective systems to be 100% effective. The costs of such systems were then used in a cost-benefit analysis.

RPI/AAR Railroad Tank Car Safety Research and Test Project, "Final Phase 02 Report on Accident Analysis," Report No. RA-02-2-18, August 1972.

This report provides a summary of tank car accidents and 1% waybills for the period 1965-1970. From the data, estimates of probabilities for accidents and the expected cost of such accidents are derived. These estimates lead to cost-benefit analyses for a number of proposed car modifications.

Sims, R. D., and Phillips, E. A., "Final Phase 10 Report on Couplers and Truck Securement," RPI-AAR Railroad Tank Car Safety Research and Test Project, Report No. RA-10-2-19, August 1972.

Trucks and couplers have been identified as the most frequent causes of tank puncture. The pros and cons of modification to these components are evaluated.

Phillips, E. A., et al., "Final Phase 05 Report on Tank Car Head Study," RPI-AAR Railroad Tank Car Safety Research and Test Project, Report No. RA-05-1-17, July 1972.

In this report are presented a number of recommended tank alterations and their cost-benefit analyses. Also documented are the preliminary tests performed on scale models and an analysis of scale model laws to establish the feasibility of such tests.

Westin, R. A., and Phillips, E. A., "Phase 01 Report on Summary of Ruptured Tank Cars Involved in Past Accidents," RPI-AAR Railroad Tank Car Safety Research and Test Program, Report No. RA-01-2-7, July 1972.

In this report, the punctures and ruptures of tank cars involved in major accidents from 1958 to 1972 are examined and described. Drawings are used to show the location, nature, and extent of damage to a number of tank cars, and the mechanisms causing failure are identified. A tabulation of car types, construction, cargo, and other characteristics is provided.

RPI/AAR Tank Car Safety Research and Test Project, "Final Phase 01 Report on Accident Review," Report No. RA-10-4-16, June 1972.

The Phase 01 Report summarizes and catalogues tank car accidents from 1965 through 1970. Methods used for gathering and cataloging data are described. Data access codes and copies of the computer programs used to maintain the tape files are also included in this report.

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> This paper documents the causes leading to the RPI-AAR effort and outlines the work to be done under each of 11 phases.

Sims, R. D., and Phillips, E. A., "Phase 10 Report on Determination of Moment Characteristics in a Horizontal Plane of Mated Combinations of Types "E" and "F" Couplers," RPI-AAR Railroad Tank Car Safety Research and Test Project, Report No. RA-10-1-11, February 1972.

> Laboratory tests were performed on mated "E" and "F" couplers to determine the horizontal angles and moments at which separation or permanent deformation takes place. The tests show the same magnitude of lateral resistance for all combinations of tested couplers. Photographs document test procedures.

Yang, T. H., and Manos, W. P., "Phase 08 Report on Computer Derailment Study," RPI-AAR Railroad Tank Car Safety Research and Test Project, Report No. RA-08-1-12, February 1972.

> A mathematical model is set forth to describe the motions, forces and accelerations experienced by derailing cars of a train. One objective of the exercise is to evaluate new car designs and to relate train makeup to derailment severity.

Reedy, C. E., and Phillips, E. A., "Phase 01 Report on Sequence of Events Following Crescent City Derailment," RPI-AAR Railroad Tank Car Safety Research and Test Program, Report No. RA-01-1-1, August 1970.

> This report contains a brief but concise synopsis of the events of the Crescent City conflagration. Of particular use is a series of sketches depicting the location and orientation of train cars and car fragments.

AAR/RPI Railroad Tank Car Safety Research and Test Project, "Summary of Ruptured Tank Cars Involved in Past Accidents," Report No. RA-01-2-3 (Phase 01), December 1970.

> Detailed data for 72 ruptured tank cars are presented, covering the period from 1958 to 1970. Two ruptures involved brittle fractures, 6 were ethylene oxide cars, 64 cars burst violently. The 28 accidents were listed chronologically and the 64 cars were categorized by type, safety valve setting, design, insulation, and capacity.

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RPI/AAR Railroad Tank Car Safety Research and Test Project, "Full-Scale Fire Test," Report No. RA-11-6-31--Phase 11, December 1975.

RPI/AAR Railroad Tank Car Safety Research and Test Project, "Material Study on Steels Used in Current and Former Tank Car Construction and from Cars Involved in Accidents," Report No. RA-03-5-33--Final Phase 03, August 1975.

RPI/AAR Railroad Tank Car Safety Research and Test Project, "Track-Train Dynamics Report--Proceedings from the Second Track--Train Dynamics Seminar Held in Chicago in December 1974." Two Volumes, R-176 and R-177.

RPI/AAR Railroad Tank Car Safety Research and Test Project, "An Introduction to the Fracture Mechanics of Railroad Materials," Report No. R-157, May 1974.

RPI/AAR Railroad Tank Car Safety Research and Test Project, "Phase 11 Report on Analysis of 1/5 Scale Fire Tests," December 12, 1973.

RPI/AAR Railroad Tank Car Safety Research and Test Project, "The Fracture Properties of Two Failed Cast Steel Wheels from the Union Pacific Railroad, R-123, May 1973.

RPI/AAR Railroad Tank Car Safety Research and Test Project, "Phase 12 Report on Tentative Tank Car Accident Investigation Guide," Report No. RA-12-1-6, April 1973.

RPI/AAR Railroad Tank Car Safety Research and Test Project, "Phase 12 Report on Analysis of Tank Car Tub Rocketing in Accidents, Report No. RA-12-2-23, December 1972.

RPI/AAR Railroad Tank Car Safety Research and Test Project, "Overall Project Summary Report," Report No. RA-00-1-22, October 1972.

RPI/AAR Railroad Tank Car Safety Research and Test Project, "Statistical Summary of Joint AAR-Railroad Survey of Cracked or Broken Couplers, Knuckles and Yokes in Freight Service on Five Railroads--10 Week Summer Period--June 1, 1971 through August 7, 1971--4 Week Winter Period--January 15, 1972 through February 14, 1972," R-118, Technical Report No. 3, September 1972.

RPI/AAR Railroad Tank Car Safety Research and Freight Car Test Project, "Summary of Visual Inspection Results Cracked or Broken Freight Car Couplers, Knuckles and Yokes--1097 Components Collected by 5 Railroads, R-117, January 15 to February 15, 1972, Technical Report No. 2, August 1972.

RPI/AAR Railroad Tank Car Safety Research and Test Project, "Phase 11 Preliminary Report on Laboratory Fire Test Apparatus for Evaluating Thermal Shield Materials," RA-11-3-15, May 1972.

RPI/AAR Railroad Tank Car Safety Research and Test Project, "Analysis of 1/5 Scale Fire Test Data," Report No. RA-11-2-14 (Phase 11), April 1972.

RPI/AAR Railroad Tank Car Safety Research and Test Project, "Phase 01 Report on Sequence of Events Following Houston, Texas Derailment," Report No. RA-01-3-9, October 1971.

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Allen, E. W., "Transportation Systems Center Bibliography of Technical Reports; July 1970-December 1976," DOT/TSC, Cambridge, Mass. Report No. DOT-TSC-OST-77-17, March 1978.

> This bibliography lists unlimited distribution reports released by the Transportation Systems Center from July 1970 through December 1976. Reports are listed by sponsoring agency, and are indexed by subject, personal author, corporate author, title, contract number, and report number.

Gay, W. F., "Transportation Safety Information Report, January, February, March 1977," DOT/TSC, Cambridge, Mass., for DOT/OST, Washington, D.C., Final Report No. NTISUB/C/244-001, June 1977.

> Published quarterly, this report is a compendium of selected national-level transportation safety statistics for all modes of transportation. Each quarterly report represents and compares transportation fatalities, accidents, and injuries on a monthly and quarterly basis for the current and preceding year. In addition, it provides an overview of modal safety hazards, safety programs, and related accident prevention information.

Tap, R., and Kaprelian, A., "Transportation Statistical Data and Information," DOT/TSC, Cambridge, Mass., for DOT/OST, Washington, D.C., Final Report No. DOT-TSC-OST-76-60, June 1977.

> The document contains an extensive review of internal and external sources of transportation data and statistics especially created for data administrators. Organized around the transportation industry and around the elements of the U.S. Department of Transportation, it is the most comprehensive single document that reviews transportation data and its history.

Petracek, S. J., et al.,"Railroad Classification Yard Technology," Stanford Research Institute, Menlo Park, California, for DOT/FRA Office of R&D, Final Report No. FRA-ORD-76/304, January 1977.

> The major objective of this study was the identification of research and development necessary for technological improvements in railroad classification yards. This involved a projection of future classification yard needs and a comparison of the requirements of existing technology. Separate tasks included a description of the hardware, costs, performance characteristics, and operational practices of existing yards; formulation of general yard-network interaction concepts;

collection of in-depth background information concerning the yard population in the United States (categorized by type, technology, and function); estimation of the demands likely to be placed on the nation's network of freight-car terminals during the foreseeable future; and an assessment and prioritization of those areas of terminal operations that warrant further research or development.

Henzi, A. N., "A Survey of Test Methods Currently Used for Simulating the Transportation Environment," General American Transportation Corporation, Research Division, Niles, Illinois, for DOT/OHM, Washington, D.C., Final Report, Contract No. DOT-OS-00038, April 1978.

This is the final report of a survey study of the testing methods and practices currently employed for package evaluation. The package environment is separated into three distinct phases: transportation, storage, and handling. The major test methods intended for the environmental hazards principal to each phase are summarized, discussed, and where possible, evaluated. A set of recommended interim test procedures, drawn basically from the existing methods, is presented.

APPENDIX B

MODELS FOR GENERATING PROBABILITY DISTRIBUTION FOR THE NUMBER OF CARS RELEASING AND THE AMOUNT RELEASED

B.1 INTRODUCTION

In addition to the models for estimating parameters of probability, distributions used in Chapters 4, 8, 9 and 10, models were developed for estimating in detail the probability distributions of the number of cars releasing and the amount released. These models are based on explicit probability distributions for each probabilistic factor involved in the event of a release. These factors include train velocity; the number of cars derailing, given the velocity; the number of hazardous-material cars derailing, given the total number of cars derailing; the number of hazardous-material cars releasing, given the number derailing; and the amount released, given the number releasing. Several numerical examples were developed using these models.

Whereas the "parameter models" are useful for general scenarios, the "distribution models" are useful for more specific scenarios that are not covered by the parameter models. The most important example of this type of application is the situation in which both the total number of cars on the train and the number of cars carrying a hazardous material are specified. It might be of interest, in this situation, to determine the potential risk due to a train of a given size carrying a given amount of hazardous material. Computerized distribution models can be used for this purpose.

The heart of the distribution model is the probability distribution of the number of hazardous-material cars derailing as a function of the total number of cars derailing. In this situation, where the total number of hazardous-material cars is unspecified, but the expected frequency is specified, the distribution is based on a simple binomial distribution with the following parameters:

- The total number of cars derailing; and
- The expected frequency of hazardous-material cars.

For the case where the number of hazardous-material cars on the train and the total number of cars on the train are specified, the distribution governing the number of hazardous materials derailing is based on a hypergeometric distribution. For both of these cases, the distributions are complicated by the assumption that the hazardous-material cars are blocked, the size of the blocks being an input parameter. These distributions are discussed in Section B.3

It should be noted that, in applying the hypergeometric model, the historical aggregated distribution for the number of cars derailing as a function of speed may not be valid. Figure B-1 shows the relationship of the average number of cars derailing for mainline accidents as a function of both speed and N_T, the total number of cars in the train. The figure shows that for train lengths of approximately 26 cars and longer, the distribution of the number of cars derailing as a function of speed may be approximately independent of train length. Thus, when using the hypergeometric model, together with an assumed train length and the historical data for the distribution of the number of cars derailing, one is implicitly assuming that the train length is 26 cars or longer. Even with this stipulation, however, the relation is only approximate.

Section B.2 presents the logical flow of the various parts of the computerized package that was developed to facilitate use of the distribution models. Section B.3 discusses the distribution of the number of hazardous material cars derailing, given the total number of cars derailing, and Section B.4 presents some examples.

B.2 LOGICAL FLOW OF COMPUTERIZED ANALYSIS PACKAGE

The complete set of programs in the distribution model treats the various phases of the probabilistic processes in the following manner:

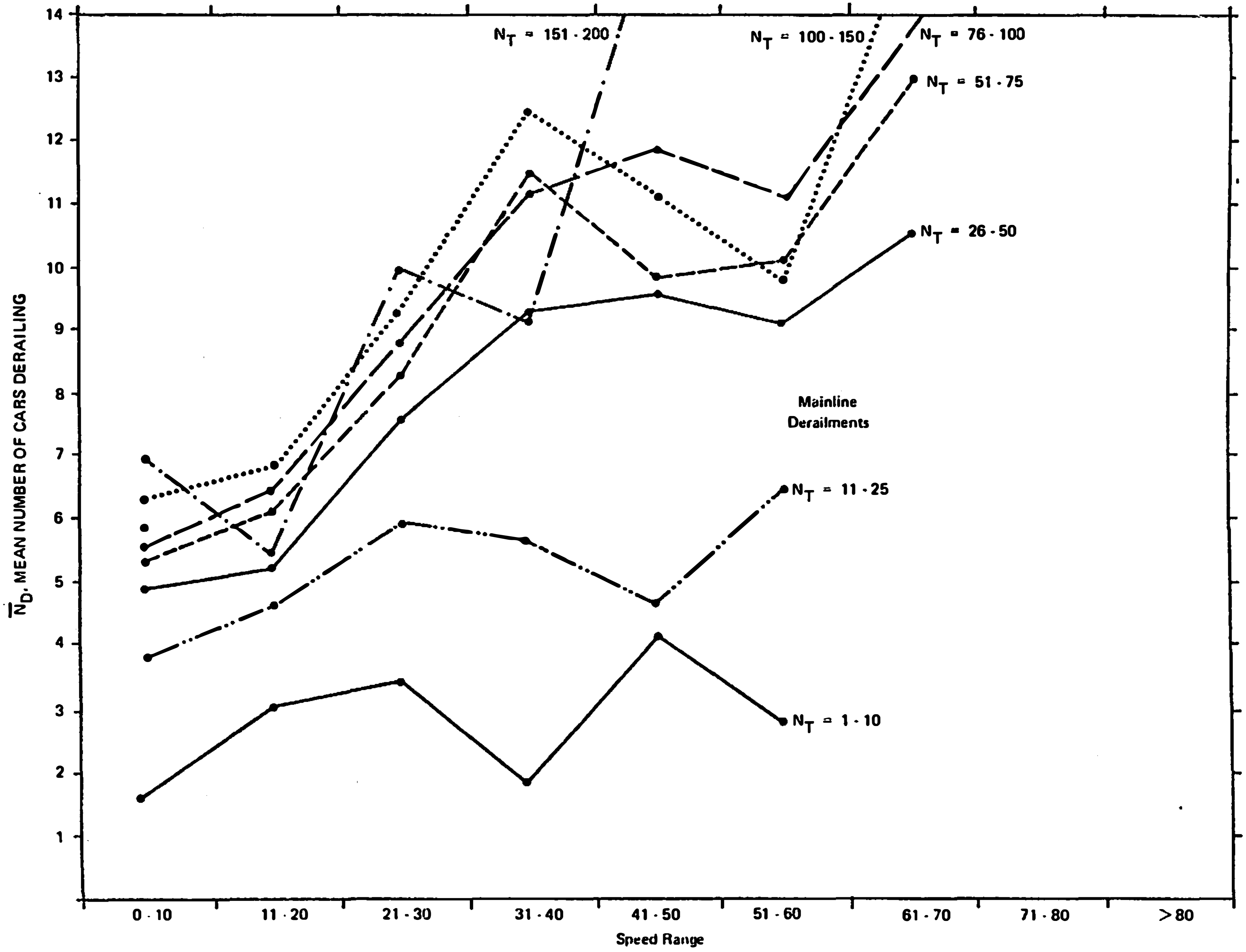


FIGURE B–1. m_{N_D} AS A FUNCTION OF DERAILMENT SPEED, V, AND TRAIN LENGTH, N_T

- The joint distribution of the number of cars derailing and the velocity is given as an input matrix.
- The distribution of the number of hazardous-material cars derailing as a function of the number of cars derailing is based on assumed block size and either a hypergeometric or binomial distribution. (The details of these distributions are presented in Section B.3.)
- The distribution of the number of hazardous-material cars releasing as a function of the number of hazardous-material cars derailing is assumed to be a binomial distribution with parameter q(v) where v is the velocity classification given in an input vector. The functional form of this binomial distribution is as follows:

$$\mathrm{PROB}(N_R = k | N_{HD} = n)$$

$$= \frac{n!}{k!(n-k)!} \, q(v)^k \, (1 - q(v))^{n-k} \, , \qquad \text{(B-1)}$$

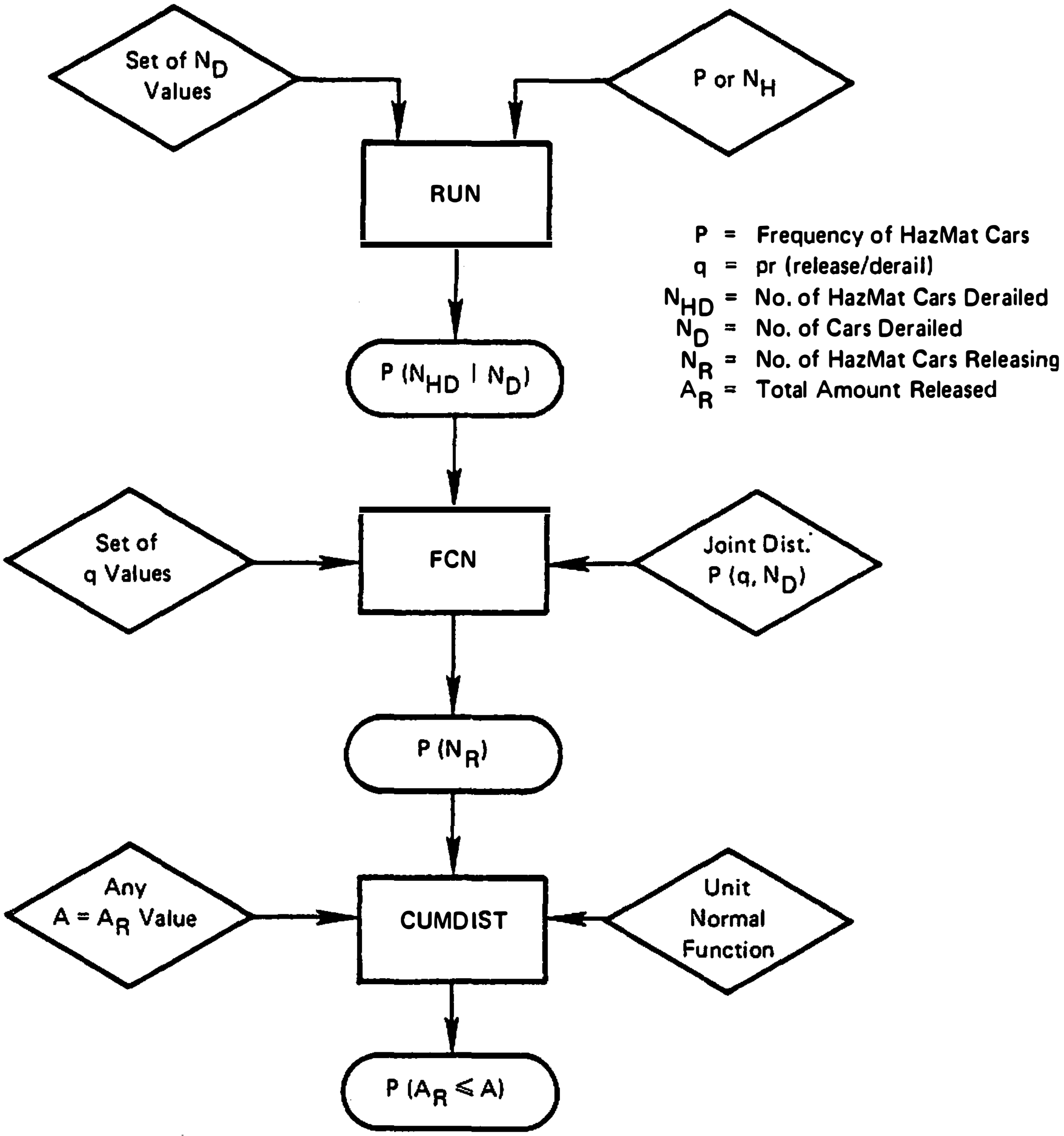
where

N_R = number of hazardous-material cars releasing, and

N_{HD} = number of hazardous-material cars derailing.

- The distribution of the amount released, given the number of cars derailing, is assumed to be the sum of the amounts released per car. The amounts released per car are assumed to be independent, identically distributed random variables. The distribution of the amount released per car is based on historical data discussed previously.

The logical flow of the synthesized computer models and the necessary inputs are depicted in Figure B-2. The interaction of some of the models can be described as follows:



P = Frequency of HazMat Cars
q = pr (release/derail)
N_{HD} = No. of HazMat Cars Derailed
N_D = No. of Cars Derailed
N_R = No. of HazMat Cars Releasing
A_R = Total Amount Released

FIGURE B–2. LOGICAL FLOW OF COMPUTERIZED DISTRIBUTION MODEL

- RUN takes a set of N_D values (which have a joint probability mass function [PMF] with velocity), together with either p or N_H, and produces a probability distribution of N_{HD} for each value of N_D, based on the distributions presented in Section B.3.
- FCN uses the output of RUN, a set of q(v) values, and the joint density of N_D and q(v) to produce a single distribution for the number of hazardous-material cars releasing. This function assumes that, as noted, the number of cars releasing is binomially distributed with parameter q(v) and N_{HD}, and it combines this result with the density function for each N_{HD} distribution, given q and N_D.

  Thus:

  $$p(N_R|q, N_D) = \sum_j p\ (N_{HD} = j)\ p(N_R|q, N_D, N_{HD} = j) \quad \text{(B-2)}$$

  and

  $$p\ (N_R) = \sum_i \sum_j p(N_R|q, N_D)\ p\ (q = i, N_D = j). \quad \text{(B-3)}$$

- CUMDIST takes the distribution for N_R and mixes it with the semi-empirical distributions of amount released, given N_R, to form an amount-released distribution. It is assumed that the releases in all other cars, so that the n-fold convolution of the distribution of the amount released per car represents the distribution of the amount released per car from n cars. For n $\leq$ 13, the convolutions are numerically computed. For n $\geq$ 14, the n-fold convolution is assumed to be normally distributed (central limit theorem). (See for example, Figure B-3.)

Examples of the output of the computerized package are presented in Section B.4.

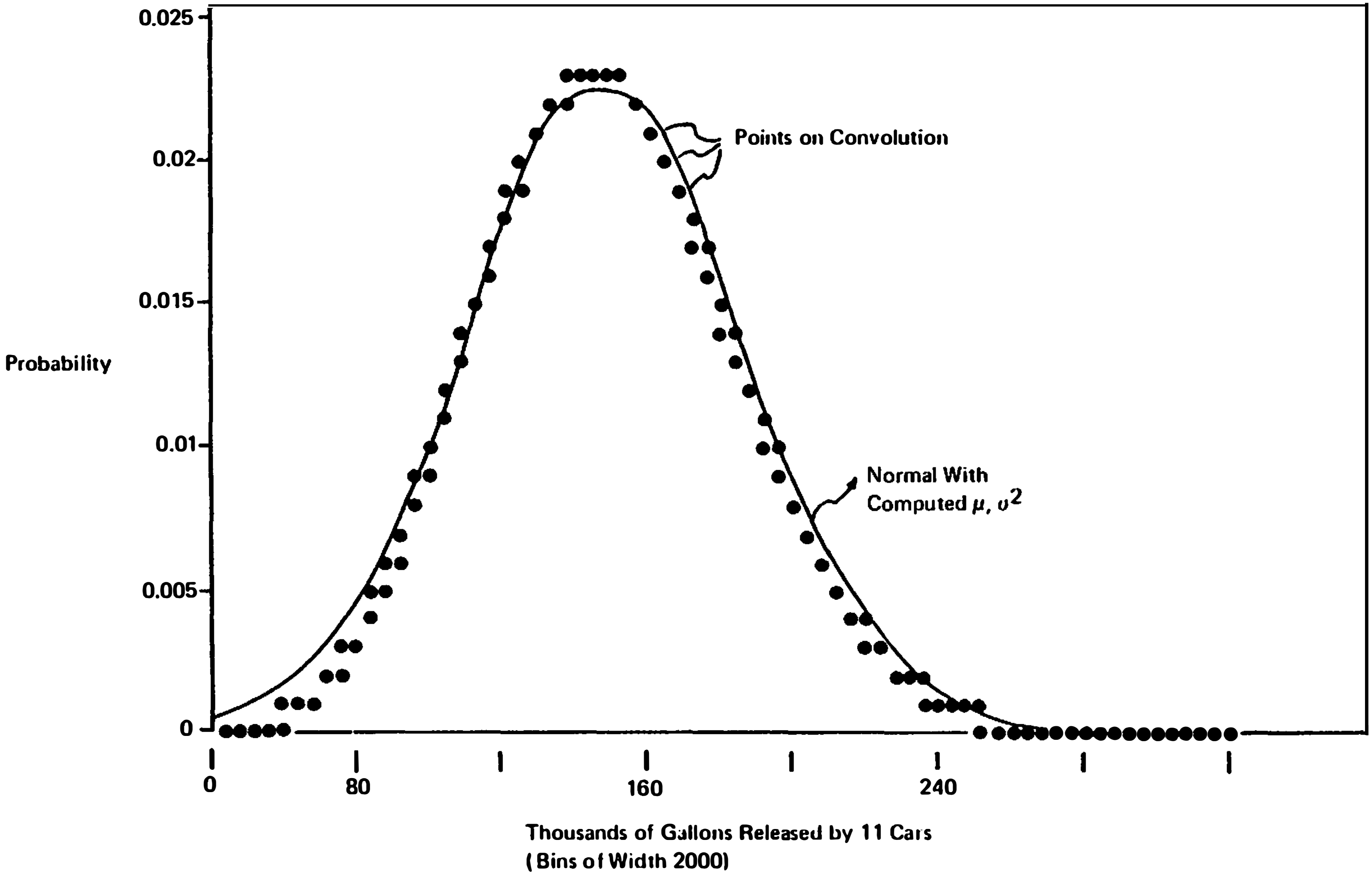


FIGURE B--3. ELEVEN-FOLD CONVOLUTION OF AMOUNT RELEASED PER CAR

B.3 MATHEMATICAL MODEL FOR EVALUATING THE PROBABILITY DISTRIBUTION OF N_{HD}, GIVEN N_D (THE NUMBER OF HAZARDOUS-MATERIAL CARS DERAILING, GIVEN THE TOTAL NUMBER OF CARS DERAILING)

The most important form of the distribution model can be applied to a specific scenario when the total number of cars and the total number of hazardous-material cars on a particular train are specified. If the hazardous-material cars are distributed randomly throughout the consist, then the hypergeometric probability distribution can be used to determine the number of hazardous-material cars derailing, given the total number of cars derailing. If the hazardous-material cars are blocked in one or more blocks, then the distribution can still be used on a hypergeometric distribution(of the number of blocks). Thus, most of the models in this section can be viewed as derivatives of the hypergeometric distribution.

The hypergeometric distribution is appropriate when the number of hazardous-material cars on the train is given. There are other situations that might occur, however. When the number of hazardous-material cars is unrestricted and each car contains hazardous materials with a certain probability, then a binomial distribution is appropriate. In addition, the hazardous-material cars on the train may be blocked together. As a result of these other considerations, we can utilize the following general model to determine the number of hazardous-material cars derailed:

1. The train is subdivided into blocks of length G_H and each block is either "hazardous materials" or "non-hazardous materials" independent of other blocks. Note that this type of model handles the situation in which cars are located randomly ($G_H = 1$), as well as the situation where all the hazardous-material cars are blocked ($G_H = N_H$). In addition, there are several intermediate types of situations.
2. The number of hazardous-material blocks of cars is either binomial (as the total number of hazardous-material blocks is unrestricted) or hypergeometric (the number of hazardous-material blocks is assumed).

For any given situation, one can compute the number of hazardous-material cars derailed from the number of hazardous-material blocks derailed. The total number of blocks derailed depends on the total number of cars derailed, as well as the location within the first block of the first derailing car. This is a somewhat involved problem in combinatorial mathematics and, in addition, one or two of the derailing blocks may be incomplete (for example, only one of the cars in the block might be derailing).

All of the possible cases were carefully examined and formulas developed for the number of hazardous-material cars derailing. The formulas will use a form of the hypergeometric or binomial distribution. For convenience, the underlying distribution of the number of hazardous-material blocks derailing is denoted by g. For the two cases, expressions for g are as follows:

$$g(a, b, c, y) = \frac{c!\ b!\ (a - b)!\ (a - c)!}{(c - y)!\ y!\ (b - y)!\ a!\ (a - b - c + y)!} \qquad \text{(B-4)}$$

for N_H given; (Hypergeometric)

and

$$g(a, b, c, y) = \frac{b!}{y!\ (b - y)!}\ p^{y}\ (1 - p)^{b-y} \qquad \text{(B-5)}$$

(Binominal)

for N_H not given.

In general:

a = number of blocks;

b = number of blocks derailing;

c = number of hazardous-material blocks on train, if given; and

y = number of hazardous-material blocks derailing.

The algorithm for computing the probability distribution of the number of hazardous-material cars derailing is described below. In the formula that follow, x represents the number of hazardous material cars derailing.

In developing these formulas, the following logic was used. In any derailment, there will generally be n blocks of cars derailing where n is defined in the algorithm. Of these blocks, n - 2 will be of length G_H and the other two will be shorter or equal to G_H and must be handled separately. The start of the derailment can occur in any one of G_H locations within the first derailing blocks. This location determines the size of the two blocks not equal to length G_H and the possibilities of the total number of cars derailing. As an example, if the derailment starts at G_H - 1 location from the start of the first derailing block, one can obtain a value of x = 1 for the number of hazardous-material cars derailing, if the first block is the hazardous-material block and all the other derailing blocks are non-hazardous materials. Thus, for each situation and for each location of the start of the derailment, what possibilities could occur if 0, 1, or 2 of the different size derailing blocks of materials were hazardous-material blocks were computed.

The algorithm for computing the distribution of x, P(x), is as follows:

- <u>If $N_D = 1$:</u>

$$P(x) = g\left(\frac{N_T}{G_H}, 1, \frac{N_H}{G_H}, x\right). \qquad \text{(B-6)}$$

- If $N_D > 1$:

Compute (where [] denotes smallest integer less than or equal to):

$$n = \left[\frac{N_D - 2}{G_H} \right] + 2, \tag{B-7}$$

$$n' = \max \left\{ 0, \left[\frac{N_D + 1}{G_H} \right] - 1 \right\}, \tag{B-8}$$

$$r = N_D - (n - 2)\, G_H \tag{B-9}$$

$$r' = N_D - n'\, G_H \tag{B-10}$$

$$h_i(x) = \left[\frac{x}{G_H} \right] + i\ . \tag{B-11}$$

There are four cases (A through D):

Case A:

$r' \le r < G_H$ (N_D is neither a multiple of G_H nor one more than a multiple of G_H)

$$\begin{aligned} P(x) = {} & \left(1 - \frac{x}{G_H n}\right)\left(1 - \frac{x}{G_H(n-1)}\right) \\ & g\left(\frac{N_T}{G_H}, n, \frac{N_H}{G_H}, \frac{x}{G_H}\right) \\ & + \frac{G_H - r + 1}{G_H}\left(1 - \frac{x + G_H}{G_H n}\right)\frac{x + G_H}{G_H(n-1)} \\ & g\left(\frac{N_T}{G_H}, n, \frac{N_H}{G_H}, \frac{x}{G_H} + 1\right), \end{aligned} \tag{B-12}$$

for $x = 0, G_H, 2G_H$, etc.

$$P(x) = \frac{2}{G_H}\left(1 - \frac{h_1(x)}{n}\right)\left(\frac{h_1(x)}{n-1}\right) g\left(\frac{N_T}{G_H}, n, \frac{N_H}{G_H}, h_1(x)\right), \tag{B-13}$$

for $x = 1, 2, 3, \ldots\ldots, r - 1, G_H + 1, G_H + 2$, etc.

$$\begin{aligned} P(x) = {} & \frac{h_2(x)(h_2(x) - 1)}{n(n-1)} g\left(\frac{N_T}{G_H}, n, \frac{N_H}{G_H}, h_2(x)\right) \\ & + \frac{G_H - r + 1}{G_H}\left(1 - \frac{h_1(x)}{n}\right)\left(\frac{h_1(x)}{n-1}\right) g\left(\frac{N_T}{G_H}, n, \frac{N_H}{G_H}, h_1(x)\right), \end{aligned} \tag{B-14}$$

for $x = r, G_H + r, 2G_H + r$, etc.

Case B:

$r' \leq r = G_H$ (N_D is a multiple of G_H)

$$P(x) = \left(1 - \frac{x}{G_H n}\right) \left(1 - \frac{x}{G_H(n - 1)} + \frac{x}{G_H^2(n - 1)}\right) g\left(\frac{N_T}{G_H}, n, \frac{N_H}{G_H}, \frac{x}{G_H}\right)$$

$$+ \frac{x + G_H}{G_H^2(n - 1)} \left(1 - \frac{x + G_H}{G_H n} + \frac{x}{n}\right) g\left(\frac{N_T}{G_H}, n, \frac{N_H}{G_H}, \frac{x + G_H}{G_H}\right), \qquad \text{(B-15)}$$

for $x = 0, G_H, 2G_H$, etc.

$$P(x) = \frac{2}{G_H} \left(1 - \frac{h_1(x)}{n}\right) \left(\frac{h_1(x)}{n - 1}\right) g\left(\frac{N_T}{G_H}, n, \frac{N_H}{G_H}, h_1(x)\right), \qquad \text{(B-16)}$$

for $x = 1, \ldots, G_H - 1, G_H + 1, \ldots$

Case C:

$r' \leq r = G_H + 1$ (N_D is one more than a multiple of G_H)

$$P(x) = \left[\left(1 - \frac{x}{G_H n}\right)\left(1 - \frac{x}{G_H(n-1)}\right) + \frac{2}{G_H}\left(1 - \frac{x}{G_H n}\right)\frac{x}{G_H(n-1)} + \frac{x(x-1)}{n(n-1)} 1_{\{G_H = 1\}} \right] g\left(\frac{N_T}{G_H}, n, \frac{N_H}{G_H}, \frac{x}{G_H}\right), \tag{B-17}$$

for $x = 0, G_H, 2G_H$, etc.

Here

$$1_{\{A\}} = \begin{cases} 1, & \text{if } A \text{ holds} \\ 0, & \text{otherwise} \end{cases} \tag{B-18}$$

$$P(x) = \frac{h_1(x)}{n-1}\left(\frac{h_1(x) - 1}{n} + \frac{2}{G_H} - \frac{2h_1(x)}{G_H n}\right) g\left(\frac{N_T}{G_H}, n, \frac{N_H}{G_H}, h_1(x)\right), \tag{B-19}$$

for $x = 1, G_H + 1, 2\,G_H + 1$, etc. and $G_H \neq 1$.

$$P(x) = \frac{2}{G_H}\left(1 - \frac{h_1(x)}{n}\right)\frac{h_1(x)}{n-1}\; g\left(\frac{N_T}{G_H}, n, \frac{N_H}{G_H}, h_1(x)\right), \tag{B-20}$$

for $x = 2, \ldots., G_H - 1, G_H + 2$, etc.

Case D:

$r < G_H < r'$ (N_D is neither a multiple of G_H nor one more than a multiple of G_H; the number of blocks derailing depends on the starting point; e.g., if $G_H = 5$ and $N_D = 7$, the number of blocks derailing can be 2 or 3)

$$P(x) \left(1 - \frac{x}{G_H(n - 1)}\right)\left[\frac{G_H - r + 1}{G_H} - \frac{x}{G_H(n - 2)} \quad \frac{(G_H - r - 1)}{G_H}\right] g\left(\frac{N_T}{G_H}, n - 1, \frac{N_H}{G_H}, \frac{x}{G_H}\right)$$

$$+ \frac{r - 1}{G_H} \left(1 - \frac{x}{G_H n}\right)\left(1 - \frac{x}{G_H(n - 1)}\right) g\left(\frac{N_T}{G_H}, n, \frac{N_H}{G_H}, \frac{x}{G_H}\right), \qquad \text{(B-21)}$$

for $x = 0, G_H, 2G_H$, etc.

$$P(x) = \frac{2}{G_H} \left(1 - \frac{h_1(x)}{n}\right) \frac{h_1(x)}{n - 1} \quad g\left(\frac{N_T}{G_H}, n, \frac{N_H}{G_H}, h_1(x)\right), \qquad \text{(B-22)}$$

for $x = 1, 2, \ldots, r - 1, G_H + 1$,

$$P(x) = \frac{G_H - r + 1}{G_H} \left(\frac{h_1(x)(h_1(x) - 1)}{(n - 1)(n - 2)}\right) g\left(\frac{N_T}{G_H}, n - 1, \frac{N_H}{G_H}, h_1(x)\right)$$

$$\left(+ \frac{r - 1}{G_H} \quad \frac{h_2(x)(h_2(x) - 1)}{(n)(n - 1)} \quad g \quad \frac{N_T}{G_H}, n, \frac{N_H}{G_H}, h_2(x)\right)$$

(continued)

$$+ \frac{2}{G_H} \left(1 - \frac{h_1(x)}{n - 1}\right) \frac{h_1(x)}{n - 2} \; g\left(\frac{N_T}{G_H}, n - 1, \frac{N_H}{G_H}, h_1(x)\right), \qquad \text{(B-23)}$$

for $x = r, G_H + r$, etc.

$$P(x) = \frac{2}{G_H} \left(1 - \frac{h_1(x)}{(n - 1)}, \frac{h_2(x)}{n - 2}\right) g\left(\frac{N_T}{G_H}, n - 1, \frac{N_H}{G_H}, h_1(x)\right), \qquad \text{(B-24)}$$

for $x = r + 1, \ldots\ldots, G_H - 1, G_H + r + 1, \ldots.$

B.4 EXAMPLES OF DISTRIBUTION MODELS

Example 1:

Two examples of the use of the distribution models are presented in this section. In the first example, we assume that the block length is 1; that is, the hazardous materials are randomly distributed throughout the train. The number of hazardous-material cars is given, and thus the distribution of the number of hazardous-material cars derailing is hypergeometric. For the example, we specify the following:

- Mainline derailments

  Class 2 track

  v = 16-20 mph

  N_T = 55 cars

  T = 6000 gross tons

  N_H = (a) 5
  (b) 10
  (c) 15
  (d) 20.

That is, we will compute $P(N_R)$ for a train of 55 cars, with 5 hazardous-material cars; then for 10 hazardous-material cars, and so on. Let

P_A = the probability of a train derailment per mile for Class 2 track, proportional to train gross tonnage.

From Chapter 3, the appropriate constant of proportionality is 1.7×10^{-8} per gross ton-mile.

For a train of 6000 gross tons traveling one mile on Class 2 mainline track, the probability of a train derailment per mile is:

$$P_A = 6000 \times 1 \times 1.7 \times 10^{-8} \qquad \text{(B-25)}$$

$$= 1.02 \times 10^{-4}$$

The probability that the derailment speed is 16-20 mph is 0.19. The computer program for $P(N_R = 0, 1, \ldots N_H)$ for a specified train length (N_T) and specified number of hazardous-material cars (N_H) can then be utilized with $P(N_D|v)$ for the given speed range.

$P(N_D|v)$ was stored in an array. Release probability for mainline derailments at 16-20 mph was equated to the empirically observed value of 0.26.

The program outputs are shown in Table B-1. For a fixed train length ($N_T = 55$), $P(N_R = 0, 1, \ldots N_H)$ is given for $N_H = 5, 10, 15, 20$. The average number of cars releasing and variance are also given for each N_H. $P(N_R)$ can now be determined.

For $N_T = 55$ and $N_H = 5$:

$P(N_R = 1) = 1.02 \times 10^{-4}$ [P_A from Eq. (B-25)]

x

0.19 [$P(V = 16\text{-}20|i = 2)$]

x

0.12 [from Table B-1 for $N_H = 5$ and $N_R = 1$].

Thus,

$$P(N_R = 1) = 2.3 \times 10^{-6}$$

If there are 10 hazardous-material cars in a train with 35 cars, then

$P(N_R = 1) = 1.02 \times 10^{-6}$

x

0.19

x

0.2 [From Table B-1 for $N_H = 10$, $N_R = 1$].

TABLE B-1. EXAMPLE OF OUTPUT OF DISTRIBUTION MODEL

N_T = 55
N_H = 5

N_R	Prob (N_R)
0	0.8572482E + 00
1	0.1236413E + 00
2	0.1134764E - 01
3	0.7298226E - 03
4	0.2978739E - 04
5	0.5752541E - 06

Average = 0.14865E + 00
Variance = 0.15399E + 00

N_T = 55
N_H = 20

N_R	Prob (N_R)
0	0.5861856E + 00
1	0.2731214E + 00
2	0.9394431E - 01
3	0.2890730E - 01
4	0.8106545E - 02
5	0.2103000E - 02
6	0.4986254E - 03
7	0.1055594E - 03
8	0.1948973E - 04
9	0.3078554E - 05
10	0.4096894E - 06
11	0.4532435E - 07
12	0.4113918E - 08
13	0.3019449E - 09
14	0.1761245E - 10
15	0.7986510E - 12
16	0.2733018E - 13
17	0.6763145E - 15
18	0.1131954E - 16
19	0.1135558E - 18
20	0.5100784E - 21

Average = 0.59459E + 00
Variance = 0.76247E + 00

N_T = 55
N_H = 10

N_R	Prob (N_R)
0	0.7484290E + 00
1	0.1997443E + 00
2	0.3792014E - 01
3	0.6007895E - 02
4	0.8000010E - 03
5	0.8784710E - 04
6	0.7598733E - 05
7	0.4878692E - 06
8	0.2151541E - 07
9	0.5751029E - 09
10	0.6962698E - 11

Average = 0.29730E + 00
Variance = 0.33241E + 00

N_T = 55
N_H = 15

N_R	Prob (N_R)
0	0.6596730E + 00
1	0.2459895E + 00
2	0.6713533E - 01
3	0.1602293E - 01
4	0.3404927E - 02
5	0.6463139E - 03
6	0.1071813E - 03
7	0.1507171E - 04
8	0.1746483E - 05
9	0.1624700E - 06
10	0.1181556E - 07
11	0.6509693E - 09
12	0.2603567E - 10
13	0.7078707E - 12
14	0.1161912E - 13
15	0.8627465E - 16

Average = 0.44594E + 00
Variance = 0.53523E + 00

Thus,

$$P(N_R = 1) = 3.8 \times 10^{-6}.$$

The mean and variance obtained from the parameter model formulas were compared with those derived from the distribution model, with the following input parameters:

$r = 0.1,$

$G_H = 1 \; (\therefore m_{G_H} = 1),$

$E(v) =$ 18 (the midpoint of the speed range), and

$(E(v))^2 = 324;$

and, assuming that mainline derailments at 16-20 mph are distributed evenly over the speed range, then:

$E(v^{1.5}) = 76.54$, and

$E(v^2) = 326.$

The values of P for the different N_H values are (for $N_T = 55$):

N_H	P
5	.09
10	.18
15	.27
20	.36

A comparison of the results of this model with the parameter model is contained in Tables B-2 and B-3.

The means are comparable, but since the hypergeometric distribution involves a lower variance than the binomial distribution, the variance of the parameter model is higher.

TABLE B-2. COMPARISON OF MEAN (N_R)

N_H	Mean N_R Model 1*	Mean N_R Model**	Difference Mean_1 - Mean_2
5	.14865	.13946	.00919
10	.29730	.27892	.01838
15	.44594	.41838	.02756
20	.59459	.55784	.03675

TABLE B-3. COMPARISON OF VAR(N_R)

N_H	Var(N_R) Model 1*	Var(N_R) Model**	Difference (Var_1 - Var_2)
5	.15399	.17989	- .02590
10	.33241	.38993	- .05752
15	.53523	.63011	- .09488
20	.76247	.90044	-. 13797

---

*Model 1 is the distribution model presented in this Appendix.

**Model 2 is the model presented in Chapter 8.

Example 2:

In a second example, a derailment was analyzed assuming the historical distribution of puncture probabilities, velocities, and derailment lengths. The block length was assumed to be four. To analyze the effect of a major change in inputs, the binomial distribution with a π_H value of 0.5 (for the probability of any car contents being hazardous) was utilized for the number of hazardous-material cars derailing. Table B-4 presents the resulting distribution of the number of cars releasing and the amount released.

B.5 SUMMARY OF INPUTS AND OUTPUTS FOR THE DISTRIBUTION MODELS

The inputs to the models include:

π_H = fraction of all cars that carry hazardous material; or

N_H, N_T = number of hazardous-material cars and total cars in a train;

A set of q values for puncture probabilities (typically as a function of velocity);

A distribution for N_D (number of cars derailed), typically as a function of velocity.

Outputs Include:

A distribution of the number of hazardous-material cars releasing; and

A distribution of the amount of hazardous materials released.

TABLE B-4. PROBABILITY DISTRIBUTIONS ASSUMING $\pi_H = 0.5$

Distribution of Number of Cars Releasing		Distribution of Amount Released (gal.)	
X	$P(N_R = X)$	X	$P(A_R \leq X)$
0	.6450	1000	.730902
1	.2026	5000	.759942
2	.0806	9000	.792304
3	.0366	15000	.839248
4	.0179	19000	.861009
5	.0090	25000	.895453
6	.0045	35000	.949913
7	.0021	45000	.970529
8	.0010	55000	.982561
9	.0004	75000	.994365
10	.0002	95000	.998154
11	.0001	125000	.999642
12	.0000	175000	.999935
		225000	.999947
		275000	.999947

APPENDIX C

OVERVIEW OF HAZARD-ASSESSMENT MODELS

C.1 INTRODUCTION

This appendix provides an overview of the hazard-assessment models utilized in this investigation. To avoid lengthy discussions, each model is described simply in terms of its basic equations. Derivations, theory, major assumptions, and other detailed attributes can be found in the references cited.

It should be noted that the scope of this study did not call for the development of any new models. Nor did satisfaction of basic objectives always warrant utilization of those available models of the greatest complexity. Rather, it will be seen that the specific models selected for use are those which have either been traditionally utilized for a given purpose, or which provide answers of an accuracy comparable to that of other study elements.

Each model is designated by a letter, by which this appendix may be cross-referenced to Figure 12-3, which shows the need for, and use of, each model.

C.2 IGNITION PROBABILITY ESTIMATION MODEL (A)

The purpose of an ignition probability estimation model is to provide an indication of "when" a released volume of flammable or combustible material is likely to ignite (if ever). This knowledge is important because the time of ignition can have considerable influence upon the sequence of events that follow a release and, consequently, upon the impact of the release to the public.

When compressed gases are released, there are five major feasible scenarios to consider:

1. Immediate ignition of venting gases due to nearby ignition sources or those caused by the accident, flame jet forms;

2. No immediate ignition and vapor cloud travels downwind; later ignition causes flash fire through cloud;
3. Same as (2) above, but ignition leads to detonation;
4. Tank car BLEVE or otherwise explodes; and
5. No ignition; impact is due to gas/vapor inhalation toxicity.

Estimates of conditional probabilities of ignition for the first and fourth of these scenarios, as well as for scenarios involving non-volatile liquids and solids, are presented in Chapter 12 of this report. For all other scenarios, the probability of ignition to any time after release is given by [C1]:[*]

$$P(t) = 1 - e^{-\eta f \alpha \int_0^t A(t)\,dt}, \qquad \text{(C-1)}$$

where

η = density of ignition sources, number/km^2,
f = mean frequency of activation of ignition sources, activations/source/second,
α = fraction of cloud area in flammable condition, dimensionless,
$A(t)$ = land area covered by cloud at time t, km^2,
t = elapsed time from release, s, and
$P(t)$ = probability of cloud ignition by time t.

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[*] See references at the end of this Appendix.

C.3 FLAME JET MODEL (B)

Reference [C2] presents a review of investigations dealing with the predictions of flame sizes for turbulent gas jets. Based on its findings, it suggests use of the following equations to define the length of the flame:

$$\frac{L}{D} = \frac{K_f}{C} \sqrt{C + (1 - C) \frac{M_a}{M_f} \frac{T_f}{\alpha T_o}} \, , \qquad \text{(C-2)}$$

and

$$C = \frac{1}{\left[1 + r \frac{M_f}{M_a} \right]}$$

where

K_f = a factor (± 5.3) which depends on the Froude number,

r = stoichiometric air-fuel ratio = $\frac{\text{kg of air}}{\text{kg of fuel}}$,

M_f, M_a = molecular weights of gas and air, respectively,

α = $\frac{\text{moles of reactants}}{\text{moles of products}}$ for stoichiometric combustion,

T_f = adiabatic flame temperature, °K,

T_o = ambient temperature, °K

D = diameter of hole in tank, m, and

L = desired flame length, m.

The value for r is obtained by balancing the chemical reaction equation for complete combustion. For methane, the procedure is demonstrated by:

$$CH_4 + CO_2 + (2 \times 3.76)\, N_2 \rightarrow CO_2 + 2H_2O + (2 \times 3.76)\, N_2$$

$$r = \frac{(2 \times 32) + (2 \times 3.76 \times 28)}{16} \simeq 17.2 \, .$$

The denominator is the weight of methane which reacts with the total weight of air shown in the numerator. The procedure is rather self-evident if it is noted that air contains 3.76 moles of nitrogen for each mole of oxygen.

The value of α is a simple ratio of the number of moles of reactants to the moles of products. In the example, the ratio is:

$$\alpha = \frac{3}{3} = 1. \qquad \text{(Note: } N_2 \text{ not counted.)}$$

Since the flame forms a cone as it travels away from its source, subsequent radiation intensity estimates are facilitated by computation of the diameter of a cylindrical flame with equal volume to the cone. The suggested equation [Ref. C2] for use is:

$$\frac{D_e}{D} = \sec\frac{\theta}{2} + \frac{L}{D} \sin\frac{\theta}{2} \sec^2\frac{\theta}{2} , \tag{C-4}$$

where

D_e = the desired equivalent cylindrical flame diameter, m, and
θ = the angle at which the cone spreads out.

Typical values for θ are said to lie between 10 and 20 degrees. Since it is not possible to define any precise value, a selection of 10.7 degrees allows simplification of Equation (C-4) to:

$$D_e \approx D + \frac{L}{10.6} . \tag{C-5}$$

The heat flux received by a "target" or "observer" from a flame is given by (Ref. C2).

$$Q = F \alpha \tau \varepsilon \sigma T_f + S , \tag{C-6}$$

where

F = view factor between flame and target,

α = target absorptivity,

τ = atmospheric transmissivity,

ε = flame emissivity,

σ = Stefan-Boltzamann constant, $W/m^2\text{-}^oK^4$,

T_f = equivalent blackbody flame temperature, ^oK,

Q = heat flux received by target, W/m^2, and

S = solar insolation at target, W/m^2.

The view factor F can be estimated from an expression given on page 247 of Reference C4 for a configuration involving a right circular cylinder and a vertical plane with a normal passing through the center of one end of the cylinder and perpendicular to the axis of the cylinder. The expression is:

$$F = \frac{1}{\pi D} \tan^{-1}\left(\frac{L}{\sqrt{D^2 - 1}}\right) + \frac{L}{\pi}\left[\frac{A - 2D}{D\sqrt{AB}} \tan^{-1}\sqrt{\frac{A(D-1)}{B(D+1)}} - \frac{1}{D} \tan^{-1}\sqrt{\frac{D-1}{D+1}}\right] \qquad \text{(C-7)}$$

where

D = d/r,

d = distance from target to center of cylinder, m,

r = radius of cylinder, m,

L = ℓ/r,

ℓ = length of cylinder,

A = $(D + 1)^2 + L^2$,

B = $(D - 1)^2 + L^2$.

The emissivity of a flame is generally [C2] computed from:

$$\varepsilon = 1 - e^{-kd},$$

where $K(m^{-1})$ is an emission coefficient (also called the attenutation coefficient) and d is the characteristic thickness dimension of the flame in meters. For an alcohol, the emissivity can be as low as 0.067. For other substances, it may approach a value of 1.0. Because of a lack of readily available experimental data for most hazardous materials of interest, it is usually necessary to assume a value of 1.0 for the parameter, thus providing an element of conservatism to the analysis.

In application of the model, a problem was realized in that it was difficult to find appropriate flame temperature data for the hazardous materials of concern. Adiabatic flame temperatures in the literature were excessively high, yet generally available. Through comparison of results obtained when adiabatic and measured flame temperatures for propane are used in the model, it was, therefore, decided to utilize adiabatic flame temperatures, and to conservatively adjust results by setting E to a value of 0.06 for all hazardous materials. In other words, it was estimated that about 6% of the energy available would be radiated from the flame when adiabatic flame temperatures are assured.

The Stefan-Boltzamann constant has a value of 5.66×10^{-8} W/m^2 - °K. The absorptivity of various objects can vary with reflective properties and color, and thus can also be conservatively assigned a value of 1.0.

The radiation from the flame to surrounding objects will be partially attenuated by absorption and scattering along the intervening path by water vapor, carbon dioxide, dust, and aerosol particles. On a clear humid day, the major component of attenuation will be that due to water vapor.

The transmissivity of water vapor can be calculated, given the distance between the flame and the receiving object, the temperature of the flame, the receiver and the intervening atmosphere, and the relative humidity. Spectral data [C15] and the mean path length are then used to determine τ_ω, the transmissivity at wave number ω. The mean transmissivity is given by:

$$\tau_{avg} = \frac{\int_0^\infty \tau_\omega E_\omega \, d\omega}{\int_0^\infty E_\omega \, d\omega} ,$$

where E_ω is the emissive power of the source at the wave number ω. A specialized and complex solution to this equation was developed by Arthur D. Little some time ago. It was utilized in this study to provide estimates of τ as a function of distance from the flame and other variables.

C.4 INSTANTANEOUS-SOURCE VAPOR DISPERSION MODEL (C)

Concentrations at ground level for gases or vapors released instantaneously at ground level are given [C2] by the point-source equation:

$$C(x,y,t) = \frac{2m}{(2\pi)^{3/2}\,\sigma_x\sigma_y\sigma_z} \exp - \left[\frac{(x - ut)^2}{2\,\sigma_x^2} + \frac{y^2}{2\,\sigma_y^2} \right] \qquad \text{(C-8)}$$

where

m = mass of gas or vapor released, kg.

$\alpha_x, \alpha_y, \alpha_z$ = variance of the Gaussian concentration profiles in the respective directions, m,

x = distance from source in downwind centerline direction, m,

y = crosswind distance from centerline, m,

z = height in vertical direction, m,

u = wind velocity, m/s,

t = elapsed time from spill, s, and

C = concentration of vapor or gas in air, kg/m^3.

Graphs giving α_y and α_x as a function of downwind distance x and atmospheric stability class can be found in [C2], [C5], [C6], and other references. (The parameter α_x is commonly assumed to equal α_y.) References C5 and C6 additionally provide guidance on how to select the atmospheric stability class most pertinent to any given combination of wind and weather conditions.

Evaluation of the area downwind that will experience a concentration at or above a specified level C^* is facilitated by use of an equation giving the width of the moving cloud associated with C^*. The appropriate expression, derived by manipulation of Equation (C-8), is :

$$W = 2\,\sigma_y \sqrt{2\,\ell n \frac{C_{max}}{C^*}}\,, \qquad \text{(C-9)}$$

where W is the width of the cloud at ground level and C_{max} is the contaminant concentration at the downwind centerline x distance at which W is desired. Obviously, the selected level C^* must be less than or equal to C_{max} in order for the expression to be valid.

During the various computations, a limitation of this approach can be partially resolved by using a downwind x value in Equation (C-8) that is determined from Ref. C2:

$$x' = x + 5D, \quad \text{(x' replaces x in Eq. (C-8))} \qquad \text{(C-10)}$$

where D is the diameter of the source. This adjustment helps to resolve the inconsistency between the assumption of a point source and the possible actuality of a significant source size.

C.5 VAPOR FLASH FIRE MODEL (D)

In a number of studies, various researchers have attempted to deal with the problem of modeling the effects of a flash fire through a gaseous cloud or plume. Review of their results during the course of this effort led to the conclusion that there is no currently available model that is reasonable in all assumptions. Consequently, it was decided to apply an approach that is logical, somewhat conservative, and quite straightforward.

Given the ground area encompassed by a flammable cloud or plume, as determined from Models C or J described herein, one can make the valid observation that ignition of the gas or vapor at any point will cause a broad flame front to pass through all parts of the affected area. For a spill of significant magnitude, this front is likely to be measured in tens of meters of thickness. Obviously then, people caught in the cloud unprotected would have a very high probability of suffering lethal injuries and, for impact-assessment purposes, it can be assumed that this probability is essentially 1.0.

An observer or other "target" to the side of the cloud or plume will see a moving, probably rectangular flame front passing by at a speed dependent on the wind velocity and other factors. At the worst, the radiation intensity experienced by the observer would be given by Equation (C-6) with the view factor F given by:

$$F = \frac{1}{\pi}\left[\frac{X}{\sqrt{1+X^2}}\cdot\tan^{-1}\left(\frac{Y}{\sqrt{1+X^2}}\right) + \frac{Y}{\sqrt{1+Y^2}}\tan^{-1}\left(\frac{X}{\sqrt{1+Y^2}}\right)\right], \qquad \text{(C-11)}$$

where

X = A/C

Y = B/C

A = one-half the width of the flame front thickness, m,

B = flame front height, m,

C = distance between flame edge and vertical targets, m, and

F = view factor, dimensionless.

This expression for F is a slightly modified form of an equation given on pages 15-50 of Ref. C9 (for configuration #8). Based on observations of flame front thickness in a burning plume of methane, "A" can be safely assigned a value of 20 meters for a large cloud or plume. Although the value for "B" is virtually undeterminable, an estimate of 30 meters should prove conservative for most releases.

> Note: Application of the model described immediately above in test problems resulted in the conclusion that thermal radiation damage to resources outside the burning cloud or plume cannot be reasonably assessed at this time. In consequence, results of this model were not utilized in the finalized impact-assessment results. Rather, it was assumed that the basic conservatism of the analysis for flash fire damages within the burning cloud or plume fully accounts for these additional zones of impact.

C.6 DETONATION MODEL (E)

Certain gases and vapors dispersed in air may detonate when their concentrations are within flammable limits and sufficient power is supplied to initiate the detonation reaction. The traditional method of evaluating the resulting blast wave characteristics involves:

1) Comparison of the energy released by a unit weight of vapor upon detonation with that of a unit weight of TNT; and
2) Utilization of extensive data for TNT and scaling laws.

The TNT yield equivalent to the detonation of a mass of gas or vapor dispersed in air is given by:

$$w = \frac{M \times \Delta}{2090 \text{ Btu/lb TNT}} , \qquad \text{(C-12)}$$

where

M = the mass of gas or vapor liberated, lb.,

ΔH = hazardous-material heat of combustion at constant pressure, Btu/lb.,

f = fraction of hazardous material available for detonation, and

w = the equivalent TNT yield, lb.

Curve-fitting of the overpressure data given in Ref. C7 and C8 and application of traditional scaling laws allows derivation of simple, approximate relationships for the peak overpressure, namely:

$$\begin{aligned} P_p &= 1500 \left(\frac{w^{1/3}}{r}\right)^{2.2} && \text{for } r/w^{1/3} < 14 , \\ &= 180 \left(\frac{w^{1/3}}{r}\right)^{1.4} && \text{for } r/w^{1/3} > 14 , \end{aligned} \qquad \text{(C-13)}$$

where

r = radial distance from detonation site, ft,

w = TNT equivalent, lb., and

P_p = peak overpressure at r, psi.

Similarly, it is possible to utilize tabulated data (Ref. C8) to derive an expression for the impulse over a particular range of interest. An equation so derived is:

$$I = \frac{0.063\ w^{0.7}}{r^{1.1}} \quad \left(\text{for } 5 < \frac{r}{w^{1/3}} < 30\right), \qquad \text{(C-14)}$$

where I is the impulse in units of psi-sec.

The model is also applicable to solids and liquids that have the potential to detonate under certain conditions. Indeed, it is more applicable to such condensed-phase substances than for dispersed gases and vapors.

C.7 TANK CAR EXPLOSION MODEL (F)

Under proper conditions, a tank car can undergo a boiling liquid expanding vapor explosion (BLEVE). The event is not an explosion in the sense that a severe blast wave is generated, but rather alludes to the formation of a massive fireball above the tank car.

Reference C10 presents a model of fireball formation and combustion that requires knowledge of two generally unknown parameters for hazardous materials; viz., "constant equivalence ratio" and a "constant entrainment coefficient." In addition, it presents experimental data from tests with methane, ethane, and propane, and favorably compares results with those predicted by the model.

Since propane is the hazardous material most notorious for BLEVE's, and since Ref. C10 provides empirical formulas for assessing propane fireball characteristics, hazard assessment can be facilitated by using these formulas across-the-board for all hazardous materials having the potential to BLEVE. This is a generally conservative and reasonable application, given the severity of the typical incident involving propane.

The maximum diameter (D), rise height (Z), and burnout time (t) for propane fireballs are functions of the initial volume (V) of fuel available. Expressions presented by the cited reference are:

$$D = 7.708\ (v)^{1/3}\ , \tag{C-15}$$

$$Z = 12.73\ (v)^{1/3}\ , \tag{C-16}$$

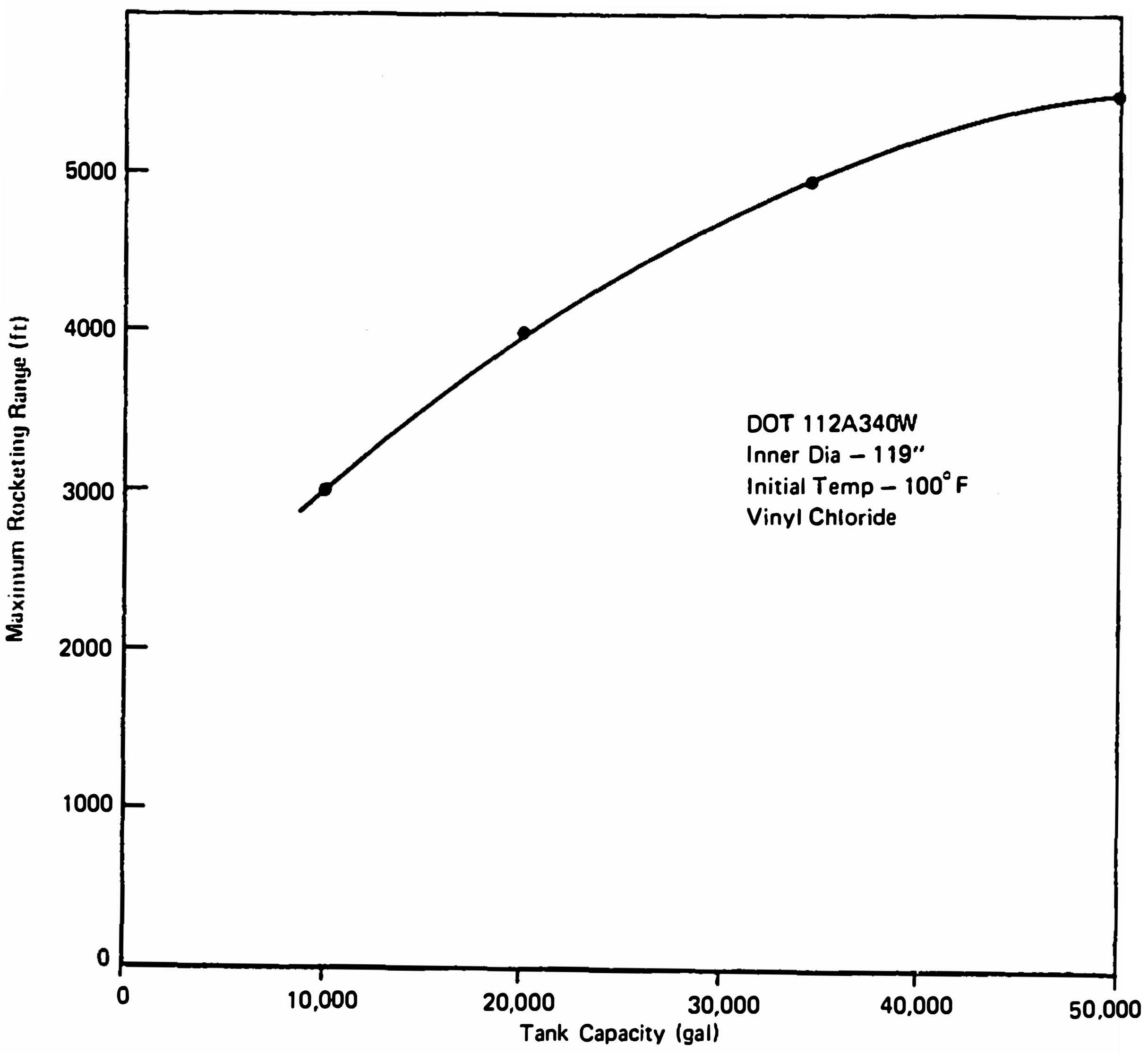
$$t = 0.28\ (v)^{1/3}\ , \tag{C-17}$$

where D and Z are in units of centimeters, v in cubic centimeters, and t in seconds.

Assuming an optically thick flame, one can estimate the maximum radiation intensity received by a target at distance r from the fireball from Equation (C-6), using the following expression to estimate a value for the view factor F:

$$F = \frac{(D/2)^2}{r^2}\ . \tag{C-18}$$

Another phenomenon that may accompany a tank car explosion is "rocketing," in which the tank tears circumferentially, forming two "tubs," one of which may then rocket through the air due to the rapid combustion of its contents. Detailed studies of the impact of rocketing are not available. However, Arthur D. Little, Inc., has prepared estimates of the maximum rocketing range, based on a study by Battelle Columbus Laboratories (Ref. C16). The results are shown in Figure C-1. These estimates are conservative, since the observed rocketing distances have not exceeded about 60% of the values shown. The actual rocketing range will be a random variable, dependent on such factors as the properties of the hazardous material, the length of the tub, the angle at which the tub takes off, and the diameter of the tank. Adequately detailed estimates of these factors are not available. We have therefore assumed a "typical" rocketing range of 300 meters. It is assumed that under the flight path of the tub, for a width of 10 meters, people will



Source: Arthur D. Little, Inc., estimates.

FIGURE C–1. TUB ROCKETING DISTANCE

be injured and property damaged, due to the spillage of burning material. The lethal zone is taken to be the actual area of impacts of the tub. This is estimated to be the length of a tank times its width, or 20m x 3m or approximately $60m^2$.

C.8 LIQUID FLASH MODEL (G)

When a compressed liquefied gas is released to the atmosphere under pressure, a certain fraction of the liquid will immediately vaporize. The remaining material, because of the cooling effect produced, will remain as liquid until such time as it strikes a warmer surface (the ground), where again an additional fraction will immediately vaporize. Any liquid which remains on the ground will then form a pool which will evaporate fairly rapidly. If the entire cargo is lost rapidly, a large distinct vapor cloud will travel downwind, followed by a considerably smaller plume of vapor evolving from the evaporating pool.

The weight fraction of any specific liquid which vaporizes upon exit from a tank can be estimated from a simple energy balance, yielding the expression:

$$f = 1 - \exp\left[\frac{C_v}{\lambda}\,(T_b - T_i)\right], \qquad \text{(C-19)}$$

where

C_v = liquid heat capacity of the hazardous material, J/kg°K,
λ = heat of vaporization, J/kg,
T_b = normal boiling point, °K,
T_i = initial temperature of the stored liquid, °K, and
f = the fraction of liquid that flashes.

To "f" must be added the fraction which rapidly boils off as the cold liquid strikes the usually warmer ground, and an additional fraction associated with entrainment of liquid aerosols. Since an analytical approach is unavailable for estimation of these latter fractions, but it has been estimated that each subsequent vaporization process increases "f" by a factor ranging from 1.0 to 2.0, the total fraction of liquid which flashes can be reasonably well determined by multiplying the computed value for "f" in Equation (C-19) by 1.5.

C.9 POOL SIZE MODEL (H)

It is virtually an impossible task to accurately estimate the ground area that will be covered when a given amount of a liquid is released from a storage vessel and a particular location is not specified. Numerous factors such as soil porosity, slope of the ground, vegetation, presence of depressions, and viscosity of the fluid can all significantly affect the outcome. Yet some estimate of the exposed surface area is necessary for vapor dispersion as well as liquid pool burning model applications.

In the vapor dispersion model, a pool diameter is used in Equation (C-10) where it allows adjustment of downwind centerline x distances to account for limitations of the point-source assumption Inspection of the impact of the diameter upon final results indicates that larger pool diameters lead to slightly smaller hazard zone areas. Thus, it is conservative to underestimate the pool size.

In the pool burning model, increasing pool diameters provide increasing flame heights and, consequently, increases in the thermal radiation flux received at any chosen location. Simultaneously, however, large pool sizes reduce the overall time to burnout, and lead to reductions in the total time-integrated radiation exposure at any location. These counteracting effects serve to reduce the influence of pool size upon final results.

Given the substantial uncertainties associated with any rigorous analytical estimation approach for the pool size, it is considered reasonable for the purposes of this study to simply assume that any amount of spilled liquid will spread to a mean pool depth of approximately 3 cm. The diameter of the pool can then be estimated from:

$$D = 2 \frac{\sqrt{33.3\ v}}{\pi} , \tag{C-20}$$

where

v = the volume of liquid released, m^3, and

D = the pool diameter, m.

The pool diameters predicted by this equation are intuitively seen to be of the correct order of magnitude. Spills of 30,000 gallons result in pools of 228 feet in diameter; those of 50 gallons in pools of 9.3 feet in diameter.

C.10 POOL EVAPORATION RATE MODEL (I)

The rate of vaporization of a liquid pool is a complex function of chemical and physical properties (both liquid and substrate), heat-transfer effects, and mass-transfer phenomena. Nevertheless, it is possible to obtain conservative estimates of vaporization rates in a fairly straightforward fashion by assuming the liquid temperature to be a constant. In the case of low-boiling-point substances that have been cooled while flashing, the appropriate temperature for use would be the normal boiling point. For all other cases, the ambient temperature would be most representative.

The basic equation for the model is Ref. C11:

$$\dot{m} \text{ (vaporization rate, kg/m}^2 \text{ - s)} = k_m C, \qquad \text{(C-21)}$$

where

C = the vapor density of the liquid at the appropriate temperature, kg/m^3, and

k_m = a coefficient described below, m/s.

To obtain a value of k_m, either of two routes are available: employment of turbulent boundary layer theory for flow across a flat plate (Ref. C12), or use of an empirical formula given in Ref. C11. Both approaches give similar results which can be averaged for general application. The pertinent relationships are:

$$k_m = 4.05 \times 10^{-3}\ U^{0.8}\ L^{-0.2}\ Sc^{-0.67} , \tag{C-22}$$

(turbulent boundary-lower theory)

$$k_m = 9.5 \times 10^{-3}\ U^{0.78}\ L^{-0.11}\ Sc^{-0.67} , \tag{C-23}$$

(Ref. C11),

where

U = wind velocity, m/s

L = lateral pool dimension, m, and

Sc = the Schmidt number of the hazardous material, dimensionless.

The Schmidt number is the ratio of the kinematic viscosity of the hazardous material to its diffusivity in air. The former is itself the ratio of the viscosity of the fluid to its density. The diffusivity in air of the substance can be obtained from tabulated values in the literature or estimated using various analytical techniques.

C.11 CONTINUOUS SOURCE VAPOR DISPERSION MODEL (J)

Concentrations at ground level for gases or vapors released continuously at ground level are given by Ref. C2 the point source equation.

$$\begin{aligned} C(x,y) &= \frac{2\ m_e}{2\pi\ U\ \sigma_y\ \sigma_z} \exp\left[\frac{y^2}{2\ \sigma_y^2}\right] \text{ for } x \leq Ut, \\ &= \text{ for } x > Ut , \end{aligned} \tag{C-24}$$

where most parameters are as defined for the instantaneous source vapor dispersion model (C). The exception, m_e, is the rate at which gas or vapor evolves from the source in units of kg/s. The width of the vapor plume is again given by Equation (C-9).

C.12 POOL BURNING MODEL (K)

A correlation for the height of the flame from a burning liquid pool fire is given by Thomas [Ref. C13] and found to be appropriate for general use in Ref. C2. The expression is:

$$\frac{L}{D} = 42 \left[\frac{m_f}{\rho_a \sqrt{gD}} \right]^{0.61} , \qquad \text{(C-25)}$$

where

m_f = the fuel burning rate, kg/m^2s,
ρ_a = density of air, kg/m^3
g = acceleration due to gravity, m/s^2,
D = diameter of pool, m, and
L = flame height, m.

The parameter m_f is found from the expression:

$$m_f = \frac{y_r}{\rho_\ell} , \qquad \text{(C-26)}$$

where

y_r = the regression rate of the fuel while burning, m/s, and
ρ_ℓ = the density of the liquid at its boiling point, kg/m^3.

Welker and Sliepcevich (Ref.C14) provide a correlation for estimating the flame tilt angle from the vertical when the flame is subjected to wind forces. As reported in Ref. C2, the expression is:

$$\frac{\tan \theta}{\cos \theta} = 3.3 \left(\frac{DU}{V_a}\right)^{0.07} \left(\frac{U^2}{gD}\right)^{0.8} \left(\frac{\rho_g}{\rho_a}\right)^{-0.6} , \qquad \text{(C-27)}$$

where

D = pool diameter, m,

u = wind velocity, m/s,

V_a = kinematic viscosity of air, m^2/s

g = acceleration due to gravity, m/s^2,

ρ_g = fuel vapor density at its boiling point,

ρ_a = air density, kg/m^3, and

θ = flame tilt angle from vertical radius.

The angle can be explicitly derived by allowing TC to equal the left side of Equation (C-27) and using the relation:

$$\theta = \sin^{-1} \left(\frac{-1 + \sqrt{1 + 4\ TC^2}}{2\ TC} \right), \qquad \text{(C-28)}$$

Given the diameter of the burning pool from Model 4, and the flame height and tilt from this model, Equations (C-6) and (C-7) are applied to estimate distances from the flame associated with selected damage criteria. The procedure is analogous to the one utilized for Model B, with the added stipulation that it is necessary to crudely estimate the duration of burning (so that total exposures can be estimated as well as incident heat flux to a target). A useful equation for this latter task is:

$$t_b = \frac{vol}{y_r\ A}, \qquad \text{(C-29)}$$

where

vol = volume of liquid spilled, m^3,

y = liquid regression rate while burning, m/s,

A = area of burning pool, m^2, and

t_b = duration of fire, s.

C.13 FIRE MODEL--FLAMMABLE SOLIDS/SPECIAL HAZARDS (L)

A variety of flammable solids can react with water to generate flammable/explosive gases such as acetylene and hydrogen. Yet others may spontaneously ignite in air and/or burn with an intensity well beyond that associated with any ordinary combustible material.

Because of the nature of these substances, the relative rarity of their release (only 86 spills recorded between 1971 through 1977), and their limited potential to cause widespread injury or property destruction, little work has been done to date in developing models for hazard assessment. In consequence, it is necessary to employ some rather crude approaches for quantifying expecting hazards.

Equation (C-6) is generally appropriate for estimating the thermal radiation intensity profile from a fire involving these materials, if the view Factor F can be estimated for an appropriate configuration of source and target. Since tall flames would be the exception rather than the rule, it is assumed that the source will resemble a vertical, rectangular "wall" when viewed from a distance. Hence, it is possible to utilize the view factor expression given by Equation (C-11). Lacking any specific historical data upon which to base estimates, the parameter "A" is assumed to be one-half the length of a typical railroad car (A ~12m), while "B" is taken to be three times the width (~2.5m) of a typical car. Thus, the overall scenario calls for the overturning of a car onto its side, spillage of flammable solid, and subsequent ignition.

C.14 FIRE MODEL--ORDINARY COMBUSTIBLES (M)

Ordinary combustible materials in solid form are unlikely to cause any significant or unusual impact upon ignition. Fires will tend to be smoky and severely limited in radiative aspects. In addition, their size will generally be limited in most envisionable scenarios. Thus, it is not considered to be a worthwhile effort to assess the rather minimal impact of such ordinary and common events.

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APPENDIX D

APPLICATION OF HAZARD-ASSESSMENT MODELS

D.1 INTRODUCTION

Appendix C describes the basic elements of the various hazard-assessment models. Appendix D discusses how these models were applied to generate desired results within the scope and resources of this study. Its contents are, therefore, essential to an understanding of the bases for the results, as well as their limitations.

D.2 SPILL QUANTITIES UTILIZED

The overall analysis presented in this report utilizes specific ranges of spill quantities to collate and analyze the accident record data base. The first seven of these ranges and the specific amounts generally utilized for impact assessment computations are listed below:

Range*	Amount Assumed*
1 - 100	50
101 - 1,000	550
1,001 - 5,000	3,000
5,001 - 10,000	7,500
10,001 - 25,000	17,500
25,000 - 50,000	37,500
50,001 - 100,000	75,000

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*All amounts in gallons.

As is evident, the midpoints of the ranges were used for both average and worst-case impact assessments. Thus, the first limitation of the analysis stems from a realization that the true means of the ranges, as would be determined from a rigorous and thorough analysis of spill records, may differ from the approximate arithmetic averages shown above. Additionally, it is to be noted that the basic conservatism of worst-case results was somewhat tempered by use of the midpoints instead of upper bounds of ranges.

D.3 ENVIRONMENTAL CONDITIONS SPECIFIED

For all assessments involving vapor-dispersion hazards, it was necessary to specify the atmospheric stability class and the wind velocity. To facilitate matters, the neutral stability class D was chosen as representative of average conditions, along with a wind velocity of 4 m/s (about 9 mph). Both classes C and D were reasonable choices, but D provided a greater degree of conservatism. For worst case conditions (an inversion with slow, steady winds), the obvious choices were stable class F and a wind velocity of 1 m/s (about 2.2 mph).

A number of models required the ambient air temperature. This was fixed at 20°C for all cases, again to facilitate the analysis. Although temperature effects are likely to be significant in the liquid flash and pool evaporation rate models, it was noted that:

- Uncertainties in the flash model (in regards to aerosol formation and boiling in contact with the ground) are likely to overshadow the significance of the air temperature; and
- The evaporation rate model is inherently conservative due to its constant temperature assumption and the large pool size estimates resulting from the pool size estimation model.

Remaining environmental specifications included a relative humidity of 50% for estimating atmospheric transmissivity, and a wind velocity of zero for pool fire assessments. The first choice was considered reasonable for universal application; the second has essentially no effect, on the average, upon the accuracy of resultant impact estimates.

D.4 VAPOR DISPERSION IMPACTS

A computer program was developed for all impact assessments involving the dispersion of gases and vapors. Using the basic equations for instantaneous and continuous-source dispersion models, the program iterated to find the maximum downwind extent and maximum width of the cloud or plume associated with each specified scenario and airborne concentration. These dimensions were then used to develop estimates of impacted area magnitudes (assuming the footprints resembled ellipses or triangles, as appropriate).

For spills of liquids, the program first applied the liquid flash, pool size, and pool evaporation rate models to estimate the size and strength of the source. In such cases, assessments entailed individual consideration of the fraction of liquid that flashed (assuming an instantaneous release) and the fraction that evolved more slowly from the resulting pool (assuming a continuous release). Impact assessment results presented were those associated with the largest impacted areas.

When the gases or vapors were flammable, it was necessary to incorporate the ignition probability model into the iterative process. This required two preliminary decisions: one dealing with the magnitudes of the ignition source densities to be assumed, and the other with the average probability at which a cloud or plume will ignite.

Estimates for ignition source densities evolved from a rather crude evaluation of ignition sources in urban, suburban, and rural settings. For the product "nf" in the pertinent equation, results were:

Setting	Range*	Geometric Mean*
Urban	80 - 800	∿ 250
Suburban	30 - 300	∿ 100
Rural	3 - 30	∿ 10

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* All units are activations/km^2-s

The means shown above were used for all impact-assessment purposes. The estimates have substantial uncertainties, but must be considered reasonable for use at this time, given the absence of a better approach.

The program followed the growth of a cloud or a plume incrementally, and calculated the probability of ignition as a function of time. Areas affected by an ignition were then estimated by assuming ignition at probabilities between 0.45 and 0.55.

A problem presented itself when the gases or vapors were simultaneously flammable and highly toxic, since ignition would preclude further dispersion of toxic contaminants (assuming no similar effect from combustion products). In such cases, impact results for toxic clouds or plumes were manually adjusted to account for ignition probabilities. This required calculation of the ratio of the downwind distance at which ignition was expected (with $P = 0.45$ to 0.55) and the maximum downwind extent of hazard with no ignition, and then multiplication of this fraction by the maximum impact area associated with a given toxic concentration (again assuming no ignition).

Finally, it must be noted that a specialized subroutine Arthur D. Little developed a number of years ago was utilized for estimation of the dispersion parameters σ_y and σ_z as a function of downwind distance. Developed with least squares regression techniques, the routine incorporates the graphically presented data in the references of Appendix C.

D.5 FIRE IMPACTS

Pool fire scenarios were addressed using a combination of the pool fire and pool size models, the latter assuming that all hazardous-materials released form a pool (i.e., liquid is not allowed to flash). Given specified damage criteria, a computer program searched the radiation flux profile[*] from the flame to find the associated separation distances and, ultimately, the magnitudes of the impacted areas. Where exposure times were necessary, it was assumed that people would find shelter or run a sufficient distance from the fire within 30 seconds. Buildings, however, were allowed continuous exposure for the duration of the fire or a maximum of 1 hour (assuming the presence of firefighting activities at or before this limit).

The procedures applied for flame jets[**] and burning flammable solids were essentially identical. In the case of vapor-cloud flash fires, results from the vapor-dispersion analysis were used to define the area that would be engulfed in flames at the time and location of ignition. These areas were taken to represent those of potential lethality and building ignition. Because of insurmountable difficulties, the radiation flux profile from the moving flame front to an observer outside the cloud or plume could not be fully evaluated, however. Thus, it was assumed that injuries would not occur because of the necessarily brief radiation exposures associated with such events.

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[*] Solar isolation assumed to be 150 Btu/hr-ft^2.

[**] Hole size assumed to be 12 inches.

The fireball impact-assessment procedure (for BLEVE effects) had three significant features:

- The fireball was fixed at its maximum diameter at one-half its maximum height.
- No limits were placed on human or property exposure times, since they could be estimated and tended to be brief.
- Average impacts were evaluated by assuming that only half the cargo participates in fireball formation, whereas worst-case impacts assumed involvement by the entire cargo.

D.6 EXPLOSION IMPACTS

The equations presented for the vapor cloud detonation model (Appendix C) were rearranged to provide explicitly the radial distances associated with specified damage criteria. The fraction of hazardous materials available for detonation was conservatively assumed to be 7.5% for the average event and 15% for the worst-case event. Explosions involving other scenarios were addressed, assuming the entire amount spilled was detonable.

D.7 OTHER LIMITATIONS

The <u>major</u> limitations of the impact-assessment methodology should be listed for consideration as future developmental efforts. They are:

1. Vapor dispersion models assume neutrally buoyant vapors or gases; they may be non-conservative for many hazardous materials; excessively conservative for others.
2. Vapor-dispersion models assume flat open land. Buildings, trees, and other obstructions tend to enhance mixing, but lessen hazard extents.
3. Impact assessments for toxic vapor or gas releases do not rigorously consider the time/concentration effects upon humans. Damage criteria require refinement through comprehensive search and analysis of toxicological literature.

4. The pool size estimation model is rather arbitrary in nature. Pool size affects impact, but a realistic spreading model is unavailable.

5. Tank car rocketing is a potentially devastating event not addressable with current knowledge.

6. Potentially toxic products of combustion were not addressed because of the considerable effort required to do so.

7. The lists of representative hazardous materials for each category were derived from data for all hazardous-material spills. An analysis of railroad accidents alone may alter results.

8. The entire concept of using representative hazardous materials in the risk-assessment procedure has an adverse effect on the validity of the analysis. Consideration should be given to chemical-specific impact assessment through automated means.

9. A more rigorous treatment of pool evaporation phenomena may be warranted.

10. The view factor estimation technique for pool fires can be improved with additional effort.

11. The entire subject area of ignition-source densities and ignition probabilities has never been treated well. Developmental work in this area might be worthwhile.

12. Impact due to vapor flash fires warrants further investigation.

13. The emissive power of flames from different hazardous materials can be quantified better; some experimental work and/or an additional literature search might lead to a better understanding of impacts from open flames.

14. Ignition criteria for wood was based upon long-term exposure data. A need exists to better review short-term, high radiation-intensity effects.

15. The analysis essentially assumed that compressed liquefied gases were shipped at ambient temperatures. Improvements are possible for those shipped in insulated or refrigerated cars at lower temperatures.

16. The hazards and impacts of hazardous solids, oxidizers, organic peroxides, and the like, have never been studied well. Most, if not all, work has been directed toward gases and liquids with common actions upon release.

17. The analysis did not consider explosives or radioactive materials.

18. Results of BLEVE model application were not always realistic. A more rigorous analysis involving the time-growth-rise history of the fireball is necessary.

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Kendall Square
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